**Geomorphic and sedimentologic imprints
of typhoons Durian and Haiyan storm surges
on the Philippine coasts**

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Summary

Typhoon Haiyan tragically attests to the vulnerability of Philippine coasts to storm surge hazard. It has also highlighted the limited and patchy knowledge that exists on the impacts to immediately affected communities despite the high frequency of storm surges in the archipelago. Moving forward, this dissertation contributes to increasing the level of local and regional science-based knowledge by laying down groundwork on the geologic investigations of storm surge impacts in the Philippines.

Two recent storm events namely the 2006 Typhoon Durian (*Reming*) and the 2013 Typhoon Haiyan (*Yolanda*) provided an opportunity to study the geomorphic and sedimentologic imprints of storm surges and the resulting coastal overwash. This dissertation though primarily built upon a geological framework of storm surge has benefited considerably from the integration of multiple disciplines including meteorology, oceanography, coastal engineering, and history. Overall, the multi-disciplinary approach led to (1) local understanding of storm surge dynamics and the factors affecting the spatial variation of amplification leading to inundation overland; (2) characterization of the onshore geomorphic and sediment imprints within the bounds of hydrodynamic conditions and sediment transport processes; and (3) historically-oriented investigation of storm surge heights and the geologic impacts to the coasts near typhoon landfalls in the Philippines.

Chapter 1

Introduction

Landfalling tropical storms or typhoons carry strong winds, heavy rainfall and storm surges causing multiple hazards overland including riverine flooding, landslides, and coastal flooding (Lin et al., 2010). These hazards commonly result in damage to property and loss of life. Amongst these hazards, storm-surge induced flooding is the most deadly. An aggregate re-insurance-based natural hazards database indicates that of the storm-related hazards between 1950 and 2010, storm surges account for 73 percent of all fatalities with death tolls exceeding 100,000 in countries like Bangladesh and Myanmar (Wirtz et al., 2014).

1.1. What is a storm surge?

A storm surge is best considered as a low-angle dome of water (**Fig. 1.1**) rising above the normal astronomical tide that is pushed towards the shore by onshore winds and low pressure associated with a cyclone system (e.g. Needham and Keim, 2011). The low atmospheric pressure of cyclonic systems was previously regarded as the main driver of increased sea-level heights during typhoons (Algue, 1898). Low atmospheric pressure means there is less atmosphere pressing down from above, in effect, the sea rises, and as such, it is commonly called the inverse barometric effect. Later, Welander (1961) argued that low pressure accounts for only a relatively small component of the storm surge. He estimated that for every millibar (mb) of air pressure reduction, there is a corresponding increase in sea level by one cm. That is, for a 1 m storm surge, there has to be a drop in pressure by 100 mb. At present, the consensus is that wind stress

Figure 1.1. Diagram showing a tropical cyclone near landfall and the relative contribution of the wind and pressure components to a storm surge (from NOAA).

Figure 1.2. Increasing level of marine inundation resulting in increasing damage to the coastal landforms and infrastructures (from Nott and Hubbert, 2005). The combined storm tide, wave setup, and wave runup causes dune erosion, and/or overtopping that consequently exposes the adjoining community inland to the destructive power of the surge and sometimes to the direct impacts of breaking waves.

dominates over low pressure in generating storm surges (Nott, 2006). Persistent onshore winds blow over the water surface and as soon as the onshore moving water comes in contact with the ocean floor, or the bathymetry is sufficiently shallow it starts to pile water up against the coast. As the storm approaches land, Nott (2006) noted a number of factors that can influence surge height including the intensity of the storm, the translational speed of the storm, radius of maximum winds, the angle of approach of the storm to the coast, offshore bathymetry, and the shape of the coastline. In most cases, it is not the dominance of one but a combination of these atmospheric, oceanographic, and geomorphological factors that will amplify or reduce the sea-level heights, and thus, determine whether the surge will or will not cause coastal flooding (Morton et al., 2000; Otvos, 2011).

Storm surge, however, cannot account for all the elevated water during coastal flooding. The total flood height is the aggregate of different components including surge, tide, and waves (Nott, 2006; **Fig. 1.2**). The dynamic coupling of storm surge and astronomical tide is referred to as the storm tide. Riding ontop of the storm tide, short-period breaking waves contribute to higher water levels through wave set up and wave runup. Wave set up is the additional elevation of water level from waves continuously breaking and piling up onshore. Wave runup is the highest elevation and most inland distance reached by the water from the breaking waves rushing up on the sloping beach profile (FEMA, 2005).

The combined destructive power of these breaking waves and the surge commonly cause damage to coastal communities during tropical cyclones (e.g. Nott and Hubbert,

2005; FEMA, 2011). Storm surges can be deemed to be a natural hazard as the United Nation International Strategy for Disaster Reduction (UNISDR) defines a natural hazard as, “a potentially damaging physical event originating from geological, hydrometeorological and biological processes that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation.”

Notable recent storm surge events such as the 2005 Hurricane Katrina, 2008 Cyclone Nargis, 2012 Hurricane Sandy, and 2013 Typhoon Haiyan effectively illustrate the high cost of damage to properties and human lives sustained from storm surges (Woodruff et al., 2013; Wirtz et al., 2014; Soria et al., 2016). But just as storm surges can be undeniably destructive, such natural phenomena are also an important agent of coastal change by the action of remobilizing and depositing sediments through overwash processes (e.g. Donnelly et al., 2004; Nott and Hubbert, 2005; Wang and Horwitz, 2007).

1.2. What is overwash?

The term overwash is classically defined by Shephard and Wanless (1971) as “the transfer of beach sand across lagoonal side of the barrier through sluiceways during a hurricane or other violent storm”. Leatherman (1981) expanded this definition from the transfer of beach sand to include any swash surge that overtops the highest points along a barrier, usually coinciding with the frontal dune line or the storm berm. These two definitions vary in the mechanism of overwash, one requires channelization (Shephard and Wanless, 1971) while the other requires overtopping (Leatherman, 1981). Building upon these principles, overwash was subsequently classified into two categories- runup overwash and inundation overwash (Sallenger, 2000). These categories are mainly established based on the relative heights between the high-water

Figure 1.3. Overwash process on a barrier-island or beach system (from Williams, 2015).

- Relative heights of the storm-elevated water level from combined surge, tide, wave set-up, and wave runup (R) against the dune profile (D).
- Runup overwash occurs when water level is just sufficient to overtop the dune creast causing dune erosion but limited inland penetration of flooding and washover deposition.
- Inundation overwash occurs water level is exceedingly higher than the dune crest causing significant dune erosion, complete submergence of the beach system, and greater inland penetration of flooding and washover deposition.

level from combined tide, surge, wave setup and wave runup against the dune or beach crest (**Fig. 1.3**). Essentially, runup overwash occurs when the high-water level is just sufficient to overtop the dune creast. Dune erosion occurs but to a limited extent. On the other hand, inundation overwash occurs when the high-water level is exceedingly higher than the dune crest thereby the entire dune or beach system is completely submerged. This is accompanied by significant dune erosion and flooding that penetrates farther inland. A similar but rather more quantified approach of the overwash process can be found in Donnelly and Sallenger (2007) and Donnelly and others (2006).

1.3. Geomorphic imprints of storm overwash

The geomorphic impact of storm overwash varies significantly depending on the local topography, coastal landforms and overwash magnitudes (**Fig. 1.4**). If an overwash event has sufficient excess runup, the elevated water level and the superimposed storm waves attack, overtop, and erode the dune crest to construct depositional landforms inland called washover fans (e.g. Pierce, 1970). Although initially documented on barrier islands, washover fans can be practically seen in any low-lying, sandy beach system affected by storm surge (e.g. Schwartz, 1982; Sedgwick and Davis, 2003; Switzer and Jones 2008). The kinetic energy and the potential energy of these waves, by virtue of the onshore directed flow and by the height above still water cause the water with entrained sediments to flow inland towards the back barrier low-lying environments (Pierce, 1970). On land, the combined effects of friction, infiltration, and lateral spreading cause the flow velocity to decelerate towards the landward side of the barrier or spit, commencing the deposition of the entrained sediments (Donnelly and Sallenger, 2007). In plan view, the washover fans have a narrow throat as the apex, in

Figure 1.4. Plan view of landform elements in a dune system that sustained overwash (from Donnelly et al., 2004). Shown are the typical morphologies of overwash deposits including (a) washover fan, (b) washover terrace, and (c) sheetwash.

Figure 1.5. Cross-shore profile of a generalized washover fan stratigraphy showing (A) foreset laminae at the terminus of the fan during subaqueous deposition and (B) planar-laminae during supratidal deposition (from Sedgwick and Davis, 2003).

most cases, and laterally spread landwards behind the dune or beach ridge to either lobate, parabolic, or flame-shaped margin (Leatherman, 1981; Otvos, 2011). Donnelly and others (2004) hypothesized that overwash can be funneled through existing gaps or lower areas along the foredune serving as the throat. Supporting evidence was shown such as the washover fans from Hurricane Isabel that were found coinciding with the pre-existing gaps in the foredune (Donnelly and Sallenger, 2007). Depending on the extent and continuity of these foredune gaps, along with the elevation of water surface level relative to the dune or beach ridge height (Sallenger, 2000), overtopping can result in washover fans that are isolated, regularly spaced, or merged to form terrace morphology (Morton and Sallenger, 2003). Sheetwash or sheet overwash is another morphological feature which is formed during complete inundation when there is a continuous flow of water over the entire dune crest causing vertical erosion of the dune. In extreme cases, persistent wave attack during inundation can completely remove dune ridges such as the impact caused by 1999 TC Vance in Western Australia (Nott and Hubbert, 2005). The eroded beach or dune sands are transported and deposited inland, spreading laterally on the backshore environments as a splay or sheet.

1.4. Sedimentologic imprints of storm overwash

The overwash sediments, sometimes also referred to as washover deposits, are commonly reported as anomalous sand layers found in the sedimentary environments of low-energy coastal settings, including coastal lakes, swamps and back-barrier tidal marshes (e.g. Leatherman, 1977; Liu and Fearn, 1993; Donnelly et al., 2004; Buynevich et al., 2004). Sand units deposited from recent intense storms are usually coarse grained and form a sharp erosional contact with the pre-existing fine-grained

sediments on the adjacent marsh or coastal woodland environments (e.g. Horton et al., 2009; Williams, 2009; Hawkes and Horton, 2012). Within sand sequences of beach ridges, however, sediments from storm events do not necessarily have to be anomalous sands but can be coarser grained, coarse skewed units with sharp erosional contact with the underlying sandy pre-storm soil surfaces (Nott et al., 2013).

Washover deposits commonly exhibit different internal stratification (**Fig. 1.5**). For example, planar horizontal to subhorizontal laminae are commonly described in modern washover deposits (e.g. Leatherman and Williams, 1977; Switzer and Jones, 2008; Williams, 2009). Foreset stratification is not universal, but whenever present it is most often found at the terminus of the washover fan and associated with subaqueous deposition in a tidal channel, pond, or lagoon (Sedgwick and Davis, 2003). The variations of flow energy during the overwash process are hypothesized to result in vertical textural trends within the washover deposits such as fining upwards or coarsening upwards (Horton et al., 2009; Nott et al., 2013). The integrity of these sedimentary structures, however, may be compromised by bioturbation or post-depositional erosion (Sedgwick and Davis, 2003; Otvos, 2011).

In the literature, the terms *overwash* and *washover* have been used interchangeably when referring to sediments, which can be confusing. Following the original definitions, these terms although closely related actually refer to two different things (Leathermann, 1981). *Overwash* refers to the process, whereas *washover* refers to the landform, which is usually fan-like, created by overwash. In this sense, the term *washover deposit* from hereon in the text will be confined to the sediments within the

washover fans or terraces, otherwise, the sediments will be referred to generally as *overwash deposit*.

1.5. Carbonate coastlines

Thus far, the majority of the previously described geomorphic and sedimentologic imprints pertain to clastic coastlines but may not necessarily be true for carbonate coastlines. Coral reefs are considered the frontline of defence against wave attack on most tropical carbonate coastlines. In most cases, coral reefs reduce wave height and significantly dissipate wave energy that would otherwise impact shorelines (Ferrario et al., 2014). But like any defence structures, reefs may also fail during extreme high-energy events (Roeber and Bricker, 2015). Regardless of the effectiveness to wave reduction, reefs are unequivocally exposed to wave attack and are vulnerable to storm impacts.

High-energy waves such as during stormy conditions can be either a destructive or a constructive force that modifies reef sedimentation (e.g. Scheffers and Scheffers, 2006; Etienne and Terry, 2012; Atwater et al., 2014). The commonly observed post-typhoon impacts on intertidal environments are the formation of coral rubble ridges (e.g. Spiske and Halley, 2014; Reyes et al., 2015) and the transport and deposition of conspicuous boulders mostly reefal clasts onto the reef flat (e.g. Terry et al., 2013; May et al., 2015; Kennedy et al., 2016). Strong waves can break living coral reef assemblages or rework pre-existing accumulations of rubble in shallow reef waters to form coral rubble ridges (Nott, 2006). Local geomorphic settings such as shallow sloping, particularly wide reef front, and leeward shores with lower wave energy were noted to normally favour the

formation of coral rubble ridges (e.g. Nott and Hayne, 2001). Moreover, extreme wave impact can also excavate boulders or blocks on the reef front and if wave energy is sufficiently strong the dislodged reef boulders can be transported onto or across the reef flat (**Fig.1.6**; Terry et al., 2013).

Figure 1.6. Schematic diagram showing high-energy wave action as one possible mode of formation for a reef-platform coral boulder (taken from Terry et al., 2013). High-energy wave action can detach (1), transport (2) and then deposit (3) a boulder on the reef platform.

1.6. Storm surges in the Philippines

1.6.1 What do we know?

The Philippine archipelago is inherently prone to storm surges as it is located along the path of seasonal typhoons generated from the northwest Pacific (**Fig. 1.7**). The state agency *PAGASA (Philippine Atmospheric, Geophysical and Astronomical Services Administration)* has a compilation list and a map of the historical storm surge occurrences in the Philippines between 1897 and 2011 (Appendix 1-2). But apart from the October 1897 typhoon (Algue, 1898), we lack detailed studies on the nature and local impact of historical storm surges. To many local coastal communities, little was known on the likely immediate and commonly devastating impacts of storm surge until the Typhoon Haiyan disaster in 2013.

Figure 1.7. Storm tracks (gray lines) of landfalling typhoons (>64 kt max 1 min-sustained wind speed) in the Philippines. Storm track data from IBTrACS database covering the period 1884 to 2014.

In the aftermath of Typhoon Haiyan, Lapidez and others (2015) combined typhoon track data from 1951 to 2013 with numerical simulations of Haiyan - like magnitude typhoons to identify coastal areas in the Philippines most likely to be impacted by storm surges. The study of Lapidez and others (2015) concluded that areas likely hit by storm surges higher than 3 m are the small islands in central Philippines, the southern coast of Luzon including Metro Manila, and the northeastern coast of Mindanao. These areas share common characteristics including gently sloping coasts, presence of shallow bays, and high frequency of typhoon landfalls since 1951. For the most part, this regional model identified the areas similarly indicated on the historical storm surges map of PAGASA to have been impacted by storm surges exceeding 1 m to 4 m.

The recent study, however, failed to replicate the historical occurrences of notable storm surges exceeding 4m along the coast of northern Luzon and the entire coast of Catanduanes Island in central eastern Philippines. The apparent disparity of the regional model from that of the historical storm surge record highlights the need for site-specific studies of local coverage.

1.6.2. What do we not know?

In as much as storm surge modelling is a powerful tool to simulate storm surges and to hindcast and forecast coastal inundation scenarios, post-typhoon surveys are equally crucial for validation of the storm surge models, impact assessment, and long-term coastal planning (Nott and Hubbert, 2005). The first order of impact assessment typically includes an inventory of casualties, damage to properties and infrastructures, high-water marks, and inundation limits (e.g. FEMA, 2006; Fritz et al., 2009; Tajima et al., 2014; Mas et al., 2015). It is also important to record geomorphic and sedimentological impacts in response to such high-energy events. For example, beach and dune erosion are the most common tangible and documented impacts of storms and storm surges on the coast (e.g. Gardner et al., 1991; Nott and Hubbert, 2005; Wang et al., 2006; Shaw et al., 2015). In the Philippines, storms have been recognized as one major driver of changes in shoreline positions over the past decades, but detailed geological investigations remain scarce (e.g. Berdin et al., 2004; Siringan et al., 2010; Siringan et al., 2012). It is fundamental to document the coastal impacts of specific storms to compare and contrast how coastal systems respond to different storm events (Houser and Hamilton, 2008).

This dissertation addresses the lack of geological investigation of storm surge impacts in the Philippines through a series of case studies. The primary objective is to document and describe the geomorphic and sedimentological imprints of two recent storm surge events along the central eastern Philippine coastlines, namely the 2006 Typhoon Durian and the 2013 Typhoon Haiyan (**Fig. 1.8**). Secondary objectives are to provide actual field observations of inundation heights for augmenting and validating storm surge models and to investigate storm surge imprints preserved on coastal sediment sequences that are similar to the recent examples. This study will pave the way to extend our record of inundation occurrences beyond historical time.

The storm surge events associated with the 2006 Typhoon Durian and the 2013 Typhoon Haiyan are the main focus of this study. We chose these events primarily because of their recent occurrence. Additional considerations were the storm surge magnitude, overwash regime, sediment lithology, and availability of historical storm surge information. Both Typhoon Durian and Typhoon Haiyan generated storm surges but of contrasting overwash regimes. Typhoon Durian corresponds to a runup overwash, whereas the sites studied for Typhoon Haiyan typify inundation overwash. The coastal areas impacted by Typhoon Haiyan and Typhoon Durian encompasses a suite of coastal lithologies including siliciclastic, carbonate, and mixed carbonate-siliciclastic landscapes, which comprehensively represent the sedimentological heterogeneity on sandy coastal environments in the tropics. The sediment characteristics of these recent storm surge events were analysed to gain deeper insights on the relationship between sediment transport and overland flow dynamics. Several independent dataset including field evidence, eyewitness

Figure 1.8. Philippine map showing the tracks of the typhoons (at equivalent intensity on the Saffir Simpson Hurricane Scale) and the specific areas covered in each chapter.

accounts, and computer simulations were integrated to provide a cohesive story.

1.7. Thesis structure

This dissertation is divided into four independent manuscripts presented successively as chapters, each featuring one specific case study. The conceptualization, methods, results and synthesis described in the chapters are direct outcomes of my own research, however, contributions from co-authors have been invaluable and their input is also detailed at the start of each chapter.

Chapter 2 presents evidences that the November 2013 Typhoon Haiyan was a repeat disaster of the October 1897 unnamed typhoon. The report of Algue (1898) comprehensively documents an October 1897 unnamed typhoon, which provided a historical context for Typhoon Haiyan. The two typhoons followed a similar track warranting direct comparison between the magnitude and impacts of these two storm surge events in Samar and Leyte islands. This case study was published in the Bulletin of the American Meteorological Society (Appendix 3).

Chapter 3 describes the inland sedimentation pattern of Typhoon Haiyan along San Pedro Bay, a small embayment in the northwestern part of Leyte Gulf. The textural, compositional, and spatial trends of the overwash sediments were compared between two contrasting coastal landscapes, one dominated by siliciclastic lithology and the other dominated by mixed siliciclastic-carbonate lithologies. Given similar storm surge conditions, the local coastal geomorphology and geology strongly influence the overwash sediment composition and spatial distribution. In addition, the Haiyan overwash sediments were compared to other overwash sediments from

recent tsunamis and storms in attempt to identify sedimentological characteristics that could be diagnostic.

Chapter 4 documents the Typhoon Haiyan sedimentation on the carbonate environment of the open-sea coastline of Hernani in Samar Island. At this location the storm surge deposited reef boulders on to the reef flat, while carbonate sands were transported farther inland and deposited on coconut groves and rice fields. The reef boulders and carbonate sands independently provide information to quantify overland flow characteristics of the storm surge using inversion models.

Chapter 5 describes the geomorphological features such as washover fans and terraces associated with a storm surge generated by Typhoon Durian in November 2006. This event affected a sandy volcanoclastic coast in Lagonoy Gulf. Six years following the breaching event, the washover fans and terraces remained evident with minimal modifications. These modern geomorphic and sedimentological imprints of storm surge inundation were used as reference to investigate similar indicators of storm inundations in the past that are potentially buried on the barrier spit surface but can be revealed from ground penetrating radar (GPR) imaging.

Chapter 6 summarises the key findings and highlights the implications to overwash sedimentation studies particularly in interpreting paleo-inundation events. This chapter also outlines the limitations and potential further studies in the field.

References

- Algué, J., 1898: El baguio de Samar y Leyte, 12-13 de Octubre de 1897, Manila Observatory, 1-74.
- Atwater, B. F., Fuentes, Z., Halley, R. B., Ten Brink, U. S., and Tuttle, M. P., 2014. Effects of 2010 Hurricane Earl amidst geologic evidence for greater overwash at Anegada, British Virgin Islands. *Adv. Geosci.* 38, 21–30.
- Berdin, R., Remotigue, C.T., Zamora, P., and Siringan, F.P., 2004, July. Coastal erosion vulnerability mapping along the southern coast of La Union, Philippines. Paper presented at the Global Symposium for Hazard Risk Reduction: Lessons Learned from the Applied Research Grants for Disaster Risk Reduction Program, Washington, DC (pp. 51-67). Washington DC: Provention Consortium, World Bank.
- Buynevich, I.V., Fitzgerald, D.M., Van Heteren, S., 2004. Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. *Marine Geology* 210, 135–148.
- Donnelly, C., N. Kraus, and M. Larson, 2006: State of knowledge on measurement and modeling of coastal overwash. *Journal Coastal Res.* 22, 4, 965-991.
- Donnelly, C., Sallenger, A.H., 2007. Characterisation and modeling of washover fans. Proceedings of Coastal Sediments '07, USACE, New Orleans, USA, pp. 2061–2073.
- Donnelly, J.P., Butler, J., Roll, S., Wengren, M., Webb, T., III, 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. *Marine Geology* 210, 107–121.
- Etienne S., and Terry J.P., 2012. Coral boulders, gravel tongues and sand sheets: features of coastal accretion and sediment nourishment by Cyclone Tomas (March 2010) on Taveuni Island, Fiji. *Geomorphology* 175–176, 54–65.
- Federal Emergency Management Agency (FEMA), 2006. High Water Mark Collection for Hurricane Katrina in Alabama. *FEMA-1605-DR-AL, Task Orders 414 and 421*. Federal Emergency Management Agency, Atlanta, GA.
- Federal Emergency Management Agency (FEMA), 2011. *Coastal Construction Manual FEMA-P55 Vol. 1*, U.S. Department of Homeland Security, 3-31 - 3-

34.

- Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., and Airolidi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat. Commun.* 5, 3794. doi: 10.1038/ncomms4794.
- Fritz, H.M., C.D. Blount, S., Thwin, M.K. Thu, and N. Chan, 2009: Cyclone Nargis storm surge in Myanmar. *Nature Geoscience* 2, 448-449.
- Gardner, L.R., Michener, W.K., Kjerfve, B., and Karinshak, D.A., 1991. The geomorphic effects of Hurricane Hugo on an undeveloped coastal landscape at North Inlet, South Carolina. *Journal of Coastal Research* 8, 181-186.
- Hawkes, A.D., Horton, B.P., 2012. Sedimentary record of storm deposits from Hurricane Ike, Galveston and San Luis Islands, Texas. *Geomorphology* 171 - 172, 180-189.
- Horton, B.P., Rossi, V., Hawkes, A.D., 2009. The sedimentary record of the 2005 hurricane season from Mississippi and Alabama coastlines. *Quaternary International* 195, 15–30.
- Houser, C., Hapke, C., Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology* 100, 223–240.
- Kennedy, A. B., Mori, N., Zhang, Y., Yasuda, T., Chen, S., Tajima, Y., Pecor, W., and Toride, K., 2016. Observations and modeling of coastal boulder transport and loading during Super Typhoon Haiyan. *Coastal Engineering Journal* 58(1), 1640005 1-27.
- Lapidez, J. P., Tablazon, J., Dasallas, L., Gonzalo, L. A., Cabacaba, K. M., Ramos, M. M. A., Suarez, J. K., Santiago, J., Lagmay, A. M. F., and Malano, V., 2015. Identification of storm surge vulnerable areas in the Philippines through the simulation of Typhoon Haiyan-induced storm surge levels over historical storm tracks, *Nat. Hazards Earth Syst. Sci.* 15, 1473–1481, doi:10.5194/nhess-15-1473-2015.
- Leatherman, S.P., Williams, A. T., 1977. Lateral textural grading in overwash sediments. *Earth Surface Processes* 2, 333-341.

- Leatherman, S.P., 1981. Overwash processes. Benchmark papers in Geology, Vol. 58. Hutchinson Ross Publishing Co., USA. 376 pp.
- Lin, I.-I., Pun, I.-F., and Lien, C.-C., 2014. "Category-6" supertyphoon Haiyan in global warming hiatus: Contribution from subsurface ocean warming, *Geophys. Res. Lett.*, 41, 8547–8553 doi:10.1002/2014GL061281.
- Liu, K.-b., Fearn, M. L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* 21, 793–796.
- Mas, E., J. Bricker, S. Kure, B. Adriano, C. Yi, A. Suppasri, and S. Koshimura, 2015: Field survey report and satellite image interpretation of the 2013 Super Typhoon Haiyan in the Philippines. *Nat. Hazards Earth Syst. Sci.* 15, 805–816, doi:10.5194/nhess-15-805-2015.
- May, S.M., Engel, M., Brill, D., Cuadra, C., Lagmay, A.M.F., Santiago, J., Suarez, J.K., Reyes, M., and Brückner, H, 2015. Block and boulder transport in Eastern Samar (Philippines) during Supertyphoon Haiyan. *Earth Surface Dynamics* 3, 543-558.
- Morton, R.A. Gonzalez, J.L., Lopez, G.I., and Correa, I.D., 2000. Frequent non-storm washover of barrier islands. Pacific coast of Columbia. *Journal of Coastal Research*, 16(1), 82-87.
- Morton, R.A., Sallenger, A.H., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research* 19, 560–573.
- Needham, H. and Keim, B.D., 2011. Storm Surge: Physical Processes and an Impact Scale. In Prof. Anthony Lupo (Ed.), *Recent Hurricane Research - Climate, Dynamics, and Societal Impacts*. Intech, pp. 385-406. Available from: <http://www.intechopen.com/books/recent-hurricane-research-climate-dynamicsand-societal-impacts/storm-surge-physical-processes-and-an-impact-scale>.
- National Oceanic and Atmospheric Administration, NOAA. Storm surge overview. Accessed 26 May 2016. Available online at <http://www.nhc.noaa.gov/surge/>.
- Nott, J. 2006. Extreme events: A physical reconstruction and risk assessment. Cambridge University Press. 297 pp.
- Nott, J., Chague-Goff, C., Goff, J., Sloss, C., Riggs, N., 2013. Anatomy of sand beach

- ridges: Evidence from severe Tropical Cyclone Yasi and its predecessors, northeast Queensland, Australia, *Journal of Geophysical Research: Earth Surface* 118, 1710–1719, doi:10.1002/jgrf.20122.
- Nott, J., and Hayne, M., 2001. High frequency of ‘super-cyclones’ along the Great Barrier Reef over the past 5,000 years. *Nature* 413, 508– 512.
- Nott, J., and Hubbert, G., 2005. Comparisons between topographically surveyed debris lines and modelled inundation levels from severe tropical cyclones Vance and Chris, and their geomorphic impact on the sand coast. *Australian Meteorological Magazine* 54,187-196.
- Otvos, E.G., 2011. Hurricane signatures and landforms—toward improved interpretations and global storm climate chronology. *Sedimentary Geology* 239, 10–22.
- Pierce, J.W. , 1970. Tidal inlets and washover fans. *The Journal of Geology* 78(2), 230-234.
- Roeber, V. and Bricker, J., 2015. Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan. *Nature Communications* 6, 7854. doi:10.1038/ncomms8854.
- Sallenger, A.H. Jr., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research* 16(3), 890-895.
- Scheffers, A., and Scheffers, S., 2006. Documentation of the imoact of Hurricane Ivan on the coastline of Bonaire (Netherlands Antilles). *Journal of Coastal Research* 22(6), 1437-1450.
- Schwartz, R.K., 1982. Bedform and stratification characteristics of some modern small-scale washover sand bodies. *Sedimentology* 29, 835-849.
- Sedgwick, P. E., Davis. R. A. Jr., 2003. Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. *Marine Geology* 200, 31-48.
- Shaw,J., You, Y., Mohrig, D., and Kocurek, G., 2015 Tracking hurricane-generated storm surge with washover fan stratigraphy. *Geology* 43(2), 127-130.
- Shepard, Francis P., and Harold R. Wanless. 1971. Our changing coastlines. New

York: McGraw-Hill. 579 pp.

Siringan, F.P., Soria, J.L.A., and Ramos, R.D. 2010, December. *Changes in shoreline positions and vulnerability to marine flooding of the Verde Island Passage Corridor, Southern Luzon*. Paper presented at the First Joint International Conference of IGCP588 and INQUA1001. University of Hong Kong.

Siringan, F.P., Soria, J.L.A., Jordan, J.C., and Zamora, P.B., 2012. Water resource and hazards assessment in Tiwi, Albay. In *Albay Sustainable Development Guidebook*, pp. 29-58. Manila Observatory, Chevron Geothermal Philippines Inc., Albay Provincial Government.

Soria, J.L.A., Switzer, A.D., Villanoy, C.L., Fritz, H.M., Bilgera, P.H.T., Cabrera, O.C., Siringan, F.P., Yacat-Sta. Maria, Y., Ramos, R.D., Fernandez, I.Q., 2016. Repeat storm surge disasters of Typhoon Haiyan and its 1897 predecessor in the Philippines. *Bulletin of the American Meteorological Society* 97(1), 31-48. doi, 10.1175/BAMS-D-14-00245.1

Spiske, M. and Halley, R. B., 2014. A coral-rubble ridge as evidence for hurricane overwash, Anegada (British Virgin Islands). *Advances in Geosciences* 38, 9–20.

Switzer, A. D., and Jones, B. G., 2008. Setup, deposition, and sedimentary characteristics of two storm overwash deposits, Abrahams Bosom Beach, Southeastern Australia. *Journal of Coastal Research* 24(sp1), 189-200.

Switzer, A. D., S. Srinivasalu, N. Thangadurai, and V. Ram Mohan, 2012. Bedding structures in Indian tsunami deposits that provide clues to the dynamics of tsunami inundation. *Geological Society London Special Publications* 361, 61-77. doi: 10.1144/SP361.6

Tajima, Y., and coauthors, 2014: Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan. *Coastal Engineering Journal* 5, doi:10.1142/S0578563414500065.

Terry, J.P., Lau, Annie A. Y., Etienne, S., 2013. Uncertainties and continuing challenges with interpreting coastal boulders. In: Reef-platform coral boulders evidence for high-energy marine inundation events on tropical coastlines. Springer Singapore. pp.70-72.

- Wang, P., and Horwitz, M.H., 2007. Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. *Sedimentology* 54, 545–564.
- Wang, P., Kirby, J.H., Haber, J.D., Horwitz, M.H., Knorr, P.O., Krock, J.R., 2006. Morphological and sedimentological impacts of hurricane Ivan and immediate poststorm beach recovery along the northwest Florida barrier-island coasts. *Journal of Coastal Research* 22, 1382–1402.
- Welanders, Pierre, 1961: Numerical Prediction of Storm Surges. In H.E. Landsberg and J. van Miegheem (Eds.) *Advances in Geophysics* 8. Academic Press, Inc., New York, USA, 316 pp.
- Williams H.F.L., 2009. Stratigraphy, sedimentology, and microfossil content of Hurricane Rita storm surge deposits in southwest Louisiana. *Journal of Coastal Research* 25(4), 1041–1051.
- Williams, H.F.L., 2015. Contrasting styles of Hurricane Irene washover sedimentation on three east coast barrier islands: Cape Lookout, North Carolina; Assateague Island, Virginia; and Fire Island, New York. *Geomorphology* 231, 182–192.
- Wirtz, A., Kron, W., Löw, P., and Steuer, M., 2014. The need for data: natural disasters and the challenges of database management. *Natural Hazards* 70, 135–157. doi 10.1007/s11069-012-0312-4.
- Woodruff, J. D., Irish, J. L., & Camargo, S. J., 2013. Coastal flooding by tropical cyclones and sea-level rise. *Nature* 504(7478), 44–52.

Chapter 2

Repeat storm surge disasters of Typhoon Haiyan and its 1897 predecessor in the Philippines

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Abstract

On 8 November 2013, Typhoon Haiyan impacted the Philippines with estimated winds of approximately 314 km h^{-1} and an associated 5 to 7 m high storm surge that struck Tacloban City and the surrounding coast of the shallow, funnel-shaped San Pedro Bay. Typhoon Haiyan killed more than 6,000 people, superseding Tropical Storm Thelma (*Uring*) of November 1991 as the deadliest typhoon in the Philippines. Globally, it was the deadliest tropical cyclone since Cyclone Nargis hit Myanmar in 2008. Here, we use field measurements, eyewitness accounts and video recordings to corroborate numerical simulations and characterize the extremely high-velocity flooding caused by the Typhoon Haiyan storm surge in both San Pedro Bay and on the more open Pacific Ocean coast. We then compare the surge heights from Typhoon Haiyan with historical records of an unnamed typhoon that took a similar path of destruction in October 1897 (Ty 1897), but which was less intense, smaller, and moved more slowly. The Haiyan surge was about twice the height of the 1897 event in San Pedro Bay, but the two storm surges had similar heights on the open Pacific coast. Until stronger prehistoric events are explored, these two storm surges serve as worst-case scenarios for this region. This study highlights that rare but disastrous events should be carefully evaluated in the context of enhancing community-based disaster risk awareness, planning, and response.

2.1. Introduction

Typhoon Haiyan affected more than 16 million people, killed 6,293 people and destroyed more than 1.1 million dwellings in the central Philippines (NDRRMC 2014). Haiyan is the deadliest typhoon recorded in the Philippines, superseding Tropical Storm Thelma that struck Ormoc City on the western coast of Leyte Island, in November 1991 (Alojado and Padua 2010, Bacani 2013, Ribera et al. 2008). Globally, Typhoon Haiyan was the deadliest cyclonic event since Cyclone Nargis devastated Myanmar in 2008 (Fritz et al. 2009). The damage to infrastructure and agriculture cost ~PhP 40B or ~US\$ 900M (NDRRMC 2014), while the total economic loss reached up to US\$ 13B (Caulderwood 2014). The damage and death toll from Typhoon Haiyan were particularly high along the coasts surrounding San Pedro Bay on the northwestern margin of the Leyte Gulf primarily due to the storm surge generated by the typhoon. The shallow bathymetry of less than 10 m depth and funnel shape make the coasts of San Pedro Bay inherently susceptible to storm surge (**Fig. 2.1** inset). Additional factors that contributed to local amplification of the storm surge in Leyte Gulf were the orientation of the typhoon track and associated seiches (Mori et al. 2014).

Eyewitnesses described the Haiyan storm surge as dramatically worse than any coastal flooding events in recent years (Amadore 2013). Longer historical records, however, reveal a comparable predecessor to Typhoon Haiyan (Algué 1898). In October 1897, an unnamed typhoon, which for brevity will be henceforth referred to as Ty 1897, took a path across Leyte Gulf that was almost parallel to Typhoon Haiyan's, but offset to the

north by ~ 6 km (**Fig. 2.1**). The similar track enables direct comparison of the two typhoons and the storm surges. Here, we first characterize the destructiveness of Typhoon Haiyan before considering the importance of the 1897 predecessor in understanding storm surge hazard in the region.

Figure 2.1. Storm tracks of three deadly typhoons crossing the central Philippines – Ty 1897, November 1991 TS Thelma, and November 2013 Super Typhoon Haiyan. Typhoon track sources: a) Algue (1898); b) IBTrACS database of Knapp et al. (2010). Inset: Comparative tracks of Ty 1897 (black dashed line) and Haiyan (colored solid lines) across Leyte Gulf.

2.2. Typhoon Haiyan

On 2 November 2013 a broad low-pressure area formed in the western Pacific, to the east of Micronesia (Joint Typhoon Warning Center 2014). By 0600 UTC on 3 November it had developed into a tropical depression. At 0000 on 4 November UTC,

the system had attained tropical storm strength and was named Haiyan. It rapidly strengthened into a typhoon and moved west towards the Philippines (**Fig. 2.1**), where it was given the local name of Yolanda (NDRRMC 2013a). By November 6 Haiyan's 1-minute maximum sustained winds had intensified to an estimated 241 km h^{-1} , classified by the Joint Typhoon Warning Center (JTWC) as Super Typhoon. To avoid ambiguity in the definition of "Super Typhoon", we will conform to the traditional classification of tropical cyclones (World Meteorological Organization, 2015) in the Pacific region with "Typhoon".

On its final northwestward approach to the Philippines, Haiyan steadily intensified until it reached the peak intensity of $\sim 895 \text{ hPa}$ minimum central pressure. This peak intensity was estimated by the JTWC and the Japan Meteorological Agency (JMA) from cloud patterns recognized on visible and infrared satellite images, in the absence of ground and in-situ instruments. In Guiuan municipality on Samar Island, Doppler radar data of the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA) indicated that just before landfall, at 2000 on 7 November UTC (0400 on 8 November Philippine Time, PHT) Haiyan attained a minimum central pressure of 910 hPa , and winds at 160 km h^{-1} with gusts of $\sim 195 \text{ km h}^{-1}$ (Paciente 2014). Extreme winds destroyed the Guiuan Doppler radar station about 16 minutes later. At 2040 on 7 November UTC (0440 PHT 8 November), Haiyan crossed the small islands off the southeast tip of Samar Island, near Guiuan. Haiyan then continued westwards across the Leyte Gulf to its main landfall south of Tolosa, Leyte Island at 2300 on 7

November UTC (0700 PHT 8 November), as captured by another PAGASA Doppler radar station in Cebu. Typhoon Haiyan then made four subsequent landfalls as it crossed the central Philippines (NDRRMC 2013b).

2.3. Material and Methods

We evaluated eyewitness accounts, video recordings, field measurements, and storm surge model hydrographs to document the flow depths, surge heights, timing and peak flood duration during Typhoon Haiyan, as well as the resulting damage. Other post-Haiyan field survey reports focused on the inundation characteristics and the impact on coastal structures (Mas et al. 2015; Tajima et al. 2014). Here, we place Typhoon Haiyan's storm surge into a historical context by comparing it with the similar Ty 1897 event (Algué 1898).

2.3.1. Field Survey

The initial field survey of the coastal areas surrounding San Pedro Bay, was conducted from 23 to 28 November 2013, as soon as relief operations and the security situation permitted access in the hardest hit areas. We recorded 73 eyewitness accounts (**Appendix 3, Supplementary Table S1**) on the maximum flow depth, the timing of the initial rise, peak and subsidence of the flood, along with wind and wave observations. Collected data were used to validate the timing and heights simulated by our storm surge models. Subsequent surveys from 16 to 25 January, 12 to 19 May and 2 to 10 June 2014 encompassed larger and more remote areas, including coastal

settlements in southern Samar facing the Leyte Gulf and the Philippine Sea of the Western Pacific (**Fig. 2.2, Table 2.1**). To record distances and build cross-shore elevation profiles from the water surface at the shoreline to the inundation limit, water marks were located and measured with a Trimble Global Positioning System (GPS) rover connected via bluetooth to a Lasercraft XLRic™ laser range finder (Fritz et al 2012). At each site, high-water marks such as mudlines on buildings, scars on the bark of trees and rafted debris were evaluated using established protocols (Fritz et al. 2007; UNESCO 2014). In inhabited areas, the water marks were discussed with eyewitnesses to constrain still-water levels, estimate the contribution of storm waves, and remove bias from localized splash-up atop the surge. The high-water measurements, based on different indicators at corresponding locations, tended to be consistent and have an individual confidence of ± 0.1 m. During post-survey processing, the measurements were differentially corrected with our daily setup of the local Ashtech™ base station and corrected for tide level at the time of peak storm surge on the basis of tide predictions provided by XTide 2 © open-source software of Flater (1998). How the Ty 1897 storm surge heights were measured remains unknown, but it is highly likely that surge heights were simply referenced to the mean sea level at the time of survey. The difference between the mean sea level and the sea level at the time of peak flood during Ty 1897 imply that the accuracy of surge height measurements is in the range of ± 0.3 m. Algué (1898) lacks description on the surge height indicators, but additional uncertainties can be potentially contributed by storm waves.

Figure 2.2. Maximum storm surge heights, surge with waves, and runup points of Typhoon Haiyan measured in the field across the coastal communities in eastern Leyte and Samar islands. Surge heights of Ty 1897 from Algue (1898) are included for comparison. The terrain map is a modified NASA land elevation radar image; dark shaded areas are ≤ 10 m, above sea level.

Table 2.1. Measured maximum storm surge heights and runup points of ST Haiyan in eastern Leyte and southern Samar islands.

Code for measurements: *z* terrain elevation, *h* flow depth above terrain, *z + h* elevation of water mark relative to normal predicted tide level at time of peak flooding, *R* runup or elevation at the limit of inundation.

Code for watermarks: *TL* trimline, *WS* wave splash, *FL* flood line, *EW* eyewitness, *RD* rafted debris, *SH* ship, *MI* mudline inside, *MO* mudline outside, *WL* wrack line.

Pt	Location	Latitude (°N)	Longitude (°E)	z (m)	h (m)	z+h (m)	R (m)	Date and Time Surveyed (UTC +8)	Watermark
1	Dulag (San Jose)	10.9869	125.0393	2.22	4.60	6.82		20/01/2014	12:23:55 TL, WS
2	Dulag (San Jose)	10.9868	125.0393	2.82	1.00	3.82		20/01/2014	12:32:41 FD, EW
3	Tanauan (Cabuynan)	11.0969	125.0207	1.64	3.70	5.34		20/01/2014	15:14:34 TL, EW
4	Tanauan (Magay)	11.1172	125.0205	2.52	2.90	5.42		20/01/2014	16:21:56 EW
5	Tanauan (Magay)	11.1165	125.0199	2.22	3.00	5.22		20/01/2014	16:30:58 EW
6	Tanauan (Magay)	11.1173	125.0182	2.62	2.70	5.32		20/01/2014	16:41:37 RD
7	Hernani (Town Proper)	11.3236	125.6177	3.88	2.70	6.58		21/01/2014	13:32:56 FD, EW
8	Tacloban (Anibong)	11.2542	124.9906	3.05	3.80	6.85		22/01/2014	11:01:57 SH
9	Tacloban (Anibong)	11.2543	124.9905	5.84	1.20	7.04		22/01/2014	10:52:19 TL, EW
10	Tacloban (Anibong)	11.2575	124.9891	3.09	2.80	5.89		22/01/2014	11:23:18 TL, EW
11	Tacloban	11.2523	124.9909	4.09	1.00	5.09		22/01/2014	11:38:29 MO, EW
12	Tacloban	11.2494	124.9934	4.10	2.90	7.00		22/01/2014	12:35:11 MI, EW
13	Tacloban	11.2465	124.9952	2.07	2.50	4.57		22/01/2014	12:51:23 MI, EW
14	Tacloban	11.2470	124.9961	2.94	3.70	6.64		22/01/2014	13:07:06 EW
15	Tacloban	11.2443	124.9991	2.39	1.60	3.99		22/01/2014	14:27:53 MI
16	Tacloban	11.2437	125.0001	1.92	1.90	3.82		22/01/2014	14:38:40 MI, EW
17	Tacloban	11.2423	125.0018	2.49	1.60	4.09		22/01/2014	14:48:35 MI, EW
18	Tacloban	11.2411	125.0032	2.69	1.55	4.24		22/01/2014	14:55:44 MI, EW
19	Tacloban	11.2394	125.0053	2.19	2.90	5.09		22/01/2014	15:11:30 MI, EW
20	Tacloban	11.2421	125.0085	7.48	0.40	7.88		22/01/2014	15:42:41 MO, WS
21	Tacloban	11.2421	125.0086	7.01			7.01	22/01/2014	15:52:02 WL, EW
22	Tacloban	11.2464	125.0095	4.22	2.10	6.32		22/01/2014	16:10:01 TL
23	Tacloban	11.2464	125.0095	4.22	1.30	5.52		22/01/2014	16:11:20 MI, EW
24	Tacloban	11.2488	125.0004	3.06	4.60	7.66		22/01/2014	16:52:00 TL, EW
25	Basey (San Antonio)	11.2731	125.0030	5.26			5.26	23/01/2014	9:44:00 WL

Pt	Location	Latitude (°N)	Longitude (°E)	z (m)	h (m)	z+h (m)	R (m)	Date and Time Surveyed (UTC +8)	Watermark
26	Basey (San Antonio)	11.2734	125.0023	6.17			6.17	23/01/2014	9:56:40 WL
27	Basey (San Antonio)	11.2739	125.0021	5.99			5.99	23/01/2014	9:47:34 WL
28	Basey (San Antonio)	11.2750	125.0015	6.32			6.32	23/01/2014	9:59:23 WL
29	Basey (San Antonio)	11.2745	125.0077	2.76	3.70	6.46		23/01/2014	10:33:59 TL, EW
30	Basey (San Antonio)	11.2775	125.0147	3.31	2.90	6.21		23/01/2014	11:24:14 WS(+0.5m)
31	Marabut	11.1078	125.2120	1.58	1.20	2.78		23/01/2014	13:24:28 EW
32	Hernani (Town Proper)	11.3236	125.6177	3.88	2.70	6.58		21/01/2014	13:32:56 EW
33	Hernani (Batang)	11.2943	125.5948	6.22	1.30	7.52		23/01/2014	15:08:45 MO, EW
34	General MacArthur	11.2463	125.5404	1.49	0.45	1.94		23/01/2014	15:48:20 MO, EW
35	Quinapondan / Sto. Nino	11.1252	125.5175	1.64	2.40	4.04		23/01/2014	16:53:58 MO, EW
36	Giporlos	11.1199	125.4507	1.62	2.40	4.02		23/01/2014	17:22:12 MO, EW
37	Balangiga	11.1068	125.3860	1.31	1.50	2.81		23/01/2014	17:39:01 MO, EW
38	Lawaan	11.1387	125.3000	1.20	1.90	3.10		23/01/2014	18:07:53 MO, EW
39	Palo (San Fernando)	11.1661	125.0085	1.98	3.70	5.68		24/01/2014	16:41:55 TL, EW
40	Palo (San Fernando)	11.1656	125.0070	2.61	3.00	5.61		24/01/2014	16:53:19 TL, EW
41	Tacloban (South of Airport)	11.2005	125.0249	3.47	2.90	6.37		24/01/2014	17:16:47 TL, EW
42	Tacloban (Bay South of Airport)	11.2115	125.0251	2.10	3.70	5.80		24/01/2014	17:35:38 TL, EW
43	Tanauan (Santa Cruz)	11.1247	125.0220	1.73	4.10	5.83		24/01/2014	13:21:50 MO, EW
44	Tanauan (Santa Cruz)	11.1237	125.0215	1.73	3.40	5.13		24/01/2014	13:26:33 MO, EW
45	Llorente	11.4124	125.5485	7.29			7.29	10/06/2014	14:09:28 EW

2.3.2. Storm Surge Modeling of Typhoon Haiyan

The Typhoon Haiyan storm surge in Leyte Gulf and San Pedro Bay was simulated using the open-source Delft3D Flow (Lesser et al. 2004) with a Matlab-based graphical user interface called Dashboard¹. A curvilinear grid is used with a minimum resolution of 200 m and a maximum resolution of 1.2 km. The domain encompasses the whole Leyte Gulf and extends into the San Juanico Strait to the north (**Fig. 2.3a**). The bathymetry of the model domain was acquired from digitized navigational charts (National Mapping and Resource Information Authority, 1980). The maximum depths are found near the Leyte Gulf mouth, and the embayment shallows northward towards the San Juanico Strait (**Fig. 3B**). Open-boundary conditions are astronomic tides using 8 dominant constituents (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , and Q_1) extracted and interpolated from the TOPEX 7.2 Global tidal model (Egbert and Erofeeva 2002) using the Dashboard tide database toolbox. The tidal pattern in San Juanico Strait interacting with the Samar Sea differs from the tidal pattern at Guiuan Station driven by the Philippine Sea (**Fig. 2.3c**). The complex tidal interaction highlights the need for accurate bathymetry of Leyte Gulf and San Juanico Strait to properly simulate the tides in Tacloban.

Typhoon wind fields for the modeling were generated from the typhoon track data of the JTWC. We recognize a ~6 km offset between the JTWC typhoon track from the Doppler radar-derived track from PAGASA (**Fig. 2.1 inset**), but JTWC provides more

¹ <http://publicwiki.deltares.nl/display/OET/DelftDashboard>

Figure 2.3. Geographical coverage, bathymetry, and tidal conditions of Leyte Gulf used in the model.

- a) The model domain is a curvilinear grid with 200 m-1.2 km resolution.
- b) Leyte Gulf bathymetry generated from digitized navigational charts with 100m-1km resolution.
- c) Predicted water levels from San Juanico Strait, Tacloban City and Guiuan, Samar.

continuous along-track wind data, required in the model. The model wind files were generated by the Delft Dashboard tropical cyclone toolbox using the model by Holland (1980) and interpolated onto the computational grid. The model was initialized by wind and tide conditions at 0000 on 5 November 2013 UTC and allowed to run until 2400 on 11 November 2013 UTC. Sea level and current outputs were saved at 1-minute intervals between 1900 on 7 November UTC and 0600 on 8 November UTC. An earlier model of Bricker et al. (2014) used the same Delft3D software with JMA wind data forcing and a Quiring's relationship of maximum wind radius. Their model yielded a maximum water level of less than 6 m in Tacloban.

2.3.3. Storm surge modeling of Ty 1897

To model the likely storm surge generated by Ty 1897, we used the same grid and boundary forcing conditions of Typhoon Haiyan, but with tides simulated from 10 to 12 October 1897. Algué (1898) reported pressures and winds recorded in various parts of the Philippines during Ty 1897, but the Dashboard typhoon module requires along-track minimum central pressures and maximum winds. This requirement limited us to use only the data recorded in areas directly hit by the eye of Ty 1897, the in-situ barometric pressures measured at Guiuan and Tanauan. Apart from these two locations, no instrumental record on the typhoon eye exists. The minimum pressures before landfall in Guiuan and after landfall in Tanauan were estimated considering the values for Ty 1897 and Typhoon Haiyan. Barometric records in Guiuan and Tanauan indicate a less intense Ty 1897 at landfall than Typhoon Haiyan. To account for the weaker

intensity of Ty 1897, we took the pressure difference between Typhoon Haiyan and Ty 1897 in Guiuan and in Tanauan, and the delta values were then subtracted from the Typhoon Haiyan pressure values.

Given the barometric records of Ty 1897 in Guiuan and Tanauan, a range of wind speed values were derived from empirical wind-pressure relationships using the storm-mapping table summarized by Nakazawa and Hoshino (2009) for the western North Pacific region (**Table 2.2**). Our model, however, used the wind speed corresponding to Atkinson and Holliday (1977), which is the most direct method among the wind-pressure relationships considering the limited instrumental data on Ty 1897. Knaff and Zehr (2007) emphasized the uncertainties inherent in the regression method of Atkinson and Holliday (1977) in estimating wind speeds of tropical cyclones over the northwest Pacific. Despite the reliability concerns, the maximum wind speed estimates for Ty 1897 using Atkinson and Holliday (1977) still yielded values similar or within the range of the mean standard error (6-9 kt) of other established robust wind-pressure relationships.

2.4. Typhoon 1897 versus Typhoon Haiyan

2.4.1. Typhoon track and forward speed

The reconstructed track of Ty 1897 (**Figs. 2.1 & 2.2**) was adopted from Algué (1898) based on the synthesis report containing maps and compilation of barometric curves. Instrumental records for the historical Ty 1897 came from modified aneroid barometers

established by Jesuit priests on land (at churches) and at sea (on ships) in different locations of the Philippine archipelago. The observed pressure, wind direction, and temperature were used to establish the distance and direction of the vortex (eye) of the typhoon from the observer (Algué 1904; Udías 1996). Algué’s map was geo-referenced to a regional map derived from a 90 m x 90 m resolution satellite radar image, and then the typhoon track was digitized. Given the different resolution of Algué’s map and the regional map, we expect that the digitized track has uncertainties of ~1 km in the N-S direction, and ~2 km in the E-W direction.

Table 2.2. Minimum barometric pressure of Ty 1897 recorded in Guiuan and Tanauan and the corresponding Current Intensity (CI)-number and maximum wind speeds.

Parameters/Location	Guiuan	Tanauan (Initial)	Tanauan (Corrected)
Date and Time	12 Oct 1897 08:45am	12 Oct 1897 11:10am	12 Oct 1897 11:10am
Minimum central pressure, mm	710	704	694
Minimum central pressure, hPa	947	938	925
Observed wind condition	Relative calm*	Absolute calm	Absolute calm
1-min Maximum sustained winds, kt (kph) Atkinson and Holliday, 1977	96 (179)	105 (194)	115 (212)
CI (Dvorak, 1975)	6	6.5	7
CI (Dvorak, 1984)	5.5	6	6
1-min Maximum sustained winds, kt (kph) Dvorak	102 (189)	115 (213)	115(213)
CI (Koba, 1990)	5.5	6	6.5
10-min Maximum sustained winds, kt (kph) Koba, 1990	85 (157)	93 (172)	100 (185)

** The relatively calm wind condition recorded in Guiuan indicates that the eye has passed close but not directly over the recording site. As such the Guiuan dataset should be considered as a near minimum value.*

Upon evaluating the pressure and wind observations, Algué (1898) estimated the landfall timing and the forward speed of Ty 1897 between Guiuan and Tanauan. Ty 1897 made its initial landfall ~10 km south of Guiuan shortly after 0800 on 12 October 1897 PHT (0000 UTC 12 October). At landfall, the barometer in Guiuan registered the lowest pressure at 710 mm (947 hPa), simultaneous with the observed relatively calm winds. The relatively calm wind condition indicates an eye passage in close proximity but not directly over the recording site. As such, the Guiuan dataset should be considered only as a near minimum value. The typhoon continued westwards almost following along the northern coastline of Leyte Gulf. At about 1100 on 12 October 1897 PHT (0300 UTC 12 October) the eye of the typhoon was about 21 km NNE of Dulag, and 13 km SSE of Tacloban, before it made a second landfall in Tanauan shortly after 1100 PHT. At landfall, the barometer in Tanauan registered the lowest pressure of 704 mm equivalent to 938 hPa, but after further analysis was lowered to 694 mm equivalent to 925 hPa (Algué 1898; Algué 1904). Simultaneous with the lowest pressure was an absolute calm wind lasting for about 40 minutes. To the north, the adjacent town of Palo also experienced the zone of absolute calm but only for 10 minutes. The longer duration of absolute calm in Tanauan compared to Palo suggests that Tanauan was located closer to the center of the typhoon's eye. In a span of 2.5 hours, Ty 1897 traversed about 43 geographical miles (~80 km) between Guiuan and Tanauan, equivalent to a forward speed of about 17 mi h⁻¹ or 28 km h⁻¹ (Algué 1898, p. 66). According to Algué's map, Ty 1897 made subsequent landfalls on three islands across the central Philippines before it exited into the South China Sea.

The Jesuits ground-based method of instrumental recording and monitoring of typhoons to establish the track and intensity prevailed for many decades (Udías 1996) until it was replaced by reconnaissance aircraft, radar, and satellite observations towards the mid 20th century (Emanuel 2005a; Velden et al 2006). Today, weather services combine instrumental recordings with satellite-based observations of the cloud patterns in visible and infrared satellite images to establish a central location of a typhoon and to estimate typhoon intensities. At the forefront of this satellite-based method of tropical cyclone intensity was Dvorak (Dvorak 1975). The Dvorak method originally developed for Atlantic conditions has been adopted and applied to other ocean basins that have different atmospheric conditions like the Pacific (e.g. Velden et al 2006; Knaff and Zehr 2007; Lander et al. 2014). Unfortunately, there is no unified operational method among weather agencies for tracking and assigning typhoon intensities, as such, the reported track and intensity of one storm are commonly variable. This was the case with Typhoon Haiyan, where the tracks across Leyte Gulf released by JMA and JTWC are consistently offset ~6 km to the south of the PAGASA Doppler radar-based track. The PAGASA track, however, appears more consistent with the local field observation and ground truthing (Morgerman 2014). We note that based on the PAGASA typhoon track, Typhoon Haiyan moved from Guiuan westwards to Tolosa at about 43 km h⁻¹ or about 1.5 times faster than Ty 1897.

2.4.2. Typhoon intensity and size

The wide range of instrumental recording through history and the variety of operational wind-pressure relationships among meteorological agencies make typhoon intensity classification based on the maximum wind speed inherently uncertain (Knaff and Zehr 2007; Nakazawa and Hoshino 2009). To address the issues arising from the wind speed-derived typhoon intensity, Knapp and Kruk (2010) and Kruk et al. (2011) proposed the use of Current Intensity (CI) in comparing typhoons particularly in establishing trends of tropical typhoon intensities. Kruk et al. (2011) recognized that due to imagery interpretation of contemporary typhoons, satellite-derived intensity T-number when converted to CI could result in intensity differences of 0.5 on the CI scale. Meanwhile, the primary sources of uncertainty for the pressure-derived intensity of historical typhoons such as the Ty 1897 arise from the sparse recordings and possible instrumental errors. The historic correction of ~ 13 hPa applied to the minimum pressure of Ty 1897 on the Tanauan barometer record may give some indication of the magnitude of instrumental errors. For intense typhoons like Ty 1897, the historic correction corresponds to a difference of 0.5 on the CI scale, which is of similar magnitude as the uncertainty of satellite-derived CI. Hence, the corresponding CI numbers for Ty 1897 and Typhoon Haiyan may provide a reasonable metric to compare the intensity between these two typhoons.

As discussed previously, the observed lowest pressure and absolute calm wind of Ty 1897 consistently indicate that the typhoon eye passed directly over Tanauan. Taking

the minimum pressure of 925 hPa as the closest approximation of the central minimum pressure, Ty 1897 was assigned an equivalent CI number of 6 to 7 upon landfall. For Typhoon Haiyan, ground instruments only recorded near-minimum pressures. The Doppler radar in Guiuan registered a mean sea-level pressure of ~940 hPa before it was totally destroyed at the peak intensity of the typhoon (IRIDeS 2014). Independent measurements of PAGASA and Morgerman (2014) indicate a lowest pressure at 960 hPa in Tacloban City, which was located on the northern eyewall of the typhoon, 24 km away from Typhoon Haiyan's center. In contrast, using the satellite-based Dvorak technique Typhoon Haiyan has a signature Typhoon Number of T8.0 (Lander et al. 2014), which corresponds to a CI number of 8, the highest on the scale. As such, the CI 8 Typhoon Haiyan was more intense than the CI 6 to 7 of Ty 1897.

Not only that Typhoon Haiyan was more intense, it was also larger than Ty 1897 based on the eyewall size. Morgerman (2014) corroborated the eye of Typhoon Haiyan based on wind observations of eyewitnesses and a radar image, indicating a 13 km radius of the eyewall. In contrast, the Jesuit approach based on the zones of absolute and relative calm winds as indicators of the relative location of the typhoon eye results in eyewall radius of 6 km to 10 km for Ty 1897.

Given the contrasting operational methods between 1897 and 2013, it remains difficult to directly compare Typhoon Haiyan and Ty 1897 with absolute certainty. The available meteorological parameters, however, suggest that Typhoon Haiyan and Ty

1897 were nearly identical based on the trajectory, while characteristic differences prevailed concerning other aspects. Typhoon Haiyan followed a parallel track direction with a ~6 km offset to the south of Ty 1897. Typhoon Haiyan was more intense, had wider eyewall coverage, and was moving faster than Ty 1897. The possible effects of the slight variations in track, minimum central pressure, estimated maximum winds, and forward movement between the two typhoons on the storm surge characteristics will be explored in the following sections.

2.5. Typhoon 1897 and Typhoon Haiyan storm surges

2.5.1. Post-typhoon field measurements

The Ty 1897 storm surge measurements of Algué (1898) were based on eyewitness accounts (**Fig. 2.2**). These field measurements indicate inundation heights exceeding 4 m in most places with a maximum height of over 7 m on the open-sea coast at Hernani (**Fig. 2.2c**). Along San Pedro Bay in Basey (**Fig. 2.2b**), the water gradually rose and reached a maximum level of 4.9 m. The peak flooding corresponded with the most violent winds from the southeast. In the nearby coast of Tacloban (**Fig. 2.2a**), water rose between 3.9 m and 4.6 m. The peak flooding coincided with the winds blowing from the east to east-southeast, directly perpendicular to the Tacloban coast. In close proximity to the eye of Ty 1897 at Tanauan and Tolosa (**Fig. 2.2a**), the water rose to 3 m.

Algué's "Ola del Huracán" or hurricane wave was the elevation of the sea, with the

surface forming like a warp pyramid whose peak approximately corresponds to the vortex (eye) of the typhoon, analogous to the water surface being sucked by a vacuum pump (Algué 1898, p. 9). Moving with the typhoon, this huge wave when launched against the shore makes the water rise to an extraordinary height, causing severe flooding, and extensive destruction (Algué 1898, p. 10). We interpret this description as equivalent to what we now call “storm surge”. Algué overestimated the contribution of the pressure drop over the wind field as the primary contributor to the significant rise of the sea surface, because of the different locations of the eye and the areas where water elevations were highest. The sea rose to about 3 m in Guiuan and Tanauan, but the rise was highest at Hernani, Basey, and Tacloban on the typhoon’s strong side to the north of the typhoon eye. The peak flooding during Ty 1897 at each of these sites consistently coincided with winds blowing directly perpendicular towards the coastline. Contrary to Algué’s attribution of the surge solely to the low central pressure, the wind field was the primary driver of the storm surge (Emanuel 2005b).

The measured high water marks after Typhoon Haiyan (**Fig. 2.2**) were separately classified into *maximum surge heights* and *surge plus storm waves*. For a wider and denser spatial coverage, we combined our field measurements with the survey of Tajima et al. (2014). In both surveys, each high-water mark indicator was referenced to the reconstructed tide level at the time of peak flooding. Heights differed by as much as 1 m at slightly different locations. Discrepancies of up to 2 m at corresponding locations were attributed to short-period storm waves superimposed on top of the surge.

High-water marks with significant storm-wave contributions were carefully identified based on eyewitness accounts, the type of physical watermark and the inland location. Surge height measurements from different high water mark indicators in both surveys were mostly consistent.

At Tacloban located some 23 km to the north of Haiyan's track (**Fig. 2.2a**), the characteristic height of the storm surge peak was 7 m. Wave contributions raised high-water marks up to almost 8 m in Tacloban and Palo. On the more open and exposed Pacific coastline at Hernani (**Fig. 2.2c**), some 45 km north of the typhoon track, significant storm-wave contributions resulted in high water marks exceeding 7 m. Further amplification by the wave runup on steep slopes such as near Guiuan resulted in a maximum runup height of 14 m (Tajima et al. 2014). Surge heights exceeding 5 m were recorded along the shores of San Pedro Bay. We detail the nature of the storm surge in San Pedro Bay, where the highest death toll was recorded, in the next section. Outside of San Pedro Bay, but still within Leyte Gulf, the surge heights were only 3 to 4 m between Marabut and Quinapondan (**Fig. 2.2b**) because the storm track was parallel to the coastline. Water marks as high as 5 m were attributed to storm-wave contributions. In close proximity to Haiyan's landfall location between Tolosa and Dulag, the surge heights ranged between 3 and 5 m (**Fig. 2.2a**). At an exceptional site in Dulag a 7 m high-water mark was compromised by significant storm-wave contribution. The lowest surge height of about 2 m was recorded at General MacArthur on the eastern coast of Samar (**Fig. 2.2c**). The site is sheltered behind fringing coral

reefs located 3 km offshore, and is on a bay with a narrow bottleneck entrance attenuating storm waves, and resulting in a measurement dominated by the storm-surge component.

2.5.2. Storm surge simulations of Typhoon Haiyan and Ty 1897 in San Pedro Bay

The Haiyan storm surge modeling results resolved an initial sea level drawdown around 2130 on 7 November 2013 UTC (0530 PHT 8 November) in accordance with eyewitness accounts and the Tacloban tide gauge recording (**Fig. 2.4**). The tide gauge recorded a drawdown of at least 0.8 m before it broke down², while modeling suggests a drawdown of at least 1.2 m at the head of San Pedro Bay (**Fig. 2.4 a & b**). The initial sea-level drawdown was also observed at Basey on Samar (Amadore 2013). The drawdown was generated by persistent strong, northerly offshore winds that initially drove the waters southwards out of San Pedro Bay (**Fig. 2.4 a & b**). Similar sea-level drawdowns or negative surges from strong offshore winds during historic hurricanes have also been reported for the western Florida coasts (Harris 1963; Lawrence and Cobb 2005). The drawdown exposed the sea floor and dramatically steepened the storm tide profile. This phenomenon is analogous to negative leading N-wave during tsunamis, usually resulting in a higher runup (Tadepalli and Synolakis 1994). Eyewitness accounts and modeling show that the storm tide arrived as an unusually fast-moving ‘tsunami like’ wave front, which caused high velocity coastal flooding to heights of more than 7 m near Tacloban and Basey. Residents in Basey, who stayed in

² The Tacloban tide data was provided by the National Mapping and Resources Information Agency (NAMRIA) of the Republic of the Philippines.

Figure 2.4. Sea-level heights in Tacloban and nearby coasts around San Pedro Bay during Typhoon Haiyan. (top) Graphical representation of the water levels from storm surge model (blue line) and from Tacloban Port tide gauge (red line). Both the actual and modeled tides show receding sea level prior to the peak surge. a-i: Storm surge model sequence of Typhoon Haiyan in San Pedro Bay from 2130 on 7 November to 0130 on 8 November 2013 UTC with colors and arrows representing water level and wind magnitude and direction, respectively.

their homes despite prior evacuation warnings, described a large wave similar to a tsunami striking soon after the water receded, providing only a few minutes of lead time to seek refuge at higher elevations.

The initial rise, peak, and lowering of flood levels due to the storm surge varied considerably in time and location. In downtown Tacloban, the peak surge occurred around 0000 UTC 8 November (0800 PHT 8 November) according to videos recorded by several eyewitnesses and the detailed coverage by storm chaser Morgerman (2014). The inundation timing was further confirmed by two wall clocks located about 14 km apart along the western shores of San Pedro Bay, which were stopped as seawater floods reached about 1.5 to 2 m high. In Tanauan, the clock stopped at 0720 PHT (2320 UTC 7 November); the clock in Tacloban City stopped few minutes later, at 0730 PHT (2330 UTC 7 November). The timing from the videos and wall clocks are consistent with the storm surge model. The modeled timing of the peak surge coincided with the timing of the onshore-directed winds closely linked to the forward motion of Typhoon Haiyan (**Fig. 2.4 c-g**). The modeled peak surge of 6 to 8 m in San Pedro Bay occurred between 0000 and 0030 UTC (0800 and 0830 PHT) on 8 November, arrived earlier along the eastern shores at the entrance of the bay, and propagated northwards to the bay head. It is likely that several eyewitnesses in Dulag observed the front of the storm surge. During the passage of the eye (calm winds), eyewitnesses saw an offshore ‘wall of water’ about 6 m high that first was moving west towards Dulag but then suddenly redirected north towards Tacloban. The peak surge lasted for at least 30 minutes, and

then just before 0100 UTC (0900 PHT) on 8 November, the water subsided (**Fig. 2.4 h-i**).

In addition, the modeled water level in **Figure 2.4** shows three apparent peaks corresponding to points C, G, and after point I. The peaks may coincide with the three “waves” reported by eyewitnesses (Amadore 2013; Morgerman 2014), although the timing could not be verified since the eyewitnesses did not track the timing of the three waves. In the open sea coast of Hernani, accounts of the storm surge coming in three waves also exist. The video footage from Hernani showed the building collapsing with the impact of the second wave, which corresponds to the highest and steepest peak in the storm surge model in San Pedro Bay.

The storm-surge simulation of Ty 1897 (**Fig. 2.5**) showed water levels and peak surge timing that are consistent with Algué’s report (Supplemental Material). In Basey, northerly-northeasterly offshore winds forced the water to recede (**Fig. 2.5a**). The initial rise of the surge occurred with the easterly-southeasterly winds (**Fig. 2.5b**) whereas; south-southeasterly winds caused the peak surge in Tacloban and Basey (**Fig. 2.5 c-d**). On the contrary, in Tolosa the model did not absolutely replicate the actual surge height. Algué reported surge height of ~3 m, but the model yielded 2 m. The discrepancy can be attributed to various factors including changes in near-shore bathymetry, storm-wave contribution, and uncertainties in the Ty 1897 typhoon parameters. For the most part of San Pedro Bay, the modeled surges indicate that Ty

Figure 2.5. Storm surge model sequence of Ty 1897 in San Pedro Bay from 0200 to 0400 on 12 October 1897 UTC with colors and arrows representing water level and wind magnitude and direction, respectively.

Figure 2.6. Modeled surge heights comparison between Ty 1897 and Typhoon Haiyan in San Pedro Bay.

- a) Graphical representation of the modeled water level at Tacloban for Ty 1897 and Typhoon Haiyan.
- b) Modeled maximum surge heights in San Pedro Bay during Ty 1897.
- c) Modeled maximum surge heights in San Pedro Bay during Typhoon Haiyan.

1897 generated lower surge heights than Typhoon Haiyan (**Fig. 2.6**), which is consistent with the field measurements for both storm surge events. The magnitude difference of the modeled surge heights between the two typhoons (**Fig. 2.7**) is also consistent with the magnitude difference of the measured water levels in both post-typhoon surveys.

Figure 2.7. Difference in water levels of the modeled maximum surge height between Ty 1897 and Typhoon Haiyan in San Pedro Bay.

2.6. Implications for disaster management

2.6.1. Understanding the local storm surge hazard

The complex interactions among several factors including typhoon intensity represented by lowest pressure and maximum wind speed, forward movement of the typhoon, storm size, bathymetry, coastline shape, and tidal phase result in varying

storm surge height and flooding duration for any storm (e.g. Emanuel 2005b; Irish et al. 2008; Needham and Keim 2014). Given the similar areas impacted by the storm surges of Ty 1897 and Typhoon Haiyan, the coastal geomorphology is assumed to be relatively constant for these two events. Lander et al. (2014) estimated a 20 cm sea-level rise between 1970 and 2013, which likely did not contribute significantly to the impact of the storm surge from Typhoon Haiyan. The effect of sea-level rise on the tidal phases of Ty 1897 and Typhoon Haiyan is beyond the scope of this study. We focused on differences in typhoon characteristics including track, intensity, size, and forward movement and their possible effect on the storm surge characteristics. Despite the atmospheric differences between the Ty 1897 and Typhoon Haiyan, the resulting two storm surges share notable similarities dictated by the local coastal configuration (**Fig. 2.2**). At exposed locations like Hernani, both typhoons generated peak surges exceeding 7 m with significant storm-wave contributions superimposed on top of the surge. In stark contrast, sheltered locations such as General MacArthur experienced the lowest flood levels with 2-m peak surges. Another similarity in both typhoons was the water receding off Basey in San Pedro Bay prior to the peak surge. Based on the historical accounts and our simulations, the 1.2 km wide strait separating Jinamoc Island from Basey can be exposed as the water recedes prior to the peak surge given the shallow water depth of ~ 1.5 m under normal conditions. In both typhoons, the surge in San Pedro Bay initially rose just before the typhoon made landfall on Leyte Island with easterly onshore winds. The surge then peaked with the southeasterly onshore winds as the typhoon eye moved west towards the interior of Leyte Island

(Figs. 2.4 & 2.5).

Irrespective of the coastal configuration, whether in exposed open-sea (e.g. Hernani) or in sheltered embayment (e.g. San Pedro Bay), the typhoon forward motion resulted in significantly different peak flooding duration between the two storm surge events. The slower forward motion of Ty 1897 resulted in longer peak floods lasting for about 3 hours. In contrast, the much faster moving Typhoon Haiyan resulted in rapid high-velocity peak floods spanning about 30 minutes to nearly one hour.

The higher and more extensive peak surge around San Pedro Bay during Typhoon Haiyan compared to Ty 1897 (**Fig. 2.6**) could be due to the latitudinal shift of the typhoon tracks, differences in the intensity and forward motion of these two typhoons, or a combination of these factors. The northerly track of Ty 1897 made Tanauan the landfall location reducing the surge near Palo and Tanauan; this is true especially given the relative absence of strong onshore winds when compared to Typhoon Haiyan. Meanwhile, the relatively more intense and larger Typhoon Haiyan generated stronger onshore winds on the northern and western shores of San Pedro Bay. The stronger onshore winds in turn induced surge heights almost twice those of Ty 1897 and extending over a wider region (**Fig. 2.6**).

Apart from typhoon intensity, the storm size was recognized as an additional important factor in generating high storm surges and extensive inundation during Hurricane Katrina (Irish et al. 2008). Given the geometry of San Pedro Bay, however, the storm

size might not be an equally significant factor in generating high storm surges in the case of Typhoon Haiyan. The distance from the Typhoon Haiyan track to the head of San Pedro Bay is ~40 km, which is well within the zone of maximum winds. Although considering the more southerly track of Typhoon Haiyan, storm size likely contributed to the extreme surge heights along the more exposed coasts of Eastern Samar such as at Hernani.

2.6.2. Multi-hazard evacuation strategies

Figure 2.8 shows the damage from Typhoon Haiyan surrounding San Pedro Bay. In the northern part Tacloban including the downtown area, the landward limit of inundation during Typhoon Haiyan exceeded 500 m (Tajima et al. 2014). Along low-lying, swampy areas south of downtown Tacloban and similarly at Tanauan, inundation extended more than 2 km inland. Overland flooding reached over 2 km, but the primary areas of damage were concentrated within 200 m of the coast, highlighting the destructive power of storm waves riding on top of the storm surge has a limited inland penetration (FEMA 2011). Very few structures withstood the energy of the storm surge and superimposed storm waves (**Fig. 2.8b, d, and f**). In areas above the surge heights, extreme typhoon winds caused greater damage, destroying roofs and wide swaths of coconut trees (**Fig. 2.8e**). Therefore, the combined hazards from storm surge flooding, extreme winds and the prevailing vulnerabilities must be considered to develop appropriate evacuation strategies.

Figure 2.8. Photos of storm damage around San Pedro Bay.

a) Location map. Most structures proximal to the coast in Tacloban (b,c) Basey (d), and Tanauan (f) were completely destroyed by the storm surge and the overriding storm waves. Like in most coastal settlements existing guidelines on foreshore easement³ were completely ignored. (c) In Anibong village, just north of downtown Tacloban, stilt houses are rebuilt seaward of the stranded ships two months after the event. (e) In Marabut, wide swaths of palm trees chopped by the extreme winds.

³ The Water Code of the Philippines (Presidential Decree 1067) states that designates an easement of 40 meters from seashore. This is supposed to be a “no build zone” area.

2.6.3. Typhoon warning and response

The Philippine government issued typhoon forecasts and warnings for evacuations at least 18 hours before Typhoon Haiyan's landfall to achieve minimum and possibly zero casualties from the imminently approaching cyclonic storm threat (Ranada 2013; NDRRMC 2013c; IRIDeS 2014). Preliminary social surveys suggest that local residents had a mixed response to the typhoon warnings emerging from complex social concerns (IRIDeS 2014; Leelawat et al. 2014). These studies highlight that communication pathways, warning systems, evacuation plans, and multi-level hazard and disaster perception were significant concerns for evacuation decisions among individuals in the areas severely impacted by Typhoon Haiyan. These findings underscore the need for the authorities responsible for disseminating weather warnings to better understand how typhoon warnings are transmitted from an initial source through intermediate relays to the final recipients, as well as how the potentially vulnerable residents receive, heed, interpret, and decide to act upon these warnings. Given the historical perspective of storm surge hazards discussed in this paper, social scientists and historians may be able to improve local historical awareness about previous typhoon experiences, to aid in hazard perception and response. Historical records show that several storms with associated storm surges have affected the area between Ty 1897 and Typhoon Haiyan (Selga 1935, PAGASA 1998, Knapp et al. 2010; **Fig. 2.9, Tables 2.3 & 2.4**). Among these storms, residents identify the November 1984 Typhoon Agnes and the associated coastal flooding ranging from 2 to 4 m in Samar and Leyte as the worst in memory (e.g. PAGASA 1998; Amadore 2013).

Leik et al. (1981) noted that many people along the Gulf and Atlantic coasts in the US incorrectly believe they have been through major cyclonic events, although Baker (1991) recognized that defining and measuring hurricane experience is a difficult task. Of particular relevance in the Philippines, several residents on Leyte and Samar islands admitted that their experience of past typhoons misled them to believe that an evacuation lead-time of minutes would be sufficient. This raises a long lasting question: How does the experience of smaller relatively less impactful events shape the response of the community to larger, unprecedented events or those with return periods outside the living memory of residents?

On a broader note, although stronger prehistoric events (Donnelly et al. 2006, Nott 2007) remain to be explored, and as long as other historical events remain unverified, the Ty 1897 and Typhoon Haiyan storm surges may serve as worst-case scenarios for this region. These rare but disastrous events should be carefully evaluated towards enhancing community-based disaster risk awareness, planning, and response.

2.7. Conclusion

Historical records reveal a predecessor to Typhoon Haiyan occurred on 12 October 1897. This typhoon referred here as Ty 1897 took a similar path of destruction through the eastern central Philippines. Ty 1897 and Haiyan had almost identical typhoon tracks, but Typhoon Haiyan was more intense, had larger maximum wind coverage, and moved faster than Ty 1897. Our combined field observations and eyewitness

accounts corroborates with computer simulations illustrate that Typhoon Haiyan's storm surge was about twice the height of the 1897 event in San Pedro Bay, but the two storm surges had similar heights on the open Pacific coast such as at Hernani. While stronger prehistoric events remain unexplored, Ty 1897 and Typhoon Haiyan storm surges may serve as extreme scenarios for this region in terms of disaster risk awareness, planning, and response.

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References

- Algué, J., 1898: El baguio de Samar y Leyte, 12-13 de Octubre de 1897, Manila Observatory, 1-74.
- Algué, J., 1904: The cyclones of the Far East. Bureau of Public Printing, Manila, 283 pp.
- Alojado, D. and D.M. Padua, 2010: “Worst Typhoons of the Philippines 1947-2009” [Available online at <http://www.typhoon2000.ph/stormstats/WorstPhilippineTyphoons.htm>].
- Amadore, L. A., 2013: Storm surge in Basey, Samar. [Available online at <http://opinion.inquirer.net/66477/storm-surge-in-basey-samar>.]
- Atkinson, G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western North Pacific. *Mon. Wea. Rev.*, **105**, 421–427.
- Bacani, L., 2013: Deadliest, most destructive cyclones of the Philippines. [Available online at <http://www.philstar.com/headlines/2013/11/11/1255490/deadliest-most-destructive-cyclones-philippines>.]
- Baker, E. J., 1991: Hurricane evacuation behavior. *International Journal of Mass Emergencies and Disasters*, **9**, 2, 287-310.
- Bricker, J., H. Takagi, E. Mas, S. Kure, B. Adriano, C. Yi, and V. Roeber, 2014: Spatial variation of damage due to storm surge and waves during Typhoon Haiyan in the Philippines. *Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering)*, **70**, 2, I_231-I_235.
- Caulderwood, K. 2014: The Ten Most Expensive Natural Disasters In 2013. [Available online at <http://www.ibtimes.com/report-ten-most-expensive-natural-disasters-2013-1540058>.]
- Donnely, C., N. Kraus, and M. Larson, 2006: State of knowledge on measurement and modeling of coastal overwash. *J. Coastal Res.*, **22**, 4, 965-991.
- Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420–430.

- Dvorak, V. F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech.Rep. NESDIS 11, 50 pp. [Available online at ftp://satepsanone.nesdis.noaa.gov/Publications/Tropical/Dvorak_1984.pdf.]
- Egbert, G.D., and S.Y. Erofeeva, 2002: Efficient inverse modeling of barotropic ocean tides. *J. Atmos. Ocean. Technol.*, **19**, 183–204.
- Emanuel, K. A., 2005a: The hunters. *Divine wind: The history and science of hurricanes*, Oxford University Press, New York, 193-202.
- Emanuel, K. A., 2005b: The storm surge. *Divine wind: The history and science of hurricanes*, Oxford University Press, New York, 147-152.
- Federal Emergency Management Agency (FEMA), 2011: *Coastal Construction Manual FEMA-P55 Vol. 1*, U.S. Department of Homeland Security, 3-31 - 3-34.
- Flater, D., 1998: XTide: Harmonic tide clock and tide predictor. [Available online at <http://www.flaterco.com/xtide/>].
- Fritz, H.M., and Coauthors, 2007: Hurricane Katrina Storm Surge Distribution and Field Observations on the Mississippi Barrier Islands. *Estuarine, Coastal Shelf Sci.*, **74**, 12-20.
- Fritz, H.M., C.D. Blount, S., Thwin, M.K. Thu, and N. Chan, 2009: Cyclone Nargis storm surge in Myanmar. *Nature Geoscience*, **2**, 448-449.
- Fritz, H.M., and Coauthors, 2012: 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LiDAR. *Geophys. Res. Lett.*, **39**, L00G23: doi:10.1029/2011GL050686.
- Harris, L.D., 1963: Characteristics of the hurricane storm surge. *U.S. Weather Bureau, Technical Paper No. 48*, Weather Bureau, 19-24.
- Holland, G.J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Mon. Wea. Rev.*, **108**, 1212-1218.
- International Research Institute of Disaster Science (IRIDeS), 2014: Initial Report of IRIDeS Fact-finding missions to Philippines. Tohoku University, 105 pp.
- Irish, J. L., D. T. Resio, and J. J. Ratcliff, 2008: The influence of storm size on hurricane surge. *J. Phys. Oceanogr.*, **38**, 2003–2013, doi:10.1175/2008JPO3727.1.

- Joint Typhoon Warning Center, 2014. JTWC Western North Pacific Best Track Data 2013. [Available online at http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php].
- Knaff, J.A. and R. M. Zehr, 2007: Reexamination of tropical cyclone wind-pressure relationships. *Wea. Forecasting*, **22**, 71-88.
- Knapp, K.R., M.C. Kruk, D.H. Levinson, H.J. Diamond, and C.J., Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bull. Amer. Meteor. Soc.*, **91**,363-376.
- Koba, H., T. Hagiwara, S. Asano, and S. Akashi, 1990: Relationships between CI number from Dvorak's technique and minimum sea level pressure or maximum wind speed of tropical cyclone (in Japanese). *J. Meteor. Res.*, **42**, 59-67.
- Kruk, M.C., P.A. Hennon, and K.R. Knapp, 2011: On the use of the Dvorak Current Intensity as a climate data record in the Western North Pacific. 91st AMS Annual Meeting-23rd Conference on Climate Variability and Change. Paper #142. [Available online at <https://ams.confex.com/ams/91Annual/webprogram/Session25263.html>].
- Lander, M., C. Guard, and S.J. Camargo, 2014: Super Typhoon Haiyan. State of the Climate 2013. *Bull. Amer. Meteor. Soc.*, S112-114.
- Lawrence, H., and H. Cobb, 2005: National Hurricane Center Tropical Cyclone Report on Hurricane Jeanne. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL112004_Jeanne.pdf.]
- Leelawat, N., C. M. R. Mateo, S. M. Gaspay, A. Suppasri, and F. Imamura, 2014: Filipinos' views on the disaster information for the 2013 Super Typhoon Haiyan in the Philippines. *International Journal Sustainable Future for Human Security J-Sustain*, **2**, 2, 16-28.
- Leik, R. K., T. M. Carter, J. P. Clark, S. D. Kendall, and G. A. Gifford, 1981: Community Response to Natural Hazard Warnings. Summary Final Report. DCPA01-79-C-0214, FEMA Work Unit No. 2234-F, 77 pp. [Available online at <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=A>

[DA099509](#)].

- Lesser, G.R., J.A. Roelvink, J.A.T.M. van Kester, and G.S. Stelling, 2004:
Development and validation of a three-dimensional morphological model.
Coast. Eng., **51**, 883–915.
- Mas, E., and Coauthors, 2015: Field survey report and satellite image interpretation of the 2013 Super Typhoon Haiyan in the Philippines. *Natural Hazards and Earth System Sciences*, **15**, 805–816.
- Morgerman, J., 2014: Super Typhoon HAIYAN in Tacloban City & Leyte, Philippines. [Available online at http://www.icyclone.com/upload/now/apr_2014/iCyclone_HAIYAN_in_Tacloban_City_040314.pdf.]
- Mori, N., and Coauthors, 2014: Local amplification of storm surge by Super Typhoon Haiyan in Leyte Gulf. *Geophys. Res. Lett.*, **41**, 5106–5113.
- Nakazawa, T. and S. Hoshino, 2009: Intercomparison of Dvorak Parameters in the tropical cyclone datasets over the Western North Pacific. *SOLA*, **5**, 33–36, doi:10.2151/sola.2009–009.
- National Disaster Risk Reduction and Management Council (NDRRMC), 2013a: Severe Weather Bulletin No.1 Re: Typhoon “Yolanda” (Haiyan). [Available online at [http://www.ndrrmc.gov.ph/attachments/article/1124/ADV%20re%20SWB%201%20for%20TY%20YOLANDA%20\(06NOV2013\).pdf](http://www.ndrrmc.gov.ph/attachments/article/1124/ADV%20re%20SWB%201%20for%20TY%20YOLANDA%20(06NOV2013).pdf)]
- National Disaster Risk Reduction and Management Council (NDRRMC), 2013b: Situational Report No. 10 Effects of Typhoon Yolanda (Haiyan) as of 10 November 2013. [Available online at <http://www.ndrrmc.gov.ph/attachments/article/1125/NDRRMC%20Update%20SitRep%20no.%2010%20re%20Effects%20of%20TY%20Yolanda,%2010%20Nov%202013,%206AM.pdf>.]
- National Disaster Risk Reduction and Management Council (NDRRMC), 2013c: Situational Report No. 3. Preparations for Typhoon “Yolanda” (Haiyan). [Available online at

<http://www.ndrrmc.gov.ph/attachments/article/1124/Update%20SWB%20No.%203%20TY%20YOLANDA%2007%20NOV%202013,%2011AM.pdf>.]

National Disaster Risk Reduction and Management Council (NDRRMC), 2014: Situational Report No. 108 Effects of Typhoon “Yolanda” (Haiyan) as of 3 April 2014. [Available online at <http://www.ndrrmc.gov.ph/attachments/article/1125/NDRRMC%20Update%20-%20Sitrep%20No%20108%20re%20TY%20Yolanda%20-%2003%20April%202014.pdf>.]

National Mapping and Resource Information Authority, 1980: Nautical chart of San Pedro Bay. 1:40,000. Sheet 4468. Manila, Philippines. Print.

Needham, H.F., and B. D. Keim, 2014: Correlating Storm Surge Heights with Tropical Cyclone Winds at and before Landfall. *Earth Interactions*, **18**,7, 1-26.

Nott, J., 2007: The importance of Quaternary records in reducing risk from tropical cyclones. *Palaeog., Palaeoclimatol., Palaeoecol.*, **251**, 137–149.

Paciente, R.B., 2014: Response and lessons learned from Typhoon “Haiyan” (Yolanda). *JMA/WMO Workshop on Effective Tropical Cyclone Warning in Southeast Asia*. Tokyo, Japan Meteorological Agency. [Available online at http://severe.worldweather.wmo.int/TCFW/JMAworkshop/6-3.THaiyan_RPaciente.pdf]

Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), 1998: Storm surge occurrences from 1800 to 1998. Compiled by Climatology and Agrometeorology Branch, 1-7.

Ranada, P., 2013: Leyte warned of storm surges. [Available online at <http://www.rappler.com/nation/43179-yolanda-storm-surges>.]

Ribera, P., R. García-Herrera, and L. Gimeno, 2008: Historical deadly typhoons in the Philippines. *Weather*, **63**,194–199.

Selga, M., 1935: Charts of remarkable typhoons in the Philippines 1902-1934. Catalogue of typhoons 1348-1934, Manila Weather Bureau, 1-55.

- Tadepalli, S., and C.E. Synolakis, 1994: The run-up of N-waves on sloping beaches. *Proc. R. Soc. Lond. A.*, **445**, 99-112.
- Tajima, Y., and Coauthors, 2014: Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan. *Coast. Eng. J.*, **5**, doi:10.1142/S0578563414500065.
- Udías, A., 1996: Jesuits' contribution to meteorology, *Bull. Am. Meteorol. Soc.*, **77**, 2307–2315.
- UNESCO, 2014: International Tsunami Survey Team (ITST) Post-Tsunami Survey Guide, 114p, UNESCO-IOC Manuals and Guides, 37, 2nd Edition, Paris, France.
- USA War Office, 1913: Typhoons. Report of the Philippine Commission to the Secretary of War. Washington, 32.
- Velden, C., and Coauthors, 2006: The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.*, **87**, 1195–1210, doi:10.1175/BAMS-87-9-1195.
- World Meteorological Organization, 2015: Typhoon Committee Operational Manual. Tropical Cyclone Program Report No. TCP 23, 169 pp. [Available online at <https://www.wmo.int/pages/prog/www/tcp/documents/TCP-23EDITION2015.pdf>]

Chapter 3

Sedimentary record of Typhoon Haiyan from Leyte Gulf coastlines shows a hybrid signature

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Contributions

Lea was the primary author, and with Adam, and Fernando conceptualized the idea, contributed to its formality and development. Lea conducted the sedimentological analysis, interpreted the data, and wrote the paper. Jessica collected, analyzed, and contributed relevant micropaleontological data. Nicole and Hermann collected data, and contributed information on data treatment and interpretation.

Janneli Lea A. Soria: 65%

Adam D. Switzer: 12%

Jessica E. Pilarczyk: 10%

Fernando P. Siringan: 6%

Nicole S. Khan: 4%

Hermann M. Fritz: 3%

Abstract

Overwash associated with the 5 to 8 m storm surge of Typhoon Haiyan left overwash sediments inland, on the coastal plain of the northwestern shores of Leyte Gulf, Philippines. We studied two locations no more than 20 km apart that experienced similar storm surge conditions. At both locations the Haiyan sediments were predominantly sand and silt, which provide a modern sedimentary record of storm surge deposition from a Category 5 landfalling typhoon. Notably, despite the similar storm surge conditions at the two sites, significant differences in sediment grainsize, composition and sorting exist. This variability is reflective of the local geology showing the different sediment composition and the availability for transport of the sediments in the nearshore environment. Thicker overwash sediments on the broad, low-lying, silicilastic coast of Tanauan exhibit planar stratification, a coarsening upward sequence, an overall but non-systematic landward fining trend, and a sharp depositional (rarely erosional) basal contact with the underlying landform. These sedimentologic and stratigraphic characteristics are consistent with other overwash sediments from comparably intense storm surges, and were also observed in recent tsunami deposits.

3.1. Introduction

Overwash associated with storm surges during land-falling storms often rework, erode and transport near-shore sediments into low-lying coastal plains (Leatherman, 1981; Morton & Sallenger, 2003; Williams & Flanagan, 2009). The overwash sediments are commonly reported as anomalous sand layers found in the sedimentary environments of low-energy coastal settings, including coastal lakes, swamps and back-barrier tidal marshes (e.g. Leatherman, 1977; Liu and Fearn, 1993; Donnelly et al., 2004; Buynevich et al., 2004). Overwash processes also create depositional landforms on back beach environments. Depending on the elevation of water surface level relative to the dune or beach ridge height, along with the extent and continuity of foredune gaps, overwash can either result in washover fans that are isolated, regularly spaced, or merged to form terrace morphology (Morton and Sallenger, 2003). These sedimentary and geomorphic products of storm-induced overwash although distinct, can be very diverse. In a recent review paper, Otvos (2011) cautioned the use of the sedimentary and geomorphic storm markers in prehistoric storm reconstructions. He argued that poor understanding of the dynamic interactions amongst several meteorological, hydrodynamic, and geologic conditions that determines the intensity of flooding, erosion, transport, deposition of sand layers during storm events including post-depositional preservation may result in unreliable sedimentologic-based prehistoric reconstructions of the frequency and the intensity of storm events. Although his review only covered paralic basins and barrier islands, the framework seems to be conceptually applicable to any low-lying coastal environment. The limitations, however true to some extents, do not diminish the capability of sedimentary and geomorphic products of modern storms as tools in understanding storm impacts to

coastlines in so far as coastal dynamics, long-term evolution, or hazard assessments are concerned (e.g. Nott and Hubbert, 2006; Houser et al., 2008; Williams, 2013).

In the Philippines, despite the high frequency of storms (locally referred to as *bagyo*) there is limited information on the dynamics and impacts of local storm surges. The state agency *PAGASA (Philippine Atmospheric, Geophysical and Astronomical Services Administration)* has a compilation list and a map of the historical storm surge occurrences in the Philippines between 1897 and 2011. But apart from the October 1897 typhoon (Algue, 1898), we lack detailed studies on the nature and local impact of storm surges. To the local coastal communities, little is known about the immediate devastating impacts of storm surge until the Typhoon Haiyan disaster in 2013. Typhoon Haiyan is now considered as the strongest and fastest moving typhoon at landfall not only in the Philippines (Takagi and Esteban, 2016) but also worldwide (Lin et al., 2014). In as much as Typhoon Haiyan was strong, it also generated a storm surge of 5 to 8 m that engulfed the northwestern shores of the Leyte Gulf over a very short period of ~1 hour (Soria et al., 2016). Notably, Typhoon Haiyan's bore-like storm surge is rare compared to the more commonly reported gradual rise inundation associated with similarly intense storm and storm surge (Mikami et al., 2016). In this study, we describe the physical sedimentology of the overwash sediments resulting from the Typhoon Haiyan storm surge at two localities in central eastern Philippines. A separate study by Pilarczyk and others (2016) documented the micropaleontological assemblages contained within the Typhoon Haiyan overwash sediments at our sampling locations.

Typhoon Haiyan provided a unique opportunity to study modern overwash sedimentation across two coastal plains no more than 20 km apart but represent contrasting sedimentological regimes, namely a siliciclastic coast and a mixed siliciclastic-carbonate coast. Given the similar hydrodynamic storm surge conditions between the two sites, we examined the possible influence of local factors such as coastal morphology and sediment source on overwash deposition. In addition, Typhoon Haiyan overwash sediments represent a rare sediment record of an intense landfalling storm with bore-like storm surge. The Haiyan overwash sediments were then compared to other overwash sediments from recent tsunamis and storms in an attempt to identify sedimentological characteristics that could be diagnostic.

3.2. Typhoon Haiyan

Typhoon Haiyan, locally known as Yolanda, was a Category 5 typhoon according to the Saffir-Simpson Hurricane Scale when it made landfall on Tacloban (**Fig. 3.1a**). The most extensive infrastructure damage and highest death toll from Typhoon Haiyan was mainly due to the high storm surge (Tajima et al., 2014; Mas et al., 2015). The storm surge in San Pedro Bay is initially characterized by a sea-level drawdown of ~2 m that exposed wide expanses of the gently sloping subtidal sand flats along the northern shores of the bay (Soria et al., 2016; Chapter 2). Soon after Typhoon Haiyan's landfall in Leyte island, the storm surge came rapidly onshore as a fast-moving wall of water exceeding 5 m high (**Fig. 3.1b**). Wave contributions raised high-water mark indicators to almost 8 m in Tacloban and Palo (Soria et al., 2016). The peak water levels lasted for 30 to 45 minutes before rapidly subsiding within 1 to 2 hours. Within the short inundation duration,

survivor accounts and storm surge simulations corroborate the occurrence of three wave sets (Soria et al., 2016). On the northern shore of San Pedro Bay, storm surge flooding at Basey reached ~800 m inland; whereas, on the western shore near Tanauan, flooding reached up to 2 km inland. The greater inundation of Typhoon Haiyan in Tanauan is primarily due to the low-lying, gently sloping terrain of the coast compared to the relatively irregular topography of raised carbonate platforms and rice paddies on terraced slopes in Basey.

3.3 Study Area

San Pedro Bay is a ~20 km wide by ~25 km long embayment that opens to the larger Leyte Gulf to the south. To the northwest San Pedro Bay narrows into the San Juanico Strait that separates the islands of Leyte and Samar. As such, the tidal pattern in San Pedro Bay is driven by the complex interaction between the mixed semidiurnal-dominated Leyte Gulf and the mixed diurnal-dominated Samar Sea. San Pedro Bay is relatively shallow (maximum water depth of ~ 20 m, average water depth of ~ 10 m) and has an average tidal range of 50 cm (NAMRIA, 1980 *In*: PMSL, 2016).

The coastal landscapes surrounding San Pedro Bay have contrasting morphology. The wide, low elevation (<3m), coastal plains of the western coast consist of beach ridges, a sand spit and patches of mangrove stands. Here, the coastal plains consist primarily of accumulations of unconsolidated siliciclastic sediments sourced from the interior highlands that are composed of Cretaceous ultramafic-mafic igneous rocks capped with pelagic sedimentary sequences and patches of Miocene-Pliocene volcanic centers and sedimentary rocks (Aurelio and Pena, 2002; Suerte

et al., 2005). In contrast, irregularly steep karstic terrains of the Oligocene to Miocene age limestones (Aurelio and Pena, 2002) are found on the northern and eastern shores. Sandy, pocket beaches are found in small embayments and narrow reefs fringe the rocky limestone headlands.

Figure 3.1. Track of Typhoon Haiyan traversing central Philippines (a). Storm surge heights along the coastlines surrounding Leyte Gulf (b).

3.4. Methods

Inland transport and deposition of sediments from Typhoon Haiyan were mapped in San Pedro Bay in January 2014 along four transects on the two different depositional regimes (**Fig. 3.2**). Three of the four transects were located on the siliciclastic coast of Tanauan and the other on the mixed carbonate-siliciclastic coast of Basey. Surveys and sampling were limited to areas that had minimal disturbance by human activities following Typhoon Haiyan. Each transect extended from the shore to the landward limit of Haiyan deposit, the distance of which varied between 400 m in Basey to 1.8 km in Tanauan. Topographic elevations along the transects were determined simultaneously with the high-water mark survey using a Trimble global positioning system (GPS) rover connected via Bluetooth to a Lasercraft XLRic laser range finder (Soria et al., 2016). Geomorphic indicators of beach erosion were also noted such as scouring and exposed roots. We used a handheld GPS to mark all the sampling locations. The transects cover back beach environments including stands of *Nypa fruticans* (a mangrove-associated palm species), patches of grassland, coconut groves, and rice fields. These environments were at elevations between 1 to 3 m above present mean sea level. We sampled the Haiyan deposit along each transect by means of a hand gouge auger or by excavating shallow trenches of ~ 10 cm deep. At all sites, we collected one sediment sample from the Typhoon Haiyan deposit and one sample from the underlying soil for subsequent sediment grain size, and sediment composition analyses.

About 1 g to 2 g of sediment was taken in each sample to determine both the

Figure 3.2. Four transects were surveyed in Basey (b) and Tanauan (c). These are two contrasting sedimentological environments inundated by comparable storm surge heights.

organic and the carbonate content following the loss-on-ignition method by Heiri and others (2001). Another set of subsamples about 1g were set apart for grainsize analysis. Samples were treated with 20% H₂O₂ to remove organics and 15% hydrochloric acid (HCl) to remove carbonate fragments. The carbonate-rich sediments of Basey were not treated with HCl. The samples were rinsed in distilled water before introducing to the Malvern Mastersizer 2000 for grainsize analyses using laser diffraction. The grainsize data were then run through the open-source program GRADISTAT version 8.0 (Blott 2001) to generate statistical grainsize distributions. The fraction of sediment by different category size (e.g. clay, very coarse silt, medium sand) along with the logarithmic (Folk and Ward, 1957) mean, median, mode, sorting, and skewness of each sample were used to establish the vertical and across-shore variations of the Haiyan sediments.

Shoreward of transects So and Ma, we found a sandy depositional landform, from the beach extending landwards to the seaward margin of the mangroves and grass stands burying grasses and mangrove roots. On the beach, berm rebuilding by sheet wash deposition from fair weather waves was evident indicating the initial phase of beach recovery has commenced immediately after typhoon Haiyan. We compared pre- and post-typhoon Haiyan Google Earth™ images accessed through Google Earth Pro to determine whether this landform corresponds to an overwash terrace formed by the storm surge inundation and if it has been modified to some extent since the initial deposition (**Fig. 3.3**).

For a detailed description of the sedimentary features of the Haiyan sediments, a

Figure 3.3. Typhoon Haiyan in Tanauan has caused significant geomorphic changes on a coast located 15 km north of the typhoon track. (a) Pre-Haiyan Google Earth™ image taken on 18 May 2013. (b-c) Post-Haiyan Google Earth™ image show massive destruction on coastal vegetation and housing by storm surge inundation. A washover terrace occur as a sandy surface ~35 m landward of high tide line. d) Coastal vegetation recolonized the beach nearly two years after Typhoon Haiyan.

follow-up field survey was conducted in May 2014. An array of six shallow trenches were excavated in two transects oriented perpendicular to the coast, starting from the terminus of a sandy landform identified on the post-typhoon Haiyan satellite image to about 100 m landward (**Figs. 3.3b and 3.3c**). The trenches were located on the grassland adjacent to transect Ma that at the time of the initial survey had ponded water of about 50 cm deep. The trench samples were labeled as MP to distinguish them from the samples taken using auger along transect Ma. The trenches have varying depths depending on the water table, ranging from 25 to 50 cm from the surface. At each trench, we noted the thickness of the Haiyan deposits, the nature of the basal contact with the underlying landform, and other sediment structures like laminations or apparent grading. Samples from the Haiyan deposits and the pre-Haiyan soil were taken at 1-cm intervals for grainsize analysis. The Haiyan deposits are predominantly coarse grained, with minimal silt or clay. Large organic debris and carbonate shells were picked from the samples using forceps. The samples were rinsed with distilled water to remove the smaller, fibrous organic debris by floatation. The sediments were successively oven dried at 50°C, and about 50g to 100 g of dry subsamples were introduced on the Retsch Technology CAMSIZER® for grainsize analyses. The CAMSIZER® provides non-destructive and rapid grain size and shape distributions for sediments ranging from 20 microns to 30 millimeters by capturing images of falling curtain of sediment at 25 Hz (Moore et al., 2006). The grainsize corresponds to the cross-sectional area of the particles in the image and reported as the diameter of a circle of equivalent area, which is similar to the grainsize measuring principle of the laser particle analyzer (Switzer and Pile, 2015). For the finer grained, pre-Haiyan sediment unit, we followed the same methods described

above for laser particle analysis. The composite grainsize data of the Haiyan deposits and the pre-Haiyan soil were then run through the open-source program GRADISTAT to generate statistical grainsize distributions.

3.5. Results

3.5.1. Beach erosion and post-storm beach recovery

The post-storm environment in Tanauan is reflective of the large-scale beach erosion associated with Typhoon Haiyan. Comparison between pre- and post-Typhoon Haiyan satellite images indicates 10 m to 25 m of erosion from the beach face and berm (**Figs. 3.3a & 3.3b**). Coconut stumps now sit ~10 m seaward of the post-Haiyan beach and re-exhumed organic-rich mangrove soil underlying the unconsolidated beach sands can be found exposed along the beach (**Fig. 3.4**). Surface elevations of the re-exhumed mangrove soil, and the top of the exposed roots of the coconut trees indicate vertical beach erosion of about 1 to 2 m.

A new landform that consists of sandy sediments extends ~ 35 m inland of the high tide line and is visible on Google Earth images following Typhoon Haiyan (**Figs. 3.3b & 3.3c**). The sandy landform terminates along the seaward margin of the mangrove stands in an irregularly undulating and in some areas lobate pattern, characteristic of a washover terrace (Morton and Sallenger, 2003). Immediately after Typhoon Haiyan, however, swash deposition and berm rebuilding indicate to some extent beach recovery (**Fig. 3.5a**). An exploratory trench reveals a laminated sandy beach sequence on the washover terrace (**Fig. 3.5b**). On the laminated beach sequence, there seems to be a fine line between

Figure 3.4. Exposed roots of coconuts trees, coconut stumps on the intertidal zone (a), and re-exhumed organic-rich mangrove soil (b) indicate significant beach erosion following Typhoon Haiyan.

Figure 3.5. Swash actions of waves re-establish a berm on top of the washover terrace (a) strongly indicating immediate beach recovery post-Haiyan in Tanauan. The repeated swash actions deposit laminated sandy beach sequence (b).

depositions from the Haiyan overwash process with that from the initial phase of beach recovery. Recognizing this limitation, we focus our study to the overwash deposits on the back beach environments, which are minimally influenced by marine processes after the storm.

The rapid establishment of the beach system post-Haiyan indicate the availability of nearshore sandy sediments during fair weather conditions along this coast to assist in beach recovery to commence immediately following an intense typhoon. A Google Earth image taken in May 2015 shows that coastal vegetation has colonized the washover terrace; thereby stabilizing this newly aggraded sandy landform from reworking (**Fig. 3.3d**).

3.5.2. Haiyan overwash sediments in Tanauan

3.5.2.a. Transect-scale lateral variation

The Haiyan overwash sediments were identified from the pre-Haiyan soil with varying degree of certainty. On the *Nypa* forest and grasslands within 200 m from the shore, the contact between the Haiyan deposit and the underlying soil was pronounced. The Haiyan overwash sediments are gray to beige, and distinctly different from the dark brown underlying pre-Haiyan soil that commonly contained buried upright grasses or root fragments. On the other hand, the contact between the Haiyan overwash sediments and the underlying soil on the rice paddies greater than 400 m from the shore was very subtle and has started to be obscured by rapid post-typhoon vegetation growth.

The Haiyan overwash sediments on the siliclastic coast of Tanauan display notable across-shore textural and compositional variations, but not necessarily systematic trends (Figs. 3.6a-c). Along each of the transects (Sc, So, and Ma), the Haiyan deposits have variable thickness, thickest accumulations of 5 to 7 cm were consistently found in mangrove stands and depressions (shallow ponds) between 200 to 400 m from the shore. These thick Haiyan sediments are predominantly gray, moderately- to well-sorted, fine to coarse sand that contain low amounts of organic matter (<10%) and carbonate (<1%). Beyond 500 m from the shore, rice paddy fields are blanketed by 1-cm to 3-cm thick silt to very fine sand. The thin sand sheet extends to ~1.6 km inland and are very poorly sorted, and contain relatively higher amounts of organic matter (>10% - 35%) and carbonate (1-2%). Collectively, the overwash sediments less than 400 m from the shore are distinctly coarser grained, better sorted, and containing less organic matter (<10 %) than the overwash sediments found greater than 400 m from the shore. This distinct sedimentologic difference with distance is consistent with the observed change in the assemblage and test size of the foraminifera, and the change in abundance of testate amoebae (Pilarczyk et al., 2016).

3.5.2.b. Trench-scale vertical variation

Slightly on landward terminus of the washover terrace, behind a swale, trenches MP 4 and MP 7 revealed two different sedimentary units that overlie the pre-Haiyan soil surface. In trench MP 4, Unit 1 is a ~10 cm thick accumulation of black, magnetite-rich, medium sand that coarsens upwards (**Fig. 3.7**). The sands of Unit 1 are moderately sorted with sorting values remaining constant at ~0.75

Figure 3.6. On the low-lying, gently sloping coast of Tanauan, the washover sediments display variable thickness, far inland extent, and across-shore textural and compositional variations.

ϕ . Thin planar laminations within the magnetite-rich Unit 1 sand were observed on the across-shore wall of trench MP7 (**Fig. 3.8a**). The planar structure, however, appears wavy on the along-shore trench wall (Fig. 3.7b). The magnetite-rich sand, Unit 1 is overlain by 12-cm thick light gray, coarse sand, Unit 2 (**Figs. 3.7 & 3.8a**). The contact between the two sediment units is very sharp, and for the most part conformable but in one instance erosional (**Fig. 3.8b**). Figure 7 shows the bulk sediment mean grain size, and the gravel fraction show that the base of Unit 2 is characterized by relatively high concentrations of gravel-sized sediments displaying a fining upwards trend. But, at 5 cm from the surface the initial fining upward sequence shifted to a coarsening upward to the surface. In contrast, the vertical grading in trench MP7 is not as complex as in trench MP 4. Figure 3.8c shows the bulk sediment mean grainsize in MP7 indicate a single and consistently coarsening upward sequence. Despite the textural grading trend in grainsize, sorting remains uniform, and the entire sequence is composed of moderately sorted sediments. The laminated, magnetite-rich basal unit (Unit 1) did not persist beyond 50 m from the shore. Inland trenches MP6 and MP1 revealed thinner Haiyan overwash sediments, which consist of light gray, medium sand (**Fig. 3.9**).

Figure 3.7. Trench MP4 reveals two contrasting sand units that buried the pre-Haiyan soil surface. The two sand units are compositionally and texturally different, which were deposited successively between the initial and the final stages of storm surge inundation.

Figure 3.8. The two contrasting sand units in MP4 are consistently seen on the pit walls in trench MP7. The sandy bottom layer, Unit 1 exhibits distinct laminations (a,b). The upper sandy layer, Unit 2 has sharp and erosional contact with Unit1 (b). These two sandy units display overall coarsening upward trend (c) indicating hyperconcentrated, elevated, high-velocity flow.

Figure 3.9. Unstratified sand sheet of Typhoon Haiyan on a section in trench MP 6 (a) and trench MP 1(b).

3.5.3. Haiyan overwash sediments in Basey

Similar to Tanauan, the Haiyan overwash sediments in Basey were identified from the pre-Haiyan soil with varying degree of certainty depending on the coastal environment and distance from the shore. The Haiyan sediments on the coconut grove within 200 m from the shore overlies the light brown, finer-grained pre-Haiyan sediments, blanketed by thin veneer of dark brown, organic-rich soil. The nature of the contact between the Haiyan sediments and the underlying soil, either depositional or erosional is uncertain, but was generally sharp, and very pronounced. Farther inland on the rice paddies, the contact between the slightly lighter colored Haiyan sediments and the darker underlying soil due to higher organics is barely recognizable. Dense re-vegetation on the

rice paddies has obscured the contact within two months after Haiyan's landfall. The Haiyan overwash sediments are beige, poorly-sorted, silt to fine sand that drapes the beach berm, coconut grove and rice fields on the coastal plain nearly 350 m from the shore (**Fig. 3.10**). We observed across-shore variations in deposit thickness, grain size, sorting, skewness, and composition. The thickest deposit was ~ 8 cm and is found 30 m from the shore. The Haiyan deposit thins rapidly landward of the shoreline and varies in thickness from 1 to 4 cm. Except for Ba 15 and Ba 13, the Haiyan sediments deposited on the berm and coconut grove were coarser (very fine to medium sand), better sorted (1 to 2 ϕ), and more finely skewed (0.1 to 0.6 ϕ), compared to the sediments deposited on the rice fields farther inland which are silt-size, very poorly sorted ($>2 \phi$), and coarse skewed (-0.1 to 0.1 ϕ). With the exception of one sample, Ba8, the sediments closer to the shore also contained less organic matter at about 10% compared to the sediments on the rice fields which yielded 15% to 20% organic content. The Typhoon Haiyan deposit contains more than 10 % carbonate within ~200 m from the shore, but sediments beyond 200 m contain consistently low carbonate at ~3 % to 8 %. This seemingly distance-related schange in the sedimentologic character of the overwash sediments is comparable with the distance-related change in the abundance of testate amoebae and small foraminifera on the same transect (Pilarczyk et al., 2016).

Figure 3.10. Topographic variations along the coast of Basey on the most part influenced the thickness and inland extent of the washover sediments. On the other hand, there is no direct relationship with topography and the across-shore textural and compositional variations of the Haiyan deposits.

3.6. Discussion

3.6.1. Haiyan overwash sediments show clear contrasting sedimentology near the shore but show similar sedimentology inland

The Haiyan overwash sediments close to the shores in Tanauan and in Basey exhibit notable differences in sediment composition, sediment textures, and stratification. At Basey, the Typhoon Haiyan sediments are generally characterized by a massive, poorly sorted, fine sand that contained carbonate material ranging from 5 to 24 %, including foraminifera, and fragments of mollusks and corals (Pilarczyk et al., 2016). In contrast, the Typhoon Haiyan sediments from Tanauan are moderately to well-sorted, medium to coarse sand containing very low carbonate concentrations of <3 %. Heavy minerals are relatively abundant and accumulate in layers. Thin planar laminations were also visible within the deposit. The significant disparity in the carbonate content of the Haiyan overwash sediments in Basey and that in Tanauan is indicative of the type of environment of the sediment source. Carbonate sediments are naturally readily available in the mixed carbonate-siliciclastic coast of Basey but rare in the non-carbonate, siliciclastic coast of Tanauan.

Another notable difference between the overwash sediments in Tanauan and in Basey is the landward extent. The overwash sediments along the transects Sc, So, and Ma in Tanauan reached greater distance inland than that of the overwash sediments along transect Ba in Basey. The inland penetration of overwash sediments is consistent with the inundation distance in these two sites, which is in turn mainly controlled by topography. The low-lying (1 to 2 m), gently sloping

terrain in Tanauan promoted greater inundation distance to ~2 km, and greater inland penetration of overwash sediments to ~1.6 km. The relatively irregular topography of raised carbonate platforms (3 m) and rice paddies on terraced slopes in Basey has limited inland inundation to ~800 m, and inland overwash sedimentation reaching to ~350 m. We can argue that given similar inundation characteristics, local topography exerts significant control on the landward extent of the deposits.

In both sites, however, the most inland Haiyan overwash sediments share commonalities in grainsize, texture, and composition. The sediments are very poorly sorted, ranging from silt to very fine sand, and contain a higher amount of organic matter ranging from 10 to 35 %, and lower carbonate at < 5%.

The Haiyan overwash sediments occur as anomalous sand layers over muddy sediments only to a limited distance of 200 m (Basey) to 400 m (Tanauan) from the shore such as in the coconut grove and mangrove areas. Beyond 200 m (Basey) to 400 m (Tanauan), sedimentologic criteria barely discriminate overwash sediments from pre-storm sedimentary sequence. As such, the textural definition of overwash sediments as “anomalous sand layer” may not be necessarily always the case on the inland portions of inundation and overwash sedimentation (Williams, 2009). Similarly, the textural and compositional signatures inherent of the local geology, which are evident on the overwash sediments closer to the shore, seemed to be indistinct inland.

3.6.2. Haiyan overwash sediments came from multiple sources.

The possible source of Haiyan overwash sediments was inferred from stratigraphic features (this study) and complemented with micropaleontological evidences (Pilarczyk et al., 2016). For example in Tanauan, exposed coconut roots and re-exhumed mangrove soils along the coast strongly indicate extensive beach erosion. The eroded sediments from the beach were most likely transported inland and then deposited as overwash sediments. The local scouring of mangroves and the relatively high organic content of the overwash sediments found > 400 m from the coast may suggest that terrestrial environments are also potential sediment source of overwash sedimentation farther inland. Terrestrial source is also strongly indicated by the abundance of freshwater testate amoebae on the underlying pre-Haiyan soils taken on the rice fields, ponds, and grassy areas as well as on the Haiyan overwash sediments (Pilarczyk et al., 2016). In addition, Pilarczyk and others (2016) claimed that unaltered, planktic and benthic foraminifera assemblages on the Haiyan overwash sediments particularly on the Basey coast suggest contribution from offshore sediments. Foraminiferal assemblages of Hurricane Ike's overwash sediments have also pointed to multiple sediment sources including offshore, nearshore, sub- to inter-tidal, and marsh environments (Hawkes and Horton, 2012). The relative contributions of the offshore, beach, and terrestrial environments to the overwash sedimentation of Typhoon Haiyan have yet to be quantified.

3.6.3. Sedimentary structures are consistent with a turbulent, high-velocity storm surge flow

The thick Haiyan overwash sediments display parallel laminations and overall coarsening upward trends (**Figs. 3.8 & 3.9**). Planar laminations in coastal settings are primarily attributed to the repeated inundation by storm waves (e.g. Sedgwick & Davis, 2003; Switzer & Jones, 2008). In other instances, planar lamination or bedding in sandy sediments is indicative of the upper flow regime (UFR) conditions of a unidirectional, turbulent, high velocity flow (Cheel, 1990; Fielding, 2006). Actual field measurements of storm overwash with a 0.7m-deep surge in Assatuague Island on the U.S. Atlantic coast during Category 1 hurricanes yielded overwash flow velocities about 2 ms^{-1} to 3.5 ms^{-1} (Leatherman, 1976; Fisher and Stauble, 1977). Comparably, a 1-m deep Typhoon Haiyan flood on the coast 15 km to the south of Tanauan has estimated flow velocities within 3 to 4 ms^{-1} (Ramos et al., unpublished report). Deeper surge flood of at least 3 m in Tacloban yielded velocities to as high as 7 ms^{-1} , but mainly due to channelized flows on the streets in an urban setting (Tagaki et al., 2016). The flow velocities in Tanauan could be within the range between 3 to 7 ms^{-1} . Ramping up of surge velocity either upon the arrival of wave or backflow was claimed to produce coarsening upward grainsize trend of overwash sediments associated with similarly intense hurricanes such as Hurricane Rita and Hurricane Ike (Horton et al., 2009; Hawkes and Horton, 2012). The laminated, overall coarsening upward Haiyan overwash sediments could be the sum of all factors including repeated inundation, turbulent, and high velocity flow, which is consistent with the bore-type storm surge of

Typhoon Haiyan. The slight fining upward trends within the overall coarsening sequence in trench MP 4 may signify local variation or flow small-scale velocity fluctuations during the inundation process (Hawkes and Horton, 2012).

3.6.4. Haiyan overwash sediments exhibit similar features with other extreme marine inundation deposits

Typhoon Haiyan's bore-like storm surge appears uncommon among the recent notable storm surges worldwide (Mikami et al., 2016). Table 3.1 shows that amongst the similarly intense modern storms, Typhoon Haiyan storm surge has exceptionally short flooding duration resulting in a steep storm surge profile (Soria et al., 2016). It is not surprising then that flow velocities of the Haiyan surge were at 3 to 7 ms⁻¹, which are comparable to tsunami flooding in similar gently sloping coastal plains (**Table 3.2**). Perhaps this apparent similarity of Haiyan's storm surge to tsunami flooding has influenced overwash sedimentation such that the sedimentary features are in the most part equivocal of either storm or tsunami deposits. The sharp, depositional contact, planar stratification, coarsening upward sequence, and overall but not systematic landward fining of Haiyan overwash sediments can be seen in both storm (**Table 3.1**) or tsunami deposits (**Tables 3.2 to 3.4**). The resemblance of overwash sediments from intense storms with that from tsunamis has been consistently raised as a major concern in pre-historical reconstructions (e.g. Sugawara et al., 2008; Williams, 2009). We reaffirm this concern in so far as Haiyan overwash sediments will serve as a benchmark for sedimentological characterization of modern storm deposits in the Philippines, and particularly so because most of the Philippine coastlines are exposed to both

Table 3.1. Comparison of the hydrodynamics and sedimentary signatures of the Typhoon Haiyan storm surge, and other recent storms of comparable intensity.

Storm Surge	Tropical Cyclone ID	Typhoon Haiyan	Typhoon Haiyan	Cyclone Yasi	Hurricane Ike	Hurricane Rita	Hurricane Katrina	Hurricane Isabel	Hurricane Carla
	Event Date	November 2013	November 2013	February 2011	September 2008	September 2005	August 2005	September 2003	September 1961
Meteorology	Peak intensity	Cat 5 (895 hPa; ~314 kph)	Cat 5 (895 hPa; ~314 kph)	Cat 5 (929 hPa ~205kph)	Cat 4 (231 kph)	Cat 5 (897 hPa; 288 kph)	Cat 5 (902 hPa; 280 kph)	Cat 4 (>270 kph)	Cat 5 (280 kph)
	Intensity at landfall	Cat 5 (~296 kph)	Cat 5 (~296 kph)	Cat 5	Cat 2 (175 kph)	Cat 3 (190 kph)	Cat 3 (920 hPa; 200 kph)	Cat 2	Cat 5 (280 kph)
	Translation speed	41 kph	41 kph		20 kph	19 kph	24 kph		
	References	Tagaki et al., 2015	Tagaki et al., 2015	Boughton et al., 2011	Doran et al., 2009; Morton & Barras, 2011	Williams, 2009; Morton & Barras, 2011	Morton et al., 2007		Morton et al., 2007
Hydrodynamic conditions	Maximum water level (m)	5 to 6 m	5 to 6 m	3 to 6 m	> 3 m	4 to 5 m	~7 m	2.7 m (open-coast); >3m to 4 m	
	Flow depth (m)	3 to 4 m	3 to 4 m		1 to 4 m	at least 3 m	5 to 6 m	1.25 m (landward limit overwash deposition)	1 to 1.5 m
	Inundation duration	~1 hour	~1 hour	12 hrs (peak inundation lasting for 2 hrs)	2 days of flooding	6 hours	~24 hrs	9 hrs (with peak inundation lasting for 5 hrs)	24 hrs
	Inundation distance	2 km	800 m	500 m	25 km	35 km	725 to 780 m (< 1 km)	15 to 30 km	15 to 35 km
Local setting	Distance from storm eye (zone of max winds)	15 km	30 km	20-40 km	~70 km		40-50 km	55 km	60 km
	References	Soria et al., 2016	Soria et al., 2016	Boughton et al., 2011; Nott et al 2013	Williams, 2010; Doran et al., 2009	Williams, 2009; McGee et al., 2013	Fritz et al., 2007; Horton et al., 2009	Morton et al., 2007	Morton et al., 2007
	Locality	Tanauan, Leyte	Basey, Samar	south of Cairns, northeast Queensland, Australia	Galveston and San Luis islands, Texas	McFaddin National Wildlife Refuge, Texas	Ocean Spring and St. Andrews, Mississippi	Hatteras Is., North Carolina	Matagorda Peninsula, Texas
	Coastal geomorphology	sandy beach coastal plain	sandy beach	sandy beach ridge plains	barrier islands (ridge and swale topography)	palustrine marshes and beach ridges separated by lo-lying, brackish lakes bounded by sandy beach with low foredunes	salt marsh	barrier island with dunes	barrier island
Sedimentary textures and structures	Ground surface elevation, m (afl)	1.5 to 2 m	2 to 3 m	ridge crests at higher than 4 to 5 m	1 to 2 m	0.5 to 1 m (ridges)	1.7 to 5 m	dunes at 3 to 4 m	
	Vertical grading of entire deposit	coupled fining and coarsening upward near the shore	no analysis	fining upward with fine-skewed trends	no analysis	coarsening upwards	massive	cycles of upward coarsening or upward fining	upward fining
	Lateral grading	overall landward fining	overall landward fining	landward fining in one site, no systematic trend in another site	thinning and fining inland	inland fining only on the distal deposit	no transect data	landward fining	
	Sorting	moderate to well-sorted	poorly sorted	not reported	not reported	well sorted	not reported	well sorted	poorly sorted (proximal) to well sorted (distal) at least 25 to 30 cm
Transect Scale	Thickness	2 cm (distal) 10-20 cm (proximal)	2 to 8 cm	5 cm (87 m from shore); 20-50cm (50 m from the shore)	51-64 cm (within 200 m); 3-10 cm (>200 m)	2 to 50 cm	9 to 13 cm	40-97 cm (2 m thick overwash terrace)	
	Sedimentary structures	subhorizontal planar laminae on thicker deposits	massive	horizontal planar laminations, basal coarse grained sediments	ripple marks on the surface	forest laminae (proximal); planar laminae (distal)	not indicated	subhorizontal planar stratification	planar parallel laminae
	Basal contact	sharp, depositional	sharp, depositional	sharp, erosional	sharp, depositional with little or no erosion	sharp, erosional	sharp, erosional	sharp	sharp, erosional and depositional
	Cross-shore geometry	highly variable thickness but generally thick in depressions	overall but not systematic landward thinning	highly variable thickness	fining and thinning landward	landward thinning	no transect data	narrow thick terrace deposits terminating in avalanche faces	narrow thick terrace deposits, moderately thin broad fans, landward thinning
Transect Scale	Landward extent	1600 m	350 m	up to 87 m	2700 m	400 to 500 m	not reported	up to 250 m	average at 193 m, up to 980 m
	References	This Study	This Study	Nott et al., 2013	Williams, 2010	Williams, 2009	Horton et al., 2009	Morton et al., 2007	Morton et al., 2007

Table 3.2. Comparison of the hydrodynamics and sedimentary signatures of the Typhoon Haiyan storm surge, and two recent tsunami deposits from the 2011 Japan tsunami, and the 2006 Indonesia tsunami.

Hydrodynamic conditions	2013 Typhoon Haiyan storm surge			2011 Tohoku-oki Tsunami		2006 Western Java Tsunami
	Maximum surge height or tsunami height, m absl	5 to 6 m	5 to 6 m	6 to 20 m	10 m	
Flow depth (m, above ground surface)	3 to 4 m	3 to 4 m	3 to 4 m	2 to 6 m	5 m	5 m
Inundation duration, hours	~ 1 hour	~ 1 hour	~ 1 hour	14 significant waves offshore with coastal flooding lasting for at least 3 hrs*		
Inundation distance	2 km	800 m	800 m	600 m to 4 km	4 km	755 m
Water Velocity (m/s)	3 to 4 m/s*			~2m/s (2km from the coast); 6 to 8 m/s (within 1 km)**		
References	Soria et al., 2016 *Famos et al., unpublished report	Soria et al., 2016		Abe et al., 2012; *Sugawara & Goto, 2012; **Hayashi & Koshimura, 2012		Moore et al., 2011
Locality	Tanauan, Leyte	Basey, Samar		Sendai Plain	Arahama coast, Sendai Plain	Adipala, central Java, Indonesia
Coastal geomorphology	sandy beach with berms and coastal plain at 1.5 to 2 m asl	sandy beach at 2 to 3 m asl		sandy beach ridge and swales; with coastal dikes	coastal lowland with beach ridges	beach ridge-swale plain
Ground surface elevation, m (asl)	1.5 to 2 m	2 to 3 m		< 5 m	0 to 3 m	0.5 to 7 m
Vertical grading of entire deposit	normal and inverse grading	no analysis		sand-dominated base capped by mud layer	normal grading	coarsening then fining upward in 2 distinct pulses
Lateral grading	overall landward fining	overall landward fining		sand-dominated (up to 2 km); mud-dominated (>2 km)	landward fining	overall landward fining
Thickness (cm)	2 cm (distal) 10-20 cm (proximal)	2 to 8 cm		10 to 40 cm (1 to 2 km from the shore); sub-mm to 5 cm (>2 km)	<10 cm	10 to 20 cm (70 m from shoreline), 1 mm to 1.5 cm (>300 m)
Sedimentary structures	subhorizontal planar laminae on thicker deposits	massive		mostly massive, at some sites parallel laminae and rip-up clasts are present	massive sand, parallel laminae, rip-up clasts	planar laminae
Basal contact	sharp, depositional	sharp, depositional		sharp, rip-up clasts indicates erosion	sharp, erosional	sharp, minimal erosion
Cross-shore geometry	highly variable thickness but generally thick in depressions	overall but not systematic landward thinning		landward thinning	overall but not systematic landward thinning	overall but not systematic landward thinning (thickest within 300 m from shore)
Landward extent	1600 m	350 m		600 m to 4 km	~4 km	720 m
References	This Study	This Study		Abe et al., 2012	Takashimizu et al., 2012	Moore et al., 2011

Table 3.3. Comparison of the hydrodynamics and sedimentary signatures of the Typhoon Haiyan storm surge and the 2004 Indian Ocean tsunami in Indonesia, Malaysia, India, and Sri Lanka.

Sedimentary textures and structures	2013 Typhoon Haiyan storm surge		2004 Indian Ocean Tsunami					
	Maximum surge height or tsunami height, m absl	5 to 6 m	5 to 6 m	4 m	2 m	6.5 to 11 m	5 m	
	Flow depth (m, above ground surface)	3 to 4 m	3 to 4 m	> 25 m		2 to 4 m	4-5 m	
	Inundation duration, hours	~ 1 hour	~ 1 hour		1 hr 40 min (Bird et al., 2007)	3 waves at 5-min interval in Kalpakkam coast		
	Inundation distance	2 km	800 m	450 m	250 m	1.5 km	900 m	
	Water Velocity (m/s)	3 to 4 m/s* (Ramos et al., unpublished)		10 m/s			> 3 m/s	
	References	Soria et al., 2016	Soria et al., 2016	Moore et al., 2006	Hawkes et al 2007	Hawkes et al 2007	Srinivasulu et al., 2007; Morton et al., 2008 Switzer et al., 2012	
Local Setting	Locality	Tanauan, Leyte	Basey, Samar	Banda Aceh, Indonesia	Langkawi, Malaysia	Penang, Malaysia	Kalpakkam and Nagipattinam, Southeast India	Yala, Sri Lanka
	Coastal geomorphology	sandy beach with berms and coastal plain at 1.5 to 2 m asl	sandy beach at 2 to 3 m asl	narrow beaches bounded by headlands 4 to 35 m	narrow, steep beach with intertidal zone	narrow, steep beach with intertidal zone	narrow beaches with coastal dunes	narrow sandy beaches bounded by sand dunes
	Ground surface elevation, m (asl)	1.5 to 2 m	2 to 3 m	0.1 to 3 m	0.5 to 3 m	0.5 to 3 m	< 5 m	0 to 4.5 m
	Vertical grading of entire deposit	normal (fining upwards) and inverse (coarsening upwards) grading	no analysis	massive units exhibiting normal grading	1 fining upward sequence	coarsening upward sequence	massive but graded units, coarsening and fining upward; dominantly fining	overall but not systematic fining upward
Trench Scale	Lateral grading	overall landward fining	overall landward fining	landward fining			inward in Kalpakkam landward fining	highly variable no predominant pattern; either coarsening or fining, but consistently poorer sorting landwards
	Thickness (cm)	2 cm (distal) 10-20 cm (proximal)	2 to 8 cm	5 to 20 cm (within 50 m to 400 m from the beach)	50 23 cm	15 cm	>10 cm to 40 cm	20 cm (within 150 m from beach) highly variable 2.5 to 22 cm (> 150m)
	Sedimentary structures	subhorizontal planar laminae on thicker deposits	massive	planar lamination, with 1 section exhibiting cross-stratification	contain shell fragments		parallel lamination on the basal unit, massive middle unit, and complex bedding such as cross lamination and micro bars on the uppermost unit	planar, horizontal to subhorizontal laminae
	Basal contact	sharp, depositional	sharp, depositional	sharp, minimal erosion	sharp	sharp	sharp	sharp, erosional
Transect Scale	Cross-shore geometry	highly variable thickness but generally thick in depressions	overall but not systematic landward thinning	sand deposition started at 50 m to 200 m from the beach, thick on topographic lows			Kalpakkam: variable thickness and can be patchy near the coast then tapers inland to nearly tabular, Nagipattinam: landward thinning	overall but not systematic landward thinning, thick deposits in topographic lows
	Landward extent	1600 m	350 m	400 m			350 m	400 m
References	This Study	This Study	Moore et al., 2006	Hawkes et al 2007	Hawkes et al., 2007	Srinivasulu et al., 2007; Switzer et al., 2012	Morton et al., 2008	

Table 3.4. Comparison of the hydrodynamics and sedimentary signatures of the Typhoon Haiyan storm surge and the 2004 Indian Ocean tsunami in Thailand.

Hydrodynamic conditions		2013 Typhoon Haiyan storm surge		2004 Indian Ocean Tsunami			
Maximum surge height or tsunami height, m absl	5 to 6 m	5 to 6 m	6 to 10 m	20 m	8 m	9 m	6 m
Flow depth (m, above ground surface)	3 to 4 m	3 to 4 m	2 m to 6 m				4 m to 5 m
Inundation duration, hours	~ 1 hour	~ 1 hour					
Inundation distance	2 km	800 m		2 km	1 km to 2 km	464 m	> 52 m
Water Velocity (m/s)	3 to 4 m/s* (Ramos et al., unpublished)						
References	Soria et al., 2016	Soria et al., 2016	Hori et al., 2007	Jankaew et al., 2008	Hawkes et al 2007	Hawkes et al 2007	Hawkes et al 2007
Locality	Tanauan, Leyte	Basey, Samar	Nam Khem and Khao Lak, Thailand	Phra Thong Island, Thailand	Khao Lak, Thailand	Phi Phi Don, Thailand	Koh Lanta, Thailand
Coastal geomorphology	sandy beach with berms and coastal plain at 1.5 to 2 m asl	sandy beach at 2 to 3 m asl	low-lying narrow coastal plain	beach-ridge plain	pocket beach in between limestone headlands	pocket beach in between limestone headlands	pocket beach in between limestone headlands
Ground surface elevation, m (asl)	1.5 to 2 m	2 to 3 m	4 to 5 m		< 7 m	0.2 to 4 m	0.1 to 3 m
Vertical grading of entire deposit	normal and inverse grading	no analysis	multiple normal grading	overall upward fining	multiple fining upward sequences separated by med to coarse sand layers	2 fining upward sequences	1 fining upward sequence
Lateral grading	overall landward fining	overall landward fining	no clear trend, coarser grained occur within 600 m from shoreline, finer sediments occur landward				
Thickness (cm)	2 cm (distal) 10-20 cm (proximal)	2 to 8 cm	>20 to 33 cm (topographic lows), <5 cm topographic highs	5 to 20 cm	15 cm	11 cm	30 cm
Sedimentary structures	subhorizontal planar laminae on thicker deposits	massive	thin, planar	horizontal bedding			shell fragments present, asymmetrical current ripples
Basal contact	sharp, depositional	sharp, depositional	sharp, erosional		abrupt and erosional	sharp and undulating	sharp
Cross-shore geometry	highly variable thickness but generally thick in depressions	overall but not systematic landward thinning					
Landward extent	1600 m	350 m	1.1 km (bounded by scarps and hills)	>1 km < 2km			
References	This Study	This Study	Hori et al., 2007	Jankaew et al., 2008	Hawkes et al., 2007	Hawkes et al., 2007	Hawkes et al., 2007
Sedimentary textures and structures		Trench Scale					
Transect Scale		Transect Scale					

storms and tsunamis.

3.7. Conclusion

We described the geomorphic and sedimentologic imprints left by Typhoon Haiyan's storm surge on the shores of Leyte Gulf. We studied the overwash sedimentation across two coastal plains no more than 20 km apart, but representing contrasting sedimentological regimes, namely a siliciclastic coast of Tanauan and a mixed siliciclastic-carbonate coast of Basey. Despite the similar storm surge conditions in Tanauan and Basey, Typhoon Haiyan left clearly contrasting sediments underscoring the effect of local geology. On the mixed siliciclastic-carbonate coast of Basey, the Haiyan overwash sediments are carbonate-rich, poorly-sorted, silt to fine sand. In contrast, on the siliciclastic coast of Tanauan, the Haiyan overwash sediments are carbonate-poor, predominantly gray, moderately- to well-sorted, fine to coarse sand. But this contrasting sedimentology is only evident on the overwash sediments deposited within 300 m from the shore in Basey, and 400 m from the shore in Tanauan. Grainsize and compositional signatures of the most inland overwash sediments are similar in both sites and also are indistinct from the pre-Haiyan sediments. As such, the textural definition of overwash sediments as "anomalous sand layer" may not be necessarily always the case on the inland portions of inundation and overwash sedimentation.

Haiyan overwash sediments in Basey and Tanauan also illustrate that as with inundation distance, local topography also exerts significant control on the landward extent of overwash sedimentation. The low-lying flat terrain in Tanauan promoted greater inland extent of the Haiyan sediments, whereas the relatively

irregular topography of raised carbonate platforms and rice paddies on terraced slopes in Basey limited landward overwash sedimentation.

In Tanauan, the Haiyan overwash sediments deposited within 100 m from the shore exhibits thin parallel to undulating laminations and overall coarsening upward trends. The laminated, overall coarsening upward Haiyan overwash sediments could be the sum of all factors including repeated inundation, turbulent, and high velocity flow, which are consistent with the bore-type storm surge of Typhoon Haiyan.

The Haiyan storm surge left overwash sediments on the shores of Basey and Tanauan that exhibit similar features to overwash sediments of comparably intense storms and storm surges elsewhere. Notably, Haiyan overwash sediments also show resemblance to recent tsunami deposits. Planar stratification, coarsening upward sequence, overall but systematic landward fining, and sharp, depositional to erosional basal contact of the Haiyan overwash sediments are equivocal as they are commonly found in both recent storm and tsunami deposits.

Overall we presented clear evidences that the interaction between hydrodynamic conditions and the local geology strongly influence inland sedimentation during extremely strong storms. However, we did not found specific sedimentological characteristics of Haiyan overwash sediments that are diagnostic from other overwash deposits. This study underscores that sedimentological characteristic alone might not yield conclusive evidence to distinguish a storm from a tsunami overwash deposit.

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References

- Abe, T., Goto, K., Sugawara, D., 2012. Relationship between the maximum extent of tsunami sand and the inundation limit of the 2011 Tohoku-oki tsunami on the Sendai Plain. *Sedimentary Geology* 282, 142–150.
- Algué, J., 1898: El baguio de Samar y Leyte, 12-13 de Octubre de 1897, Manila Observatory, 1-74.
- Andrade, C., M.C. Freitas, J. Moreno, S.C. Craveiro. 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. *Marine Geology* 210, 339–362.
- Aurelio, M. A, Peña, R. E., 2002. Geology and mineral resources of the Philippines, Vol. 1., Department of Environment and Natural Resources Mines and Geosciences Bureau, Philippines. 277-300.
- Blott, S.J. Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface*

Processes and Landforms 26,1237-1248. GRADISTAT Program.

Downloaded at <http://www.kpal.co.uk/gradistat.html>

- Borrero, J. C., Synolakis, C. E., Fritz, H., 2006. Northern Sumatra Field Survey after the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami. *Earthquake Spectra* 22(S3), S93–S104.
- Boughton, G.N., Henderson, D.J., Ginger, J.D., Holmes, J.D., Walker, G.R., Leitch, C.J., Somerville, L.R., Frye, U., Jayasinghe, N.C., Kim, P.Y., 2011. Tropical Cyclone Yasi: Structural damage to buildings. Technical Report No. 57. James Cook University pp. 1-15.
- Buynevich, I.V., Fitzgerald, D.M., Van Heteren, S., 2004. Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. *Marine Geology* 210, 135–148.
- Cheel, R. J. 1990. Horizontal lamination and the sequence of bed phases and stratification under upper-flow-regime conditions. *Sedimentology* 37, 517–529.
- Donnelly, J.P., Butler, J., Roll, S., Wengren, M., Webb, T., III, 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. *Marine Geology* 210, 107–121.
- Doran, K. S., Plant, N. G., Stockdon, H. F., Sallenger, A. H., Serafin, K. A., 2009, Hurricane Ike: observations of coastal change: U.S. Geological Survey Open-File Report 2009-1061.
- Fielding, C. R. 2006. Upper flow regime sheets, lenses and scour fills: extending the range of architectural elements for fluvial sediment bodies. *Sedimentary Geology* 190, 227–240.
- Fisher, J.S. and Stauble, D.K., 1978. Washover and dune interaction on a barrier island. Proceedings Coastal Zone '78 (San Francisco, California, ASCE). pp. 1611-1618.
- Folk, R.L., W.C. Ward. 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27, 3–26.

- Fritz, H. M., Borrero, J. C., Synolakis, C. E., Yoo, J., 2006. 2004 Indian Ocean tsunami flow velocity measurements from survivor videos, *Geophysical Research Letters* 33, L24605, doi:10.1029/2006GL026784.
- Fritz, H.M., Blount, C., Sokoloski, R., Singleton, J., Fuggle, A., McAdoo, B.G., Moore, A., Grass, C., Tate, B., 2007. Hurricane Katrina Storm surge distribution and field observations on the Mississippi barrier islands. *Estuarine, Coastal and Shelf Sciences* 74 (1–2), 12–20. doi:10.1016/j.ecss.2007.03.015.
- Hawkes, A.D., Bird, M., Cowie, S., Grundy-Warr, C., Horton, B., Tan Shau Hwai, A., Law, L., Macgregor, C., Nott, J., Eong Ong, J., Rigg, J., Robinson, R., Tan-Mullins, M., Tiong Sa, T., Zulficar, Y., 2007. The sediments deposited by the 2004 Indian Ocean Tsunami along the Malaysia–Thailand Peninsula. *Marine Geology* 242, 169–190.
- Hawkes, A.D., Horton, B.P., 2012. Sedimentary record of storm deposits from Hurricane Ike, Galveston and San Luis Islands, Texas. *Geomorphology* 171–172, 180–189.
- Hayashi, S., Koshimura, S., 2012. Measurement of the 2011 Tohoku tsunami flow velocity by the aerial video analysis. *Journal of JSCE, Series B2 (Coastal Engineering)* 68, 366–370.
- Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability. *Journal of Paleolimnology* 25, 101–110.
- Hori, K., Kuzumoto, R., Hirouchi, D., Umitsu, M., Janjirawuttikul, N., Patanakanog, B. 2007. Horizontal and vertical variation of 2004 Indian tsunami deposits: an example of two transects along the western coast of Thailand. *Marine Geology* 239, 163–172.
- Horton, B.P., Rossi, V., Hawkes, A.D., 2009. The sedimentary record of the 2005 hurricane season from Mississippi and Alabama coastlines. *Quaternary International* 195, 15–30.
- Houser, C., Hapke, C., Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms.

Geomorphology 100, 223–240.

Jaffe, B.E., Borrero, J.C., Prasetya, G.S., Peters, R., McAdoo, B., Gelfenbaum, G., Morton, R., Ruggiero, P., Higman, B., Dengler, L., Hidayat, R., Kingsley, E., Kongko, W., Lukijanto, Moore A., Titov, V., Yulianto, E., 2006. Northwest Sumatra and offshore islands field survey after the December 2004 Indian Ocean Tsunami. *Earthquake Spectra* 22, 105–135.

Jankaew, K., Atwater, B.F., Sawai, Y., Choowong, M., Charoentitirat, T., Martin, M.E., Prendergast, A., 2008. Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. *Nature* 455, 1228–1231.

Leathermann, S.P., Williams, A. T., 1977. Lateral textural grading in overwash sediments. *Earth Surface Processes* 2, 333–341.

Leathermann, S.P., 1981. Overwash processes. Benchmark papers in Geology, Vol. 58. Hutchinson Ross Publishing Co., USA. 376 pp.

Lin, I.-I., Pun, I.-F., and Lien, C.-C., 2014. “Category-6” supertyphoon Haiyan in global warming hiatus: Contribution from subsurface ocean warming. *Geophys. Res. Lett.* 41, 8547–8553 doi:10.1002/2014GL061281.

Liu, K.-b., Fearn, M. L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* 21, 793–796.

Mas, E., J. Bricker, S. Kure, B. Adriano, C. Yi, A. Suppasri, and S. Koshimura, 2015: Field survey report and satellite image interpretation of the 2013 Super Typhoon Haiyan in the Philippines. *Nat. Hazards Earth Syst. Sci.* 15, 805–816, doi:10.5194/nhess-15-805-2015.

McGee, B. D., Goree, B. B., Tollett, R. W., Woodward, B. K., and Kress, W. H., 2013. Hurricane Rita Surge Data, Southwestern Louisiana and Southeastern Texas, September to November 2005. LC11. U.S. Geological Survey. <http://pubs.usgs.gov/ds/2006/220/index.htm#elevsurveys> accessed on 6 May 2016.

Mikami, T., Shibayama, T., Takagi, H., Matsumaru, R., Esteban, M., Thao, N.D., De Leon, M., Valenzuela, V.P., Oyama, T., Nakamura, R., Kumagai, K., Li, S., 2016. Storm surge heights and damage caused by the 2013 Typhoon Haiyan along the Leyte Gulf coast. *Coastal Engineering Journal* 58 (1), doi:

10.1142/S0578563416400052.

- Monecke, K., Finger, W., Klarer, D., Kongko, W., McAdoo, B.G., Moore, A.L., Sudrajat, S.U., 2008. A 1,000-year sediment record of tsunami recurrence in northern Sumatra. *Nature* 455, 1232–1234.
- Moore A., Goff, J., Mc Adoo, B. G., Fritz, H. M., Guzman, A., Kalligeris, N., Kalsum, K., Susanto, A., Suteja, D., Synolakis, C. E., 2011. Sedimentary deposits from the 17 July 2006 Western Java Tsunami, Indonesia: Use of grain size analyses to assess tsunami flow depth, speed, and traction carpet characteristics. *Pure Appl. Geophys.* 168, 1951–1961.
- Moore, A., Nishimura, Y., Gelfenbaum, G., Kamataki, T., Triyono, R., 2006, Sedimentary deposits of the 26 December 2004 tsunami on the northwest coast of Aceh, Indonesia: *Earth, Planets, and Space* 58, 253-258.
- Morton, R.A., Barras, J.A., 2011. Hurricane impacts on coastal wetlands: a half-century record of stormgenerated features from southern Louisiana. *Journal of Coastal Research* 27(6A), 27–43.
- Morton, R.A., Gelfenbaum, G. and Jaffe, B.E. 2007: Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology* 200, 184–207.
- Morton, R.A., Goff, J.R., Nichol, S.L., 2008. Hydrodynamic implications of textural trends in sand deposits of the 2004 tsunami in Sri Lanka. *Sedimentary Geology* 207, 56–64.
- Morton, R.A., Sallenger, A.H., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research* 19, 560–573.
- Nott, J., Chague-Goff, C., Goff, J., Sloss, C., Riggs, N., 2013. Anatomy of sand beach ridges: Evidence from severe Tropical Cyclone Yasi and its predecessors, northeast Queensland, Australia, *Journal of Geophysysical Research: Earth Surface* 118, 1710–1719, doi:10.1002/jgrf.20122.
- Nott, J., Hubbert, G., 2005. Comparisons between topographically surveyed debris lines and modelled inundation levels from severe tropical cyclones Vance and Chris, and their geomorphic impact on the sand coast. *Australian Meteorological Magazine* 54, 187-196.

- Otvos, E.G., 2011. Hurricane signatures and landforms—toward improved interpretations and global storm climate *chronology*. *Sedimentary Geology* 239, 10–22.
- Pilarczyk, J.E., Horton, B. P., Soria, J. L. A., Switzer, A. D., Siringan, F., Fritz, H. M., Khan, N. S., Ildefonso, S., Ramos, R., Doctor, A. A., Garcia, M. L., 2016. Micropaleontology of the 2013 Typhoon Haiyan overwash sediments from the Leyte Gulf, Philippines. *Sedimentary Geology* 339, 104-114.
- Permanent Service on Mean Sea Level, PMSL accessed on 16 February 2016. <http://www.psmsl.org/data/obtaining/stations/664.php>.
- Sedgwick, P. E., Davis, R. A. Jr., 2003. Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. *Marine Geology* 200, 31-48.
- Soria, J.L.A., Switzer, A.D., Villanoy, C.L., Fritz, H.M., Bilgera, P.H.T., Cabrera, O.C., Siringan, F.P., Yacat-Sta. Maria, Y., Ramos, R.D., Fernandez, I.Q., 2016. Repeat storm surge disasters of Typhoon Haiyan and its 1897 predecessor in the Philippines. *Bulletin of the American Meteorological Society* 97(1), 31-48. doi, 10.1175/BAMS-D-14-00245.1
- Srinivasalu, S., Thangadurai, N., Switzer, A. D., Ram Mohan, V., Ayyamperumal, T. 2007. Erosion and sedimentation in Kalpakkam (N Tamil Nadu, India) from the 26th December 2004 tsunami. *Marine Geology* 240, 65–75.
- Suerte, L.O., Yumul, G.P.Jr., Tamayo, R.A.Jr., Dimalanta, C.B., Zhou, M.-F., Maury, R.C., Polvé, M., Balce, C.L., 2005. Geology, Geochemistry and U-Pb SHRIMP age of the Tacloban Ophiolite Complex, Leyte (Central Philippines): Implications for the existence and extent of the Proto-Philippine Sea Plate. *Resource Geology* 55(3), 207-216.
- Sugawara, D., Goto, K., 2012. Numerical modeling of the 2011 Tohoku-oki tsunami in the offshore and onshore of Sendai Plain, Japan. *Sedimentary Geology* 282, 110–123.
- Sugawara, D., Minoura, K., Imamura, F., Tsunamis and tsunami sedimentology. In: Shiki, T. et al. (Eds.) *Tsunamiites-features and implications*. Elsevier B.V., pp. 9-49.

- Switzer, A.D., B.G. Jones , 2008. Set-up, deposition and sedimentary characteristics of two storm overwash deposits, Abrahams Bosom Beach, eastern Australia. *Journal of Coastal Research* 24–1A, 189–200.
- Switzer, A.D., and J. Pile, 2015. Grain size analysis. In: Shennan, I. et al. (Eds.) *Handbook of Sea-Level Research*. John Wiley & Sons, Ltd., pp. 331–346.
- Switzer, A. D., S. Srinivasalu, N. Thangadurai, and V. Ram Mohan, 2012. Bedding structures in Indian tsunami deposits that provide clues to the dynamics of tsunami inundation. Geological Society, London, Special Publications 361, 61–77. doi: 10.1144/SP361.6
- Tajima, Y., Yasuda, T., Pacheco, B. M., Cruz, E. C., Kawasaki, K., Nobuoka, H., Miyamoto, M., Asano, Y., Arikawa, T., Ortigas, N. M., Aquino, R., Mata, W., Valdez, J. & Briones, F., 2014: Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan. *Coastal Engineering Journal* 56, 1450006, doi:10.1142/S0578563414500065.
- Takagi, H., Esteban, M., 2016. Statistics of tropical cyclone landfalls in the Philippines:unusual characteristics of 2013 Typhoon Haiyan. *Natural Hazards* 80, 211–222. doi 10.1007/s11069-015-1965-6.
- Takagi, H., Esteban, M., Shibayama, T., Mikami, T., Matsumaru, R., De Leon, M., Thao, N.D., Oyama, T., Nakamura, R., 2015. Track analysis, simulation, and field survey of the 2013 Typhoon Haiyan storm surge. *Journal of Flood Risk Management*. doi: 10.1111/jfr3.12136.
- Takagi, H., Li, S., de Leon, M., , Esteban, M., Mikami, T., Matsumaru, R., Shibayama, T., Nakamura, R., 2016. Storm surge and evacuation in urban areas during the peak of a storm. *Coastal Engineering* 108, 1–9.
- Takashimizu, Y., Urabe, A., Suzuki, K., Sato, Y., 2012. Deposition by the 2011 Tohoku-oki tsunami on coastal lowland controlled by beach ridges near Sendai Japan. *Sedimentary Geology* 282, 124–141.
- Williams H.F.L., 2009. Stratigraphy, sedimentology, and microfossil content of Hurricane Rita storm surge deposits in southwest Louisiana. *Journal of Coastal Research* 25(4), 1041–1051.

- Williams, H. F. L., 2010. Storm surge deposition by Hurricane Ike on the McFaddin National Wildlife Refuge, Texas: Implications for paleotempestology studies. *Journal of Foraminiferal Research* 40(3), 210-219.
- Williams, H.F.L., Flanagan, W.M., 2009. Contribution of Hurricane Rita storm surge deposition to long-term sedimentation in Louisiana coastal woodlands and marshes. *Journal of Coastal Research, Specail Issue* 56, 1671–1675.

Chapter 4

Typhoon Haiyan storm surge carried two distinct sediment assemblages on the carbonate coast of Hernani, Samar, central Philippines

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Contributions

Lea is the primary author, and with Adam, and Fernando conceptualized the idea, identified appropriate methods, and contributed to its formality and development. Lea set-up the laboratory protocol for sample and data treatment based on established methods on sedimentology, supervised student interns conducting grainsize analysis, interpreted and synthesized data, and wrote the paper. Linlin carried out sediment transport modeling using TsuSedMod, and contributed the data to this study. Michelle and Adonis helped in collecting data on the field and discussed data analysis based on other boulder sites in the Philippines. Annie provided a comprehensive overview on coral reef boulder studies and provided the spreadsheet for automated boulder data analysis. Amanda and Tracy worked closely with Lea on the boulder data analysis and grainsize analysis as part of the undergraduate student internship program of the Asian School of the Environment.

Janneli Lea A. Soria: 50%

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Abstract

A combination of wave set-up and infragravity waves steepened and accentuated the storm surge during Typhoon Haiyan in November 2013 resulting in a tsunami-like wave with surge heights of 7 m and flow velocities reaching 5 ms^{-1} on the open-sea coastal plain near Hernani. This study investigates two distinct sediment assemblages left behind by the coastal flooding associated with this surge. The first assemblage consists of numerous coastal boulders that now occupy the reef flat, and the second pertains to a laterally extensive sand sheet that blanketed the coconut groves and rice fields of the coastal plain up to ~ 300 m inland. Boulder transport models indicate that minimum flow velocities ranging from 2 to 5 ms^{-1} were required to initially transport the boulders. Landward of the boulder field and behind a mangrove stand completely defoliated by the Haiyan surge we identify and characterize a coarse carbonate sand sheet on the coastal plain. The sandsheet represents the onshore sediment record of Haiyan and is up to 10 cm thick. It starts ~ 10 m inland of the beach representing the current shoreline and extends up to 300 m inland. The sand drapes the landscape, thinning and becoming patchy as it spreads and fines to a silty sand only a few mm thick at its landward extent. Preliminary inverse modeling using the grainsize distribution and thickness of the sandsheet on TsuSedMod yielded maximum flow velocities exceeding 4 ms^{-1} on the coastal plain. The sediment-derived flow velocity estimates are remarkably consistent with values reconstructed previously from video recordings, and wave modeling. Collectively, the bore-like Haiyan storm surge had travelled across the wide reef flat and inundated the coast with sustained high flow velocity causing significant damage to coastal vegetation and coastal structures along its path.

4.1. Introduction

High waves and storm tides associated with tropical and extratropical cyclones can strongly affect coastal morphology and ecosystems. Tropical cyclones commonly generate large ocean waves that when combined with storm surges have the demonstrated capability of causing significant geomorphic change at the coast (e.g. Nott and Hubbert, 2005; Fritz et al., 2009; Etienne and Terry, 2012). In tropical environments such impacts are commonly recorded by the large-scale erosion of beaches (e.g. Nott and Hubbert, 2005), damage to coastal vegetation including mangrove systems (e.g. Primavera et al., *in press*) and modifications to reef and coastal plain sedimentation (e.g. Scheffers and Scheffers, 2006; Etienne and Terry, 2012; Atwater et al., 2014). In carbonate reef systems the impacts of such events are commonly observed in the formation of coral rubble ridges (e.g. Spiske and Halley, 2014; Reyes et al., 2015), and the transport and deposition of conspicuous boulders mostly reefal clasts onto the reef flat (e.g. Etienne and Terry, 2012; May et al., 2015; Kennedy et al., 2016).

Typhoon Haiyan impacted several carbonate coastlines across different Philippine islands as it made its path across the archipelago. One such coast is the open-sea coast of Eastern Samar and it is here that Roeber and Bricker (2015) demonstrated that the combined wave-breaking setup and infragravity waves caused an elevated, high-velocity, bore-like storm surge flooding in Hernani (**Fig. 4.1**). The unusual flooding characteristics of the ‘tsunami-like’ bore contrast with the dominantly wind-induced setup on the coasts surrounding the shallow waters of Leyte Gulf including Tacloban City (Soria et al., 2016) and the combined wave-breaking setup and infragravity waves seem to be unique on the open-sea, fringing reef

Figure 4.1. Typhoon Haiyan showing the track and intensity while crossing central Philippines, and the measured storm surge and runup heights (b) along the eastern coast of Samar Island (modified from Soria et al., 2016).

coast (Roeber and Bricker, 2015). Notably, similar flooding characteristics were recognized in Guiuan, ~30 km southeast of Hernani and more proximal to Haiyan's landfall site (Kennedy et al., 2016). The most notable geomorphic and sedimentologic impacts of the extreme inundation of Haiyan on the carbonate Philippine coastlines were the conspicuous dislocated boulders now emplaced at elevations ranging from 2 to 10 m and weighing up to 30 t in Guiuan (Kennedy et al., 2016) and up to 180 t in Hernani (May et al., 2015). In comparison, moderate flooding of the carbonate coasts on the more interior Philippine islands during Haiyan has formed conspicuous coral rubble ridge about 10 to 20 m wide and ~0.5 m high (Reyes et al., 2015; Brill et al., 2016).

Recognizing the highly variable coastal setting and potentially different exposure to Haiyan's storm surge, this study primarily aims to document the sedimentologic impact of Haiyan on the coast south of Hernani. This area offers a unique opportunity to investigate two different sediment assemblages along the same transect, from the boulders emplaced on the reef flat to the sand sheet deposited inland in a coconut forest and on ricefields. The transect also crosses a small mangrove forest which was completely defoliated and partially uprooted during typhoon Haiyan. Hernani is also a strategic site given that different independent methods including actual video recording, post-typhoon field surveys, and storm surge modeling consistently and accurately constrained the inundation depths, flow velocities, and flooding mechanism (e.g. Tajima et al., 2014; Bricker et al., 2014, Roeber and Bricker, 2015; Soria et al., 2016).

With our dataset we can 1) test the boulder-derived flow velocity estimates in this study against the flow velocity estimated using forward wave modeling; 2) apply an inverse sediment transport model TsuSedMod to the sand deposits; 3) compare the velocity measurements from the reef flat, coconut forest and rice fields; and 4) assess whether the sediment information provides insights into whether the mangrove forest that separates the reef and coastal plain or the hydraulic jump associated with a raised ridge on which the road sat pre Haiyan had any effect on overland velocity.

4.2. Typhoon Haiyan and storm surge

Typhoon Haiyan was an extremely intense and fast moving typhoon and one of the most intense in history (Lin et al., 2014; Tagaki et al., 2016). Typhoon Haiyan severely affected more than 16 million people, killed more than 6000 and destroyed more than 1.1 million dwellings in the central Philippines (Lagmay et al., 2015; Soria et al., 2016). The true intensity of Haiyan remains debatable. The Dvorak-based intensity scale indicates that Typhoon Haiyan reached peak intensity of maximum wind speed at ~314 kph near landfall, far exceeding the upper limits of Saffir Simpson Hurricane Scale (Lin et al., 2014). In contrast, local Doppler radar data from the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA) in Guiuan registered a much lower intensity with minimum central pressure of 910 hPa, and winds at 160 km h^{-1} with gusts of $\sim 195 \text{ km h}^{-1}$ at 2000 on 7 November UTC (0400 on 8 November Philippine Time, PHT), just before Haiyan's landfall (Paciente, 2014). Extreme winds destroyed the Guiuan Doppler radar station about 16 minutes later. Haiyan crossed the small islands off the southeast tip of Samar Island, near Guiuan at 2040 on 7 November

UTC (0440 PHT 8 November). Haiyan then continued westwards with minimal dissipation and then made five subsequent landfalls as it crossed the central Philippines (NDRRMC 2013b).

On the more open and exposed Pacific coastline at Hernani, some 45 km north of the typhoon track, significant storm-wave contributions resulted in high water marks exceeding 7 m (**Fig. 4.1b**). Further amplification by the wave runup on steep slopes such as near Guiuan resulted in a maximum runup height of 14 m (Tajima et al. 2014). But on a relatively sheltered coast such as General MacArthur (**Fig 4.1**), surge height was recorded at its lowest of about 2 m (Soria et al., 2016). The fringing coral reefs located 3 km offshore and the narrow bottleneck entrance of the bay likely attenuated storm waves in this site, as such, the measurement is most likely dominated by the smaller atmospheric storm-surge component. Using the surge height in General Macarthur as a baseline we can assume that the wave setup and infragravity waves could have contributed to the super-elevation of coastal flooding by as much as 5 m.

4.3. Study Area

The town of Hernani is situated on a narrow coastal plain at about 3 m above mean sea level (Roeber and Bricker, 2015), underlain by late Pliocene to Pleistocene reefal limestone (Aurelio and Peña, 2002). Mangroves and a fringing reef shelter the shore against normal fair weather waves. The mangrove area is ~100 m to 300 m wide natural stands of *Sonneratia alba*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Aegiceras floridum* and *Aegiceras corniculatum* (Primavera et al., 2016). Seaward of the mangrove extends a reef flat ~ 400 to 500 m wide. A narrow

inlet divides the reef flat into a northeastern and a southwestern segment. The reef edge is at ~1 m below mean sea level (msl), but just a few hundred meters offshore the seafloor rapidly drops to 50 m (Roeber and Bricker, 2015). The coast is microtidal and exposed to Pacific Ocean swell systems (Maeda et al., 2004; May et al., 2015).

Hernani sustained significant damage from Typhoon Haiyan. A satellite image taken 5 days after landfall shows the extent of damage to properties and coastal vegetation within the inundation limit (**Fig. 4.2b**). Sand surfaces extend landwards from the beach indicating inland deposition. Seven months following Typhoon Haiyan, coastal vegetation has significantly recovered, except for the mangrove stands (**Fig. 4.2c**).

4.4. Methods

4.4.1. Post-typhoon Haiyan survey

Our field surveys were conducted in May and June 2014 on a transect about 1.5 km south of Hernani, through a village called Carmen. The transect is about 1-km long from the reef edge through the coconut groves and the rice paddies inland, through to the back of a limestone ridge (**Fig. 4.3**). The reef edge is defined in this study as the landward limit of the spurs and grooves exposed during low tide at the time of survey, which closely corresponds to the seaward limit of wave refraction on satellite imagery. Reef flat and land surface elevations were measured using two units of Ashtech Promark 2 Survey System™ on a base/rover configuration for differential global positioning system (dgps). Raw elevation values were post-processed with GNSS Solutions software for vertical accuracy. A local GPS

Figure 4.2. Pre- and post-typhoon Haiyan satellite images and photos of Hernani town. The satellite images were purchased from Digital Globe through the Centre of Remote Imaging, Sensing and Processing (CRISP).

- a) Open-sea coast of Hernani is fringed by natural barriers including a prominent reef-flat, and intact mangrove stands.
- b) Post-typhoon Haiyan image showing the extent of damage to properties, defoliated mangroves, and damage to coastal vegetation within the inundation limit.
- c) Recovery condition in Hernani seven months after typhoon Haiyan's landfall. Coastal vegetation has recovered except for the mangrove stands. Enclosed in the rectangle is the study area.
- d) Defoliated mangroves south of Hernani showing initial stages of recovery in June 2014.
- e) The reef flat south of Hernani is strewn with boulders after Typhoon Haiyan.

Figure 4.3. Detailed map of the study area showing the samples taken across different coastal environments south of Hernani (a). The actual inundation limit verified by witnesses accounts is ~100m inland of the satellite-image derived inundation limit. Gray dashed line indicates the transect for the topographic profile and the samples taken onland (b).

station PIMO established by IGS (International GNSS Service) was used as a reference alongside tide level observations in the field for local datum topographic adjustment. In fair weather conditions, the reef flat is within the intertidal zone with water depths not exceeding 1 m at high tide. Typhoon Haiyan, however, has completely inundated the reef flat and the adjoining coastal plain. Residents of the houses built on top of a limestone ridge ~6 m above msl attest overland flooding on the ridge by 1.5 m.

4.4.2. Reef flat boulders

The extreme flooding during Typhoon Haiyan has emplaced boulders on the reef flat south of Hernani. However, only the boulders found on the southwestern segment of the reef flat were mapped in this study. Coastal boulders with intermediate axis >1 m were considered because this size criterion falls within the usual size of boulders associated with high-energy wave conditions such as storm and tsunami (Switzer and Burston, 2010; Paris et al., 2011; Terry et al., 2013).

The dimension along three axes a (longest), b (intermediate), and c (shortest) of 21 boulders was determined using a measuring tape. The volume of each boulder was estimated based on the geometric shape classified as triangular, ellipsoidal, and rectangular (Lau, 2015; Terry et al., 2013). Most of the boulders closely approximate but do not perfectly fit a rectangular shape. Previous studies highlight that the conventional equation $V_{abc} = a*b*c$ for rectangular boulders usually overestimates by as much as 50 to 60 % the actual volume and weight of limestone (Engel and May, 2012; May et al, 2015). The maximum value of 0.6 was factored in the conventional equation to minimize overestimation of boulder volume and mass. The bulk density of 2.4 gcm^{-3} calculated by May et al. (2015) from the reef

boulders located 5 km north of Hernani was adopted to determine the weight. A lower bulk density value of 1.99 gcm^{-3} derived from other Philippine coral boulders (Siringan et al., unpublished) was also considered.

The boulder dimensions were used as inputs on established boulder transport equations of Nandasena et al. (2011) to infer minimum flow velocity conditions for varying mode of transport initiation such as sliding, rolling, and lifting. All these processes can occur on a reef boulder in either a subaerial or submerged setting. The required minimum velocity for each condition is:

$$\text{Sliding: } u^2 \geq \frac{2\left(\frac{\rho_s}{\rho_w}-1\right)gc(\mu_s \cos \theta + \sin \theta)}{C_d\left(\frac{c}{b}\right) + \mu_s C_l} \quad (1)$$

$$\text{Rolling: } u^2 \geq \frac{2\left(\frac{\rho_s}{\rho_w}-1\right)gc\left(\cos \theta + \left(\frac{c}{b}\right)\sin \theta\right)}{C_d\left(\frac{c^2}{b^2}\right) + C_l} \quad (2)$$

$$\text{Lifting: } u^2 \geq \frac{2\left(\frac{\rho_s}{\rho_w}-1\right)gc \cos \theta}{C_l} \quad (3)$$

where ρ_s = density of the boulder = 2.4 gcm^{-3} ; ρ_w = density of sea water = 1.02 gcm^{-3} ; g = gravitational acceleration = 9.81 ms^{-1} ; c = shortest axis; b = intermediate axis; μ_s = coefficient of static friction = 0.5; θ = angle of the bed slope = 0; C_d = coefficient of drag = 1.95; C_l = coefficient of lift = 0.178.

In each scenario the flow will generate drag, inertia, and lift forces to initiate the movement of a boulder that is assumed to be already detached from the reef. But, for a boulder, which is originally attached to the reef with only the top surface

exposed, lift is the only force that can possibly initiate movement expressed by the equation:

$$\text{Lifting (Joint-bounded): } u^2 \geq \frac{2\left(\frac{\rho_s}{\rho_w}-1\right)gc(\cos\theta + u_s \sin\theta)}{c_t} \quad (4)$$

In the case of a reef flat with a bed slope θ equal to 0° such as in our study area, the term $\sin\theta$ is equivalent to 0. As such, the minimum flow velocity required to initiate boulder movement by lifting is the same for both of the subareal and submerged non-obstructed (Eqn 3) and joint-bounded (Eqn 4) scenarios.

4.4.3. Onshore carbonate sediments

Inland transport and deposition of sediments from Typhoon Haiyan were also mapped extending to >300 m from the beach. A large diameter (50 mm) hand auger was used for the inventory of Haiyan sediment thickness on the coconut grove and rice paddies (Fig. 4.3). At all sites, one sediment sample from the Haiyan deposit on the surface and one sample from the underlying soil were collected for sediment grainsize, and sediment composition analyses. Shallow trenches were subsequently excavated to expose thicker accumulations of Haiyan sediments on the coconut grove that were sampled at 1cm intervals.

The relative amounts of the organic and carbonate components were determined following the loss-on-ignition method (Heiri et al., 2001). About 1g to 2g of sediment from each sample was burned on a muffle furnace at 550°C for 4 hours and the weight loss corresponded to the organic content. Carbonate content, in contrast, was determined using two different methods depending on the grainsize of the sediments. For muddy sediments, loss-on ignition method

was continued by successively burning the sediments at 950° C for 2 hours (Heiri et al., 2001). Alternatively, coarse sand samples from the shallow trenches were treated with 10% HCl. Acid leaching ensures more efficient carbonate dissolution particularly for sediments that are predominantly carbonate but do not contain significant amount of mud (Dean, 1974).

Particle size analysis was performed using composite methods of laser diffraction for fine-grained fractions and digital imaging for coarse-grained sediments. For fine-grained sediments, subsamples of about 1g were treated with 15 % H₂O₂ to remove organics. The samples were then rinsed in distilled water before introducing to the Malvern Mastersizer 2000 for grainsize analysis using laser diffraction (as outlined in Switzer, 2013). In contrast, a CAMSIZER® was used for samples that are predominantly coarse grained (>1.5mm), beyond the range of the laser particle machine, and with minimal mud content. The CAMSIZER® provides non-destructive and rapid grain size and shape distributions for sediments ranging from 20 microns to 30 millimeters by capturing images of a falling curtain of sediment at 25 Hz (Moore et al., 2006). Prior to grainsize analysis, large organic debris were picked using forceps while the smaller, fibrous organic debris were removed by floatation on distilled water. The sediments were then oven dried at 50° C, and about 50 g to 100 g of dry subsamples were introduced on the Retsch Technology CAMSIZER®. The grainsize corresponds to the cross-sectional area of the particles in the image and reported as the diameter of a circle of equivalent area, which is similar to the grainsize measuring principle of the laser particle analyzer (Switzer and Pile, 2015). The composite grainsize data of

the Haiyan sediments and the pre-Haiyan soil were then run through the open-source program GRADISTAT version 8.0 (Blott and Pye 2001) to generate statistical grainsize distributions. The logarithmic mean, d_{90} , sorting, and skewness (Folk and Ward, 1957) of each sample were used to establish the vertical and across-shore variations of the Haiyan sediments.

4.4.4. Application of the TsuSed model (TsuSedMod)

The inverse model of Jaffe and Gelfenbaum (2007), TsuSedMod, has been field tested against deposits of the 1998 Papua New Guinea tsunami (Jaffe and Gelfenbaum, 2007), the Indian Ocean Tsunami of 2004 (Spiske et al., 2010), the 2009 Samoa tsunami (Jaffe et al., 2011), and the 2011 Tohoku-oki tsunami (Jaffe et al., 2012). Given the tsunami-like properties of the Haiyan surge on this coast, however, provides the opportunity to apply the model on the Haiyan sediments found on the coastal plain. The model can be applied only to the two adjacent samples in the coconut forest (Ca4) and on the rice field (Ca 11) as these samples fall within the size particle and deposit thickness requirement of the model.

The model is constrained by several simplifying assumptions including (1) onshore flow is steady and uniform, (2) transport and deposition of sediment are dominated by suspension load (>90%), and (3) no erosion is caused by following waves or backwash (Brill et al., 2014) and the model is only considered to provide reliable values for onshore flow speed in cases where these assumptions apply. It has also been stated that ideally the model should be used in shallow and gently sloping coastal plains that are flooded by long tsunami waves (Apotsos et al., 2012). The collective Hernani reef flat-mangrove-coastal plain studied here spans more than

900 m and rises less than 4 m. The duration and flow characteristics from local resident accounts and video footage suggest that the flow was indeed long wave in nature.

For tsunami studies on siliciclastic coast the TsuSedMod requires the averaged grain-size distribution and deposit thickness of only those sections of the deposit, interpreted as deposited from suspension during a single inflow (Jaffe et al., 2011, Brill et al., 2014), and as the flow depth. We used the whole sediment deposit thickness because the deposits at Hernani show only minor inverse grading and though Jaffe et al., (2011) suggest normal grading (presumably from suspension) is common in tsunami deposits there are several reasons why inverse grading can equally be found in washover deposits. For example Shanmugan (2012) noted that inverse grading has been associated with deposits of both tropical cyclones (Spiske and Jaffe 2009) and tsunamis (Jaffe et al. 2003). The origin of inverse grading at Hernani is likely related to shell fragments and the biotic composition including the many foraminifera.

The flow depth was estimated between 3 m to as high as 5 m from eyewitness accounts and field evidence. Other model parameters were kept constant for all samples. Like Brill et al. (2014) we adopted resuspension coefficient, eddy viscosity, and settling velocity from Jaffe and Gelfenbaum (2007) and a Manning's n of 0.03 for bottom roughness was adopted from Jaffe et al. (2011, 2012). We applied a sediment density (2.5 gcm^{-3}), salinity (33%), and water temperature of 25°C to adapt to the local conditions at Hernani.

4.5. Results and Discussion

4.5.1. Reef flat boulder deposition

Carbonate boulders on the reef flat south of Hernani area most likely derived from two sources, they are either detached from the limestone cliffs or from the active reef edge. But, in some cases the boulders could also be pre-existing, deposited by previous high-energy wave conditions and were lying loosely on the reef prior to Haiyan just as what has deduced from the boulder deposition in Guiuan, more proximal to Haiyan's landfall (Kennedy et al., 2015). Four of the boulders (i.e. CB1, CB2, CB3, CB4) are found near the limestone cliffs (**Fig. 4.3**) with attached roots and stumps in growth position indicating a former upper boulder surface that was subaerially exposed (**Fig. 4.4a**). The proximity to the limestone cliffs and the subaerial pre-transport position suggest that the boulders were transported to the reef flat by cliff-top collapse. Notably, these boulders are larger than all others on the platform with the b axis exceeding 2 m in all cases and calculated weights from 13 t to as much as 84 t (**Table 4.1**). In contrast, the smaller boulders which represent the majority of the clasts have an indeterminate source. However, boulders with bleached encrusting coral or macroalgae on their surfaces were most likely submerged prior to transport and may have come from the reef slope. The dark color, and absence of fresh cut marks on the landward most boulders argue for detachment from the original source and potentially lying loosely on the reef flat prior to Haiyan (**Fig. 4.4b,d**). On a rare instance, fresh detached surface on boulder CB5 indicates clear overturning with a vertical displacement of ~1 m and a lateral displacement of 50 cm to 1 m (**Fig. 4.4c**). Majority of these boulders have b axis between 1 to 2 m and weigh no more than 10 t (**Table 4.1**).

Figure 4.4. Boulders on the reef flat surface south of Hernani.

- a) Boulder CB4 is about 84 t and the largest on the reef flat. The boulder is now lying upside down on the reef flat surface.
- b) Boulder CB9 showing dead but well preserved corals in growth position as evidence of former surface position.
- c) Irregular shaped boulder CB5 showing a recently exposed surface an indication of overturning.
- d) Boulder CB18 is a coral block in an upside down position.

Table 4.1. Description of boulder clasts on the reef flat south of Hernani.

Boulder ID	Dimensions (m)			Particle Size (based on b-axis)	Shape	Volume (m ³) V _{calc} by shape	Weight (t)		Remarks	Pre-transport condition
	a axis	b axis	c axis				p=2.4gcm ⁻³	p=1.99gcm ⁻⁴		
CB1	4.4	2.7	1.75	Very Coarse Boulder	Rectangular	20.8	12.47	29.94	cliff collapse	Group I (cliff-top collapse)
CB2	1.34	1.3	0.78	Coarse Boulder	Rectangular	1.4	0.82	1.96	cliff collapse	
CB3	2.8	2	1.9	Very Coarse Boulder	Rectangular	10.6	6.38	15.32	in-situ vegetation at the bottom surface of the boulder; cliff collapse	
CB4	4.7	4.6	2.7	Fine Block	Rectangular	58.4	35.02	84.06	in-situ vegetation at the bottom surface of the boulder; cliff collapse	
CB5	3.1	2.8	1.05	Very Coarse Boulder	Rectangular	9.1	5.47	13.12	fresh detached surface indicate overturning	Group II (submerged or subaerial)
CB6	1.8	1.6	1.05	Coarse Boulder	Triangular	3.0	1.81	4.35	one surface with bleached coral head	
CB7	1.8	1.1	0.65	Coarse Boulder	Rectangular	1.3	0.77	1.85	one surface with bleached encrusting coral	
CB8	1.3	1	0.7	Coarse Boulder	Rectangular	0.9	0.55	1.31	one surface with macroalgae Halimeda	
CB9	2.2	1.6	0.8	Coarse Boulder	Triangular	2.8	1.41	3.38	one surface with bleached encrusting coral	
CB10	1.7	1.5	0.7	Coarse Boulder	Rectangular	1.8	1.07	2.57	one surface with bleached encrusting coral	
CB11	2.6	1.95	1.2	Coarse Boulder	Elliptical	6.1	3.19	7.65	one surface with bleached encrusting coral one with bleached coral, and macro algae Halimeda	
CB12	1.9	1.3	1.2	Coarse Boulder	Rectangular	3.0	1.78	4.27		
CB13	1.9	1.5	0.85	Coarse Boulder	Rectangular	2.4	1.45	3.49		
CB14	2.9	2.1	1	Very Coarse Boulder	Rectangular	6.1	3.65	8.77	one surface with bleached encrusting coral	
CB15	2	1.8	0.7	Coarse Boulder	Rectangular	2.5	1.51	3.63		
CB16	2.3	1.5	1.1	Coarse Boulder	Rectangular	3.8	2.28	5.46	onse surface with bleached encrusting coral	
CB17	3.5	2.6	0.95	Very Coarse Boulder	Elliptical	8.6	4.53	10.86		
CB18	2.1	2	1.15	Very Coarse Boulder	Elliptical	4.8	2.53	6.07	coral block, no fresh cut marks indicating pre-transport even before typhoon Haiyan	
CB19	2	1.6	1.1	Coarse Boulder	Rectangular	3.5	2.11	5.07	no fresh cut marks indicating pre-transport even before typhoon Haiyan	
CB20	3.2	2.9	2.2	Very Coarse Boulder	Rectangular	20.4	12.25	29.40	no fresh cut marks indicating pre-transport even before typhoon Haiyan	
CB21	2.2	1.65	1.05	Coarse Boulder	Rectangular	3.8	2.29	5.49	no fresh cut marks indicating pre-transport even before typhoon Haiyan	

Boulder dimensions based on the equations of Nandasena and others (2011) yielded flow velocities on the reef flat ranging from 2.5 ms⁻¹ to 12 ms⁻¹ depending on transport mechanism (**Fig. 4.5**). Assuming that the boulders are previously detached from the reef prior to transport during Haiyan, a minimum flow velocity of 2.5 ms⁻¹ to 3 ms⁻¹ is required to initiate sliding transport. For the boulders to be moved by rolling or overturning requires minimum flow velocity of 4 to 6 ms⁻¹. Flow velocity of at least 10 ms⁻¹ is needed to initiate boulder transport by saltation. Based on the rarity of fresh cut boulder surfaces and impact marks, transport by rolling is the most likely transport scenario. Approximately 1.5 km north of our boulder field on the reef in front of Hernani township (**Fig. 4.1**) Roeber and Bricker (2015) summarise a Boussinesq-type phase-resolving wave model BOSZ that flow velocities caused by surf beat on the reef front and immediate reef flat would be around 3 ms⁻¹. Their modelled flow velocity of at least 3 ms⁻¹ suggests flow capable of moving reef boulders by rolling and sliding.

Figure 4.5. Estimated flow velocities required to initiate transport of a subaerial (Sa), submerged (Sm), or joint-bounded (Jb) boulder through three different mechanisms like sliding, rolling, and saltation using Nandasena et al. (2011) equations.

In comparison at two different sites along Eastern Samar, May and others (2015) and Kennedy and others (2016) independently documented that Typhoon Haiyan dislocated and transported large boulders onshore to elevations between 8 to 10 m. At both locations these authors used the size and the transport distance of the Haiyan-emplaced boulders to strongly challenge pre-existing hypothesis of attributing similar-sized boulders to tsunami events. In contrast, this study illustrates that despite the proximity and potential similarity of flooding mechanism at our study sites, we find no boulders larger than 80 t and relatively short transport distances. Boulder deposition on the fringing reef south of Hernani was limited to the reef flat surface and no boulders onshore. Also comparing boulder dimensions, the boulders south of Hernani with <4 m (*a axis*) and <2 m (*b-axis*) are smaller compared to the boulders investigated by May and others (2015) on a site 5 km north of Hernani. Such local variability in size and spatial distribution may imply that size and transport distance do not necessarily translate directly to flooding intensity. Majority of the large boulders in Guiuan were derived from the heavily weathered headland limestone (Kennedy et al., 2016). The same applies at the north Hernani site of May et al., (2015). In contrast, we found that only four of the boulders found south of Hernani came from cliff collapse with the large majority from indeterminate pre-transport locations though likely to be the reef front.

4.5.2. Onshore sediment deposition

The inundation limit of the Haiyan storm surge in Carmen reached as far as 400 m inland of the beach, however, identifiable onshore sediment deposition reached only about 300 m at the front of the limestone ridge (**Fig. 4.6**). The sand sheet is

Figure 4.6. Lateral variation in thickness (b), texture (c-e), and composition (f) of the Haiyan overwash sediments south of Hernani.

composed of carbonate sand and coral rubble that blankets the slightly inclined topographic surface at elevations of 2 m to 3 m above msl occupied by coconut groves and rice paddies. A sharp contact separates the light beige sandy unit interpreted as Haiyan deposit and the dark brown, densely rooted pre-Haiyan soil unit below (**Fig. 4.7**).

The most seaward trench Ca1 revealed the thickest accumulation of the Haiyan deposit at 10 cm thick. The Haiyan deposit gradually thins to about 4 cm through the landward edge of coconut grove. The boundary between the coconut grove and adjoining rice paddies mark an abrupt decrease in sediment thickness to 1 cm at Ca10 then spreading thinly to few mm and becoming patchy at Ca9 and Ca8 (**Fig. 4.6b**). A 3 cm thick Haiyan deposit was encountered in the trench Ca2 a few meters landward of Ca1, but was subsequently disregarded and abandoned because residents confirm that the site was disturbed by previous clearing operations.

Apart from the landward thinning trend, the Haiyan deposit also exhibits prominent textural and compositional variation landward. Figure 4.6c shows that the grainsize fines inland. The sand unit is predominantly coarse sand (-1ϕ) near the beach and it remains coarse to around 150 m inland before it rapidly becomes fine to very fine sand (2 to 4ϕ). Consistent with this abrupt decrease in grainsize is the shift from negatively skewed to positively skewed sediments indicating a landward shift towards a dominance of fine material (**Fig. 4.6d**). On the other hand, there is an apparent overall increase in sorting values inland, from moderately-sorted sediments in Ca1 to subsequently poorer sorted sediments

Figure 4.7. Photos of the shallow trenches showing the distinct light-colored sediments deposited by Typhoon Haiyan (TH) conformably overlying a dark-brown, pre-Haiyan (pre-TH) soil cover underneath the coconut grove. The sharp stratigraphic contact also corresponds to sharp changes in grainsize, sorting, and skewness in trenches Ca3 (b) and Ca4 (c).

landwards to Ca8 possibly reflecting the incorporation of material from different environments as the flow moves across the land surface.

The sharp stratigraphic contact between the Haiyan deposit and the pre-Haiyan soil corresponds to evident vertical change in grainsize, sorting and skewness (Fig. 4.7). Though devoid of internal layering, the thicker and sandier parts of the Haiyan deposit exhibit an overall inverse grading or coarsening upward sequence. Inverse grading in sandy deposits has been identified and characterised in both storm (Spiske and Jaffe 2009) and tsunami deposits (Jaffe et al. 2003). In a coastal overwash settings inverse grading is likely the product of changes in flow density and characteristics analogous to dispersive pressure in grain flows (Bagnold, 1954), traction carpets in high-density turbid currents (Lowe, 1982) and kinetic sieving similar to that observed in submarine gravity flows (Middleton, 1970). The base of the Haiyan deposit is marked by either a more negatively skewed (Ca1 or Ca3) or a more positively skewed (Ca4) sediments compared to the underlying pre-Haiyan soil. Notably, despite the compositional differences and local flooding mechanism these onshore carbonate Haiyan sediments seem to display a similar coarsening upward sequence typically observed on the siliciclastic Haiyan sediments in Tanauan along the San Pedro Bay coast (Chapter 3).

Inverse modeling of flow speed and flow depth was conducted for Haiyan deposits to get a first order estimate flow velocity on the coastal plain. The TsuSedMod output for Ca4 and Ca11 is shown in Table 4.2. The onshore flow depths of 3 m and 5.1 m were used on these two adjacent samples. The derived flow velocities at 130 m inland is $>7 \text{ m s}^{-1}$ and at 220 m inland decreases to 4 m s^{-1} .

Table 4.2. Across transect summary of the deposit thickness, grainsize, and flow characteristics in Carmen, south of Hernani.

Sample ID	Distance from beach (m)	Thickness (cm)	Grainsize d_{90} (phi)	Grainsize Mean (phi)	Surface Elevation (m)	Flow depth (m)	Flow velocity (ms^{-1})
Ca1	10	10	0.76	-0.28	1.70	5.8	-
Ca3	60	8	1.70	-0.35	2.30	5.2	-
Ca4	137	6	6.89	2.91	2.40	5.1	7.16 (7.5*)
Ca11	224	4	6.05	2.52	2.40	5.1	3.9 (4*)
Ca10	233	1	5.80	2.20	2.40	5.1	-
Ca9	247	0.3	7.42	3.56	2.50	5	-
Ca8	285	0.3	7.51	3.57	3.10	4.4	-
Ca6	340	0	x	x	4.20	3.3	-

* Flow velocity values using flow depth of 3 m.

Storm surge inundation and onshore sedimentation has occurred in the past along this coast. Notably, Hernani town was described to have turned into a “sand desert” in the aftermath of the October 1897 typhoon (Algue, 1898). Still lacking from this study is the identification of the sediment source and thus, inferring to some extent several aspects of flow dynamics such as backwash contribution similar to what has been done on the Haiyan sediments in Leyte Gulf (Pilarczyk et al., 2016). Nonetheless, this documentation of onshore Haiyan sediments can potentially provide clues in investigating previous records of storm sedimentation on this carbonate coast.

4.5.3. Across-shore flow velocity

The boulder assemblages and modelling of surf beat induced flow by Roeber and Bricker (2015) both indicate that flow velocities across the reef flat were likely to have exceeded 3 ms^{-1} with flow depths of more than 3 m. A relatively higher onshore flow velocity of 5 ms^{-1} was estimated on the house located about 200 m from the beach (Roeber and Bricker, 2015). The TsuSedMod results indicate

consistently high flow velocity exceeding 4 ms^{-1} on the coastal plain at about 220 m from the beach across the narrow mangrove forest, coconut grove and rice paddies. In both cases, it seems that neither the seawall on the shore in Hernani town proper nor the narrow mangrove stand in Carmen were sufficient to slow down the flow and failed as coastal protection. Given that there is no significant topographic change, it would be interesting to know whether the coastal segment between Hernani and Carmen has been impacted by similar flow velocity or perhaps the relatively wider and dense mangrove stand was able to reduce the onshore flow.

4.6. Conclusion

This study investigated two distinct sediment assemblages that were transported and emplaced by the extreme flooding during Typhoon Haiyan on the open-sea coast of Hernani town. The sediment assemblages include distinct carbonate boulders now occupying the reef flat surface, and a sand sheet that blanketed the coconut groves and rice fields of the coastal plain reaching up to ~300 m inland. We documented boulders up to ~80 t, most of which were originally submerged, but were transported onto the reef flat during Haiyan's surge. Boulder transport models indicate minimum flow velocities ranging from 2 to 6 ms^{-1} were required to initiate boulder movement by sliding and rolling. Inland of the boulder field, we find a coarse carbonate sand draping the landscape by about 10 cm thick near the beach thinning to 1 cm to few mm and becoming patchy up to 300 m inland. Preliminary inverse modeling using TsuSedMod yielded velocity values of $> 4 \text{ ms}^{-1}$ for the flow that transported and deposited the onshore Haiyan deposits across the coastal plain.

Separate inverse modeling of flow velocity from boulder dimensions on the reef flat and sediment thickness and grainsize distribution inland indicate that the bore-like storm surge travelled across the wide reef flat and inundated the coast at a sustainably high flow velocity exceeding 4 ms^{-1} . The sediment-derived flow velocity estimates are remarkably consistent with previous flow velocities reconstructed from video recordings, and forward wave modeling. Our study of two, distinct, storm-induced sediment assemblages supplement present understanding of the storm surge dynamics and provide clues for initial investigation of geologic records of storm inundation on this coast.

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References

- Algué, J., 1898: El baguio de Samar y Leyte, 12-13 de Octubre de 1897, Manila Observatory, 1-74.
- Apotsos, A., Gelfenbaum, G., and Jaffe, B., 2012. Time-dependent onshore tsunami response. *Coastal Engineering* 64, 73–86.
- Atwater, B.F., Fuentes, Z., Halley, R. B., Ten Brink, U. S., and Tuttle, M. P., 2014. Effects of 2010 Hurricane Earl amidst geologic evidence for greater overwash at Anegada, British Virgin Islands. *Advances in Geosciences* 38, 21-30.
- Aurelio, M. A, Pea, R. E., 2002. Geology and mineral resources of the Philippines, Vol. 1., Department of Environment and Natural Resources Mines and Geosciences Bureau, Philippines. 277-300.
- Bagnold, R.A., 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proc. R. Soc. London A225*, 49–63.
- Blott, S.J. and Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26,1237-1248.
- Bricker, J., Takagi, H., Mas, E., Kure, S., Adriano, B., Yi, C., and Roeber, V., 2014. Spatial variation of damage due to storm surge and waves during Typhoon Haiyan in the Philippines. *Journal of the Japan Society of Civil Engineers, Series B2* 70, 231–235.
- Brill, D.,Pint, A., Jankaew, K., Frenzel, P., Schwarzer, K., Vött, A., Brückner, H., 2014. Sediment transport and hydrodynamic parameters of tsunami waves recorded in onshore geoarchives – A case study from Thailand. *Journal of Coastal Research* 30, 922-941.
- Brill, D., May, S. M., Engel, M., Reyes, M., Pint, A., Opitz, S., Dierick, M., Gonzalo, L. A., Esser, S., and Brückner, H., 2016. Typhoon Haiyan's sedimentary record in coastal environments of the Philippines and its palaeotempestological implications. *Nat. Hazards Earth Syst. Sci. Discuss.*, doi:10.5194/nhess-2016-224, In review.

- Engel, M. and May, S. M., 2012. Bonaire's boulder fields revisited: evidence for Holocene tsunami impact on the Leeward Antilles. *Quaternary Science Reviews* 54, 126–141.
- Etienne S., and Terry J.P., 2012. Coral boulders, gravel tongues and sand sheets: features of coastal accretion and sediment nourishment by Cyclone Tomas (March 2010) on Taveuni Island, Fiji. *Geomorphology* 175–176, 54–65.
- Folk, R.L., and W.C. Ward. 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27, 3–26.
- Fritz, H.M., C.D. Blount, S., Thwin, M.K. Thu, and N. Chan, 2009: Cyclone Nargis storm surge in Myanmar. *Nature Geoscience*, 2, 448-449.
- Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability. *Journal of Paleolimnology* 25, 101–110.
- Jaffe, B. E. & Gelfenbaum, G. 2007. A simple model for calculating tsunami flow speed from tsunami deposits. *Sedimentary Geology* 200, 347–361.
- Jaffe, B., Buckley, M., Richmond, B., Strotz, L., Etienne, S., Clark, K., Watt, S., Gelfenbaum, G., and Goff, J., 2011. Flow speed estimated by inverse modeling of sandy sediment deposited by the 29 September 2009 tsunami near Satitua, east Upolu, Samoa. *Earth-Science Reviews* 107(1–2), 23–37.
- Jaffe, B., Goto, K., Sugawara, D., Richmond, B., Fujino, S., and Nishimura, Y., 2012. Flow speed estimated by inverse modelling of sandy tsunami deposits: results from the 11 March 2011 tsunami on the coastal plain near the Sendai Airport, Honshu, Japan. *Sedimentary Geology* 282, 90–109.
- Jaffe, B., Gelfenbaum, G. et al. 2003. Tsunami deposits – Identification and interpretation of tsunami deposits from the June 23, 2001, Peru' tsunami. In: Proceedings of the International Conference on Coastal Sediments 2003. World Scientific Publishing Corp and East Meets West Productions, Corpus Christi, TX.
- Kennedy, A. B., Mori, N., Zhang, Y., Yasuda, T., Chen, S., Tajima, Y., Pecor, W., and Toride, K., 2016. Observations and modeling of coastal boulder transport and loading during Super Typhoon Haiyan. *Coastal Engineering*

Journal 58(1), 1640005 1-27.

Lagmay, A. M. F., Agaton, R. P., Bahala, M. A., Briones, J. B. L. T., Cabacaba, K. M. C., Caro, C. V. C., Dasallas, L. L., Gonzalo, L. A. L., Ladiero, C. N., Lapidez, J. P., Mungcal, M. T. F., Puno, J. V. R., Ramos, M. M. A. C., Santiago, J., Suarez, J. K., and Tablazon, J. P., 2015. Devastating storm surges of Typhoon Haiyan. *International Journal of Disaster Risk Reduction* 11, 1–12.

Lau, A. Y. Annie, 2015. Assessing coastal hazards with high-energy wave-deposited boulders: case studies from three tropical pacific islands. Doctoral dissertation. National University of Singapore. Singapore., pp. 47-49.

Lin, I.-I., Pun, I.-F., and Lien, C.-C., 2014. “Category-6” supertyphoon Haiyan in global warming hiatus: Contribution from subsurface ocean warming. *Geophysical Research Letters* 41, 8547–8553 doi:10.1002/2014GL061281.

Lowe, D. R. ,1982. Sediment gravity flows: II Depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Research* 52(1). 279-297

Maeda, Y., Siringan, F., 5 Omura, A., Berdin, R., Hosono, Y., Atsumi, S., and Nakamura, T., 2004. Higher-than-present Holocene mean sea levels in Ilocos, Palawan and Samar, Philippines, *Quaternary International* 115–116, 15–26.

May, S.M., Engel, M., Brill, D., Cuadra, C., Lagmay, A.M.F., Santiago, J., Suarez, J.K., Reyes, M., and Brückner, H, 2015. Block and boulder transport in Eastern Samar (Philippines) during Supertyphoon Haiyan. *Earth Surface Dynamics* 3, 543-558.

Middleton, G.V., 1970. Experimental studies related to the problem of flysch sedimentation. *Geological Association of Canada Special Paper* 7, 253–272.

Moore A., Goff, J., Mc Adoo, B. G., Fritz, H. M., Guzman, A., Kalligeris, N., Kalsum, K., Susanto, A., Suteja, D., and Synolakis, C. E., 2011. Sedimentary deposits from the 17 July 2006 Western Java Tsunami, Indonesia: Use of grain size analyses to assess tsunami flow depth, speed,

- p>and traction carpet characteristics.
- Pure and Applied Geophysics*
- 168, 1951–1961.
- Nandasena, N. A. K., Paris, R., and Tanaka, N., 2011. Reassessment of hydrodynamic equations: minimum flow velocity to initiate boulder transport by high energy events (storms, tsunamis). *Marine Geology* 281, 70–84.
- Nott, J., Chague-Goff, C., Goff, J., Sloss, C., and Riggs, N., 2013. Anatomy of sand beach ridges: Evidence from severe Tropical Cyclone Yasi and its predecessors, northeast Queensland, Australia. *Journal of Geophysical Research: Earth Surface* 118, 1710–1719, doi:10.1002/jgrf.20122.
- Paciente, R.B., 2014: Response and lessons learned from Typhoon “Haiyan” (Yolanda). *JMA/WMO Workshop on Effective Tropical Cyclone Warning in Southeast Asia*. Tokyo, Japan Meteorological Agency. [Available online at http://severe.worldweather.wmo.int/TCFW/JMAworkshop/6-3.THaiyan_RPaciente.pdf]
- Paris, R., Naylor, L.A., Stephenson, W.J., 2011. Boulders as a signature of storms on rock coasts. *Marine Geology* 283,1–11.
- Pilarczyk, J.E., Horton, B.P., Soria, J.L.A., Switzer, A.D., Siringan, F., Fritz, H.M., Khan, N.S., Ildefonso, S., Doctor, A.A., Garcia, M.L., 2016. Micropaleontology of the 2013 Typhoon Haiyan overwash sediments from the Leyte Gulf, Philippines. *Sedimentary Geology* 339, 104–114.
- Primavera, J.H., Dela Cruz, M., Montilijao, C., Consunji, H., Dela Paz, M., Rollon, R.N., Maranan, K., Samson, M.S., Blanco, A., 2016. Preliminary assessment of post-Haiyan mangrove damage and short-term recovery in Eastern Samar, central Philippines. *Marine Pollution Bulletin* 109(2),744–750.
- Reyes, M., Engel, M., May, S.M., Brill, D., and Brückner, H., 2015. Life and death after Super Typhoon Haiyan, *Coral Reefs* 34, 419.
- Roeber, V. and Bricker, J., 2015. Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan. *Nature Communications* 6,

7854. doi:10.1038/ncomms8854,

- Scheffers, A., and Scheffers, S., 2006. Documentation of the impact of Hurricane Ivan on the coastline of Bonaire (*Netherlands Antilles*). *Journal of Coastal Research* 22(6), 1437-1450.
- Shanmugam, G., 2012. Process-sedimentological challenges in distinguishing paleo-tsunami deposits. *Natural Hazards* 63(1), 5-30.
- Siringan, F.P., Gallentes, A., and Manglicmot, M. 2016. Coral inferred contemporary tsunami history of the Verde Island Passage. Unpublished Technical Report submitted to the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development. Laguna, Philippines.
- Soria, J.L., Switzer, A., Villanoy, C., Fritz, H., Bilgera, P.H., Cabrera, O., Siringan, F., Sta. Maria, Y., Ramos, R., and Fernandez, I, 2016: Repeat storm surge disasters of Typhoon Haiyan and its 1897 predecessor in the Philippines. *Bulletin of the American Meteorological Society* 97, 31– 48
- Spiske, M. and Jaffe, B. E., 2009. Sedimentology and hydrodynamic implications of a coarse-grained hurricane sequence in a carbonate reef setting. *Geology* 37, 839–842, doi:10.1130/G30173A.1.
- Spiske, M., Spiske, M., Weiss, R., Bahlburg, H., Roskosch, J., and Amijaya, H., 2010. The TsuSedMod inversion model applied to the deposits of the 2004 Sumatra and 2006 Java tsunami and implications for estimating flow parameters of paleo-tsunami. *Sedimentary Geology* 224(1–4), 29–37.
- Spiske, M. and Halley, R. B., 2014. A coral-rubble ridge as evidence for hurricane overwash, Anegada (British Virgin Islands). *Advances in Geosciences* 38, 9–20.
- Switzer, A.D., and J. Pile, 2015. Grain size analysis. In: Shennan, I. et al. (Eds.) *Handbook of Sea-Level Research*. John Wiley & Sons, Ltd., pp. 331-346.
- Takagi, H., and Esteban, M., 2016. Statistics of tropical cyclone landfalls in the Philippines:unusual characteristics of 2013 Typhoon Haiyan. *Natural Hazards* 80, 211–222.
- Tajima, Y., Yasuda, T., Pacheco, B.M., Cruz, E.C., Kawasaki, K., Nobuoka, H.,

- Miyamoto, M., Asano, Y., Arikawa, T., Ortigas, N.M., Aquino, R., Mata, W., Valdez, J., and Briones, F., 2014: Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan. *Coastal Engineering Journal* 56, 1450006, doi:10.1142/S0578563414500065.
- Terry, J.P., Lau, Annie A. Y., Etienne, S., 2013. Uncertainties and continuing challenges with interpreting coastal boulders. In: Reef-platform coral boulders evidence for high-energy marine inundation events on tropical coastlines. Springer Singapore. pp.70-72.

Chapter 5

Geomorphological and sedimentological records of recent storm history of the volcanoclastic coast in Lagonoy Gulf, central eastern Philippines

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Contributions

Lea is the primary author, and with Adam, and Fernando conceptualized the idea, identified appropriate methods, and contributed to its formality and development. Lea conducted the sedimentological analyses, supervised student interns conducting grainsize analysis, interpreted and synthesized sediment and GPR data, and wrote the paper. Jeremy collected, analyzed and contributed GPR data used in this study. Dominik conducted OSL-dating and interpreted OSL results. The Philippine Institute of Volcanology and Seismology through Art provided the GPR equipment and discussed geological insights of the volcanoes found in the study area.

Janneli Lea A. Soria: 60 %

Jeremy Pile: 15 %

Adam D. Switzer: 10 %

Fernando P. Siringan: 7 %

Dominik Brill: 5 %

Arturo Daag: 3 %

Abstract

The Philippine islands lie in the path of tropical cyclones, and many of the coastlines are prone to marine inundations due to storm surges. One recent event was Typhoon Durian, which made landfall in Bicol on 30 November 2006 and generated a storm surge. However, we lack understanding of the storm surge inundation process because instrumental records and immediate post-typhoon surveys were limited. Satellite imagery from 2007 reveal evidences that Typhoon Durian significantly eroded and breached a barrier sand spit north of Tabaco City. Typhoon Durian has left significant geomorphic and sedimentological imprints in the volcanoclastic landscape including overwash fans and terraces. We used the surface elevation of the overwash fans, terraces and relict dunes to estimate inundation heights. In the same way, the Typhoon Durian's geomorphic and sedimentological imprints serve as modern reference to investigate similar inundation events in the geologic past using ground penetrating radar (GPR) imaging. The remnants of the pre-storm dune profile have elevations ranging from 3.5 to 4 m, which imply that breaching likely resulted from inundation considerably higher than 1.5 m but not exceeding 3 m. The typhoon washover deposit resembles the typical washover fan stratigraphy, and exhibits horizontal to sub-horizontal lamination on the front to mid-fan and foreset stratification at the fan terminus. The Durian washover deposit has a sharp, erosional base marked by abrupt coarsening of the sediments. The internal stratigraphy was investigated using Ground Penetrating Radar (GPR), and shore-normal transects reveal at least two and possibly 3 buried erosional surfaces farther inland of the erosional surface of Typhoon Durian. Similar to Durian, the older erosional surfaces were probably sustained from previous typhoons.

5.1. Introduction

Typhoon Durian in December 2006 generated a storm surge that caused landscape changes and left storm deposits on a volcanoclastic barrier spit along Lagonoy Gulf in central eastern Philippines (**Fig. 5.1**). Though this storm surge was a fraction of the size of that of 2013 Typhoon Haiyan (Soria et al., 2016), it has breached segments of the dune. We have limited knowledge on the local hydrodynamic conditions of Typhoon Durian's storm surge. The tide gauge installed by the National Mapping and Resources Agency (NAMRIA) has failed and there was no wave gauge information. The only available information is that of Loy and others (2010), who estimated the storm surge reaching about 1 m in Lagonoy Gulf. However, their study suffered from a number of limitations. Their 2D shallow-water model, only used pressure and wind field forcing, which is typically only applicable to the offshore region. Consequently, their model fails to account for contributions of high-water level from wave set-up and wave run-up onshore, and would almost certainly only provide a conservative estimate of storm surge height (Nott, 2006).

To account for the wave set-up and the wave run-up components including the likely extent of erosion caused by Typhoon Durian we will follow the marine inundation concept of Nott and Hubbert (2005). They showed that inundation magnitude of cyclones Vance and Chris in Australia could be reconstructed from geomorphological indicators provided that post-storm modifications are carefully considered. On the Malinao spit, erosional and depositional landforms such as washover fans and terraces from Typhoon Durian remain evident. Similar erosional and depositional features induced by storms were documented elsewhere particularly along barrier islands on the US Atlantic and Gulf coasts (e.g. Leatherman, 1981; Sedgwick and

Davis, 2003; Williams, 2015). We will adopt the terms for the breached-related erosional and depositional features as defined by Leathermann (1981), Morton (2002) and Morton and Sallenger (2003).

Figure 5.1. Typhoon Durian crossing central Philippines.

- a) Snapshot of the track of Typhoon Durian from 28 November to 01 December 2006.
- b) Along track changes in central pressure.
- c) Satellite image (MTSAT-1R) of typhoon Durian upon landfall on the western coast of Lagonoy Gulf as processed by National Institute of Informatics in Japan.

In addition to characterizing the landform features of Durian overwash we also investigate whether storm-induced erosion and deposition of the past events are preserved in the barrier sand spit stratigraphy. The storm erosion and recovery cycle in coastal environments is well known (e.g. Yu et al., 2013; Switzer, 2015) and where defined by ‘cut and fill’ in the subsurface it can commonly be revealed from ground penetrating radar (GPR) imaging (e.g Buynevich et al., 2004, 2007; Lindhorst et al., 2008; Cunningham et al., 2011). Apart from being a hazard to coastal communities, storm-induced erosion and deposition has been also recognized as an important mechanism for sediment redistribution along the coast, and as such, a vital

component in the evolution of barrier islands and beach ridges (e.g. Moller and Anthony, 2003; Buynevich et al., 2004; Wang and Horwitz, 2007; Nott et al., 2013).

5.2. Study Area

5.2.1. Typhoon Durian in the Philippines

Between 30 November 2006 and 1 December 2006, Typhoon Durian packed with strong wind accompanied with heavy rainfall crossed over central Philippines. A snapshot of typhoon Durian's track is shown in Figure 5.1a. On 28th November, tropical storm Durian entered the Philippine Area of Responsibility and the Philippine Atmospheric, Geophysical and Astronomical Services (PAGASA) assigned it a local name *Reming*. The international name Durian, however, will be used in this paper. On the same day, Durian intensified to a typhoon category. On 29th November, Durian had reached maximum sustained wind speeds of about 250 kph and a central pressure of 915 hPa (**Fig. 5.1b**); and the Joint Typhoon Warning Center (JTWC) classified it as a Super Typhoon. On 30th November, Durian weakened again into a typhoon as it came ashore along the southern coast of Catanduanes Island. At landfall, a synoptic station of PAGASA in Catanduanes recorded a minimum sea-level pressure of 934 hPa, and peak gusts reaching as high as 320 kph. Durian continued its westerly track and made a second landfall along the western coast of Lagonoy Gulf (**Fig. 5.1c**).

5.2.2. Notable historical storms in Lagonoy Gulf and surrounds

Figure 5.2 shows the tracks of the storms that have impacted Lagonoy Gulf and nearby coastlines. These storms, according to the data compiled by Alojado (2015), were notable either because of their typhoon intensity (e.g. Durian, Joan), high cost of

damage (Angela), or human death toll exceeding 500 (e.g. Durian, Angela, Nina, Joan). Similarly, based on unpublished PAGASA dataset and map of historical storm surge occurrences in the Philippines covering the period 1897 to 2011, we highlight the typhoons that have generated storm surges in Lagonoy Gulf (**Table 5.1**). Typhoon Durian was just one among the five known storm surge events that have occurred in the recent past (**Fig. 5.2**). Local residents also recounted an event when Typhoon Joan (*Sening*) on October 1970 generated a storm surge that washed away the houses in a small village called *Natunawan* (which literally means dissolved) at the terminus of the barrier sand spit (**Fig. 5.3b**). So far, the most notable event was the 2 to ~7 m storm surges generated by the 1897 Typhoon Nina (PAGASA, 2000 and PAGASA, 2011).

Figure 5.2. Landfalling tropical cyclones in the surrounding area of Lagonoy Gulf between 1897 and 2013. Storm tracks were from the IBTrACS database of Knapp and others (2010). The attributes of each typhoon are summarized in Tables 5.1 and 5.2.

Table 5.1. Tropical cyclones with known storm surge occurrence (PAGASA 2000)
(Represented in black solid lines in Fig. 5.2).

No.	International name	Local name	Landfall date	Max winds at landfall	Affected area	Storm surge height (m)
1	Harriet		30 December 1959	225 kph		undetermined
2	Kit		6 October 1960			undetermined
3	Vera	Bebeng	14 July 1983	130 kph	Legazpi	0.65 m
4	Nina	Sisang	25 November 1987	240 kph	Tiwi Tabaco Legazpi	6.88 m 2.6 m 3.9 m
5	Durian	Reming	30 November 2006	320 kph	Lagonoy Gulf San Miguel Bay	1 m 6.6 m

Table 5.2. Tropical cyclones with unknown storm surge occurrence (Represented in gray dashed lines in Fig. 5.2).

No.	International name	Local name	Landfall date	Max winds at landfall
6	Jean		25 December 1947	150 kph
7	Fran		29 December 1950	150 kph
8	Trix		21 October 1952	215 kph
9	Emma	Welming	3 November 1967	205 kph
10	Joan	Sening	13 October 1970	275 kph
11	Ora	Konsing	24 June 1972	130 kph
12	Ruby	Huaning	24 June 1976	185 kph
13	Vera	Yayang	5 November 1979	240 kph
14	Irma	Anding	24 November 1981	260 kph
15	Lee	Dinang	25 December 1981	175 kph
16	Betty	Herming	12 August 1987	240 kph
17	Ruby	Unsang	24 October 1988	215 kph
18	Dan	Saling	10 October 1989	120 kph
19	Angela	Rosing	2 November 1995	255 kph
20	Babs	Loleng	21 October 1998	290 kph
21	Muifa	Unding	19 November 2004	130 kph
22	Nida	Dindo	17 May 2004	185 kph
23	Xangsane	Milenyo	27 September 2006	180 kph
24	Nock-ten	Juaning	27 July 2011	95 kph
25	Rammasun	Glenda	15 July 2014	130 kph

5.2.3. Coastal geomorphology

Lagonoy Gulf is a narrow, elongate embayment openly interacting with the Philippine Sea on the central eastern Philippines (**Fig. 5.3**). Compared to the other neighboring embayments like San Miguel Bay and Albay Gulf, Lagonoy Gulf is uniquely deep, characterized by a steep continental shelf with maximum water depths of 1,300 m. This study focuses on an elongate barrier sand spit referred to herein as the Malinao spit along the southeastern coast of Lagonoy Gulf. It is located on the narrow coastal plain downstream of three active stratovolcanoes Malinao, Masaraga, and Mayon, which are predominantly basaltic to andesitic (Divis, 1980; Knittel-Weber & Knittel, 1999; Castillo & Newhall, 2004; Ozawa et al., 2004; Andal et al., 2005). Sandy to gravelly volcaniclastic sediments directly sourced from Malinao, Masaraga, and Mayon volcanoes are transported downstream through the Quinale River towards the coast. A net southeastward longshore transport redistributes the sediments on the southern bank of the Quinale River to form the spit. On the average, the Malinao spit is about 150 m wide and extends 7 km long to the southeast towards Tabaco City.

5.3. *Materials and Methods*

5.3.1. Image interpretation and initial field investigation

We compared satellite images taken before and after the storm to map the landscape changes caused by Typhoon Durian (**Fig. 5.4**). The pre-storm image was acquired on 22 March 2006, while the post-storm images were acquired on 04 May 2007 and 29 September 2011. The images were accessed through Google Earth Pro server and compiled on a Global Information System (GIS) platform using Manifold[®] Systems for georeferencing.

Figure 5.3. Geomorphology of the coast surrounding Lagonoy Gulf (a). The study area is located on a sandy barrier spit, on a segment of the coast that is relatively sheltered from open-sea waves.

The initial survey was conducted on June 2012 to validate the geomorphological features identified on the satellite images. Residents of the coastal village Baybay recounted that strong waves during the passage of Typhoon Durian as it breached a portion of the Malinao spit (**Fig.5.5a**). One prominent breaching site is about 250 m wide, and indicated by a disrupted line of *Casuarina* trees, along with a relatively lower and flatter surface bounded by erosional scarps on its northern and southern margins. The *Casuarina* trees, according to local officials, were planted as part of a coastal protection project in the early 1990s.

The washover fans on the two breaching sites and their associated deposits were studied in detail. Six shallow trenches, TP1 to TP6 were excavated along a transect perpendicular to the coast. The trenches were typically about 1 m wide and 40 to 90 cm deep, but varied in lengths from 1 to 7 m. A leveling survey was conducted to

Figure 5.4. Pre- and post-storm coastal geomorphology derived from satellite images. The dune was totally breached at two sites indicated by washover fan or terrace morphology.

Figure 5.5. Two most prominent washover fans (terrace) on the barrier spit.

- a) Google Earth image taken on 29 September 2011 showing the location of the GPR transects and trenches (TP) .
- b) The northern washover terrace bounded by an erosional scarp of the dune.
- c) Along-shore profile showing that post-storm dune elevations are laterally variable. Elevations of the pedestals and washover fans suggest that the inundation level during Typhoon Durian was at least 1.5 m but not exceeding 3 m.
- d) Elevation profile across the southern washover fan.
- e) Elevation profile across the northern washover terrace.

determine the elevations of the trenches and the surfaces of washover features above local sea level. Using the actual tide data at Legazpi station for the duration of the survey, the raw elevations were then referenced to regional mean sea level (msl). Sediment sequences were logged and photographed. Sediment samples were successively collected in 2-cm intervals, and on the sedimentary contacts identified in the trenches. Grab samples of surface sediments were obtained from the beach face, berm, dune, and tidal channel.

Grainsize analysis was performed only on the lithic component of the sediments. Large organic debris and carbonate grains were picked using forceps, whereas, the smaller, fibrous organic debris were removed by floatation. The sediments were successively oven dried at 50°C, and about 50g to 100 g of dry subsamples were introduced on the Retsch Technology CAMSIZER® for grainsize analyses. The CAMSIZER® provides non-destructive and rapid grain size and shape distributions for sediments ranging from 20 microns to 30 millimeters by capturing images of a falling curtain of sediment at 25 Hz (Moore et al., 2006). For the mud deposits capping several trenches, about 1g to 2g was taken in each sample for grainsize analysis. Samples were treated with 20% H₂O₂ to remove organics and 15% hydrochloric acid (HCl) to remove carbonate fragments. The samples were rinsed in distilled water before introducing to the Malvern Mastersizer 2000 for grainsize analyses using laser diffraction following procedures outlined by Switzer (2013).

The grainsize corresponds to the cross-sectional area of the particles in the image from the CAMSIZER and on the laser particle analyzer. The grainsize data were then run through the open-source program GRADISTAT version 8.0 (Blott 2001)

to generate statistical grain size distributions. The fraction of sediment by different category size (e.g. clay, very coarse silt, medium sand) along with the logarithmic (Folk and Ward, 1957) mean, median, sorting, and skewness were used to establish vertical and across-shore variations of the sedimentology of the washover fan deposits.

5.3.2. Ground penetrating radar (GPR) survey and chronological control

Subsequent field investigations in 2013 were focused on the breached portions of the dune and unbreached areas where erosional surfaces were likely to be preserved. A GPR survey was carried out on 13 to 16 June 2013 to image possibly buried erosion surfaces on the barrier spit (**Fig. 5.5**). On each of the breaching sites, a shore-normal GPR transect scanned across the barrier spit from the highwater mark of the beachface landward to the edge of the tidal channel. Shore parallel surveys were also conducted along the top of the barrier and along the landward margin of the barrier. GPR profiles were collected using a 100 MHz Sensors and Software Noggin system on Smart Cart with antennae separation fixed at 0.5 m. Acquisition was controlled by odometer wheel with a step size 0.1 m and a time window 400 ns. Depth of penetration varied from 2 m to 8 m and we used hyperbolae matching to determine near surface velocities in order to estimate depth. Velocities of 0.07 m/ns were used as these lie between published values of 0.06 m ns⁻¹ for wet coastal dune sand (Switzer et al., 2006) and 0.09 m ns⁻¹ for wet though finer, volcaniclastic sand in lahars and fans (Ettinger et al., 2014). Topographic and positional data along the GPR transects were simultaneously collected using a South Survey S82-T GNSS differential global positioning system. All the points were referenced to the benchmark AL-270, a National Mapping Resources Information Agency established levelling datum located

~1.6 km west of the study area. Post-survey processing and plotting utilised both EKKO_View and ReflexW software programs. Simple processing including Dewow filtering, automatic gain control, horizontal and vertical averaging were applied to the data. The radar reflection profiles for each transect were examined and interpreted using a radar facies approach (e.g. Van Heteren et al., 1998; Neal and Roberts, 2000; Jol and Bristow, 2003; and Neal, 2004).

On September 2013, additional trenches (TP7 to TP10) were excavated seaward of the earlier pits to validate sedimentary structures revealed in the radar profiles and to collect sediments for grainsize analysis and to attempt Optically Stimulated Luminescence (OSL) dating of the sediments from either side of identified erosional unconformities. Sediments for luminescence dating were obtained following the publicly available sampling protocol of the Utah State University Luminescence Laboratory (Accessible online at <http://www.usu.edu/geo/luminlab/how2osl.pdf>). Opaque metal tubes were driven horizontally into the sediment units above and below the erosional contacts to obtain samples for luminescence dating. Sediments within 20-cm radius surrounding the metal tubes were collected into a ziplock freezer bag for the measurement of the environmental dose rate. A total of five samples were sent to University of Cologne in Germany, for initial examination on the potential to use Optically Stimulated Luminescence (OSL) dating analysis (**Table 5.3**) for a chronology of past storm events.

5.3.3. Luminescence dating

A preliminary luminescence analysis was conducted on sample TP10 to test the suitability of the young volcanoclastic sediments for OSL dating. The sample was

prepared following standard procedures for coarse grained samples, including (i) sieving to retrieve the 100-200 μm fraction, (ii) treatment with 10% HCl and 10% H_2O_2 to remove carbonates and organics, (iii) density separation using heavy liquid to extract quartz (2.62-2.68 g/cm^3) and potassium feldspar ($<2.58 \text{ g}/\text{cm}^3$), and (iv) etching with 40% HF for 40 minutes to remove the alpha irradiation affected rim of the quartz grains. The extracted quartz and potassium feldspar grains were then subjected to dose rate measurements using a standard blue-OSL SAR protocol in the case of quartz (Murray and Wintle, 2003) and a standard IR_{50} SAR protocol for the feldspar (Wallinga et al., 2000).

Table 5.3. List of samples for OSL Dating.

#	Sample ID (field)	Long	Lat	Depth from surface, m	Surface Elevation (msl), m	Sample Elevation (msl), m	Mean grainsize, μm
1	TP7-1	123.43	13.23	0.48 - 0.52	2.083	1.56 - 1.60	366.9
2	TP7-2	123.43	13.23	0.86 - 0.90	2.083	1.18 - 1.22	560.3
3	TP8	123.43	13.23	1.3 - 1.35	3.08	1.73 - 1.78	559.8
4	TP9	123.72	13.39	0.93 - 0.97	2.242	1.27 - 1.31	326.1
5	TP10	123.43	13.23	0.85 - 0.90	1.785	0.88 - 0.93	355.3

5.4. Results

5.4.1. 2006 Typhoon Durian landscape changes and post-Durian modifications

Typhoon Durian has left prominent landscape changes that are visible on the satellite images taken before and after the storm (**Fig. 5.4**). The satellite imagery taken eight months prior to Typhoon Durian revealed a segment of the spit with extensively vegetated backshore with a treeline marking the dune crest (**Fig. 5.4a**). On the landward edge of the barrier spit are patches of mangrove along a meandering tidal channel. Six months after Typhoon Durian, the image showed minimal lateral shore

erosion, but the spit was stripped of vegetation (**Fig. 5.4b**). Tongue- and fan-shaped surfaces, which indicate localized dune breaching were also prominent. On these breached portions of the dune, the depositional features ranged from isolated perched fans to closely spaced fans merged to form washover terraces.

The study is focused on the two most prominent breaching sites (**Fig. 5.5**). Narrow bands of light brown surfaces on the barrier spit visible on the September 2011 image (**Fig. 5.5a**) are accumulations of mud from a large fluvial flood caused by heavy rainfall with the July 2011 tropical storm Nock-ten (NASA, 2011). The mud line, which approximates the upper limit of standing flood levels, indicates that the washover fan surfaces were most probably submerged during the flood. On the other hand, the higher portions of the barrier dune have not been flooded, and were most likely minimally disturbed. The washover fans and terraces are bounded on the sides by either a gentle topographic rise to steep scarps of the unbreached portions of the dune called pedestals. These pedestals typically stand at 3 to 4 m above sea level (asl) are remnants of the pre-storm dune elevation (**Fig. 5.5b**). A transect parallel to the coast shows the dune pedestals rising above washover fans and terraces, which are at much lower elevations between 1.5 to 2.5 m across the breached portions (**Fig. 5.5c**). The elevations of the pedestals and washover fans suggest that the inundation level must be higher than 1.5 m but likely did not exceed 3 m.

The sedimentology was investigated along two shore normal transects. But the detailed washover stratigraphy will only be presented for the southern fan containing trenches TP4 to TP8. This is because compared to the northern fan; the southern fan has not been significantly modified post-deposition by the tidal channel.

5.4.2. Stratigraphy on the washover fan

The transect on the southern fan reveals a sequence of laminated coarse-grained sands deposited by the breaching-related overwash of Typhoon Durian (**Fig. 5.6**). Most proximal to the shore, TP8 shows a planar-laminated coarse sand unit that exhibit little significant vertical variation in grainsize except at the depth between 1 to 1.2 m from the surface where a discrete 10-cm thick gravelly layer is found (**Fig. 5.6a**).

Moving inland, the walls of trenches TP7, TP6 and TP 5 consistently show a sequence of pre-Durian sand, overlain by the Durian washover sand, and capped by a muddy sand. In TP7 the pre-Durian stratigraphy is composed of two sand units that are separated by a gently dipping, 3 cm-thick bed of black sand. The lower sand unit (pre-TD2) contains coarse sand (0 to -1 ϕ). The upper sand unit (pre-TD1) contains mostly fine to medium sand, no coarser than 1 ϕ , that exhibits thin planar to slightly undulating laminations. The upper part of the pre-TD1 sand unit, contains laminae that are truncated highlighting a sharp contact that separates it from the overlying coarser sand unit interpreted as the Durian washover (**Fig. 5.6b**). The Durian washover deposit (TD) is identified as a 35 cm thick laminated gravel basal layer (40-60% gravel) that grades into a laminated coarse sand towards the top. Unlike in TP7, the Durian washover deposit (TD) inland at TP6 and TP5 is much thinner at about 12 to 15 cm thick (**Fig. 5.6c-d**), and mostly coarse sand containing discrete thin layer of gravel (<10% gravel). Though the sedimentology is similar the sequence in TP5 shows a slight contrast where a 3 cm thick grayish brown medium sand marks the sharp boundary between the darker colored pre-Durian sand (pre-TD1) and the lighter colored Durian washover sand (TD). Grass roots penetrate into the Durian washover sand obscuring the apparent lamination. At the terminus of the washover fan, the washover deposit in trench TP4 can be as thick as 60 cm and exhibit prominent

Figure 5.6. Stratigraphy and vertical textural variation of the sedimentary units revealed in trenches TP8 (a), TP7 (b), TP6 (c) and TP5 (d) located on the southern washover fan.

Figure 5.7. Trench TP4 showing foreset stratification (a,b) , and slight coarsening upward sequence (c) at the terminus of the washover fan.

foreset stratification (**Fig. 5.7**). The foresets dip at angles ranging from 14° to 22° . Discrete very coarse-grained laminae contain about 4 to 6 percent gravel. A 5 cm thick, brown mud caps the Durian washover deposit in trench TP7, TP6 and TP5. This mud unit most likely corresponds to the flood deposit of the July 2011 tropical storm Nock-ten.

5.4.3. Vertical and lateral textural trends of the washover deposit

The Typhoon Durian washover deposits on the southern washover fan exhibit both fining and coarsening upward sequence (**Fig. 5.6 & 5.7**). Trench TP8, TP7 and TP5 exhibit fining upward trends with mean grain size at the base ranging between -2ϕ , (granule) to 1ϕ (coarse sand), grading to 0.5ϕ (coarse sand) to 1.5ϕ (medium sand) towards the top. This fining upward trend is accompanied by a generally high gravel component (6% to as high as 60% in TP7) at the base of the Durian washover deposit, and then decreases towards the top. In contrast, trench TP6 and TP4 show coarsening upward trends.

The erosional base and the mud cap unit on top were used as stratigraphic boundaries to constrain the thickness of the washover deposit across the washover fan (**Figs 5.6 to 5.8**). At trench TP8, the washover deposit can be as thick as 1 m. In TP7 the washover deposit is about 30 cm. A slightly thinner deposit was found in TP6 (15 cm) and in TP 5 (10 cm). At the terminus of the fan in TP4, the washover deposit was up to 60 cm thick. The deposit thickness, however, does not necessarily correspond to the deposition directly associated with Typhoon Durian, but most likely represent the cumulative effect of post-depositional changes such as erosion at the terminus of the fan by tidal action, or beach recovery near the shore by swash action. In contrast to

Figure 5.8. Across-shore profile (a) and lateral variation in thickness and grainsize (b) of the Typhoon Durian washover deposit on the southern washover fan.

the highly variable thickness, bulk sediment mean and d_{90} grain size show an overall fining landward trend of the washover deposit near the shore at TP8 towards the fan terminus at TP4 (**Fig. 5.8**).

5.4.4. Sediment source of the Typhoon Durian washover deposit

A comparison of the textural characteristics of the grab samples from the beach face, berm, dune and tidal channel reveals that moderately sorted, medium to coarse sands are readily available for transport in the barrier spit system (**Fig. 5.9**). The sediments on the beach face are relatively finer compared to the inland berm, dune and tidal channel sediments. The coarsest sediments are found on the berm.

The mean grain size and sorting of the washover deposits are more similar to the coarser sediments found in the berm, dune and tidal channel. The washover deposits were most probably sourced from the locally breached part of the dune. There is very little gravel in the dune sediments and the abundance of gravel components in the washover deposits imply an additional contribution from other sources. Such sediments would need to be fairly high energy suggesting a likely source would be the shoreface or swash zone.

5.4.5. Ground penetrating radar profiles

A shore-normal GPR profile on the southern washover fan reveals a combination of dipping, sub-horizontal, and horizontal reflections (**Fig. 5.10**). Seaward dipping reflections (apparent dip: 20 to 25°) occur from the beach until 20 m inland. Beyond 20 m the reflectors merge with initially shallow, sub-horizontal to landward dipping (<10°) reflections, and subsequently with predominantly horizontal reflections extending landwards to the edge of the tidal channel. At least three steep, shoreward

Figure 5.9. Textural comparison of the washover deposits with surface sediments of the possible source environments including the beach face, berm, dune, and tidal channel.

Figure 5.10. Internal stratigraphy across the southern washover fan revealed on a GPR profile, presented here as processed and topographically corrected section (a) and interpreted section (b). Trench TP7 (c) validates the erosional surface identified on the GPR profile to be pre-Durian. The erosional surface separates two pre-Durian sand units (pre-TD1 and pre-TD2). TD corresponds to the Typhoon Durian washover deposit. TSN corresponds to the mud deposit of tropical storm Nock-ten.

dipping reflections (apparent dip: 15 to 30°) subsequently truncate the sub-horizontal to horizontal reflections across the barrier spit. Trench TP7 taken through one of the prominent seaward dipping reflections revealed a seaward, gently dipping (apparent dip: 10°) feature at depths between 60 to 70 cm from the surface. The seaward dipping feature is marked by a 3 cm thick black magnetite sand that truncates planar-laminated sand and gravelly sand units below, which indicate that it is an erosional surface. Above the erosional surface the sequence consists of the pre-2006 Durian laminated sand unit, overlain by the 2006 Durian laminated gravelly to coarse sand washover deposit, and capped by the 2011 tropical storm Nock-ten muddy flood deposit.

Other miscellaneous reflections identified in the profile include air and ground waves and water table. The continuous double reflection at the top of the GPR profile corresponds to the air and ground waves. Another continuous, horizontal reflection at ~2 m depth represents the freshwater table. Reflections are strongly attenuated below 3 m depth. Attenuation of the electromagnetic radar signal by saltwater is a common issue in low-lying coastal settings.

The GPR profile on the northern washover terrace displays reflection patterns nearly similar to that on the southern washover fan (**Fig. 5.11**). Seaward dipping reflections (apparent dip: 25 to 30°) dominate within 20 m from the beach. The reflections dip gently landwards (apparent dip: 10°) between 20 m and 40 m, and then join with sub-horizontal to horizontal reflections throughout the remainder of the transect. Trench TP10 taken through the prominent seaward dipping reflections at 20 m from the shore revealed a seaward, steeply dipping (apparent dip: 20 to 30°) feature at depths

Figure 5.11. Internal stratigraphy across the northern washover fan revealed on a GPR profile, presented here as processed and topographically corrected section (a) and interpreted section (b). Trench TP10 (c) validates the erosional surface identified on the GPR profile to be associated with Typhoon Durian. The erosional surface truncates horizontally laminated pre-Durian sand unit (pre-TD). The sand unit above the erosional surface most likely correspond to the Durian washover deposit (TD) including newly accreted sediments during post-Durian beach recovery (post-TD).

between 40 to 50 cm from the surface, which is bounded above and below by laminated sand and gravelly units. The seaward dipping feature is marked by a black magnetite sand unit, which varies in thickness from 10 cm to 4 cm and truncates planar-laminated sand and gravelly sand units below. This is consistent with the erosional nature of the seaward dipping surface in trench TP7. A wedge-like gravelly sand unit (~50% gravel) sits immediately above the erosional surface. The gravelly sand unit gradually transitions to laminated sand and then to unstratified sand units towards the top.

5.4.6. Chronological control

Although measured on large aliquots with 8-mm diameter (equivalent to ~1000 quartz or feldspar grains, and the largest aliquot size that can be measured), the luminescence signals of both minerals appeared to be extremely weak (**Fig. 5.12**). Most aliquots did not show any visible response to laboratory stimulation even after the application of relatively large laboratory doses of 10-30 Gy. Only some of the quartz and feldspar aliquots revealed visible signal curves (**Figs 5.12a,b**), but these are extremely dim and hardly distinguishable from background scatter in case of the feldspars (**Fig. 5.12b**). In addition to the dim signals, quartz also yielded an unstable and slowly bleaching medium component (**Fig. 5.12a**). As a consequence, the corresponding dose-response curves are associated with large fitting error due to signal scatter indicating very high uncertainties (**Fig. 5.12c,d**). The combined very low recycling ratios and recuperation do not fulfill the reproducibility and recuperation criteria, which are a prerequisite for reliable dating. In the absence of precise chronological control, the 2006 Typhoon Durian washover deposit can however be used as a stratigraphic marker. The ages of the erosional surfaces and

Figure 5.12. OSL signals of the sediment sample in trial pit TP7-1.
a) Decay curves of the natural (red) and regenerated (grey) quartz show weak and scattered luminescence signals and fitting of the signal curves (inset) points to a strong influence of slowly bleaching and unstable medium component.
b) Decay curves of the natural (red) and regenerated (grey) IR50 feldspar luminescence signals.
c) Dose-response curves for quartz and feldspar.

remaining sediment units will be defined relative to their stratigraphic relation to the Durian washover deposit.

5.5. Discussion

5.5.1. Geomorphologic imprints of coastal inundation and their preservation

This study demonstrates and further reinforces the concept that in cases when in-situ instrumentation and immediate post-typhoon surveys are limited or non-existent, geomorphologic investigations of the erosional and depositional features can augment information gaps on inundation levels. A series of pre- and post-Durian images further aid in identifying possible landscape modifications before the actual field survey such as the July 2011 tropical storm Nock-ten flooding. The relatively good preservation of the erosional and depositional imprints of Typhoon Durian on the Malinao spit implies a preservation potential of nearly 7 years on this coastline is possible. The preservation potential of 7 years, however, is still very short. In certain areas, relict or inactive washover fans on the west-central Florida barrier coast remained recognizable on aerial photographs even after 30 to 40 years (Sedgwick and Davis, 2003).

Typhoon tracks from local and international weather agencies show no record of a landfalling typhoon at or near Lagonoy Gulf following Typhoon Durian until the end of 2013, except for tropical storm Nock-ten. This tropical storm brought heavy rainfall resulting in extensive floods (NASA, 2011; Salaverria, 2011) but not enough strong winds to generate storm surge capable of overtopping the previously lowered breached portions of the spit. Furthermore, there was neither geomorphic indicator nor first-hand account of barrier washout during the flood. In fact, even after the tropical storm Nock-ten flood, the washover fans remained recognizable on the satellite

images. This period of relative typhoon quiescence perhaps aided in the preservation of the geomorphic imprints of inundation in Malinao.

5.5.2. Storm surge history reconstructed from sediment record

The Typhoon Durian washover deposit has a distinct sediment signature of a sharp erosional base overlain by coarse-grained unit composed of either coarse to very coarse sand or gravel. A similar trend of abrupt textural coarsening of the sediments, which represent the onset of tropical cyclone-induced inundation and sedimentation within the frontal beach ridge, has been observed along the northeast coast of Australia (Nott et al., 2013). This textural signature has been useful to constrain stratigraphic boundaries within the barrier spit sediment sequence containing fairly homogenous components.

The Typhoon Durian washover deposit also exhibit notable planar horizontal laminations, which then terminate into foreset laminations at the landward terminus of the fan. These internal stratifications are similar to the generalized washover stratigraphy, and the foreset laminae indicate subaqueous deposition when the overwash enters into the tidal channel (Sedgwick and Davis, 2003). Although the washover deposit does not exhibit consistent vertical textural trends across the fan, there is a discernable overall fining trend towards the terminus of the fan (**Fig. 5.8**). Landward fining trend is typically attributed to the diminishing flow of the surge across the fan towards the terminus (Leatherman and Williams, 1977).

The two shore-normal GPR profiles consistently show at least three seaward-dipping prominent reflections, which were confirmed at two locations as erosional surfaces. The seaward most erosional surface corresponds to 2006 Typhoon Durian, while the two erosional surfaces inland were most probably sustained from earlier similarly intense landfalling typhoons. Prior to Durian, other intense typhoons have generated storm surge in Lagonoy Gulf including the 1987 Nina, 1960 Kit and 1959 Harriet (**Fig. 5.2**). The storm surge of Typhoon Nina exceeded 2 m in Tabaco City to as high as ~7 m in the town of Tiwi (PAGASA, 2000). The storm surges associated with typhoons Kit and Harriet are unknown. At this point, we cannot determine for certain whether the older dune erosion or breaching events were caused by these typhoons due to the absence of accurate chronological constraints on the erosional surfaces.

Unfortunately, this study also highlights the challenge of obtaining chronological control on coarse, volcanoclastic sediment systems. OSL-dating failed to produce age dates for the sedimentary units bounding the erosional surfaces. Both quartz and feldspar grains yielded extremely dim signals owing to either their volcanic origin or perhaps incomplete bleaching (Kolstrup, 2007; Davids et al., 2010). Aside from the weak quartz and feldspar signals for effective OSL-dating, fine-grained or organic-rich sediments are also not available for alternative age-dating techniques such as radiocarbon dating or ^{210}Pb .

6. Conclusions

Typhoon Durian generated a storm surge that caused significant erosion and breached segments of the Malinao barrier sand spit in central eastern Philippines. Satellite imagery in September 2011 showed signs of beach recovery but the geomorphological indications of the inundation were still evident and were

successively studied in 2012 and 2013. Remnants of the pre-storm dune profile have elevations ranging from 3.5 to 4 m, which imply that breaching might have resulted from inundation higher than 1.5 m but not exceeding 3 m. The typhoon washover deposit resembles the typical washover fan stratigraphy, and exhibits horizontal to sub-horizontal lamination on the front to mid-fan and foreset stratification at the fan terminus. The Durian washover deposit has sharp, erosional base marked by abrupt coarsening of the sediments. Shore-normal GPR transects reveal at least two buried erosional surfaces farther inland of the erosional surface of Typhoon Durian. Similar to Durian, the older erosional surfaces were probably formed from previous typhoons. But because of limited datable materials, the timing of the erosional surfaces remain unknown, highlighting the persisting challenge of obtaining chronological control on coarse, volcanoclastic sediments.

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References

- Alojado, D., and Padua, D.M.V., 2015. Strongest typhoons in the Philippines (1947-2014). Accessed on 25 June 2016. (Available online at http://www.typhoon2000.ph/stormstats/WPF_StrongestTyphoonsPhilippines_2015Ed.pdf.)
- Andal, E.S., Yumul, G.P. Jr., Listanco, E.L., Tamayo, R. A. Jr., Dimalanta, C.B., and Ishii, T., 2005. Characterization of the Pleistocene volcanic chain of the Bicol Arc, Philippines: implications for geohazard assessment. *TAO* 16 (4), 865-883.
- Blott, S.J. and Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26, 1237-1248.
- Buynevich, I.V., Fitzgerald, D.M. and Van Heteren, S., 2004. Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. *Marine Geology* 210, 135-148.
- Buynevich, I. V., FitzGerald, D. M., & Goble, R. J. (2007). A 1500 yr record of North Atlantic storm activity based on optically dated relict beach scarps. *Geology* 35(6), 543-546.
- Castillo, P. R., and C. G. Newhall, 2004: Geochemical constraints on possible subduction components in lavas of Mayon and Taal volcanoes, Southern Luzon, Philippines. *Journal of Petrology* 45, 1089-1108.
- Cunningham, A. C., Bakker, M. A., van Heteren, S., van der Valk, B., van der Spek, A. J., Schaart, D. R., & Wallinga, J. (2011). Extracting storm-surge data from coastal dunes for improved assessment of flood risk. *Geology* 39(11), 1063-1066.
- Davids, F., Duller, G.A.T., and Roberts, H.M., 2010. Testing the use of feldspars for optical dating of hurricane overwash deposits. *Quaternary Geochronology* 5, 125-130.
- Divis, A. F., 1980: The petrology and tectonics of recent volcanism in the central Philippine Islands. *AGU Geophysical Monograph Series* 23, 127-124.
- Ettinger, S., Manville, V., Kruse, S., & Paris, R. (2014). GPR-derived architecture of

- a lahar-generated fan at Cotopaxi volcano, Ecuador. *Geomorphology* 213, 225-239.
- Folk, R.L., W.C. Ward. 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27, 3–26.
- Jol, H.M., Bristow, C.S., 2003. GPR in sediments: advice on data collection, basic processing and interpretation, a good practice guide. In: Bristow, C.S., Jol, H.M. (Eds.), *Ground Penetrating Radar in Sediments. Geological Society London Special Publication 211*, 9-27.
- Knittel-Weber, C., and U. Knittel, 1990: Petrology of the volcanic rocks on the eastern flank of Mount Malinao, Bicol Arc (S. Luzon, Philippines). *Journal Southeast Asian Earth Sciences* 4, 267-280.
- Kolstrup, E., 2007. OSL dating in paleoenvironmental reconstructions. A discussion from a user’s perspective. *Estonian Journal of Earth Sciences* 56 (3), 157-166.
- Leatherman, S.P., 1981. Overwash processes. *Benchmark papers in Geology*, Vol. 58. Hutchinson Ross Publishing Co., USA. 376 pp.
- Leatherman, S.P., Williams, A. T., 1977. Lateral textural grading in overwash sediments. *Earth Surface Processes* 2, 333-341.
- Lindhorst, S., Betzler, C., & Hass, H. C. (2008). The sedimentary architecture of a Holocene barrier spit (Sylt, German Bight): Swash-bar accretion and storm erosion. *Sedimentary Geology* 206(1), 1-16.
- Loy, K.C., Sinha, P.C., Liew, J., Tangang, F., and Husain, M.L. 2010. Modeling storm surges associated with super typhoon Durian in South China Sea. *Natural Hazards*. DOI 10-1007/s11069-010-9674-7.
- Møller, I. and Anthony, D., 2003. GPR study of sedimentary structures within a transgressive coastal barrier along the Danish North Sea coast. In: *Ground-penetrating Radar in Sediments* (Eds C.S. Bristow and H.M. Jol). *Geological Society London Special Publication 211*, 55–67.
- Morton, R.A., 2002. Factors controlling storm impacts on coastal barriers and beaches — a preliminary basis for real-time forecasting. *Journal of Coastal Research* 18, 486–501.

- Morton, R.A., and Sallenger Jr., A. H., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research* 19 (3), 560-573.
- Ozawa, A., Tagami, T., Listanco, E. L., Arpa, C. B., and Sudo, M. 2004: Initiation and propagation of subduction along the Philippine Trench: evidence for the temporal and spatial distribution. *Journal of Asian Earth Sciences* 23, 105-111.
- National Aeronautics and Space Administration (NASA). 27 July 2011. NASA measures heavy rain in tropical storm Nock-ten over Philippines. Accessed online 10 April 2012. Available online at [http://www.nasa.gov/mission_pages/hurricanes/archives/2011/h2011_Nock-ten.html].
- Neal, A., 2004. Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth-Science Reviews* 66, 261–330.
- Neal, A., Roberts, C.L., 2000. Applications of ground penetrating radar (GPR) to sedimentological, geomorphological and geoarchaeological studies in coastal environments. In: Pye, K., Allen, J.R.L. (Eds.), *Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarchaeology*, *Geological Society of London Special Publications* 175, 139-171.
- Nott, J. 2006. *Extreme events: a physical reconstruction and risk assessment*. Cambridge University Press. 297 pp.
- Nott, J., Chague-Goff, C., Goff, J., Sloss, C., Riggs, N., 2013. Anatomy of sand beach ridges: evidence from severe Tropical Cyclone Yasi and its predecessors, northeast Queensland, Australia. *Journal of Geophysical Research: Earth Surface* 118, 1710-1719.
- Nott, J. and Hubbert, G., 2005. Comparisons between topographically surveyed debris lines and modeled inundation levels from severe tropical cyclones Vance and Chris, and their geomorphic impact on the sand coast. *Australian Meteorological Magazine* 54, 187-196.

- Padua, D.M.V., 2008. 29 Most intense typhoons of Bicol Region, Philippines.
Accessed on 25 June 2016. (Available online at
<http://www.typhoon2000.ph/25mostb.htm>.)
- Salaverria, L., 27 July 2011. Tropical storm 'Juaning' slams Bicol provinces; 9 killed.
Inquirer Southern Luzon, Philippine Daily Inquirer. Accessed on 10 April
2012. Available online at [<http://newsinfo.inquirer.net/30793/tropical-storm-juaning-slams-bicol-provinces-9-killed>].
- Sedgwick, P. E., Davis, R. A. Jr., 2003. Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. *Marine Geology* 200, 31-48.
- Soria, J.L.A., Switzer, A.D., Villanoy, C.L., Fritz, H.M., Bilgera, P.H.T., Cabrera, O.C., Siringan, F.P., Yacat-Sta. Maria, Y., Ramos, R.D., Fernandez, I.Q., 2016. Repeat storm surge disasters of Typhoon Haiyan and its 1897 predecessor in the Philippines. *Bulletin of the American Meteorological Society* 97(1), 31-48.
- Switzer, A.D., 2013. Measuring and analyzing particle size in a geomorphic context. In: Shroder, J. (Editor in Chief), Switzer, A.D., Kennedy, D.M. (Eds.), *Treatise on Geomorphology*. Academic Press, San Diego, CA, vol. 14, *Methods in Geomorphology*, pp. 224-242.
- Switzer, A.D., Bristow, C.S., and Jones, B.G., 2006. Investigation of large-scale washover of a small barrier system on the southeast Australian coast using Ground Penetrating Radar. *Sedimentary Geology* 183(1), 145-156.
- Wang, P., and Horwitz, M.H., 2007. Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. *Sedimentology* 54, 545-564.
- Williams, H.F.L., 2015. Contrasting styles of Hurricane Irene washover sedimentation on three east coast barrier islands: Cape Lookout, North Carolina; Assateague Island, Virginia; and Fire Island, New York. *Geomorphology* 231, 182-192.

Chapter 6

Synthesis

Typhoon Haiyan tragically attests to the vulnerability of Philippine coasts to storm surge hazard. It also highlighted the limited and patchy knowledge that exists on the impacts to immediately affected communities despite the high frequency of storm surges in the archipelago. Moving forward, this dissertation contributes to increasing the level of local and regional science-based knowledge by laying down groundwork on the geologic investigations of storm surge impacts in the Philippines. Two recent storm events namely the 2006 Typhoon Durian (*Reming*) and the 2013 Typhoon Haiyan (*Yolanda*) provided an opportunity to study the geomorphic and sedimentologic imprints of storm surges and the resulting coastal overwash.

This dissertation though primarily built upon a geological framework of storm surge has benefited considerably from the integration of multiple disciplines including meteorology, oceanography, coastal engineering, and history (Switzer et al., 2014). Overall, the multi-disciplinary approach led to (1) local understanding of storm surge dynamics and the factors affecting the spatial variation of amplification leading to inundation overland; (2) characterization of the onshore geomorphic and sediment imprints within the bounds of hydrodynamic conditions and sediment transport processes; and (3) historically-oriented investigation of storm surge heights and the geologic impacts to the coasts near typhoon landfalls. In this chapter, the key results of this study are

highlighted, limitations are recognized, and finally potential future studies are identified.

6.1. Key Results

In retrospect, the historical record reveals an unnamed typhoon on 12 October 1897 October a typhoon that is now noted as a predecessor to Typhoon Haiyan. The typhoon referred here as Ty 1897 took a similar path of destruction through the eastern central Philippines. In contrast to the almost identical typhoon tracks, Typhoon Haiyan differs from Ty 1897 in several ways. Haiyan was more intense, had larger maximum wind coverage, and moved faster than Ty 1897. The comparative study between Typhoon Haiyan and Ty 1897 reveals that Typhoon Haiyan's storm surge was about twice the height of the 1897 event in San Pedro Bay, but the two storm surges had similar heights on the open Pacific coast (Soria et al., 2016; Chapter 2). One of the key elements to this comparative study is the availability of a reliable historical post-typhoon technical report of Ty 1897 which provided essential information such as typhoon track, barometric readings, photos of damage and coastal impacts, and somewhat uniquely the spatial surge height data. Historical records of Philippine typhoons cover a relatively extensive period extending back to the Spanish colonial era (1521 to 1898), but detailed reports for a specific event are rare and perhaps biased towards high-impact events such as those with a high death toll. Notably, uncertainties due to different instrumentation between two periods of time cannot be avoided due to technological development through time but to some extent the uncertainties can be overcome (Chapter 2, Appendix 3).

Apart from written records, typhoons and storm surges also leave a legacy of geomorphic and sedimentologic imprints on the coasts. The coastal response to a specific event can vary across sites due to variations in coastal setting and landscapes, and the varying overwash regimes. A segment of siliciclastic coast of Tanauan sustained lateral beach erosion from 10 m to 25 m from Typhoon Haiyan (Chapter 3). Surface elevations of the re-exhumed mangrove soil, and the top of the exposed roots of the coconut trees indicate vertical beach erosion of about 1 to 2 m. The complete inundation overwash of Typhoon Haiyan also left a vast sheet of sand that is fining to silt on the most inland extent about 1.5 to 1.8 km. Near the coast immediate post-storm recovery rebuilt the beach dune system with a combination of overwash, vertical and lateral accretion. In comparison, Typhoon Durian's storm surge, which was only a fraction of the size of that of 2013 Typhoon Haiyan had caused minimal lateral erosion on a volcanoclastic coast of Lagonoy Gulf (Chapter 5). However, wave runup caused breaching on weaker portions of the barrier spit resulting in the formation of washover fans and washover terraces. Two prominent breaching sites are about 50 m to 250 m wide accompanied by vertical erosion of 2 m and 1 m, respectively. Despite the different storm surge magnitudes and overwash regimes, washover fans and terraces seem to be a common sediment landform on these clastic coastlines. On the contrary, no washover fans or terraces were found on the carbonate coast of Hernani, Samar (Chapter 4). Instead, Typhoon Haiyan left conspicuous coral reef boulders strewn on the reef flat, and carbonate sand sheet that draped the coastal plain. The contrast between overwash sediments from Haiyan in areas that experienced similar storm surge conditions like Tanauan and Basey underscore

the effect of local geology and the type of sediments available for transport (Chapter 3).

Haiyan's overwash sediment units represent an extreme storm surge event, which is valuable in expanding dataset for storm deposits between clastic and non-clastic carbonate coastal settings. On the clastic coast, the overwash sediments exhibit sharp depositional contact, planar stratification, coarsening upward sequences, and overall but not systematic landward fining (Chapter 3). On the carbonate coast, the overwash sediment assemblages include distinct carbonate boulders now occupying the reef flat surface, and a sand sheet that blanketed the coconut groves and rice fields of the coastal plain reaching up to ~300 m inland (Chapter 4). A separate inverse modeling of flow velocity from boulder dimensions on the reef flat and sediment thickness and grainsize distribution inland indicate that the bore-like storm surge travelled across the wide reef flat and inundated the coast at a sustainably high flow velocity exceeding 4 ms^{-1} . The sediment-derived flow velocity estimates are remarkably consistent with flow velocity values previously reconstructed from video recordings, and forward wave modeling. But considering the bore-like surge characteristic of Haiyan, which is similar to tsunami flow, Haiyan's overwash sediments as a representative of Philippine modern storm deposits should then be used with caution for pre-historic storm reconstructions. This cautionary note is particularly important because most of the Philippine coastlines are exposed to both storms and tsunamis.

The coastlines impacted by Typhoon Haiyan and Typhoon Durian exhibit high potential recovery to their pre-typhoon conditions by active berm rebuilding on the beach and re-colonization of beach vegetation (Chapter 3 and Chapter 5). Even mangrove stands albeit sustaining massive defoliation during Typhoon Haiyan seemed to recover quickly (Chapter 3), though recovery in other areas was much slower (Chapter 5). It is also apparent that the recovery may only persist for as long as no disturbance will occur or if succeeding events are not capable of inducing more coastal impact (e.g. Chapter 5).

6.2. Limitations

This dissertation focused only on the geomorphic and sedimentologic imprints of overwash onshore. The impacts of storm surges on the shoreface were not investigated, but changes in sedimentation patterns are expected following storms particularly on areas with shallow and gently sloping offshore bathymetry such as Leyte Gulf (e.g. Kumar and Sanders, 1976; Morton, 1988; Siringan and Anderson, 1994). The onshore depositional conditions naturally expose these geomorphic and sedimentologic imprints to active agents of erosion or reworking which can likely reduce the potential longevity of preservation of such geologic storm archives. For example, the rapid recolonization of vegetation on the coastal plains following Typhoon Haiyan commonly obscured internal stratification and the stratigraphic contact between the Haiyan overwash sediments and the pre-Haiyan soil unit (Chapter 3). In contrast, despite re-vegetation and flooding occurrence, the geomorphic imprints of Typhoon Durian remain intact and prominent to at least 7 years (Chapter 5). There seems to be a good indication that this volcanoclastic coast has high preservation potential for overwash

records. Shore-normal GPR transects also reveal at least two buried erosional surfaces farther inland of the erosional surface of Typhoon Durian. Unfortunately, the nature of volcanoclastic sands prohibited traditional dating techniques applied to overwash sands. Instead we are limited to comparing our results to historical storms in the long history of the Philippines.

6.3. Future studies

Typhoon Haiyan revealed scientific weak points other than those covered in this dissertation. Several key ideas for further investigations are identified as follows:

- (1) A vast pool of historically documented typhoons is available and was previously used to establish long-term trends in landfall frequency, intensity, and location (e.g. Garcia-Herrera et al., 2007; Ribera et al., 2008; Kubota and Chan, 2009). There might not be another historical document as detailed as that of the Ty 1897 (Chapter 2), but we could still glean knowledge from piecing together patchy but reliable historical accounts to bring clarity for other historical typhoons. One event of interest can be the November 1912 which was reported to have caused extensive damage in Tacloban and Capiz on the nearby island of Panay and was believed to have claimed 15,000 lives (<http://chroniclingamerica.loc.gov/lccn/sn83045433/1912-11-30/ed-1/seq-1.pdf>).
- (2) The Philippines has highly variable coastal configuration, landscapes, and exposure to storm surge which require local-based scenarios for hazard assessment (Chapters 2 to 5). Highly developed and densely populated coastal areas can be prioritized for storm surge modeling and historical-

based scenario studies (e.g. Manila Bay, northwest Luzon including Ilocos coastlines).

- (3) A more detailed storm surge model of Typhoon Durian in Lagonoy Gulf is needed to assess contributions from storm tide and wave set-up, and then compare with geomorphic-based estimates from Chapter 5.
- (4) Rapid coastal erosion from a single extreme event like Typhoon Haiyan can be in the order of few tens of meters (Chapter 3). How does this single event, with a recurrence interval of most probably nearly over 100 years, compare to the magnitude of longer-term coastal change?
- (5) Compared to Tanauan (Chapter 3) there seems to be a higher preservation potential of onshore storm deposits in Hernani (Chapter 4). The search for geological archives of storm deposits will thus be more likely to be fruitful if pursued around Hernani.
- (6) The hydrodynamic and sediment information from Typhoon Haiyan studies (Chapters 3-4) should be maximized for improved sediment transport modeling to better understand the relationship of storm surge flow dynamics and sedimentation patterns including particle size, thickness, inland extent, sediment source and supply.

References

- García-Herrera, R., P. Ribera, E. Hernández, and L. Gimeno, 2007. Northwest Pacific typhoons documented by the Philippine Jesuits, 1566–1900, *Journal of Geophysical Research* 112, D06108, doi:10.1029/2006JD007370.
- Ribera, P., García-Herrera, R., and Gimeno, L., 2008. Historical deadly typhoons in the Philippines. *Weather* 63(7), 194-199.

- Kubota, H., and Chan, J. C. L., 2009. Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005. *Geophysical Research Letters* 36, L12802, doi:10.1029/2009GL038108.
- Kumar, N., and Sanders, J.E., 1976. Characteristics of shoreface storm deposits: modern and ancient examples. *Journal of Sedimentary Petrology* 46 (1), 145-162.
- Morton, R.A. 1988. Nearshore responses to great storms. *GSA Special Papers* 229, 7-22. doi: 10.1130/SPE229-p7.
- Siringan, F.P., and Anderson, J.B., 1994. Modern shoreface and inner-shelf storm deposits off the east Texas coast, Gulf of Mexico. *Journal of Sedimentary Research* 64B (2), 99-110.
- Switzer, A.D., Yu F., Gouramanis C., Soria, J.L.A., & Pham D.T., 2014. Integrating different records to assess coastal hazards at multicentury timescales. *Journal of Coastal Research SI* 70, 723-729.

APPENDIX 1

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ARTICLES

REPEAT STORM SURGE DISASTERS OF TYPHOON HAIYAN AND ITS 1897 PREDECESSOR IN THE PHILIPPINES

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Typhoon Haiyan's storm surge was about twice the height of the 1897 event in San Pedro Bay, but the two storm surges had similar heights on the open Pacific coast.

Typhoon Haiyan affected more than 16 million people, killed 6,293 people, and destroyed more than 1.1 million dwellings in the central Philippines (NDRRMC 2014). Haiyan is the deadliest

typhoon recorded in the Philippines, superseding Tropical Storm Thelma, which struck Ormoc City on the western coast of Leyte Island, in November 1991 (Alojado and Padua 2010; Bacani 2013; Ribera et al. 2008). Globally, Typhoon Haiyan was the deadliest cyclonic event since Cyclone Nargis devastated Myanmar in 2008 (Fritz et al. 2009). The damage to infrastructure and agriculture cost about PHP \$40 billion or about USD \$900 million (NDRRMC 2014), while the total economic loss reached up to USD 13 billion (Caulderwood 2014). The damage and the death toll from Typhoon Haiyan were particularly high along the coasts surrounding San Pedro Bay on the northwestern margin of the Leyte Gulf primarily due to the storm surge generated by the typhoon. The shallow bathymetry of less than 10-m depth and funnel shape make the coasts of San Pedro Bay inherently susceptible to storm surge (Fig. 1, inset). Additional factors that contributed to local amplification of the storm surge in Leyte Gulf were the orientation of the typhoon track and associated seiches (Mori et al. 2014). Eyewitnesses described the Haiyan storm surge as dramatically worse than any coastal flooding events in recent years (Amadore 2013). Longer historical records,

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FIG. 1. Storm tracks of three deadly typhoons crossing the central Philippines: Ty 1897, Nov 1991 Tropical Storm Thelma, and Nov 2013 Super Typhoon Haiyan. Typhoon track sources: (a) Algué (1898) and (b) International Best Track Archive for Climate Stewardship (IBTrACS) database of Knapp et al. (2010). The inset shows the comparative tracks of Ty 1897 (black dashed line) and Haiyan (colored solid lines) across Leyte Gulf.

however, reveal a comparable predecessor to Typhoon Haiyan (Algué 1898). In October 1897, an unnamed typhoon, which for brevity will be henceforth referred to as Ty 1897, took a path across Leyte Gulf that was almost parallel to Typhoon Haiyan's but offset to the north by ~6 km (Fig. 1). The similar track enables direct comparisons of the two typhoons and the storm surges. Here, we first characterize the destructiveness of Typhoon Haiyan before considering the importance of the 1897 predecessor in understanding storm surge hazard in the region.

TYPHOON HAIYAN. On 2 November 2013, a broad low pressure area formed in the western Pacific, to the east of Micronesia (Joint Typhoon Warning Center 2014). By 0600 UTC 3 November, it had developed into a tropical depression. At 0000 UTC 4 November, the system had attained tropical storm strength and was named Haiyan. It rapidly strengthened into a typhoon and moved west toward the Philippines (Fig. 1), and it was given the local name of Yolanda (NDRRMC 2013a). By 6 November, Haiyan's 1-min maximum sustained winds had intensified to an estimated 241 km h⁻¹, classified by the Joint Typhoon Warning Center (JTWC) as a super typhoon. To avoid ambiguity in the definition of "super typhoon," we will conform to the traditional classification of tropical cyclones (World Meteorological Organization 2015) in the Pacific region with "typhoon."

On its final north-westward approach to the Philippines, Haiyan steadily intensified until it reached the peak intensity of ~895 hPa minimum central pressure. This peak intensity was estimated by the JTWC and the Japan Meteorological Agency (JMA) from cloud patterns recognized on visible and infrared satellite images, in the absence of ground and in situ instruments. In Guiuan municipality on Samar Island, Doppler radar data of the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) indicated that just before landfall, at

2000 UTC 7 November [0400 Philippine Time (PHT) 8 November], Haiyan attained a minimum central pressure of 910 hPa and winds at 160 km h⁻¹ with gusts of ~195 km h⁻¹ (Paciente 2014). Extreme winds destroyed the Guiuan Doppler radar station about 16 min later. At 2040 UTC 7 November (0440 PHT 8 November), Haiyan crossed the small islands off the southeast tip of Samar Island, near Guiuan. Haiyan then continued westward across the Leyte Gulf to its main landfall south of Tolosa, Leyte Island, at 2300 UTC 7 November (0700 PHT 8 November), as captured by another PAGASA Doppler radar station in Cebu. Typhoon Haiyan then made four subsequent landfalls as it crossed the central Philippines (NDRRMC 2013b).

MATERIAL AND METHODS. We evaluated eyewitness accounts, video recordings, field measurements, and storm surge model hydrographs to document the flow depths, surge heights, timing, and peak flood duration during Typhoon Haiyan as well as the resulting damage. Other post-Haiyan field survey reports focused on the inundation characteristics and the impact on coastal structures (Mas et al. 2015; Tajima et al. 2014). Here, we place Typhoon Haiyan's storm surge into historical context by comparing it with the similar Ty 1897 event (Algué 1898).

Field survey. The initial field survey of the coastal areas surrounding San Pedro Bay was conducted from 23

to 28 November 2013, as soon as relief operations and the security situation permitted access to the hardest hit areas. We recorded 73 eyewitness accounts (Table ES1; more information can be found online at <http://dx.doi.org/10.1175/BAMS-D-14-00245.2>) on the maximum flow depth, the timing of the initial rise, and peak and subsidence of the flood, along with wind and wave observations. Collected data were used to validate the timing and heights simulated by our storm surge models. Subsequent surveys from 16 to 25 January, 12 to 19 May, and 2 to 10 June 2014 encompassed larger and more remote areas, including coastal settlements in southern Samar facing the Leyte Gulf and the Philippine Sea of the western Pacific (Fig. 2; Table 1). To record distances and build cross-shore elevation profiles from the water surface at the shoreline to the inundation limit, water marks were located and measured with a Trimble global positioning system (GPS) rover connected via Bluetooth to a Lasercraft XLRic laser range finder (Fritz et al. 2012). At each site, high water marks such as mud lines on buildings, scars on the bark of trees, and rafted debris were evaluated using established protocols (Fritz et al. 2007; UNESCO 2014). In inhabited areas, the water marks were discussed with eyewitnesses to constrain still water levels, estimate the contribution of storm waves, and remove bias from localized splashup atop the surge. The high water measurements, based on different indicators at corresponding locations, tended to be consistent and have an individual

confidence of ± 0.1 m. During post-survey processing, the measurements were differentially corrected with our daily setup of the local Ashtech base station and corrected for tide level at the time of peak storm surge on the basis of tide predictions provided by XTide 2, an open-source software of Flater (1998). How the Ty 1897 storm surge heights were measured remains unknown, but it is highly likely that surge heights

Figure 2.

FIG. 2. Maximum storm surge heights, surge with waves, and runup points of Typhoon Haiyan measured in the field across the coastal communities in eastern Leyte (a), and Samar (b) and (c). Surge heights of Ty 1897 from Algue (1898) are also included for comparison. The terrain map is a modified NASA land elevation radar image; dark shaded areas are ≤ 10 m, above sea level.

TABLE 1. Measured maximum storm surge heights and run-up points of Super Typhoon Haiyan in eastern Leyte and the southern Samar Islands. The code for measurements is as follows: z is terrain elevation, h is the flow depth above terrain, z + h is the elevation of the watermark relative to normal predicted tide level at time of peak flooding, and R is run-up or elevation at the limit of inundation. The code for watermarks is as follows: TL is the trimline, WS is wave splash, FL is the flood line, EW is eyewitness, RD is rafted debris, SH is ship, MI is mud line inside, MO is mud line outside, and WL is wrack line.										
Point	Location	Latitude (°N)	Longitude (°E)	z (m)	h (m)	z + h (m)	R (m)	Date and time surveyed (PHT)	Watermark	
1	Dulag (San Jose)	10.9869	125.0393	2.22	4.60	6.82		20 Jan 2014	1223	TL, WS
2	Dulag (San Jose)	10.9868	125.0393	2.82	1.00	3.82		20 Jan 2014	1232	FL, EW
3	Tanauan (Cabuynan)	11.0969	125.0207	1.64	3.70	5.34		20 Jan 2014	1514	TL, EW
4	Tanauan (Magay)	11.1172	125.0205	2.52	2.90	5.42		20 Jan 2014	1621	EW
5	Tanauan (Magay)	11.1165	125.0199	2.22	3.00	5.22		20 Jan 2014	1630	EW
6	Tanauan (Magay)	11.1173	125.0182	2.62	2.70	5.32		20 Jan 2014	1641	RD
7	Hernani (town proper)	11.3236	125.6177	3.88	2.70	6.58		21 Jan 2014	1332	FL, EW
8	Tacloban (Anibong)	11.2542	124.9906	3.05	3.80	6.85		22 Jan 2014	1101	SH
9	Tacloban (Anibong)	11.2543	124.9905	5.84	1.20	7.04		22 Jan 2014	1052	TL, EW
10	Tacloban (Anibong)	11.2575	124.9891	3.09	2.80	5.89		22 Jan 2014	1123	TL, EW
11	Tacloban	11.2523	124.9909	4.09	1.00	5.09		22 Jan 2014	1138	MO, EW
12	Tacloban	11.2494	124.9934	4.10	2.90	7.00		22 Jan 2014	1235	MI, EW
13	Tacloban	11.2465	124.9952	2.07	2.50	4.57		22 Jan 2014	1251	MI, EW
14	Tacloban	11.2470	124.9961	2.94	3.70	6.64		22 Jan 2014	1307	EW
15	Tacloban	11.2443	124.9991	2.39	1.60	3.99		22 Jan 2014	1427	MI
16	Tacloban	11.2437	125.0001	1.92	1.90	3.82		22 Jan 2014	1438	MI, EW
17	Tacloban	11.2423	125.0018	2.49	1.60	4.09		22 Jan 2014	1448	MI, EW
18	Tacloban	11.2411	125.0032	2.69	1.55	4.24		22 Jan 2014	1455	MI, EW
19	Tacloban	11.2394	125.0053	2.19	2.90	5.09		22 Jan 2014	1511	MI, EW
20	Tacloban	11.2421	125.0085	7.48	0.40	7.88		22 Jan 2014	1542	MO, WS
21	Tacloban	11.2421	125.0086	7.01			7.01	22 Jan 2014	1552	WL, EW
22	Tacloban	11.2464	125.0095	4.22	2.10	6.32		22 Jan 2014	1610	TL
23	Tacloban	11.2464	125.0095	4.22	1.30	5.52		22 Jan 2014	1611	MI, EW
24	Tacloban	11.2488	125.0004	3.06	4.60	7.66		22 Jan 2014	1652	TL, EW
25	Basey (San Antonio)	11.2731	125.0030	5.26			5.26	23 Jan 2014	0944	WL
26	Basey (San Antonio)	11.2734	125.0023	6.17			6.17	23 Jan 2014	0956	WL
27	Basey (San Antonio)	11.2739	125.0021	5.99			5.99	23 Jan 2014	0947	WL

28	Basey (San Antonio)	11.2750	125.0015	6.32				6.32	23 Jan 2014	0959	WL
29	Basey (San Antonio)	11.2745	125.0077	2.76	3.70	6.46			23 Jan 2014	1033	TL, EW
30	Basey (San Antonio)	11.2775	125.0147	3.31	2.90	6.21			23 Jan 2014	1124	MO, WS
31	Marabut	11.1078	125.2120	1.58	1.20	2.78			23 Jan 2014	1324	EW
32	Hernani (town proper)	11.3236	125.6177	3.88	2.70	6.58			21 Jan 2014	1332	EW
33	Hernani (Batang)	11.2943	125.5948	6.22	1.30	7.52			23 Jan 2014	1508	MO, EW
34	General MacArthur	11.2463	125.5404	1.49	0.45	1.94			23 Jan 2014	1548	MO, EW
35	Quinapondan/Santo Niño	11.1252	125.5175	1.64	2.40	4.04			23 Jan 2014	1653	MO, EW
36	Giporlos	11.1199	125.4507	1.62	2.40	4.02			23 Jan 2014	1722	MO, EW
37	Balangiga	11.1068	125.3860	1.31	1.50	2.81			23 Jan 2014	1739	MO, EW
38	Lawaan	11.1387	125.3000	1.20	1.90	3.10			23 Jan 2014	1807	MO, EW
39	Palo (San Fernando)	11.1661	125.0085	1.98	3.70	5.68			24 Jan 2014	1641	TL, EW
40	Palo (San Fernando)	11.1656	125.0070	2.61	3.00	5.61			24 Jan 2014	1653	TL, EW
41	Tacloban (south of airport)	11.2005	125.0249	3.47	2.90	6.37			24 Jan 2014	1716	TL, EW
42	Tacloban (bay south of airport)	11.2115	125.0251	2.10	3.70	5.80			24 Jan 2014	1735	TL, EW
43	Tanauan (Santa Cruz)	11.1247	125.0220	1.73	4.10	5.83			24 Jan 2014	1321	MO, EW
44	Tanauan (Santa Cruz)	11.1237	125.0215	1.73	3.40	5.13			24 Jan 2014	1326	MO, EW
45	Llorente	11.4124	125.5485	7.29				7.29	10 Jun 2014	1409	EW

were simply referenced to the mean sea level at the time of survey. The difference between the mean sea level and the sea level at the time of peak flood during Ty 1897 implies that the accuracy of surge height measurements is in the range of ± 0.3 m. Algué (1898) lacks description on the surge height indicators, but additional uncertainties can be potentially contributed by storm waves.

Storm surge modeling of Typhoon Haiyan. The Typhoon Haiyan storm surge in Leyte Gulf and San Pedro Bay was simulated using the open-source Delft3D Flow (Lesser et al. 2004) with a MATLAB-based graphical user interface called Dashboard.¹ A curvilinear grid is used with a minimum resolution of 200 m and a maximum resolution of 1.2 km. The domain encompasses the whole Leyte Gulf and extends into the San Juanico Strait to the north (Fig. 3a). The bathymetry of the model domain was acquired from digitized navigational charts (National Mapping and Resource Information Authority 1980). The maximum depths are found near the Leyte Gulf mouth, and the embayment shallows northward toward the San Juanico Strait (Fig. 3b). Open boundary conditions are astronomic tides using eight dominant constituents (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , and Q_1) extracted and interpolated from the Ocean Topography Experiment (TOPEX7.2) global tidal model (Egbert and Erofeeva 2002) using the Dashboard tide database toolbox. The tidal pattern in San Juanico Strait interacting with the Samar Sea differs from the tidal pattern at Guiuan station driven by the Philippine Sea (Fig. 3c). The complex tidal interaction highlights the need for accurate bathymetry of Leyte Gulf and San Juanico Strait to properly simulate the tides in Tacloban.

Typhoon wind fields for the modeling were generated from the typhoon track data of the JTWC. We recognize an approximately 6-km offset between the JTWC typhoon track from the Doppler radar-derived track from PAGASA (Fig. 1, inset), but JTWC provides more continuous along-track wind data, required in the model. The model wind

¹<http://publicwiki.deltares.nl/display/OET/DelftDashboard>

files were generated by the Delft Dashboard tropical cyclone toolbox using the model by Holland (1980) and interpolated onto the computational grid. The model was initialized by wind and tide conditions at 0000 UTC 5 November 2013 and allowed to run until 2400 UTC 11 November 2013. Sea level and current outputs were saved at 1-min intervals between 1900 UTC 7 November and 0600 UTC 8 November. An earlier model of Bricker et al. (2014) used the same Delft3D software with JMA wind data forcing and a Quiring's relationship of maximum wind radius. Their model yielded a maximum water level of less than 6 m in Tacloban.

Storm surge modeling of Ty 1897. To model the likely storm surge generated by Ty 1897, we used the same grid and boundary forcing conditions of Typhoon Haiyan, but with tides simulated from 10 to 12 October 1897. Algué (1898) reported pressures and winds recorded in various parts of the Philippines during Ty 1897, but the Dashboard typhoon module requires

along-track minimum central pressures and maximum winds. This requirement limited us to use only the data recorded in areas directly hit by the eye of Ty 1897: the in situ barometric pressures measured at Guiuan and Tanauan. Apart from these two locations, no instrumental record on the typhoon eye exists. The minimum pressures before landfall in Guiuan and after landfall in Tanauan were estimated considering the values for Ty 1897 and Typhoon Haiyan. Barometric records in Guiuan and Tanauan indicate a less intense Ty 1897 at landfall than Typhoon Haiyan. To account for the weaker intensity of Ty 1897, we took the pressure difference between Typhoon Haiyan and Ty 1897 in Guiuan and in Tanauan, and the delta values were then subtracted from the Typhoon Haiyan pressure values.

Given the barometric records of Ty 1897 in Guiuan and Tanauan, a range of wind speed values were derived from empirical wind–pressure relationships using the storm-mapping table summarized by Nakazawa and Hoshino (2009) for the western North Pacific region (Table 2). Due to the limited instrumental data on Ty

1897 we opted to use in our model the wind speed values derived from Atkinson and Holliday (1977), which is the most direct method among the wind–pressure relationship equations. Knaff and Zehr (2007) emphasized the uncertainties inherent in the regression method of Atkinson and Holliday (1977) in estimating wind speeds of tropical cyclones over the northwest Pacific. Despite the reliability concerns, the maximum wind speed estimates for Ty 1897 using Atkinson and Holliday (1977) still yielded values similar or within the range of the mean standard error [6–9 kt ($1 \text{ kt} = 0.5144 \text{ m s}^{-1}$)] of other established robust wind–pressure relationships.

FIG. 3. Geographical coverage, bathymetry, and tidal conditions of Leyte Gulf used in the model. (a) The model domain is a curvilinear grid with 200-m to 1.2-km resolution. **(b)** Leyte Gulf bathymetry generated from digitized navigational charts with 100-m to 1-km resolution. **(c)** Predicted water levels from San Juanico Strait, Tacloban City, and Guiuan, Samar.

TYPHOON 1897 VERSUS TYPHOON HAIYAN. Typhoon track and forward speed. The reconstructed track of Ty 1897 (Figs. 1, 2) was

TABLE 2. Minimum barometric pressure of Ty 1897 recorded in Guiuan and Tanuan and the corresponding CI number and maximum wind speeds.

Parameters/location	Guiuan	Tanauan (initial)	Tanauan (corrected)
Time and date	0815 PHT 12 Oct 1897	1110 PHT 12 Oct 1897	1110 PHT 12 Oct 1897
Minimum central pressure (mm)	710	704	694
Minimum central pressure (hPa)	947	938	925
Observed wind condition	Relative calm ^a	Absolute calm	Absolute calm
1-min maximum sustained winds [kt (km h ⁻¹)] (Atkinson and Holliday 1977)	96 (179)	105 (194)	115 (212)
CI (Dvorak 1975)	6	6.5	7
CI (Dvorak 1984)	5.5	6	6
1-min maximum sustained winds [kt (km h ⁻¹)] (Dvorak 1984)	102 (189)	115 (213)	115 (213)
CI (Koba et al. 1990)	5.5	6	6.5
10-min maximum sustained winds [kt (km h ⁻¹)] (Koba 1990)	85 (157)	93 (172)	100 (185)

^a The relatively calm wind condition recorded in Guiuan indicates that the eye passed close but not directly over the recording site. As such the Guiuan dataset should be considered a near-minimum value.

adopted from Algué (1898) based on the synthesis report containing maps and compilation of barometric curves. Instrumental records for the historical Ty 1897 came from modified aneroid barometers established by Jesuit priests on land (at churches) and at sea (on ships) in different locations of the Philippine Archipelago. The observed pressure, wind direction, and temperature were used to establish the distance and direction of the vortex (eye) of the typhoon from the observer (Algué 1904; Udías 1996). Algué’s map was georeferenced to a regional map derived from a 90 m × 90 m resolution satellite radar image, and then the typhoon track was digitized. Given the different resolutions between Algué’s map and the regional map, we expect that the digitized track has uncertainties of ~1 km in the north–south direction and ~2 km in the east–west direction.

Upon evaluating the pressure and wind observations, Algué (1898) estimated the landfall timing and the forward speed of Ty 1897 between Guiuan and Tanauan. Ty 1897 made its initial landfall ~10 km south of Guiuan shortly after 0800 PHT 12 October 1897 (0000 UTC 12 October). At landfall, the barometer in Guiuan registered the lowest pressure at 710 mm (947 hPa), simultaneous with the observed relatively calm winds. The relatively calm wind condition indicates an eye passage in close proximity but not directly over the recording site. As such, the Guiuan dataset should be considered only as a near-minimum value. The typhoon continued westward almost following along the northern coastline of Leyte Gulf. At about 1100 PHT 12 October 1897 (0300 UTC 12 October) the eye of the typhoon was about 21 km

north-northeast (NNE) of Dulag, and 13 km south-southeast (SSE) of Tacloban, before it made a second landfall in Tanauan shortly after 1100 PHT. At landfall, the barometer in Tanauan registered the lowest pressure of 704 mm equivalent to 938 hPa, but after further analysis was lowered to 694 mm equivalent to 925 hPa (Algué 1898, 1904). Simultaneous with the lowest pressure was an absolute calm wind lasting for about 40 min. To the north, the adjacent town of Palo also experienced the zone of absolute calm but only for 10 min. The longer duration of absolute calm in Tanauan compared to Palo suggests that Tanauan was located closer to the center of the typhoon’s eye. In a span of 2.5 h, Ty 1897 traversed about 43 geographical miles (~80 km) between Guiuan and Tanauan, equivalent to a forward speed of about 17 mi h⁻¹ or 28 km h⁻¹ (Algué 1898, p. 66). According to Algué’s map, Ty 1897 made subsequent landfalls on three islands across the central Philippines before it exited into the South China Sea.

The Jesuits ground-based method of instrumental recording and monitoring of typhoons to establish the track and intensity prevailed for many decades (Udías 1996) until it was replaced by reconnaissance aircraft, radar, and satellite observations toward the midtwentieth century (Emanuel 2005b; Velden et al. 2006). Today, weather services combine instrumental recordings with satellite-based observations of the cloud patterns in visible and infrared satellite images to establish a central location of a typhoon and to estimate typhoon intensities. At the forefront of this satellite-based method of tropical cyclone intensity was Dvorak (1975). The Dvorak method originally

developed for Atlantic conditions has been adopted and applied to other ocean basins that have different atmospheric conditions like the Pacific (e.g., Velden et al. 2006; Knaff and Zehr 2007; Lander et al. 2014). Unfortunately, there is no unified operational method among weather agencies for tracking and assigning typhoon intensities, and as such, the reported track and intensity of one storm are commonly variable. This was the case with Typhoon Haiyan, where the tracks across Leyte Gulf released by JMA and JTWC are consistently offset ~6 km to the south of the PAGASA Doppler radar-based track. The PAGASA track, however, appears more consistent with the local field observation and ground truthing (Morgerman 2014). We note that based on the PAGASA typhoon track, Typhoon Haiyan moved from Guiuan westward to Tolosa at about 43 km h⁻¹ or about 1.5 times faster than Ty 1897.

Typhoon intensity and size. The wide range of instrumental recording through history and the variety of operational wind–pressure relationships among meteorological agencies make typhoon intensity classification based on the maximum wind speed inherently uncertain (Knaff and Zehr 2007; Nakazawa and Hoshino 2009). To address the issues arising from the wind speed–derived typhoon intensity, Knapp and Kruk (2010) and Kruk et al. (2011) proposed the use of current intensity (CI) in comparing typhoons, particularly in establishing trends of tropical typhoon intensities. Kruk et al. (2011) recognized that because of the imagery interpretation of contemporary typhoons, the satellite-derived intensity *T* number when converted to CI could result in intensity differences of 0.5 on the CI scale. Meanwhile, the primary sources of uncertainty for the pressure-derived intensity of historical typhoons such as Ty 1897 arise from the sparse recordings and possible instrumental errors. The historic correction of ~13 hPa applied to the minimum pressure of Ty 1897 on the Tanauan barometer record may give some indication of the magnitude of instrumental errors. For intense typhoons like Ty 1897, the historic correction corresponds to a difference of 0.5 on the CI scale, which is of similar magnitude as the uncertainty of satellite-derived CI. Hence, the corresponding CI numbers for Ty 1897 and Typhoon Haiyan may provide a reasonable metric to compare the intensity between these two typhoons.

As discussed previously, the observed lowest pressure and absolute calm wind of Ty 1897 consistently indicate that the typhoon eye passed directly over Tanauan. Taking the minimum pressure

of 925 hPa as the closest approximation of the central minimum pressure, Ty 1897 was assigned an equivalent CI number of 6–7 upon landfall. For Typhoon Haiyan, ground instruments only recorded near-minimum pressures. The Doppler radar in Guiuan registered a mean sea level pressure of ~940 hPa before it was totally destroyed at the peak intensity of the typhoon (IRIDeS 2014). Independent measurements of PAGASA and Morgerman (2014) indicate lowest pressure at 960 hPa in Tacloban City, which was located on the northern eyewall of the typhoon, 24 km away from Typhoon Haiyan's center. In contrast, using the satellite-based Dvorak technique Typhoon Haiyan has a signature typhoon number of T8.0 (Lander et al. 2014), which corresponds to a CI number of 8, the highest on the scale. As such, the CI 8 Typhoon Haiyan was more intense than the CI 6 to 7 of Ty 1897.

Not only was Typhoon Haiyan more intense, it was also larger than Ty 1897 based on the eyewall size. Morgerman (2014) corroborated the eye of Typhoon Haiyan based on wind observations of eyewitnesses and a radar image, indicating a 13-km radius of the eyewall. In contrast, the Jesuit approach based on the zones of absolute and relative calm winds as indicators of the relative location of the typhoon eye results in an eyewall radius of 6–10 km for Ty 1897.

Given the contrasting operational methods between 1897 and 2013, it remains difficult to directly compare Typhoon Haiyan and Ty 1897 with absolute certainty. The available meteorological parameters, however, suggest that Typhoon Haiyan and Ty 1897 were nearly identical based on the trajectory, while characteristic differences prevailed concerning other aspects. Typhoon Haiyan followed a parallel track direction with a ~6-km offset to the south of Ty 1897. Typhoon Haiyan was more intense, had wider eyewall coverage, and was moving faster than Ty 1897. The possible effects of the slight variations in track, minimum central pressure, estimated maximum winds, and forward movement between the two typhoons on the storm surge characteristics will be explored in the following sections.

TYPHOON 1897 AND TYPHOON HAIYAN STORM SURGES.

Posttyphoon field measurements. The Ty 1897 storm surge measurements of Algué (1898) were based on eyewitness accounts (Fig. 2). These field measurements indicate inundation heights exceeding 4 m in most places with a maximum height of over 7 m on the open sea coast at Hernani (Fig. 2c). Along San Pedro Bay in Basey (Fig. 2b), the water gradually rose and reached a maximum level

of 4.9 m. The peak flooding corresponded with the most violent winds from the southeast. In the nearby coast of Tacloban (Fig. 2a), water rose between 3.9 and 4.6 m. The peak flooding coincided with the winds blowing from the east to east-southeast, directly perpendicular to the Tacloban coast. In close proximity to the eye of Ty 1897 at Tanauan and Tolosa (Fig. 2a), the water rose to 3 m.

Algué's "Ola del Huracán" or hurricane wave was the elevation of the sea, with the surface forming like a warp pyramid whose peak approximately corresponds to the vortex (eye) of the typhoon, analogous to the water surface being sucked by a vacuum pump (Algué 1898, p. 9). Moving with the typhoon, this huge wave, when launched against the shore, makes the water rise to an extraordinary height, causing severe flooding and extensive destruction (Algué 1898, p. 10). We interpret this description as equivalent to what we now call "storm surge." Algué overestimated the contribution of the pressure drop over the wind field as the primary contributor to the significant rise of the sea surface because of the different locations of the eye and the areas where water elevations were highest. The sea rose to about 3 m in Guiuan and Tanauan, but the rise was highest at Hernani, Basey, and Tacloban on the typhoon's strong side to the north of the typhoon eye. The peak flooding during Ty 1897 at each of these sites consistently coincided with winds blowing directly perpendicular toward the coastline. Contrary to Algué's attribution of the surge solely to the low central pressure, the wind field was the primary driver of the storm surge (Emanuel 2005a).

The measured high water marks after Typhoon Haiyan (Fig. 2) were separately classified into maximum surge heights and surge plus storm waves. For a wider and denser spatial coverage, we combined our field measurements with the survey of Tajima et al. (2014). In both surveys, each high water mark indicator was referenced to the reconstructed tide level at the time of peak flooding. Heights differed by as much as 1 m at slightly different locations. Discrepancies of up to 2 m at corresponding locations were attributed to short-period storm waves superimposed on top of the surge. High water marks with significant storm-wave contributions were carefully identified based on eyewitness accounts, the type of physical watermark, and the inland location. Surge height measurements from different high water mark indicators in both surveys were mostly consistent.

At Tacloban, located some 23 km to the north of Haiyan's track (Fig. 2a), the characteristic height of the storm surge peak was 7 m. Wave contributions raised high water marks up to almost 8 m in Tacloban and Palo. On the more open and exposed Pacific coastline at Hernani (Fig. 2c), some 45 km north of the typhoon track, significant storm-wave contributions resulted in high water marks exceeding 7 m. Further amplification by the wave run-up on steep slopes such as near Guiuan resulted in a maximum run-up height of 14 m (Tajima et al. 2014). Surge heights exceeding 5 m were recorded along the shores of San Pedro Bay. We detail the nature of the storm surge in San Pedro Bay, where the highest death toll was recorded, in the next section. Outside of San Pedro Bay, but still within Leyte Gulf, the surge heights were only 3–4 m between Marabut and Quinapondan (Fig. 2b) because the storm track was parallel to the coastline. Water marks as high as 5 m were attributed to storm-wave contributions. In close proximity to Haiyan's landfall location between Tolosa and Dulag, the surge heights ranged between 3 and 5 m (Fig. 2a). At an exceptional site in Dulag, a 7-m-high water mark was compromised by significant storm-wave contribution. The lowest surge height of about 2 m was recorded at General MacArthur on the eastern coast of Samar (Fig. 2c). The site is sheltered behind fringing coral reefs located 3 km offshore and is on a bay with a narrow bottleneck entrance attenuating storm waves and resulting in a measurement dominated by the storm surge component.

Storm surge simulations of Typhoon Haiyan and Ty 1897 in San Pedro Bay. The Haiyan storm surge modeling results resolved an initial sea level drawdown around 2130 UTC 7 November 2013 (0530 PHT 8 November) in accordance with eyewitness accounts and the Tacloban tide gauge recording (Fig. 4). The tide gauge recorded a drawdown of at least 0.8 m before it broke down,² while modeling suggests a drawdown of at least 1.2 m at the head of San Pedro Bay (Figs. 4a,b). The initial sea level drawdown was also observed at Basey on Samar (Amadore 2013). The drawdown was generated by persistent, strong, northerly offshore winds that initially drove the waters southward out of San Pedro Bay (Figs. 4a,b). Similar sea level drawdowns or negative surges from strong offshore winds during historic hurricanes have also been reported for the western Florida coasts (Harris 1963; Lawrence and Cobb 2005). The drawdown exposed

² The Tacloban tide data were provided by the National Mapping and Resources Information Agency (NAMRIA) of the Republic of the Philippines.

FIG. 4. Sea level heights in Tacloban and nearby coasts around San Pedro Bay during Typhoon Haiyan. (top) Graphical representation of the water levels from storm surge model (blue line) and from Tacloban Port tide gauge (red line). Both the actual and modeled tides show receding sea level prior to the peak surge. (a)–(i) Storm surge model sequence of Typhoon Haiyan in San Pedro Bay from 2130 UTC 7 Nov to 0130 UTC 8 Nov 2013 with colors and arrows representing water level and wind magnitude and direction, respectively.

the seafloor and dramatically steepened the storm tide profile. This phenomenon is analogous to the negative leading N-wave during tsunamis, usually resulting in a higher run-up (Tadepalli and Synolakis 1994). Eyewitness accounts and modeling show that the storm tide arrived as an unusually fast-moving “tsunami like” wave front, which caused high velocity coastal flooding to heights of more than 7 m near Tacloban and Basey. Residents in Basey, who stayed in their homes despite prior evacuation warnings, described a large wave similar to a tsunami striking soon after the water receded, providing only a few minutes of lead time to seek refuge at higher elevations.

The initial rise, peak, and lowering of flood levels due to the storm surge varied considerably in time and location. In downtown Tacloban, the peak surge occurred around 0000 UTC 8 November (0800 PHT 8 November), according to videos recorded by several eyewitnesses and the detailed coverage by storm chaser Morgerman (2014). The inundation timing was further confirmed by two wall clocks located about 14 km apart along the western shores of San Pedro Bay, which were stopped as seawater floods reached about 1.5–2 m high. In Tanauan, the clock stopped at 0720 PHT (2320 UTC 7 November); the clock in Tacloban City stopped a few minutes later at 0730 PHT (2330 UTC 7 November). The timing from the videos and wall clocks is consistent with the storm surge model. The modeled timing of the peak surge coincided with the timing of the onshore-directed winds closely linked to the forward motion of Typhoon Haiyan (Figs. 4c–g). The modeled peak surge of 6–8 m in San Pedro Bay occurred between 0000 and 0030 UTC (0800 and 0830 PHT) 8 November, arrived earlier along the eastern shores at the entrance of the bay, and propagated northward to the bay head. It is likely that several eyewitnesses in Dulag observed the front of the storm surge. During the passage of the eye (calm winds), eyewitnesses

FIG. 5. Storm surge model sequence of Ty 1897 in San Pedro Bay from 0200 to 0400 UTC 12 Oct 1897 with colors and arrows representing water level and wind magnitude and direction, respectively.

saw an offshore “wall of water” about 6 m high that first was moving west toward Dulag but then suddenly redirected north toward Tacloban. The peak surge lasted for at least 30 min, and then just before 0100 UTC (0900 PHT) 8 November, the water subsided (Figs. 4h–i).

In addition, the modeled water level in Fig. 4 shows three apparent peaks corresponding to points C, G, and after point I. The peaks may coincide with the three “waves” reported by eyewitnesses (Amadore 2013; Morgerman 2014), although the timing could not be verified since the eyewitnesses did not track the timing of the three waves. In the open sea coast of Hernani, accounts of the storm surge coming in three waves also exist. The video footage from Hernani showed the building collapsing with the impact of the second wave, which corresponds to the highest and steepest peak in the storm surge model in San Pedro Bay.

The storm surge simulation of Ty 1897 (Fig. 5) showed water levels and peak surge timing that are consistent with Algué’s report (see the supplemental information online at <http://dx.doi.org/10.1175/BAMS-D-14-00245.2>). In Basey, north-northeasterly offshore winds forced the water to

recede (Fig. 5a). The initial rise of the surge occurred with the east-southeasterly winds (Fig. 5b), whereas south-southeasterly winds caused the peak surge in Tacloban and Basey (Figs. 5c,d). On the contrary, in Tolosa the model did not absolutely replicate the actual surge height. Algué reported surge height of ~3 m, but the model yielded 2 m. The discrepancy can be attributed to various factors including changes in nearshore bathymetry, storm-wave contribution, and uncertainties in the Ty 1897 typhoon parameters. For the most part of San Pedro Bay, the modeled surges indicate that Ty 1897 generated lower surge heights than Typhoon Haiyan (Fig. 6), which is consistent with the field measurements for both storm surge events. The magnitude difference of the modeled surge heights between the two typhoons (Fig. 7) is also consistent with the magnitude difference of the measured water levels in both posttyphoon surveys.

IMPLICATIONS FOR DISASTER MANAGEMENT. *Understanding the local storm surge hazard.* The complex interactions among several factors including typhoon intensity represented

by the lowest pressure and maximum wind speed, forward movement of the typhoon, storm size, bathymetry, coastline shape, and tidal phase result in varying storm surge height and flooding duration for any storm (e.g., Emanuel 2005a; Irish et al. 2008; Needham and Keim 2014). Given the similar areas impacted by the storm surges of Ty 1897 and Typhoon Haiyan, the coastal geomorphology is assumed to be relatively constant for these two events. Lander et al. (2014) estimated a 20-cm sea level rise between 1970 and 2013, which likely did not contribute significantly to the impact of the storm surge from Typhoon Haiyan. The effect of sea level rise on the tidal phases of Ty 1897 and Typhoon Haiyan is beyond the scope of this study. We focused on differences in typhoon characteristics including track, intensity, size, and forward movement and their possible effect on the storm surge characteristics.

Despite the atmospheric differences between Ty 1897 and Typhoon Haiyan, the resulting two storm surges share notable similarities dictated by the local coastal configuration (Fig. 2). At exposed locations like Hernani, both typhoons generated peak surges exceeding 7 m with significant storm-wave contributions superimposed on top of the surge. In stark contrast, sheltered locations such as General MacArthur experienced the lowest flood levels with 2-m peak surges. Another similarity in both typhoons was the water receding off Basey in San Pedro Bay prior to the peak surge. Based on the historical accounts and our simulations, the 1.2-km-wide strait separating Jinamoc Island from Basey can be exposed as the water recedes prior to the peak surge given the shallow-water depth of ~1.5 m under normal conditions. In both typhoons, the surge in San Pedro Bay initially rose just before the typhoon made landfall on Leyte Island with easterly onshore winds. The surge then peaked with the southeasterly onshore winds as the typhoon eye

FIG. 6. Modeled surge heights comparison between Ty 1897 and Typhoon Haiyan in San Pedro Bay. (a) Graphical representation of the modeled water level at Tacloban for Ty 1897 and Typhoon Haiyan. (b) Modeled maximum surge heights in San Pedro Bay during Ty 1897. (c) Modeled maximum surge heights in San Pedro Bay during Typhoon Haiyan.

moved west toward the interior of Leyte Island (Figs. 4, 5).

Irrespective of the coastal configuration, whether in exposed open sea (e.g., Hernani) or in a sheltered embayment (e.g., San Pedro Bay), the typhoon forward motion resulted in significantly different peak flooding duration between the two storm surge events. The slower forward motion of Ty 1897 resulted in longer peak floods lasting for about 3 h. In contrast, the much-faster-moving Typhoon Haiyan resulted in rapid high velocity peak floods spanning about 30 min to nearly 1 h.

The higher and more extensive peak surge around San Pedro Bay during Typhoon Haiyan compared to Ty 1897 (Fig. 6) could be due to the latitudinal shift of the typhoon tracks, differences in the intensity and forward motion of these two typhoons, or a combination of these factors. The northerly track of Ty 1897 made Tanauan the landfall location, reducing the surge near Palo and Tanauan; this is true especially given the relative absence of strong onshore winds when compared to Typhoon Haiyan. Meanwhile, the relatively more intense and larger Typhoon Haiyan generated stronger onshore winds on the northern and western shores of San Pedro Bay. The stronger onshore winds in turn induced surge heights almost twice those of Ty 1897, thereby extending over a wider region (Fig. 6).

Apart from typhoon intensity, the storm size was recognized as an additional important factor in generating high storm surges and extensive inundation during Hurricane Katrina (Irish et al. 2008). Given the geometry of San Pedro Bay, however, the storm size might not be an equally significant factor in generating high storm surges in the case of Typhoon Haiyan. The distance from the Typhoon Haiyan track to the head of San Pedro Bay is ~40 km, which is well within the zone of maximum winds. Although when considering the more southerly track of Typhoon Haiyan, the storm size likely contributed to the extreme surge heights along the more exposed coasts of eastern Samar such as at Hernani.

Multihazard evacuation strategies. Figure 8 shows the damage from Typhoon Haiyan surrounding San Pedro Bay. In the northern part of Tacloban, including the downtown area, the landward limit of inundation during Typhoon Haiyan exceeded 500 m (Tajima et al. 2014). Along low-lying, swampy areas south of downtown Tacloban, and similarly at Tanauan, inundation extended more than 2-km inland. Overland flooding reached over 2 km, but the primary areas of damage were concentrated within 200 m of the coast, highlighting that the destructive power of storm

FIG. 7. Difference in water levels of the modeled maximum surge height between Ty 1897 and Typhoon Haiyan in San Pedro Bay.

waves riding on top of the storm surge has a limited inland penetration [Federal Emergency Management Agency (FEMA 2011). Very few structures withstood the energy of the storm surge and superimposed storm waves (Figs. 8b,c,d,f). In areas above the surge heights, extreme typhoon winds caused greater damage, destroying roofs and wide swaths of coconut trees (Fig. 8e). Therefore, the combined hazards from storm surge flooding, extreme winds, and the prevailing vulnerabilities must be considered when developing appropriate evacuation strategies.

Typhoon warning and response. The Philippine government issued typhoon forecasts and warnings for evacuations at least 18 h before Typhoon Haiyan's landfall to achieve minimum and possibly zero casualties from the imminently approaching cyclonic storm threat (Ranada 2013; NDRRMC 2013c; IRIDeS 2014). Preliminary social surveys suggest that local residents had a mixed response to the typhoon warnings emerging from complex social concerns (IRIDeS 2014; Leelawat et al. 2014). These studies highlight that communication pathways, warning systems, evacuation plans, and multilevel hazard and disaster perception were significant concerns for evacuation decisions among individuals in the areas severely impacted by Typhoon Haiyan. These findings underscore the need for the authorities responsible for disseminating weather warnings to better understand how typhoon warnings are transmitted from an initial source through intermediate relays to the final recipients, as well as how the potentially vulnerable

FIG. 8. Photos of storm damage around San Pedro Bay. (a) Location map. Most structures proximal to the coast in (b) Tacloban, (d) Basey, and (f) Tanauan were completely destroyed by the storm surge and the overriding storm waves. Like in most coastal settlements, existing guidelines on foreshore easement³ were completely ignored. (c) In Anibong village, just north of downtown Tacloban, stilt houses are rebuilt seaward of the stranded ships 2 months after the event. (e) In Marabut, wide swaths of palm trees chopped by the extreme winds.

that many people along the Gulf and Atlantic coasts in the United States have incorrectly believed that they have been through major cyclonic events, although Baker (1991) recognized that defining and measuring hurricane experience is a difficult task. Of particular relevance to the Philippines, several residents on Leyte and Samar Islands admitted that their experience of past typhoons misled them

residents receive, heed, interpret, and decide to act upon these warnings.

Given the historical perspective of storm surge hazards discussed in this paper, social scientists and historians may be able to improve local historical awareness about previous typhoon experiences to aid in hazard perception and response. Historical records show that several tropical cyclones have made landfall in the area surrounding Leyte Gulf (Fig. 9; Tables 3 and 4). According to an unpublished data of PAGASA4, nine of the tropical cyclones have generated storm surges (Table 3). Among these storms, residents identify the November 1984 Typhoon Agnes and the associated coastal flooding of more than 2-m deep in Samar and Leyte as the worst in living memory (e.g., Amadore 2013). Leik et al. (1981) noted

to believe that an evacuation lead time of minutes would be sufficient. This raises a long-lasting question: How does the experience of smaller, relatively less impactful events shape the response of the community to larger, unprecedented events or those with return periods outside the living memory of residents?

On a broader note, although stronger prehistoric events (Donnelly et al. 2006; Nott 2007) remain to be explored, and as long as other historical events remain unverified, the Ty 1897 and Typhoon Haiyan storm surges may serve as worst-case scenarios for this region. These rare but disastrous events should be carefully evaluated toward enhancing community-based disaster risk awareness, planning, and response.

³ The Water Code of the Philippines (Presidential Decree 1067) designates an easement of 40 m from seashore. This is supposed to be a “no build zone” area.

CONCLUSIONS.

Historical records reveal a predecessor to Typhoon Haiyan occurred on 12 October 1897. This typhoon, referred to here as Ty 1897, took a similar path of destruction through the eastern central Philippines. Ty 1897 and Haiyan had almost identical typhoon tracks, but Typhoon Haiyan was more intense, had larger maximum wind coverage, and moved faster than Ty 1897. Our combined field observations, eyewitness accounts, and computer simulations consistently indicate that Typhoon Haiyan's storm surge was about twice the height of the 1897 event in San Pedro Bay, but the two storm surges had similar heights on the open Pacific coast such as at Hernani. While stronger prehistoric events remain unexplored, Ty 1897 and Typhoon Haiyan storm surges may serve as extreme scenarios for this region in terms of disaster risk awareness, planning, and response.

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TABLE 3. Tropical cyclones with known storm surge occurrence (represented as white solid lines in Fig. 9).				
No.	Name	Date	Max winds (kt) ^a	Min pressure (hPa)
1	No name	12 Oct 1897		(694 mm ^{b,c}) 925
2	No name	4 May 1913		(727.8 mm ^c) 970
3	No name	3 Jun 1923		(739.52 mm ^c) 973
4	26W	14 Dec 1948	35 ^a , JTWC	
5	Wanda	23 Apr 1971	40 ^a , JMA	993 ^a , JMA
6	Agnes	4 Nov 1984	100 ^a , JMA	925 ^a , JMA
7	Skip	7 Nov 1988	70 ^a , JMA	955 ^a , JMA
8	Mike	12 Nov 1990	90 ^a , JMA	935 ^a , JMA
9	Haiyan	8 Nov 2013	125 ^a , JMA	895 ^a , JMA

TABLE 4. Tropical cyclones with unknown storm surge occurrence (represented as white dashed lines in Fig. 9).				
No.	Name	Date	Max winds (kt) ^a	Min pressure (hPa)
1	No name	24 Nov 1912 ^d		(693.08 mm ^e) 923
2	Wanda	20 Nov 1951	90 ^a , JTWC	985 ^a , JMA
3	Wilma	27 Oct 1952	130 ^a , JTWC	930 ^a , JMA
4	Tilda	29 Nov 1954	120 ^a , JTWC	980 ^a , JMA
5	Irma	15 May 1966	100 ^a , JTWC	974 ^a , JMA
6	Jean	14 July 1971	75 ^a , JTWC	980 ^a , JMA
7	Kit	7 Jan 1972	75 ^a , JTWC	975 ^a , JMA
8	Nelson	25 Mar 1982	105 ^a , JTWC	940 ^a , JMA
9	Axel	21 Dec 1994	95 ^a , JTWC	960 ^a , JMA

^a IBTrACS database of Knapp et al. (2010) using either JTWC or JMA data.
^b Data of Algué (1898).
^c Data of Algué (1904).
^d This Nov 1912 typhoon is believed to be deadly (<http://chroniclingamerica.loc.gov/lccn/sn83045433/1912-11-30/ed-1/seq-1/>), but other reports on the damage and impact to human life were insufficient for verification (U.S. War Office 1913).
^e Data of Selga (1935).

Fig. 9. Landfalling tropical cyclones in the surrounding area of Leyte Gulf between 1897 and 2013. Storm tracks were from the IBTrACS database of Knapp et al. (2010). The attributes of each typhoon are summarized in Tables 3 and 4.

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REFERENCES

- Algué, J., 1898: El baguio de Samar y Leyte, 12–13 de Octubre de 1897. Manila Observatory, 74 pp.
- , 1904: *The Cyclones of the Far East*. Bureau of Public Printing, 283 pp.
- Alojado, D., and D. M. Padua, 2010: Worst typhoons of the Philippines 1947–2009. Accessed 06 July 2014. [Available online at www.typhoon2000.ph/stormstats/WorstPhilippineTyphoons.htm.]
- Amadore, L. A., 2013: Storm surge in Basey, Samar. Accessed 03 April 2013. [Available online at <http://opinion.inquirer.net/66477/storm-surge-in-basey-samar>.]
- Atkinson, G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western North Pacific. *Mon. Wea. Rev.*, **105**, 421–427, doi:10.1175/1520-0493(1977)105<0421:TCMSLP>2.0.CO;2.
- Bacani, L., 2013: Deadliest, most destructive cyclones of the Philippines. Accessed 11 July 2014. [Available online at www.philstar.com/headlines/2013/11/11/1255490/deadliest-most-destructive-cyclones-philippines.]
- Baker, E. J., 1991: Hurricane evacuation behavior. *Int. J. Mass Emerg. Disasters*, **9**, 287–310.
- Bricker, J., H. Takagi, E. Mas, S. Kure, B. Adriano, C. Yi, and V. Roeber, 2014: Spatial variation of damage due to storm surge and waves during Typhoon Haiyan in the Philippines. *J. Japan Soc. Civil Eng.*, **70**, 2, I_231–I_235.
- Caulderwood, K., 2014: The ten most expensive natural disasters in 2013. Accessed 03 March 2014. [Available online at www.ibtimes.com/report-ten-most-expensive-natural-disasters-2013-1540058.]
- Donnelly, C., N. Kraus, and M. Larson, 2006: State of knowledge on measurement and modeling of coastal overwash. *J. Coastal Res.*, **22**, 965–991, doi:10.2112/04-0431.1.
- Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420–430, doi:10.1175/1520-0493(1975)103<0420:TCIAAF>2.0.CO;2.
- , 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 50 pp. [Available online at ftp://satepsanone.nesdis.noaa.gov/Publications/Tropical/Dvorak_1984.pdf.]
- Egbert, G. D., and S. Y. Erofeeva, 2002: Efficient inverse modeling of barotropic ocean tides. *J. Atmos. Oceanic Technol.*, **19**, 183–204, doi:10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2.
- Emanuel, K. A., 2005a: The storm surge. *Divine Wind: The History and Science of Hurricanes*. Oxford University Press, 147–152.
- , 2005b: The hunters. *Divine Wind: The History and Science of Hurricanes*. Oxford University Press, 193–202.
- FEMA, 2011: Coastal construction manual: Principles and practices of planning, siting, designing, constructing, and maintaining residential buildings in coastal areas. U.S. Department of Homeland Security FEMA P-55, Vol. 1, 242 pp.
- Flater, D., 1998: XTide: Harmonic tide clock and tide predictor. Accessed 25 May 2014. [Available online at www.flaterco.com/xtide/.]
- Fritz, H. M., and Coauthors, 2007: Hurricane Katrina storm surge distribution and field observations on the Mississippi Barrier Islands. *Estuarine Coastal Shelf Sci.*, **74**, 12–20, doi:10.1016/j.ecss.2007.03.015.
- , C. D. Blount, S. Thwin, M. K. Thu, and N. Chan, 2009: Cyclone Nargis storm surge in Myanmar. *Nat. Geosci.*, **2**, 448–449, doi:10.1038/ngeo558.
- , and Coauthors, 2012: The 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LiDAR. *Geophys. Res. Lett.*, **39**, L00G23, doi:10.1029/2011GL050686.
- Harris, D. L., 1963: Characteristics of the hurricane storm surge. U.S. Department of Commerce Weather Bureau Tech. Paper 48, 19–24. [Available online at https://coast.noaa.gov/hes/images/pdf/CHARACTERISTICS_STORM_SURGE.pdf.]
- Holland, G. J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Mon. Wea. Rev.*, **108**, 1212–1218, doi:10.1175/1520-0493(1980)108<1212:AAMOTW>2.0.CO;2.
- IRIDeS, 2014: Initial Report of International Research Institute of Disaster Science (IRIDeS): IRIDeS Fact-Finding Missions to Philippines. Tohoku University, 105 pp.
- Irish, J. L., D. T. Resio, and J. J. Ratcliff, 2008: The influence of storm size on hurricane surge. *J. Phys. Oceanogr.*, **38**, 2003–2013, doi:10.1175/2008JPO3727.1.
- Joint Typhoon Warning Center, 2014: JTWC western North Pacific best track data 2013. Joint Typhoon Warning Center, accessed 10 July 2014. [Available

- online at www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php]
- Knaff, J. A., and R. M. Zehr, 2007: Reexamination of tropical cyclone wind-pressure relationships. *Wea. Forecasting*, **22**, 71–88, doi:10.1175/WAF965.1.
- Knapp, K. R., and M. C. Kruk, 2010: Quantifying inter-agency differences in tropical cyclone best track wind speed estimates. *Mon. Wea. Rev.*, **138**, 1459–1473.
- Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bull. Amer. Meteor. Soc.*, **91**, 363–376, doi:10.1175/2009BAMS2755.1.
- Koba, H., T. Hagiwara, S. Asano, and S. Akashi, 1990: Relationships between CI number from Dvorak's technique and minimum sea level pressure or maximum wind speed of tropical cyclone (in Japanese). *J. Meteor. Res.*, **42**, 59–67.
- Kruk, M. C., K. R. Knapp, and P. A. Hennon, 2011: On the use of the Dvorak current intensity as a climate data record in the western North Pacific. *23rd Conf. on Climate Variability and Change*, Seattle, WA, Amer. Meteor. Soc., 142. [Available online at <https://ams.confex.com/ams/91Annual/webprogram/Paper179185.html>]
- Lander, M., C. Guard, and S. J. Camargo, 2014: Super Typhoon Haiyan [in "State of the Climate 2013"]. *Bull. Amer. Meteor. Soc.*, **95** (7), S112–S114.
- Lawrence, H., and H. Cobb, 2005: Tropical cyclone report: Hurricane Jeanne, 13–28 September 2004. Accessed 11 March 2014. [Available online at www.nhc.noaa.gov/data/tcr/AL112004_Jeanne.pdf]
- Leelawat, N., C. M. R. Mateo, S. M. Gaspay, A. Suppasri, and F. Imamura, 2014: Filipinos' views on the disaster information for the 2013 Super Typhoon Haiyan in the Philippines. *Int. J. Sustainable Future Hum. Secur.*, **2** (2), 16–28.
- Leik, R. K., T. M. Carter, J. P. Clark, S. D. Kendall, and G. A. Gifford, 1981: Community response to natural hazard warnings. Summary Final Rep. DCPA01-79-C-0214, FEMA Work Unit 2234-F, 77 pp. [Available online at <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA099509>]
- Lesser, G. R., J. A. Roelvink, J. A. T. M. van Kester, and G. S. Stelling, 2004: Development and validation of a three-dimensional morphological model. *Coastal Eng.*, **51**, 883–915, doi:10.1016/j.coastaleng.2004.07.014.
- Mas, E., J. Bricker, S. Kure, B. Adriano, C. Yi, A. Suppasri, and S. Koshimura, 2015: Field survey report and satellite image interpretation of the 2013 Super Typhoon Haiyan in the Philippines. *Nat. Hazards Earth Syst. Sci.*, **15**, 805–816, doi:10.5194/nhess-15-805-2015.
- Morgerman, J., 2014: Super Typhoon HAIYAN in Tacloban City & Leyte, Philippines: Data & documentation from the landfall zone of a category-5 cyclone. iCyclone Rep., 47 pp. [Available online at www.icyclone.com/upload/now/apr_2014/iCyclone_HAIYAN_in_Tacloban_City_040314.pdf]
- Mori, N., M. Kato, S. Kim, H. Mase, Y. Shibutani, T. Takemi, K. Tsuboki, and T. Yasuda, 2014: Local amplification of storm surge by Super Typhoon Haiyan in Leyte Gulf. *Geophys. Res. Lett.*, **41**, 5106–5113, doi:10.1002/2014GL060689.
- Nakazawa, T., and S. Hoshino, 2009: Intercomparison of Dvorak parameters in the tropical cyclone datasets over the western North Pacific. *SOLA*, **5**, 33–36, doi:10.2151/sola.2009-009.
- National Mapping and Resource Information Authority, 1980: Nautical chart of San Pedro Bay. 1:402000. Sheet 4468.
- NDRRMC, 2013a: Preparations for Typhoon "YOLANDA" (HAIYAN). NDRMMC Situational Rep. 2, 10 pp. [Available online at [www.ndrrmc.gov.ph/attachments/article/1329/Preparations_for_Typhoon_YOLANDA_\(HAIYAN\)_SitRep_No_02_07NOV2013_0600H.pdf](http://www.ndrrmc.gov.ph/attachments/article/1329/Preparations_for_Typhoon_YOLANDA_(HAIYAN)_SitRep_No_02_07NOV2013_0600H.pdf)]
- , 2013b: Effects of Typhoon "YOLANDA" (HAIYAN). NDRRMC Situational Rep. 10, 43 pp. [Available online at [www.ndrrmc.gov.ph/attachments/article/1329/Effects_of_Typhoon_YOLANDA_\(HAIYAN\)_SitRep_No_10_10NOV2013_0600H.pdf](http://www.ndrrmc.gov.ph/attachments/article/1329/Effects_of_Typhoon_YOLANDA_(HAIYAN)_SitRep_No_10_10NOV2013_0600H.pdf)]
- , 2013c: Preparations for Typhoon "YOLANDA" (HAIYAN). NDRMMC Situational Rep. 3, 13 pp. [Available online at [www.ndrrmc.gov.ph/attachments/article/1329/Preparations_for_Typhoon_YOLANDA_\(HAIYAN\)_SitRep_No_03_07NOV2013_0000H.pdf](http://www.ndrrmc.gov.ph/attachments/article/1329/Preparations_for_Typhoon_YOLANDA_(HAIYAN)_SitRep_No_03_07NOV2013_0000H.pdf)]
- , 2014: Effects of Typhoon "YOLANDA" (HAIYAN). Situational Rep. 108, 67 pp. [Available online at [www.ndrrmc.gov.ph/attachments/article/1329/Effects_of_Typhoon_YOLANDA_\(HAIYAN\)_SitRep_No_108_03APR2014.pdf](http://www.ndrrmc.gov.ph/attachments/article/1329/Effects_of_Typhoon_YOLANDA_(HAIYAN)_SitRep_No_108_03APR2014.pdf)]
- Needham, H. F., and B. D. Keim, 2014: Correlating storm surge heights with tropical cyclone winds at and before landfall. *Earth Interact.*, **18**, doi:10.1175/2013EI000527.1.
- Nott, J., 2007: The importance of quaternary records in reducing risk from tropical cyclones. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **251**, 137–149, doi:10.1016/j.palaeo.2007.02.024.
- Paciente, R. B., 2014: Response and lessons learned from Typhoon "Haiyan" (Yolanda). *JMA/WMO Workshop*

- on *Effective Tropical Cyclone Warning in Southeast Asia*, Session 6: Effective Early Warning: Lessons learnt from past TC Disasters. Tokyo, Japan, Japan Meteorological Agency. [Available online at www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/2014_Effective_TC_Warning/documents.html.]
- Ranada, P., 2013: Leyte warned of storm surges. Accessed 10 November 2013. [Available online at www.rappler.com/nation/43179-yolanda-storm-surges.]
- Ribera, P., R. García-Herrera, and L. Gimeno, 2008: Historical deadly typhoons in the Philippines. *Weather*, **63**, 194–199, doi:10.1002/wea.275.
- Selga, M., 1935: Charts of remarkable typhoons in the Philippines 1902–1934. *Catalogue of Typhoons 1348–1934*, Manila Weather Bureau, 1–55.
- Tadepalli, S., and C. E. Synolakis, 1994: The run-up of N-waves on sloping beaches. *Proc. Roy. Soc. London*, **A445**, 99–112, doi:10.1098/rspa.1994.0050.
- Tajima, Y., and Coauthors, 2014: Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan. *Coastal Eng. J.*, **56**, 1450006, doi:10.1142/S0578563414500065.
- Udías, A., 1996: Jesuits' contribution to meteorology. *Bull. Amer. Meteor. Soc.*, **77**, 2307–2315, doi:10.1175/1520-0477(1996)077<2307:JCTM>2.0.CO;2.
- UNESCO, 2014: International Tsunami Survey Team (ITST) post-tsunami survey guide. UNESCO-IOC Manuals and Guides 37, 114 pp. [Available online at <http://unesdoc.unesco.org/images/0022/002294/229456E.pdf>.]
- U.S. War Office, 1913: Typhoons. *Report of the Philippine Commission to the Secretary of War*, Washington Government Printing Office, 32.
- Velden, C., and Coauthors, 2006: The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.*, **87**, 1195–1210, doi:10.1175/BAMS-87-9-1195.
- World Meteorological Organization, 2015: Typhoon committee operational manual: Meteorological component. Tropical Cyclone Programme Rep. TCP-23, 169 pp. [Available online at www.wmo.int/pages/prog/www/tcp/documents/TCP-23EDITION2015.pdf.]

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RONALD D. BRUNNER AND AMANDA H. LYNCH

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APPENDIX 2

Storm surge occurrences in the Philippines 1897-1998

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CLIMATOLOGY AND AGROMETEOROLOGY BRANCH
Climate Change, Drought Early Warning and Monitoring Center

CONCURRENT STORM SURGE IN THE PHILIPPINES (1897 – 1998)

Prepared: February 29, 2000

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NAME OF T.C. AND DATES IN WHICH THE SURGE IS ASSOCIATED WITH	OBSERVED MAX WINDS(kph)	AFFECTED COASTAL AREAS -TOWN/PROVINCE	ACTUAL STORM SURGE HEIGHT(M)
1) Typhoon of Samar and Leyte October 12, 1897		Banay, Samar Hernani, Tanglad, Samar Pambujan, Samar Basey, Samar Tacloban, Leyte	4.4 M 7.3 M 1.5 M 4.9 M 0.9 M
2) Typhoon May 15 - 19, 1901		Mamburao, Mindoro	1.5 M
3) 1904		Bacolod Dipolog Nonoc Island, Surigao Placer, Surigao, City	UND UND UND UND
4) Typhoon September 25 - 27, 1905		Manila Area and Vicinity	UND
5) Typhoon in W. Carolines January 1907		Borongan, Samar	UND
6) Typhoon of Samar September 22 - 25, 1908		Tuminobo and Ando Is., Borongan, Samar	UND
7) Typhoon of Cagayan October 11 - 13, 1908		Aparri, Cagayan	2.4 M
8) Typhoon of Cagayan and Batanes Is., September 27-29, 1912		San Vicente, Cagayan & Palaui Island	UND
9) Typhoon of Leyte & Cebu October 15-16, 1912		Sogod, Northern Leyte Consolacion, Cebu Malitbog, Northern Leyte	9.1 M 4.6 M
10) Typhoon of Samar, Leyte & Panay, November 24-25, 1912		All towns and Barrios along Maqueda Bay in Samar	UND
11) Typhoon of Samar, Leyte & Ilocos, May 4 - 11, 1913		Coastal Barrios in Hernani, Llorente and Pambuyan in Samar, parts of Tacloban. Sinait, Cagugao & Narva- can, Ilocos Sur	UND
12) Typhoon of Samar & Luzon, June 17 - 21, 1914		Tubabao, Hilaban & Dolores, Samar	2.3 M
13) Typhoon of Biliran & Northern Leyte, January 14-16, 1916		Merida, Leyte	UND

NAME OF T.C. AND DATES IN WHICH THE SURGE IS ASSOCIATED WITH	OBSERVED MAX WINDS(kph)	AFFECTED COASTAL AREAS -TOWN/PROVINCE	ACTUAL STORM SURGE HEIGHT(M)
14) Typhoon August 1, 1920		Bagac, Morong, Bataan	8.0 M
15) Typhoon of Samar, Leyte & Southern Luzon, June 3-4, 1923		Eastern coast of Samar	UND
16) Tropical Storm November 28 - 03 December 1924		Calapan, Mindoro	UND
		Carcar, Naga	UND
		Mabibi, Bohol	UND
17) Typhoon of Bicol June 24 - 26, 1925		Paracale, Cam. Norte	UND
18) Typhoon of Visayas December 3 - 8, 1930		Sibuyan Island and Busuanga, Culion	UND
19) Typhoon of Visayas January 2 - 5, 1931		Camotes Island, Borbon in Cebu	UND
20) Typhoon November 1 - 4, 1933		East Coast, Borongan, Samar	9.8 M
21) Typhoon of Visayas November 2 - 5, 1934		Dulong, Leyte	UND
22) 1944		Solvec, Ilocos Sur	10 M
23) Typhoon December 12 - 16, 1948		Tacloban, Leyte	UND
24) Typhoon Nona August 31 - 05 September 1952		Currimao, Ilocos Norte	UND
25) Typhoon Nora September 5 - 12, 1959		Banawe, Bangar, Ilocos, Sur	UND
26) Typhoon Harriet December 29, 1959	225- Virac, Catanduanes	Coastal areas of Bicol and Visayas	UND
27) Typhoon Karen April 25, 1960	65-Surigao	Visayas	UND
28) Typhoon Olive June 23 -28, 1960	185-Legaspi City	Manila	UND
29) Typhoon Kit October 3 - 9, 1960	185-Calapan, Or. Mindoro	Legaspi City	UND

NAME OF T.C. AND DATES IN WHICH THE SURGE IS ASSOCIATED WITH	OBSERVED MAX WINDS(kph)	AFFECTED COASTAL AREAS -TOWN/PROVINCE	ACTUAL STORM SURGE HEIGHT(M)
30) Typhoon Kate July 9 - 22, 1962	104-Port Area, Manila	West coast of Luzon	UND
31) Typhoon Karing June 12 - 18, 1963	67-Port Area	Luzon Coast	UND
32) Typhoon Dading June 26 - 30, 1964	127-Infanta	Manila, Cavite & Paranaque	UND
33) Typhoon Ining(Louise) November 16 - 21, 1964	230-over water	Surigao del Norte & Bacolod	UND
34) Typhoon Miling(Freda) July 9 - 14, 1965	176-Tuguegarao Cagayan	Manila	UND
35) Typhoon Klaring(Irma) May 11 - 12, 1966	195-Tacloban, Leyte	Masbate	
36) Typhoon Gening (Anita) June 26 - 29, 1967	106-Laoag City	San Nicolas, Batac & Paoay, Ilocos Norte	UND
37) Typhoon Didang July 21 - 28, 1968	158-Basco, Batanes	Solvec, Narvacan, I. S., Sta. Cruz & Mamburao	9.0 M
38) Typhoon Elang (Viola) July 26 - 29, 1969	222-Basco, Batanes	Manila, Coastal towns of Bauang & Sudipen, L.U.	
39) Typhoon Atang (Nancy) February 23-27, 1970	230-Virac, Cat.	Catbalogan, Samar	UND
40) Typhoon Emang (Ruby) July 11-15, 1970	90-Northern Quezon	Eastern coasts of Cagayan, Babuyan Is. & Catanduanes	UND
41) Typhoon Pitang (Georgia) September 8-12, 1970	240-over water	Casiguran, Aurora; and Disalag & Dipaculag, Quezon	UND
42) Typhoon Sening (Joan) October 10-15, 1970	225-Catanduanes	Cavite, Sorsogon, Ilocos Sur, Bagac, Morong, Bataan	3.0-5.0 M
43) Typhoon Yoling (Patsy) November 17-20, 1970	200-MIA	Calagua Is., Manila Bay, Cavite, Katakian Is. in Poililo.	
44) Typhoon Diding (Wanda) April 23- 28, 1971	160-Tacloban	Guiuan Is. & Palo-Palo in Samar	UND
45) Typhoon Herming (Dinah) May 25-27, 1971	150-Legaspi City	Dalahican, Lucena	UND

NAME OF T.C. AND DATES IN WHICH THE SURGE IS ASSOCIATED WITH	OBSERVED MAX WINDS(kph)	AFFECTED COASTAL AREAS -TOWN/PROVINCE	ACTUAL STORM SURGE HEIGHT(M)
46) Typhoon Rosing July 16-21, 1971	190-Basco, Batanes	Manila	UND
47) Typhoon Uring (Rose) August 11 - 14, 1971	139-Tuguegarao, Cagayan	Ilocos, Pangasinan & Zambales Provinces	UND
48) Typhoon Barang (Elaine) September 31-October 6, 1971	95-Virac, Cat.	From Ilocos Sur to Bataan, Batangas and Palawan	UND
49) Typhoon Dadang October 1 - 9, 1971	78-Calapan Or. Mindoro	Cavite and Las Pinas	UND
50) Typhoon Asiang (Kit) January 5 - 9, 1972	104-Tacloban	Abuyog & Baybay, Leyte	UND
51) Tropical Storm Edeng(Susan) July 7, 1972	55-over water	Manila Bay	UND
52) Typhoon Gloring(Rita) July 10, 1972	273-over water	Manila Bay	UND
53) Typhoons Huaning & Isang July 29-August 1, 1972	40-Virac, Cat.	Batanes Island	UND
54) Typhoon Auring (Lola) January 22-23, 1975	110-Mactan	Surigao del Sur	UND
55) Typhoon Atang April 18-27, 1978	180-Romblon	San Vicente, Cagayan, Bataan & Itbayat Island	UND
56) Typhoon Daling(Kelly 8106) June 28-July 5, 1981	150-Virac, Cat.	Calapan,Naujuan,Socorro, Pola,Pinamalayan,Gloria, Mindoro Oriental	UND
57) Typhoon Anding(Irma 8126) November 22-27, 1981	260-Daet 240-Recon	Binagasbasan,Garchitorena Poblacion Sta. Cruz, Lagonoy Port Tambang,Tinambac Poblacion, Tinambac Digisit, Baler Cemento, Baler Tibag, Baler Sabang, Baler	8.2 M 2.9 M 2.2 M 4.0 M 4.4M 8.4 M 4.0 M 2.7 M
58) Typhoon Norming August 19 - 07 September 1982	220- Iba, Zambales 150-over water	Orani, Bataan	.8 - 1.7 M

APPENDIX 3

Historical storm surge occurrences in the Philippines
1897-2011

Historical Storm Surge Occurrences in the Philippines (1897-2011)

Scale: 1:1,978,804
WGS 1984 UTM Zone 51 N
Luzon 1911 Datum

LEGEND:

- Storm Surge Occurrences (1m)
- Storm Surge Occurrences (>1m to 4m)
- Storm Surge Occurrences (>4m to 12m)
- Reported Undefined Points
- Reported New Points
- Municipal Boundary

Republic of the Philippines
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Source:
Data: GASRU, AGSSRS, AGSSB
Storm Surge Occurrences in the Philippines (1897-1998), CAB
Basemap: Shuttle Radar Topography Mission (SRTM)