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GNSS characterization of hydrological loading in South and Southeast Asia

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Abstract

The elastic response of the lithosphere to surface mass redistributions produces geodetically measurable deformation of the Earth. This deformation is especially pronounced in South and Southeast Asia, where the annual monsoon produces large-amplitude hydrological loads. The Myanmar-India-Bangladesh-Bhutan (MIBB) network of about 20 continuously operating Global Navigation Satellite Systems (GNSS) stations, established in 2011, provides an opportunity to study the Earth's response to these loads. In this study, we use GRACE temporal gravity products as an estimate of long-wavelength surface water distribution and use this estimate in an elastic loading calculation. We compare the predicted vertical deformation from GRACE with that observed with GNSS. We find that elastic loading inferred from the GRACE gravity model is able to explain the phase and much of the peak-to-peak amplitude (typically 2-3 cm) of the vertical GNSS oscillations, especially in northeast India and central Myanmar. GRACE-based corrections reduce the RMS scatter of the GNSS data by 30-45% in these regions. However, this approach does not capture all of the seasonal deformation in central Bangladesh and southern Myanmar. We show by a synthetic test that local hydrological effects may explain discrepancies between the GNSS and GRACE signals in these places. Two independent hydrological loading models of water stored in soil, vegetation, snow, lakes, and streams display phase lags compared to the GRACE and GNSS observations, perhaps indicating that groundwater contributes to the observed loading in addition to near-surface hydrology. The results of our calculations have implications for survey-mode GNSS measurements, which make up the majority of geodetic measurements in this region. By using the GNSS data together with estimates of hydrological loading from independent observations and models, we may be able to more accurately determine crustal motions caused by tectonic processes in South and Southeast Asia, while also improving our ability to monitor the annual monsoon and resulting water storage changes in the region.

Keywords: Satellite geodesy, Loading of the Earth, Time-variable gravity

64

65 1. Introduction

66 On seasonal timescales, hydrological cycles redistribute masses of water, ice, and air
67 around the globe. As these masses move, they impose gravitational loads on the solid Earth,
68 and the Earth's deformation in response to the loads reveals information about both the
69 sources of loading and the Earth itself (Blewitt et al. , 2001). For example, loading deformation
70 provides a means of understanding the exchange of mass between the atmosphere, surface
71 water, soil moisture, and groundwater (Argus et al., 2014; Argus et al., 2017; Milliner et al.,
72 2018). With respect to the solid Earth, the surface response to time-varying loads also allows us
73 to probe the elastic and viscoelastic structure of the crust and upper mantle (Chanard et al.,
74 2018a; Chanard, 2018b). Furthermore, hydrological loads can be important sources of stress on
75 faults, contributing to the timing and occurrence of earthquakes and non-volcanic tremor
76 (Bettinelli et al., 2008; Craig et al., 2017; Johnson et al., 2017; Pollitz et al., 2013). For these
77 applications as well as for the study of tectonic transients, it is valuable to understand the
78 hydrological loading effects in geodetic data as accurately as possible.

79 For the study of tectonic processes, it is necessary to isolate deformation caused by
80 mass loading from that caused by the earthquake cycle (e.g., Fu & Freymueller, 2012). This can
81 be a challenging task but is important in regions with transient earthquake cycle deformation
82 and hydrological loads that vary from year to year. Accurate knowledge of hydrological loading
83 in a region can also help with the interpretation of horizontal and vertical intermittent survey-
84 mode GNSS measurements, which record the effects of both long-term tectonic deformation
85 and hydrological loading but are sampled too sparsely in time to allow for their separation.

86 Hydrological processes generally produce millimeter-to-centimeter-level deformation of
87 the Earth's surface through two dominant mechanisms. The first is elastic loading, in which the
88 Earth's surface is deflected downward due to the weight of a load placed on or near the surface
89 (Farrell, 1972). The second mechanism is poroelastic loading, in which the addition of
90 groundwater produces upward deflection by filling pore spaces and increasing fluid pressure
91 within the rock below, and is often observed in aquifer settings (Chaussard et al., 2015;
92 Galloway et al., 1999; Miller & Shirzaei, 2015; Ojha et al., 2019). Both mechanisms primarily

93 affect the vertical component of GNSS measurements, although they also act to a smaller
94 degree on the horizontal components (Silverii et al., 2016; Wahr et al., 2013).

95 The typical methods used for studying hydrological loads in GNSS time series involve
96 applying either mathematical function fitting or hydrological models from independent
97 datasets to assess the effects of elastic loading at GNSS stations. One of the most commonly
98 used external models comes from the Gravity Recovery And Climate Experiment (GRACE)
99 mission, which produces spatiotemporal descriptions of the Earth's gravity field and inferred
100 redistribution of near-surface mass. A large body of research supports the general agreement
101 between GRACE-based models of deformation and the hydrological loads observed in GNSS
102 data (Chanard et al., 2018; Fu et al., 2013; Fu & Freymueller, 2012; Gu et al. , 2017; Hao et al.,
103 2016; Tregoning et al., 2009; Yan et al., 2019; Saji et al., 2020). However, GRACE data products
104 are relatively coarsely sampled in both space and time, having a spatial wavelength of 350-500
105 km and monthly sampling, and an inherent tradeoff between temporal and spatial resolution in
106 the processing. GRACE cannot capture local hydrological loading effects at individual GNSS
107 stations, such as effects from large nearby streams or reservoirs, nor can it typically capture
108 short-term temporal variations (Springer et al., 2019). Other types of information, such as
109 water storage models derived from independent hydrological data sets, can be used to improve
110 the spatial resolution of load sources near GNSS stations.

111 In this work, we seek to evaluate the performance of several techniques to model the
112 seasonal deformation at GNSS stations in South and Southeast Asia (Figure 1), an important
113 tectonic region that also has a strong monsoon climate and large seasonal loading deformation
114 (Fu et al., 2013; Steckler et al., 2010). We compute the average amplitude and phase of several
115 loading models and compare them with the GNSS time series and precipitation data. We assess
116 how well the models reduce the variance of the GNSS data with the goal of separating the
117 hydrological versus tectonic contributions to the deformation signal.

118

Figure 1: A) Map of GNSS stations in South and Southeast Asia from two networks – the MIBB (Myanmar, India, Bangladesh and Bhutan) network and the BanglaPIRE network. Active faults are shown (Wang et al., 2014). B) Vertical velocities of GNSS stations shown in (A), computed using least-squares fitting to the time series.

2. Methods

2.1 GNSS Data

We used data from the Myanmar-India-Bangladesh-Bhutan (MIBB) GNSS network operated by the Earth Observatory of Singapore (EOS) and their regional partners in each country in the network: the Department of Meteorology and Hydrology of Myanmar, the Myanmar Earthquake Committee, North Eastern Hill University in India, the Geological Survey of Bangladesh, and Sherubtse College, Royal University of Bhutan. The network was first established in 2011. Most of the 24 stations began operation in 2012 and remain in operation, although some have significant data gaps. We used data until the summer of 2017, focusing on the period before the GRACE/GRACE-FO gap. We excluded 2 MIBB stations with less than two years of data during this period. The list of excluded stations is shown in Table S1.

We processed the GNSS time series using the GIPSY-OASIS software version 6.2 (Zumberge et al., 1997) following the processing strategy in Feng et al. (2015), with model corrections applied for solid Earth and pole tides and ocean tidal loading. We calculated ocean tidal loading relative to the center of mass of the whole Earth including the solid Earth, oceans and atmosphere with the FES2004 model (Lyard et al., 2006), using the free ocean tidal loading calculator provided by the Onsala Space Observatory (<http://holt.oso.chalmers.se/loading/>). The coordinate time series were produced in the International Terrestrial Reference Frame 2008 (ITRF2008) (Altamimi et al., 2011) and subsequently rotated into a Sunda-fixed frame (Altamimi et al., 2012). The ITRF2008 reference frame is by definition a center-of-mass frame, but in practice, it has been shown to more closely follow the Earth's center-of-figure on seasonal and shorter timescales (Dong et al., 2003); this distinction is important for proper comparison with hydrological models in later sections. After processing the GNSS time series, we then removed the effects of non-tidal atmospheric and non-tidal ocean loading using the "NTAL" and "NTOL" loading products provided by the Earth System Modeling group at the German Research Centre for Geosciences (GFZ) (Dill & Döbslaw, 2013) in the center-of-figure frame. At two stations in central Myanmar (SDWN and SWBO), we also modeled and removed the signal related to the 2012 M_w 6.8 Thabeikkyin earthquake (Soe Thura Tun & Watkinson, 2017) using Heaviside step functions for coseismic offsets and logarithmic functions for postseismic deformation (Feng et al., 2015). Where available, we also included 11 stations from a separate GNSS network in Bangladesh that was installed in 2007 as part of the NSF- and UNAVCO-supported BanglaPIRE project (Figure 1) (Steckler et al., 2016, 2010). Most of these stations have data from 2007-2011 (Figure S4). These data are available from UNAVCO and were processed using the GIPSY-OASIS software with the same processing strategy as above.

2.2 Hydrological Loading Models

As the simplest model for yearly hydrological load cycles, we used a mathematical function to fit the average seasonal components in the GNSS time series using least squares. In Equation 1, the coefficients A - E describe annual loading, semi-annual loading, and a constant velocity; w is the angular frequency associated with an annual period. This simple model is

constrained to have constant-amplitude seasonal terms, so it cannot capture multi-annual hydrological variations.

$$x(t) = A\cos(wt) + B\sin(wt) + C\cos(2wt) + D\sin(2wt) + Et + F \quad \text{Eq. 1}$$

We then evaluated several physically based elastic loading models starting with a GRACE-gravity derived estimate of monthly surface mass changes. Our models are derived from the global Mascon gridded solution from NASA's Jet Propulsion Lab (JPL). GRACE Mascon data are available at <http://grace.jpl.nasa.gov> (Watkins et al., 2015; Wiese et al., 2016). The GRACE Level 2 data are corrected for ocean tidal loading, non-tidal ocean loading, and non-tidal atmospheric mass, meaning that contributions from those signals are not included in the product. We then computed the resulting elastic deformation at each GNSS station from all grid cells assuming a Preliminary Reference Earth Model (PREM) structure (Dziewonski & Anderson, 1981) (Figure S1). We used loading Love numbers (Farrell, 1972) for the loading Green's functions following the formulation of Fu & Freymueller (2012) and Johnson et al. (2020). The amplitude and phase of these models are estimated also using Equation 1.

In addition to GRACE, we considered several other elastic loading models from ground- and satellite-based hydrological products. The first of these is the Land Surface Discharge Model (LSDM), which models the elastic loading displacements driven by high-resolution hydrological models of terrestrial water storage and can be directly compared with geodetic time series (Dill & Dobslaw, 2013; Moreira et al., 2016). The LSDM estimates loads from shallow soil moisture, snow, and surface water stored in rivers and lakes. The loading displacements are computed using an elastic "ak135" Earth structure (Kennett, Engdahl, & Buland, 1995). While ak135 is slightly different from PREM, these differences have been shown to produce only small changes (~1% change in amplitude reduction) in modeled hydrological loading (Gu et al., 2017; H. Wang et al., 2012); furthermore, the differences in Earth models are smallest in the vertical component that we study here (Wang et al., 2012). Hydrological loading displacement time series for each coordinate were extracted from the LSDM website (<http://rz-vm115.gfz->

potsdam.de:8080/repository/entry/show?entryid=24aacdfef9b0-43b7-b4c4-bdbe51b6671b,
last accessed on 7 July 2019) in the center-of-figure frame.

We also considered loading driven by the Global Land Data Assimilation System (GLDAS) hydrological model (Rodell et al., 2004). This model contains 1°x1° monthly estimations of surface water in shallow soil moisture (upper 2m), snow pack, and vegetation. Elastic loading deformation was computed on a PREM Earth structure following the technique of Wahr et al. (2013) and as implemented in North America for the Plate Boundary Observatory dataset (Puskas, Meertens, & Phillips, 2017). The summary of the three loading models (GRACE, LSDM, and GLDAS) is presented in Table 1.

We assessed the performance of each of these models by evaluating the reduction in the weighted root mean square error (WRMS) of each detrended time series before and after correction. The percent improvement after correction shows the effectiveness of the seasonal correction technique. Following van Dam et al. (2007), the WRMS reduction is calculated by:

$$WRMS_{reduction} = \frac{WRMS_{GNSS} - WRMS_{GNSS-model}}{WRMS_{GNSS}} \quad (\text{Eq. 2})$$

For comparisons between GRACE-based loading models and vertical GNSS time series, typical WRMS reductions around the globe and in South/Southeast Asia range from 20%-50% (Fu & Freymueller, 2012; Li et al., 2016; Saji et al., 2020), with higher being better. Understanding the differences between these time series and increasing the WRMS reductions achieved by hydrological loading models (Chanard et al., 2018a) is an important aim of current research.

	GNSS	GRACE	LSDM	GLDAS
Ocean Tidal	✗ (Corrected for)	✗ (Corrected for)	✗ (Not modeled)	✗ (Not modeled)
Ocean Non-Tidal	✗	✗	✗	✗
Atmosphere	✗	✗	✗	✗
Soil Moisture	✓	✓	✓	✓
Snow	✓	✓	✓	✓
Vegetation	✓	✓	✗	✓

Lakes + Rivers	✓	✓	✓	✗
Groundwater	✓	✓	✗	✗
Resolution	–	350-500 km	0.125° x 0.125°	1° x 1°
Earth Model	–	PREM	ak135	PREM

Table 1: Summary of datasets and products. Red crosses indicate that the specific loading source is not included or considered in the model. Blue crosses indicate that the loading source has been removed from the data through a separate model prior to its inclusion in this study. Green checkmarks indicate that the loading source is included in the loading model or is expected to be present in the GNSS/GRACE data.

3. Results

3.1 Least-squares results

When we fit the GNSS time series with Equation 1, we find that GNSS stations across South and Southeast Asia record significant deformation at seasonal periods, generally in phase with the local hydrological cycle. Peak uplift is around April, at the end of the dry period, and peak subsidence is around October, at the end of the monsoon (Figure S2). The amplitudes of the vertical displacements are about 20 mm peak-to-peak (Figure 2). In Figure 3, the phase and amplitude information of seasonal oscillations, such as from GNSS time series, are plotted as phasors rather than physical vectors. The length of the phasor represents the peak-to-peak amplitude of the seasonal signal, and the phasor orientation represents the timing of peak uplift in the seasonal cycle.

3.2 Comparison with GRACE-derived load models

The GRACE mass loading model results are shown in Figure 3a and 3b. Although the phases of the models are generally consistent with GNSS, the seasonal amplitudes of the GRACE models are systematically lower than the GNSS, especially in Myanmar. When the GRACE models are used to correct the GNSS time series, the WRMS reduction is generally 20-45% (Figure 3b). The oscillations from hydrological loading are visibly reduced in the time series

after the GRACE correction is applied (Figures S3 and S5). However, a few stations, typically those with misaligned phases between the GNSS and GRACE data, experience little WRMS reduction after seasonal correction by this technique (Figure 3b). We assessed the GRACE model fit to the horizontal GNSS data as well but found the seasonal signals in the horizontal components are generally small and sometimes spatially incoherent (Figure S7); more research into these horizontal seasonal oscillations is warranted in the future.

Figure 2: A) GNSS vertical time series from the MIBB network spanning from 2012 to 2017. B and C) Two stations' vertical time series with their corresponding hydrological loading models.

3.3 Comparison with LSDM and GLDAS hydrological load models

We find that the LSDM model predicts larger seasonal displacement patterns than the GRACE-derived model. The LSDM generally fits the amplitude of the GNSS seasonal oscillations very well across the network in South Asia. However, these models systematically reach peak uplift ~1 month earlier than the GNSS. Because of the better match between the GNSS and

258 LSDM seasonal amplitudes, the typical WRMS reduction for this model is slightly higher than for
259 the GRACE corrections (Figure 3d).

260
261 **Figure 3:** a) Average phase and amplitude results for GNSS observations using a least-squares
262 model fit (black) and GRACE models computed from the CSR solution (red). The length of the
263 vector shows the peak-to-peak amplitude of the seasonal oscillation and the angle shows the
264 phase by denoting the timing of peak uplift as shown in the legend. b) WRMS reduction (in %)
265 between the uncorrected and corrected GNSS time series using GRACE predicted displacements
266 as corrections. c & d) Phase and amplitude results for the LSDM, with its WRMS reduction. e &
267 f) Phase and amplitude results for the GLDAS model, with its WRMS reduction.

The GLDAS results are similar in phase to the LSDM, and similar in seasonal amplitude to the GRACE models. As a result, they disagree with the GNSS data by displaying lower amplitudes and phases that are ~1 month too early. Correcting the GNSS data using this model is less effective than the other two methods, generally resulting in only 10-25% WRMS reductions (Figure 3f).

Overall, we find that the GRACE-derived and LSDM-derived hydrological loading models capture the majority of seasonal signals in the vertical GNSS time series (Figures 3 and 4), although in slightly different ways. We find that GRACE models best match the phase of the observed data, suggesting that the gravity data successfully capture the overall temporal pattern of seasonal mass loading experienced at most stations. On the other hand, the LSDM-based models best match the GNSS seasonal amplitudes. LSDM seems to provide a similar phase estimate but larger seasonal amplitude estimate compared to GLDAS.

Analyzing region by region, we find that GRACE models generally have the highest WRMS reduction in the upland or mountainous parts of the study region, including the Indoburman Range, the Shillong Plateau, Bhutan, and the foreland of the Indian Himalaya (Figure 4). However, the LSDM is the model with the highest WRMS reduction in India/Bangladesh and in the southern part of Myanmar.

	Avg amplitude (mm)	Avg phase (DOY)	Avg amplitude misfit (mm)	Avg phase misfit (days)	Avg WRMS (%)
GNSS	23.3	74	-	-	-
GRACE	16.5	79	6.8	14.0 (mostly neg)	28.5
LSDM	22.9	65	3.5	17.4 (mostly pos)	29.7
GLDAS	13.8	65	9.5	17.3 (mostly pos)	24.3

Table 2: Summary of seasonal deformation detected in the MIBB GNSS network (top row) and predicted by three hydrological model products. Their typical misfits and WRMS reductions with respect to the GNSS data are characterized in the three right columns.

Figure 4: Station by station performance of each seasonal model. Higher WRMS reduction values indicate a stronger model fit. The LSSQ model is the reference model, derived from fitting Equation 1 to the GNSS time series. Stations are grouped geographically and ordered north-to-south within groups where possible.

4. Discussion

The patterns in our estimates of seasonal loading phase and amplitude (both across datasets and across the region) may help illuminate the underlying physical processes evident in the vertical GNSS time series. As one example, the GRACE models and the GNSS data have a systematic phase lag compared to the LSDM and GLDAS of about 15 days (Table 2). One hypothesis for this phase difference is the slow movement of water through the groundwater system; the loading due to groundwater should be visible in GRACE and GNSS but not in LSDM and GLDAS, contributing a phase lag. An order-of-magnitude calculation of diffusive groundwater transport using typical hydraulic diffusivities (Barbour & Wyatt, 2014) shows that 15 days is too short a timescale for significant lateral groundwater flow to take place; however, it could account for the flow of surface water into unconfined aquifers, removing it from the surface-water-only models (LSDM and GLDAS) but not the mass-sensitive observations (GNSS and GRACE) (Figure S9). A similar phase lag (20 days in the same direction) was inferred between GRACE-based groundwater estimates and terrestrial water storage from hydrological models in India (Rodell et al., 2009). Further work to better understand the phase difference between these hydrological models and GNSS data should consider spatial heterogeneity in the size, depth, and structure of aquifers.

The GRACE loading models in our study underpredict observed GNSS seasonal amplitudes at nearly all stations (Figure 5a), an effect that has also been observed in other parts of the world (Fu et al., 2013; Tregoning et al., 2009; Zhao, Wu, & Wu, 2017). Fu et al. (2013) suggested that scaling GRACE models by a factor of 1.22 was needed to match vertical GNSS data in South Asia, and we find comparable seasonal amplitude differences between GRACE models and GNSS data. Similarly, our GRACE amplitude predictions are systematically lower than LSDM, a surprising result given that LSDM should represent a subset of GRACE's total mass budget (i.e., only the water associated with rivers, lakes, and shallow soil moisture). The same amplitude discrepancy was also found in Yunnan Province and several other regions of China (Yan et al., 2019). Earth model differences between these two models should not be able to explain the magnitude of the GRACE vs. LSDM discrepancy, as PREM and ak135 produce similar vertical displacements for the same load distribution (Martens et al., 2016, their Figure 10; Wang et al., 2012, their Table 2).

Through quantitative tests of loading distributions, we instead suggest that the reduced GRACE-modeled seasonal amplitudes are due in large part to unmodeled loading from local water sources below the measurement resolution of GRACE. We modeled loading from the same hypothetical total mass under both localized loads from rivers and lakes (similar to the LSDM resolution) and distributed loads (similar to the GRACE resolution). The distributed model shows widespread 10%-40% reductions in displacement across almost the entire region (Figure 6), with very few stations experiencing increased loading amplitude as a result of the smoothing. The largest discrepancies naturally occur where local loading sources are expected to be dominant (Figure 6c), such as near large rivers. This apparent smoothing mechanism could explain the GRACE model's overall smaller seasonal displacements relative to the higher-resolution LSDM, as well as the modeled differences in the two largest deltas, the Ganges-Brahmaputra and Irrawaddy river deltas in Bangladesh and Myanmar (Figure 4).

Specifically for GNSS stations located in sedimentary basins, Earth model effects from the shallow sedimentary layers may play a small secondary role in the discrepancy between the GNSS and GRACE amplitudes. The addition of a 5-km-thick surface layer of clay to PREM can result in a several-fold increase in loading response for loads on the order of several km from

the observation point (Bos, 2010). However, because near-surface effects only amplify loads that are very close to GNSS stations (Martens et al., 2016), and because much of the seasonal amplitude of the GNSS data is already captured with the LSDM model, we consider these effects to be second-order at most stations. An even higher-resolution representation of loading from rivers, streams, and lakes, perhaps focused on a particular sub-region, could help quantify these approximations in the future.

We note that the phase and amplitude of hydrological loading signatures in GNSS time series contain some inherent uncertainty and may include small contributions from other processes. For example, here we make the assumption that the phase and amplitude of seasonal deformation are consistent from year to year, but in reality, these vary slightly. In addition, estimation of the seasonal deformation is thought to depend somewhat on the GNSS processing. GNSS processing software and approaches may differ in their treatment of reference frame and Earth center realization, draconitic errors, and corrections for ocean tidal loading effects; these effects can impact both phase and amplitude of GNSS seasonal oscillations, but are usually much smaller than loading from the hydrological cycle (Chanard et al., 2018b; Laroche et al., 2018; Van Dam et al., 2016). Thermoelastic strains may contribute on the order of 1 mm to the GNSS-observed loading (Fang et al., 2014) but would not be included in hydrological models.

Figure 5: Comparisons of estimates of seasonal amplitude and phase from observed GNSS data and three models of hydrological loads. A) GNSS Amplitude vs. GRACE model amplitude. B) GNSS Amplitude vs. LSDM amplitude. C) GNSS Amplitude vs. GLDAS model amplitude. D-F) Comparisons of GNSS and model phase of peak uplift, in day of year. G) Regional map with stations color-coded for reference.

Figure 6: a-c) Synthetic test of two identical-volume loads on the solid Earth, one locally distributed along rivers and lakes and one broadly distributed in large cells. The effect of local water bodies on the loading problem is shown by the residuals. Most stations have 10-40% higher loading amplitudes from localized loads compared to distributed loads of the same mass. d) Example calculation from two equivalent-mass loads with different widths. e) Residuals between panels (a) and (b).

The results presented here can be used in a number of applications. In the future, a combined GNSS- and GRACE-derived estimate of total water storage would be higher resolution than a GRACE-based estimate alone (Adusumilli et al., 2019; Fu et al., 2015), and may provide new insights into the hydrological system in a monsoon region. An improved understanding of

vertical seasonal and longer-term motion from elastic mass loading could also be used to extract more accurate tectonic velocity measurements from short time series that contain a mix of hydrological loading effects and earthquake cycle deformation such as postseismic transients. Model predictions of hydrological loading can be used to correct sparse time series such as from survey-mode GNSS measurements (Zhao et al., 2017). Depending on the location of particular stations, we suggest that either GRACE or LSDM, or a combination of both, may provide the most accurate model from which to derive a hydrological correction for survey GNSS data. From a hazards perspective, it is important to have as precise a 3-dimensional velocity field as possible in South and Southeast Asia, given that significant first-order questions still remain about the present-day activity of the Arakan megathrust and continental faults in the region (Mallick et al., 2019; Steckler et al., 2016). As more GNSS data are collected in Myanmar in the future, these corrections will help to further characterize tectonic activity in this complex plate boundary zone.

The study of vertical velocities from GNSS time series is also an important research area that would benefit from accurate characterization of hydrological loads in Asia. Vertical velocities can reveal regions of elastic strain accumulation, active mountain-building, lower crustal flow, mantle upwelling, groundwater withdrawal, isostatic response to ice melt, sea level change, and more (Hammond, Blewitt, & Kreemer, 2016; Higgins et al., 2014; Hill, Davis, Tamisiea, Ponte, & Vinogradova, 2011; Serpelloni, Faccenna, Spada, Dong, & Williams, 2013; Yi, Freymueller, & Sun, 2016). In and around Myanmar, little is known about the processes affecting vertical deformation and the rheology of the crust. Separating the annual and multiannual hydrological signals from the existing GNSS datasets will provide insight into these questions by revealing regions where significant present-day vertical motion is attributable to tectonics.

5. Conclusions

In this work, we analyze continuous GNSS data from South and Southeast Asia to understand the patterns of hydrological loading deformation evident in their vertical time series, which result in seasonal cycles of about 2-3 cm in amplitude. We then compare the

observed loading signals to three hydrological modeling techniques to learn about the sources of loading on the solid Earth. We find that the best fitting models derive from GRACE gravity data and a hydrological model (Dill & Dobslaw, 2013) that contains estimates of water in soil moisture, snow, and surface water. The loading component due to surface water in lakes and streams appears to be significant in this area, especially in the Ganges-Brahmaputra and Irrawaddy river deltas. At a larger scale, the comparison and integration of these data sets has the potential to provide insights into both the active tectonics and the spatiotemporal hydrological properties of South and Southeast Asia.

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