The 2011 La Niña: So strong, the oceans fell

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[1] Global mean sea level (GMSL) dropped by 5 mm between the beginning of 2010 and mid 2011. This drop occurred despite the background rate of rise, 3 mm per year, which dominates most of the 18-year record observed by satellite altimeters. Using a combination of satellite and *in situ* data, we show that the decline in ocean mass, which explains the sea level drop, coincides with an equivalent increase in terrestrial water storage, primarily over Australia, northern South America, and Southeast Asia. This temporary shift of water from the ocean to land is closely related to the transition from El Niño conditions in 2009/10 to a strong 2010/11 La Niña, which affected precipitation patterns world-wide. **Citation:** Boening, C., J. K. Willis, F. W. Landerer, R. S. Nerem, and J. Fasullo (2012), The 2011 La Niña: So strong, the oceans fell, *Geophys. Res. Lett.*, *39*, L19602, doi:10.1029/2012GL053055.

1. Introduction

[2] Observations from satellite altimeters, along with tide gauge data since the late 19th Century, reveal a fairly steady increase in global mean sea level (GMSL) of about 1.7 mm/year, with a modest acceleration detectable over the 130 year record [*Church and White*, 2011]. The rising seas have already had impacts on coastal infrastructure and the potential for future socioeconomic impacts is very high, yet very uncertain [*Nicholls et al.*, 2011]. Understanding the causes of modern-day GMSL change and distinguishing natural and anthropogenic variations is therefore a top scientific priority.

[3] Since the early 1990s, satellite altimeter observations have made it possible to distinguish interannual variations of several millimeters in amplitude from the background rate of GMSL rise [*Nerem et al.*, 2010]. Although a great deal of uncertainty remains regarding future projections of global sea level rise, almost all projections imply a significant acceleration during the 21st Century [*Grinsted et al.*, 2010; *Meehl et al.*, 2007; *Rahmstorf*, 2007; *Vermeer and Rahmstorf*, 2009]. In order to distinguish such longer-term accelerations from natural variations in GMSL, it is necessary to understand the causes of these interannual variations. As natural variations in GMSL can be explained and quantified, satellite altimeter observations will become a key indicator of anthropogenic influence on the global climate.

[4] Recent studies have indicated that interannual fluctuations in GMSL are connected to the tropical El Niño Southern Oscillation (ENSO) [*Nerem et al.*, 2010; *Ngo-Duc et al.*, 2005], which influences ocean surface temperatures in the tropical Pacific as well as evaporation and precipitation patterns globally [*Gu et al.*, 2007]. ENSO is known to constitute the largest year-to-year climate signal on the planet [*McPhaden et al.*, 2006]. Strong El Niño events have the potential to temporarily increase global sea level [*Ngo-Duc et al.*, 2005; *Cazenave et al.*, 2012] whereas in the cold La Niña phase the opposite occurs and sea level may see a temporary fall. In 2010, the Central Pacific El Niño evolved into a strong La Niña, leading to a decrease in upper ocean temperatures in the eastern Pacific and higher temperatures in the western tropical Pacific [*Bell et al.*, 2011; *Evans and Boyer-Souchet*, 2012]. During this time, the altimetry record shows a significant drop of approximately 5 mm in GMSL within a period of about 16 months (Figure 1).

[5] Interannual changes in GMSL can be attributed to changes in the ocean's mass or its heat content. The Gravity Recovery and Climate Experiment (GRACE) satellites are capable of measuring changes in the mass of the ocean on monthly time scales with an accuracy of a few millimeters. The Argo array of profiling floats observes changes in the volume averaged temperature of the upper ocean with an accuracy that allows the thermosteric contribution to GMSL change to be computed with similar accuracy [*Willis et al.*, 2008]. To complement the ARGO estimates, we also provide an independent estimate of changes in ocean heat content from top of the atmosphere radiation estimates from CERES. Using these four independent observing systems, we can attribute the changes in GMSL to their root causes [*Leuliette and Willis*, 2011]. The combination of the new observing systems – available after 2005 – allows for direct observations of all of the contributions to ENSO-related sea level change, and the relative importance of heat exchange and water mass transport. Previous studies either inferred the relative contributions [*Willis et al.*, 2004] or modeled one of the components [*Llovel et al.*, 2011; *Cazenave et al.*, 2012; *Ngo-Duc et al.*, 2005]. *Llovel et al.* [2011] also discuss the correlation between interannual sea level variations and GRACE derived terrestrial water storage from the 33 largest river basins. In particular, water storage variability in tropical river basins is identified to be strongly related to global ocean mass changes.

[6] In the past, it has been complicated to draw a conclusive, fully observation-based connection between these interannual sea level fluctuations and ENSO due to a) missing or insufficient observations before 2005 and b) significant ENSO events during the time where sufficient data are

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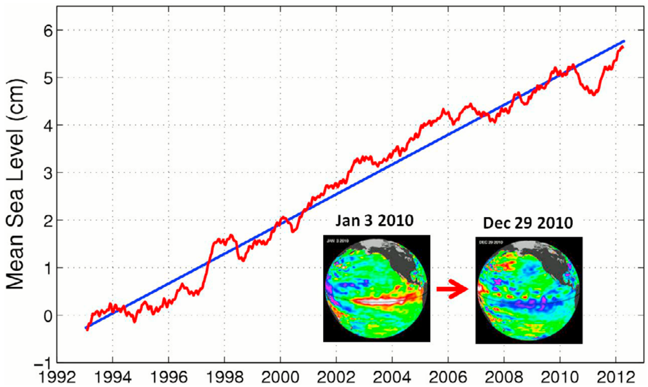

Figure 1. Global mean sea level from altimetry from 1992 to 2012 with annual and semi-annual variations removed and smoothed with a 60-day running mean filter [*Nerem et al.*, 2010]. The slope of the trend (blue line) is 3.2 mm/year after a GIA correction has been applied (0.3 mm/year). The insets show maps of SSH anomaly relative to the background trend and seasonal climatology, for 10-day averages centered on Jan 3 2010 (near the peak of the El Niño) and Dec 29 2010 (the peak of La Niña).

available. The strong 2010/11 La Niña and concurrent sea level drop provides an opportunity to gain a better understanding of the underlying processes. Using altimetry, GRACE, and ARGO this study discusses relative contributions of ocean cooling and freshwater exchange between ocean and land. Additional information on terrestrial water storage (TWS) from GRACE provides a better insight into La Niña related precipitation events at low and mid latitudes and the effect on GMSL.

2. Data and Methods

[7] Global mean sea level is computed using a weighted average of along track data from TOPEX/Poseidon, Jason-1 and Jason-2. The weights are chosen to account for increased data density at height latitudes and all standard corrections have been applied [*Nerem et al.*, 2010]. The time series has been smoothed with a 60-day boxcar filter to remove a spurious 59-day cycle in the data [*Leuliette et al.*, 2004]. Uncertainties in the global mean sea level curve are on the order of 1.6 mm for a single 60-day average [*Leuliette and Miller*, 2009].

[8] Maps of sea level anomaly shown inset in Figure 1 are computed using alongtrack data from TOPEX/Poseidon, Jason-1 and Jason-2 observations. A seasonal cycle and trend computed over the period 1993–2008 has been removed and a Gaussian spatial smoothing filter of 2 degrees longitude by 1 degree latitude has been used to produce the maps. Each map represents a 10-day average centered on the date shown.

[9] We estimate the global mean ocean mass using GRACE data derived from the recently released JPL RL05 time variable gravity field solutions. The data have been corrected for geocenter motion using estimates by *Swenson et al.* [2008]; glacial isostatic adjustment is subtracted from the GRACE solutions using the model of *Paulson et al.* [2007]. The $C_{2,0}$ spherical harmonic coefficients, describing the Earth's oblateness, derived from satellite laser ranging measurements using the estimates by *Cheng and Tapley* [2004] are substituted for the $C_{2,0}$ coefficients in the GRACE product.

[10] The impact of land signals on the GRACE oceanic mass estimates are reduced by applying a land mask omitting data over land and within 300 km from the coast [*Chambers*, 2006]. An inverse mask has been used to derive averages of TWS. The maps of TWS were filtered for correlated errors using the method by *Swenson and Wahr* [2006] and smoothed using a 500 km Gaussian filter.

[11] Maps of thermosteric sea level are calculated as detailed in *Willis et al.* [2008]. Monthly maps are estimated relative to a regionally varying climatology and seasonal cycle, using thermosteric sea level anomalies between the surface and 900 m computed from individual Argo profiles. The covariance function and noise-to-signal ratio are the same as those used by *Willis et al.* [2008].

[12] The net flux at the top-of-atmosphere is computed from CERES-EBAF v2.6 fluxes through 2010 and extended with the CERES Flashflux dataset through September 2011 [*Loeb et al.*, 2009] . The timeseries are combined based on adjusting the mean flux from Flashflux data to agree with that from EBAF from Jan. 2009 through Dec. 2010. The CERES mean flux is then adjusted to agree with the mean ARGO tendency from 2005 through mid 2011.

[13] Uncertainties shown in Figure 2 (top) reflect the combined uncertainty in Argo estimates of globally averaged thermosteric sea level and GRACE estimates of ocean mass. For the monthly averages, uncertainty in ocean mass is

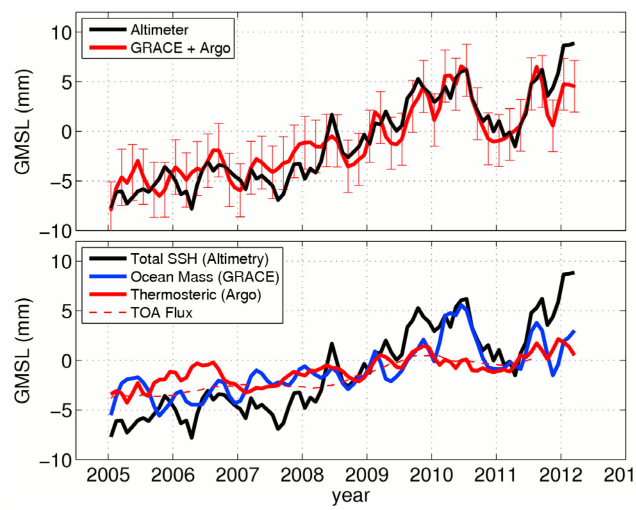

Figure 2. (top) Global mean sea level from altimetry from 2005 to 2012 (black line). The red line shows the sum of the ocean mass contribution (as measured by GRACE) and thermal expansion contribution (as measured by Argo). Error bars are 2.5 mm (as discussed in the Methods Section). (bottom) Contributions to global sea level rise from 2005 to 2012. As in the top panel, the black line shows GMSL as observed by satellite altimeters. Ocean mass changes are shown in blue and thermosteric sea level change is shown in red. The red dashed line shows an estimate of ocean warming based on estimates of radiative imbalance at the top of the atmosphere. The mean warming rate is adjusted to agree with Argo and heat content is scaled assuming that 3×10^{22} J is equivalent to 5 mm of thermosteric sea level rise as in *Church et al.* [2005].

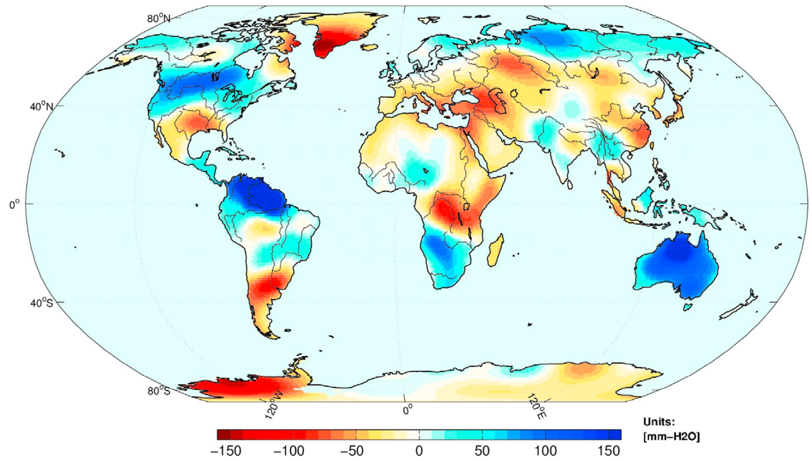

Figure 3. Change in water mass from beginning of 2010 (JFM average) to mid 2011 (MAM average). Blue colors indicate an increase in water mass over the continents.

estimated to be approximately 2 mm and uncertainties in thermosteric sea level range from 2.9 to 2.4 mm, consistent with *Willis et al.* [2008] and *Leuliette and Miller* [2009]. The uncertainties in the sum of these components are calculated under the assumption that errors in Argo and GRACE observations are uncorrelated (total error ^{2} = GRACE error^2 + Argo error^2). The error bars shown in Figure 2 (top) have been reduced by sqrt(2) to account for the 60-day smoothing. The RMS difference between the GMSL curve and the GRACE + Argo curve is 1.5 mm, suggesting that the uncertainties presented here may be overly conservative.

3. Results

[14] Figure 1 indicates that the drop starts in mid-2010, concurrent with the onset of La Niña (Figure S3 in Text S1 in the auxiliary material).[1] Omitting the background trend, the interannual fluctuations in GMSL largely follow the occurrences of El Niño and La Niña [*Nerem et al.*, 2010]. Past La Niña events have led to a temporary deceleration of sea level rise as seen for example during the events in 1998–99 or 2007–08. However, with an amplitude of 5 mm the drop in GMSL during the transition between the 2009/11 Central Pacific El Niño to the 2010/11 La Niña is exceptional compared to previous events.

[15] The 5 mm decrease in GMSL from March 2010 to May 2011 is explained by an equivalent decrease in global ocean mass (about 1800 Gt of mass) during this period (Figure 2) while thermosteric sea level is almost unchanged. Argo observations show cooling of about 2 mm near the beginning of 2010 and a small increase of approximately 1 mm in May of 2011, near the end of the La Niña event. The decrease in ocean mass lags the cooling, beginning in mid 2010 near the peak of the La Niña event. It is clear from the close agreement between ocean mass and sea level observations during this period that loss of mass from the ocean was the primary cause of the 2010 drop in GMSL. Note that sampling biases in the float array or land leakage effects in GRACE potentially influence the signal-to-noise ratio, which affects the representation of weaker events in the sum of GRACE and ARGO. These effects are taken into account in the uncertainty calculation discussed in the Data and Methods section. The CERES estimate of net radiation (Figure 2, dashed line) confirms that any cooling of the ocean across the 2010 drop is likely to be small and unable to account for most of the altimetry signal.

[16] Given that the atmospheric contribution to the total mass in the form of water vapor is small on interannual time scales (<1 mm [*Landerer et al.*, 2008]), the significant loss in ocean mass coincides with a mass gain of a comparable amount over land. We use GRACE satellite gravity observations to diagnose changes in TWS [*Rodell et al.*, 2007; *Swenson et al.*, 2006; *Syed et al.*, 2008]. Figure 3 shows that TWS over the northern part of South America and Australia substantially increased by early 2011 compared to 2010. Southeast Asia also gained water over this period. It is worth noting that both South America and South-East Asia suffered larger water deficits in the prior year (Figure S1 in Text S1), due to the El Niño event in 2009/10 and thus are significant contributors to the oceanic mass loss as precipitation replenished these regions, which had experienced intense drought.

[17] Data from the Tropical Rainfall Measuring Mission (TRMM) indicates that most of the observed mass gain is consistent with a significant change in rainfall during the period from 2010 to 2011 (Figure S2 in Text S1). Precipitation patterns over regions such as South America, Australia, and Southeast Asia are highly affected by ENSO [*Hoerling and Kumar*, 2000]. During La Niña episodes, rainfall is enhanced across the western equatorial Pacific, Indonesia and the Philippines and is nearly absent across the eastern equatorial Pacific. Wetter than normal conditions tend to be observed from December through February over northern South America and southern Africa, and from June through August over southeastern Australia. During El Niño, dryer than normal conditions typically exist in South America and southeast Asia. TRMM data reflect the transition El Niño to La Niña during 2010, with the regions of enhanced precipitation corresponding well with the regions of increased TWS (Figure S2 in Text S1). Note that the precipitation data also exhibit negative anomalies over the tropical Pacific between 2010 and 2011. The increase in precipitation over land, and simultaneous decrease over the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053055.

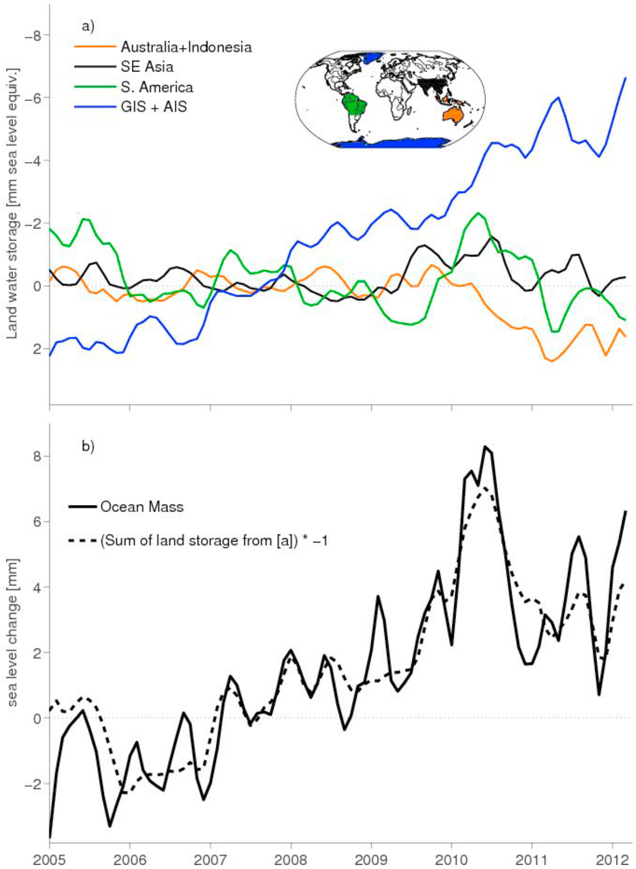

Figure 4. (a) TWS (terrestrial water storage) for the regions that played a significant role in the 2010 drop in GMSL. Mass loss in Greenland and Antarctica are also shown. The amount of TWS expressed in units of equivalent sea level change. Note that the vertical axis is reversed for ease of comparison with ocean mass increase. (b) The sum of TWS over the regions plotted in Figure 4a. For comparison, global ocean mass increase is also shown.

ocean, are consistent with findings of *Gu et al.* [2007], who showed similar anomalies occurring during La Niña events in general. This indicates a strong connection between the transition to the 2010/11 La Niña, the changes in TWS and mass related sea level.

[18] To quantify the amount of water storage increase, Figure 4 shows fluctuations in TWS in the regions that are most strongly affected, expressed in terms of their impact on global ocean mass. Averages over Australia and Indonesia, South America, and Southeast Asia indicate that most of the TWS gain was accumulated in these regions. Other regions account mostly for short-term variability, apart from Greenland and Antarctica, which consistently lose mass over the entire GRACE record. The sum of TWS storage in Australia and Indonesia, South America and Southeast Asia is equivalent to a total mass increase of about 5 mm of GMSL equivalent height between March 2010 and May 2011 (Figure 4b).

[19] The time series of ENSO events represented by the Southern Oscillation Index (SOI) indicates that the 2010/11 La Niña was the strongest over the altimetry period starting in 1992 – and one of the strongest La Niña events for that season in the last 80 years. High precipitation events leading to flooding in Australia, Pakistan and China have been associated with the 2010/11 La Niña and also with record high sea surfaces temperatures in the Arabian Sea and north of Australia [*Trenberth and Fasullo*, 2012]. The cumulative influence of related synoptic events appears to have transported enough water to the continents to explain the 2010 drop in GMSL.

4. Conclusions

[20] In summary, we have presented direct observations of a 5 mm drop in GMSL driven by an ENSO-related transfer of mass between the oceans and the continents. Observational closure of the sea level budget provides strong evidence that interannual changes in GMSL on the order of half a centimeter can be driven by this mechanism. The comparison between TWS increase and ocean mass decrease indicates that the decline in sea level was primarily related to the La Niña induced precipitation anomalies over Australia, Southeast Asia, and northern South America. The 5 mm drop in GMSL is associated with an excess transport of freshwater from ocean to land. In contrast, the thermosteric component of this event was very small.

[21] The 2010/11 La Niña was by many measures the strongest ENSO cold event in the past 8 decades and led to a significant decrease in GMSL. While the warming trend in the west Pacific has been well documented [*Cravatte et al.*, 2009], it's relationships to global warming remains unclear [*Collins et al.*, 2010]. Nonetheless, higher surface temperatures in the warm pool are likely to augment the effect of La Niña on regional precipitation, particularly over Australia [*Evans and Boyer-Souchet*, 2012]. Thus, given their significant implications for both precipitation and sea level, SST anomalies and their interaction with ENSO teleconnections in a warming climate will subjects of considerable importance.

[22] The connection to ENSO and the fact that most of the additional water on the continents at low and mid latitudes will be subject to runoff suggests a rather short-lived hiatus in GMSL rise. Indeed, the most recent data suggest a recovery of more than 5 mm (Figure 1) in the last few months of the GMSL time series despite the subsequent La Niña in 2011/12. ENSO-driven changes in GMSL like the one described here might mask GMSL variations related to anthropogenic forcing over short time periods, but as expected from the lag of continental freshwater outflows relative to precipitation anomalies, they are unable to curtail the longer timescale trends associated with persistent ice melt and ocean warming as observed in recent decades.

[23] Predicting future rates of sea level change and detecting any acceleration in GMSL rise will require the ability to distinguish such events from increases in the net heat content of the ocean, as well as rapid changes in the amount of ice lost from the glaciers and ice sheets. This underscores the importance of complementary global observing systems such as Jason, GRACE and Argo, without which such distinctions would be impossible.

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