Contributions of GRACE to Climate Monitoring

sidebar for "State of the Climate in 2011"

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The NASA/German Gravity Recovery and Climate Experiment (GRACE) was launched in March 2002. Rather than looking downward, GRACE continuously monitors the locations of and precise distance between twin satellites which orbit in tandem about 200 km apart. Variations in mass near Earth's surface cause heterogeneities in its gravity field, which in turn affect the orbits of satellites. Thus scientists can use GRACE data to map Earth's gravity field with enough accuracy to discern month to month changes caused by ocean circulation and redistribution of water stored on and in the land (Tapley et al., 2004; Wahr et al., 2004). Other gravitational influences, such as atmospheric circulation, post-glacial rebound, and solid earth movements are either independently determined and removed or are negligible on a monthly to sub-decadal timescale. Despite its coarse spatial (>150,000 km^2 at mid-latitudes) and temporal (~monthly) resolutions, GRACE has enabled significant advancements in the oceanic, hydrologic, and cryospheric science, and has great potential for climate monitoring, because it is the only global observing system able to measure ocean bottom pressures, total terrestrial water storage, and ice mass changes.

The best known GRACE results are estimates of Greenland and Antarctic ice sheet loss rates (Figure 1). Previously, scientists had estimated ice mass losses using ground and satellite based altimetry and surface mass balance estimates based on snowfall accumulation and glacier discharge. While such measurements are still very useful for their spatial detail, they are imperfectly correlated with large-scale ice mass changes, due to snow and ice compaction and incomplete spatial coverage. GRACE enables scientists to generate monthly time series of Greenland and Antarctic ice mass, which have confirmed the shrinking of the polar ice sheets, one of the most obvious and indisputable manifestations of climate change (e.g., Velicogna and Wahr, 2006a; 2006b). Further, GRACE has located and quantified hot spots of ice loss in southeastern Greenland and western Antarctica (e.g., Luthcke et al., 2006). For 2002 to present, the rate of ice mass loss has been 200 to 300 GT/yr in Greenland and 70 to 210 GT/yr in Antarctica, and some scientists are suggesting that the rates are accelerating (Velicogna, 2009). Similarly, GRACE has been used to monitor mass changes in alpine glaciers. Tamisiea et al. (2005) first characterized glacier melt along the southern coast of Alaska, more recently estimated to be occurring at a rate of 84 GT/yr (Luthcke et al., 2008). Chen et al. (2007) estimated that Patagonian glaciers are melting at a rate of 28 GT/yr, and Matsuo and Heki (2010) estimated that the high mountains of central Asia lose ice at a rate of 47 GT/yr.

Tapley et al. (2004) and Wahr et al. (2004) presented the first GRACE based estimates of changes in column-integrated terrestrial water storage (TWS; the sum of groundwater, soil moisture, surface waters, snow, ice, and water stored in vegetation) at continental scales. Since then, dozens of studies have shown that GRACE based estimates of regional to continental scale TWS variations agree with independent information, and some innovative uses of GRACE data have been developed. Rodell et al. (2004) and Swenson and Wahr (2006) demonstrated that by combining GRACE derived terrestrial water storage changes with observations of precipitation and runoff in a river basin scale water budget, it was possible to produce new estimates of evapotranspiration and atmospheric moisture convergence, essential climate variables that are difficult to estimate accurately. Similarly, GRACE has been used to constrain estimates of global river discharge and the contribution of changes in TWS to sea level rise (Seo et al., 2009; Syed et al, 2009; Syed et al., 2010). Crowley et al. (2006) observed a negative correlation between interannual TWS anomalies in the Amazon and the Congo River basin. Yeh et al. (2006) and Rodell et al. (2007) estimated regionally averaged groundwater storage variations based on GRACE and auxiliary observations. Rodell et al. (2009) and Tiwari et al. (2009) applied that method to quantify massive groundwater depletion in northern India caused by over reliance on aquifers for irrigation (Figure 2), and Famiglietti et al. (2011) found a similar situation in California's Central Valley. Zaitchik et al. (2008) and Lo et al. (2010) described approaches to use GRACE to constrain hydrological models, enabling integration of GRACE data with other observations and achieving much higher spatial and temporal resolutions than GRACE alone. Such approaches are now supporting applications including drought and water resources monitoring (Houborg and Rodell, 2010; Bolten et al., 2010).

Oceanography has likewise benefitted from the independent nature of GRACE observations. One application is measurement of the mass component of sea level rise, which complements radar altimetry and in situ measurements. GRACE also measures ocean bottom pressures (OBP), which help to refine understanding and modeling of ocean circulation and the ocean's fresh water budget, among other things (Figure 3). For example, Hayakawa et al. (2009) showed that GRACE observes OBP patterns absent from the background models of oceanic variability. Morison et al. (2007) used GRACE to describe important decadal scale shifts in circulation and an ongoing trend of freshening of the western Arctic, important indicators of climate variability. The research of Song and Zlotnicki (2008) and Chambers and Willis (2008) on GRACE-derived ocean bottom pressures in the sub-polar gyre led to the discovery of an ENSO teleconnection and a long-term change in OBP in the North Pacific sub-polar gyre that was not predicted by an ocean model. Further, Chambers and Willis (2009) were able to identify an internal redistribution of mass between Atlantic and Pacific Oceans lasting at least six years, which was not predicted by ocean models and was the first direct evidence of sustained mass transport from one ocean basin to another on periods longer than a year. Boening et al. (2011) observed a record increase in OBP over part of the southeastern Pacific in late 2009 and early 2010, primarily caused by wind stress curl associated with a strong and persistent anticyclone and likely related to the concurrent Central Pacific El Nino.

GRACE has far surpassed its 5-year design lifetime, but it will likely succumb to the aging of batteries and instrument systems sometime in the next few years. NASA has begun initial development of a follow-on to GRACE with very similar design, which could launch as soon as 2016 and would provide continuity in the data record while improving resolution slightly. Higher resolution time variable gravity missions are also on the drawing board (NRC, 2007).

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Figures

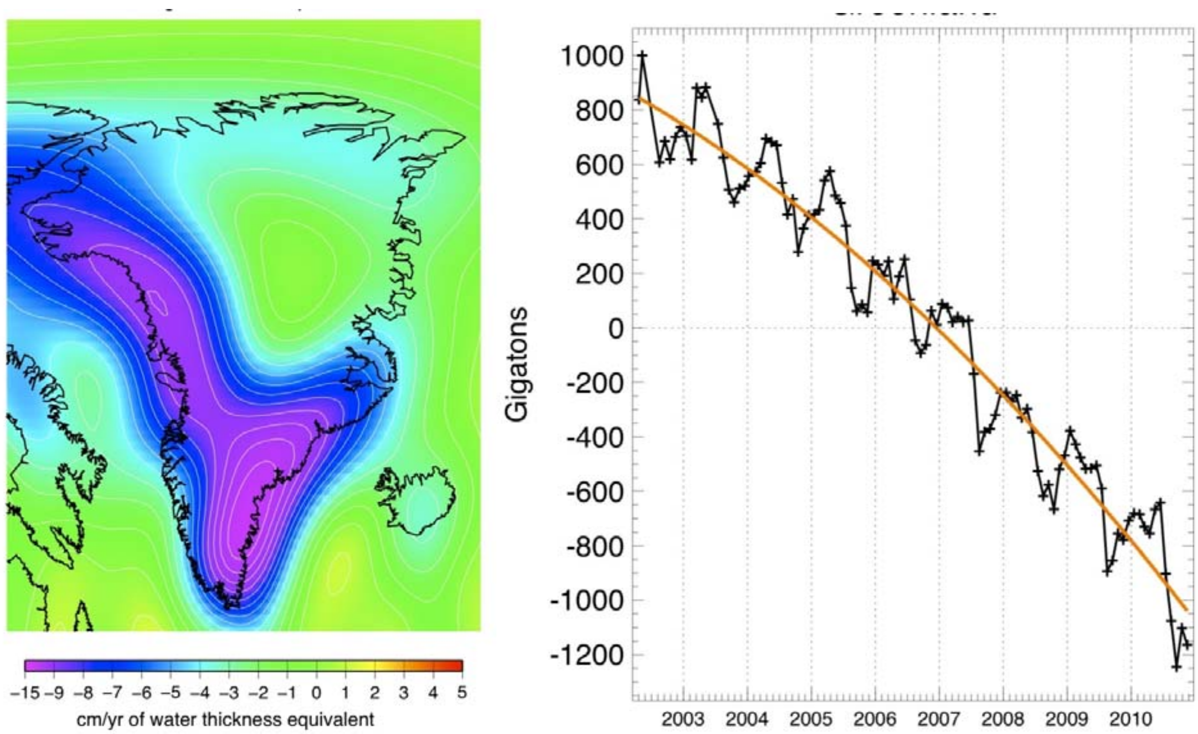

Figure 1. (Left) Rate of ice sheet mass change (cm/yr, equivalent height of water) in Greenland, from GRACE, from April 2002 to November, 2010. (Right) Time series of Greenland total ice sheet mass (GT) relative to the period mean.

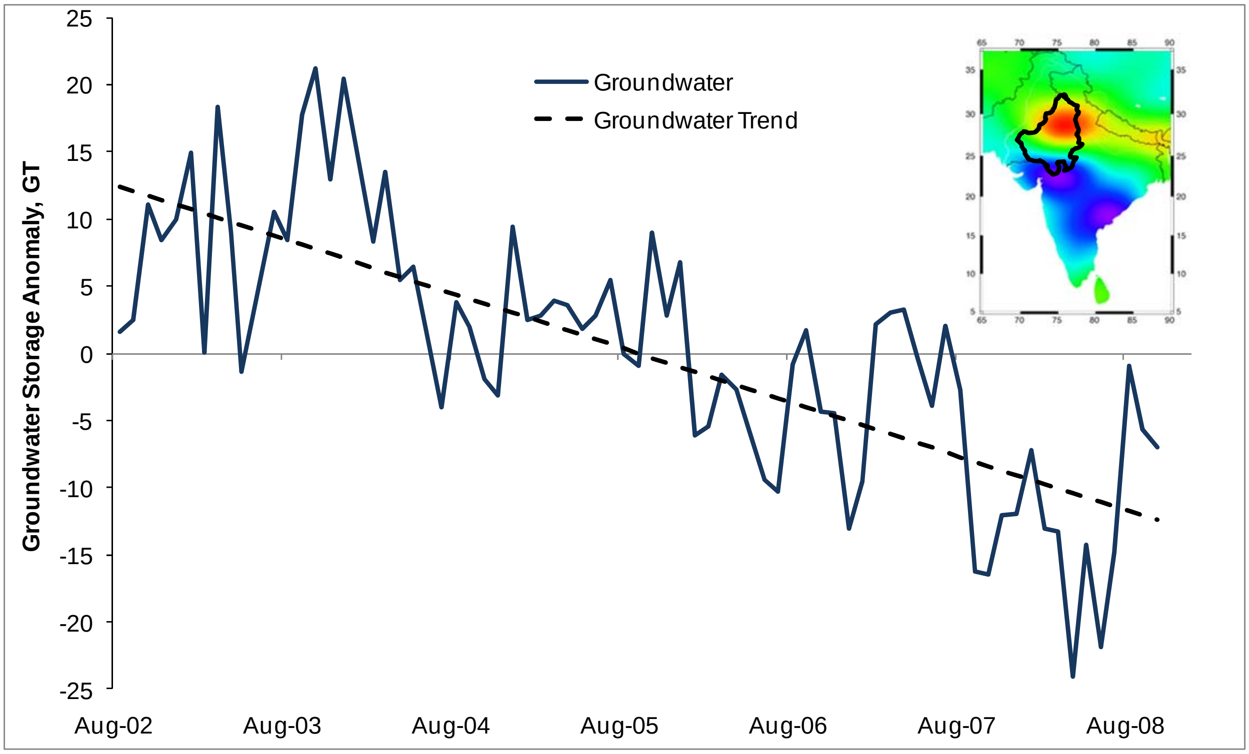

Figure 2. Time series of groundwater storage (GT) in northwest India from August 2002 to October 2008 relative to the period mean. The inset panel shows areas of depletion in warm colors and areas of increase in cool colors, with the study region (the Indian states of Rajastan, Punjab, and Haryana) outlined in black. Based on data from Rodell et al., 2009.

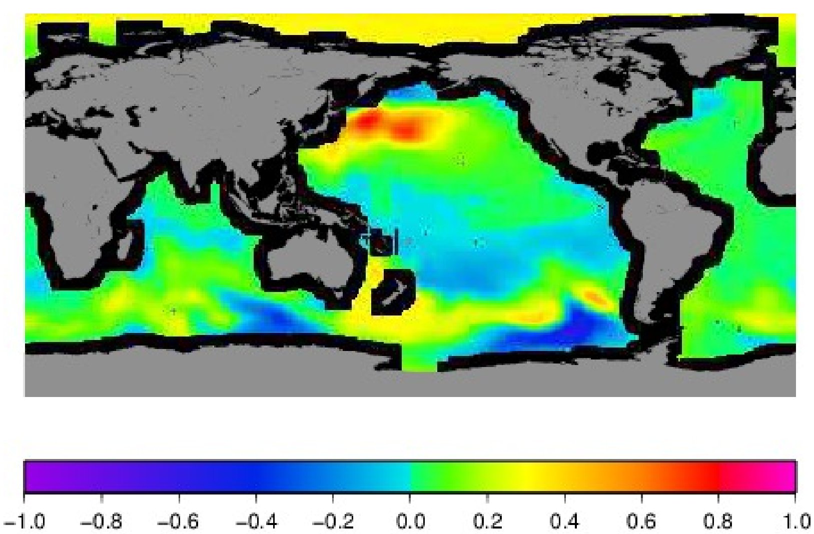

Figure 3. Mean rate of change of ocean bottom pressure (cm/yr in equivalent sea level) from January 2003 until August 2010, computed from GRACE data projected onto EOF modes from a model (Chambers and Willis, 2008). The large trends in the North Pacific, South Pacific, and Arctic are related to changing circulation and wind-stress, and have been described by Chambers and Willis (2008), Boening et al. (2011), and Morison et al. (2007), respectively.