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Spacebased observations of oceanic influence on the annual variation of South American water balance

W. Timothy Liu,[1] Xiaosu Xie,[1] Wenqing Tang,[1] and Victor Zlotnicki[1]

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[1] The mass change of South America (SA) continent measured by the Gravity Recovery and Climate Experiment (GRACE) imposes a constraint on the uncertainties in estimating the annual variation of rainfall measured by Tropical Rain Measuring Mission (TRMM) and ocean moisture influx derived from QuikSCAT data. The approximate balance of the mass change rate with the moisture influx less climatological river discharge, in agreement with the conservation principle, bolsters not only the credibility of the spacebased measurements, but supports the characterization of ocean's influence on the annual variation of continental water balance. The annual variation of rainfall is found to be in phase with the mass change rate in the Amazon and the La Plata basins, and the moisture advection across relevant segments of the Pacific and Atlantic coasts agrees with the annual cycle of rainfall in the two basins and the Andes mountains. **Citation:** Liu, W. T., X. Xie, W. Tang, and V. Zlotnicki (2006), Spacebased observations of oceanic influence on the annual variation of South American water balance, *Geophys. Res. Lett.*, *33*, L08710, doi:10.1029/2006GL025683.

1. Introduction

[2] The controlling influence of the water cycle on climate changes and the need of interdisciplinary and multisensor approaches to study water cycle have been well expounded [e.g., *Chahine*, 1992]. Past studies of oceanic influence on the SA water balance were largely demonstrations of the relation between precipitation (P) over the landmass and the sea surface temperature (SST) of surrounding oceans [e.g., *Nobre and Shukla*, 1996; *Fu et al.*, 2001]. The analyses were based on numerical model simulation, operational products of numerical weather prediction (NWP), in situ measurements of rainfall, and spacebased observations of outgoing longwave radiation. Three sets of spacebased observations have recently become available and may give new perspectives of continental water balance and the oceanic influence. These data are described in Section 2. The scope of this study is limited by resolution and duration of GRACE data available to only large-scale and annual variation.

[3] While sufficient coverage and resolution can be best achieved from the vantage point of space, the validation of spacebased measurements has always been difficult because there is a lack of appropriate standards. Useful scientific application may be the best validation of their usefulness. The possible closure of continental water balance, as revealed by the three sets of data, is discussed in Section 3.

[4] The relations among variations of regional rainfall, the Atlantic intertropical convergence zone, and the South Atlantic convergence zone have been well studied, but the direct influence of the Pacific is less well known and thought to be small [e.g., *Fu et al.*, 2001]. Past NWP data were shown to be deficient in describing the surface wind vector [*Liu et al.*, 1998] and precipitable water [*Liu et al.*, 1992] along the Pacific coast of SA, where SST is constantly low and covered by the veil of stratocumulus cloud. With the assimilation of spacebased data, the simulation by NWP models has been improved, but spacebased observations may provide independent evidence of both the Pacific and Atlantic influences on the annual variations of regional water balances, as discussed in Section 4.

2. Data

[5] GRACE is a geodesy mission to measure Earth's gravity field, but the variations of the gravity field are largely the result of the movement of water [*Tapley et al.*, 2004; *Chambers et al.*, 2004]. The first public release of 21 months of GRACE data was used. (The data and their description are available at http://gracetellus.jpl.nasa.gov/month_mass.html.) The mass of the atmosphere is removed during data processing using atmospheric NWP pressure field from European Center for Medium Weather Forecast. The monthly mass change rates, dM/dt, for two annual cycles, from August 2002 to July 2004, were computed for this study. Three months of missing data, December 2002, January 2003, and June 2003, are obtained through linear interpolation.

[6] While SST influences large scale atmospheric circulation and, consequently, continental convection and rain-

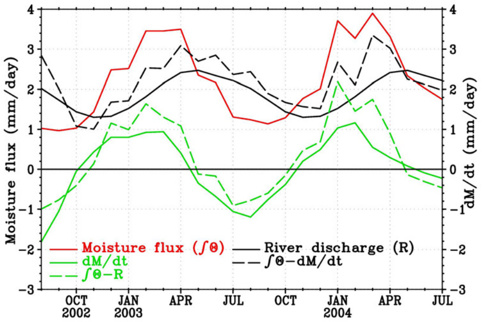

Figure 1. Annual variation of hydrologic parameters over South America: mass change rate dM/dt (solid green line), climatological river discharge R (solid black line), total moisture transport across coastline into the continent $\int\Theta$ (red line), $\int\Theta$-R (dashed green line), and $\int\Theta$-dM/dt (dashed black line).

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[1] Jet Propulsion Laboratory, Californian Institute of Technology, Pasadena, California, USA.

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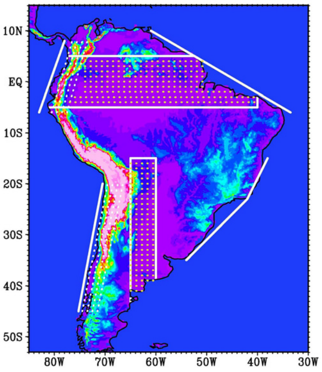

Figure 2. Topographic map of South America, showing four coastline segments across which Θ (as shown in Figures 3 and 4) were computed. P and/or dM/dt averaged over the shaded cross-sections are also shown in Figures 3, 4, and 5.

fall, the most direct link between ocean and continental water balance is through moisture transport integrated over the depth of the atmosphere (Θ). The method of deriving Θ from ocean surface wind vector (u_s) measured by QuikSCAT and precipitable water (W) measured by Special Sensor Microwave/Imager (SSM/I) is based on *Liu and Tang* [2005]. They viewed Θ as the column of W advected by an equivalent velocity (u_e), which is the depth-averaged wind velocity weighted by humidity, and it was related to u_s through a statistical relation. The line integral of normal component of Θ along the entire coastline of SA was computed as $\int\Theta$, for the same period as GRACE.

[7] Spacebased infrared and microwave observations have been used to estimate P in the past decades, and TRMM has provided important calibration since 1998. TRMM data product 3B42 [*Huffman et al.*, 1995], a merged infrared and microwave spacebased data set, covering from 50°N to 50°S, with 3-hourly, 0.25° × 0.25° resolutions was used.

[8] There is no spacebased measurement of river discharge (R) from the continent to the ocean, and considerable uncertainties were found in climatology derived from in situ measurements. There is large flow variation among SA rivers [e.g., *Garcia and Vargas*, 1998]. River gauges are sparse and not situated at the mouth of the river. The climatological R compiled by *Dai and Trenberth* [2002], is shown in Figure 1, as a reference in this study.

3. Continental Balance

[9] The mass change rate integrated over the SA continent should satisfy

$$\frac{dM}{dt} = \int \Theta - R, \text{ and } \int \Theta = P - E \qquad (1)$$

where E is the evaporation/transpiration. As shown in Figure 1, dM/dt peaks in summer (January–March) and is in approximate quadrature with M from GRACE. $\int\Theta$ (positive going onshore) has high values during summer, similar to dM/dt. When R is subtracted out from $\int\Theta$, the result is approximately in phase with dM/dt, but with slightly higher value. With dM/dt subtracted out from $\int\Theta$, the value, which should represent R, is approximately in phase but slightly higher than one of the climatologies derived from in situ measurements.

[10] Over large geographical regions, where the variations of E and surface/ground water outflow are small, P should dominate the annual variation of dM/dt (see equation (1)). The large-scale geographic patterns of P and dM/dt were found to follow similar annual changes over the northern half of SA (maps of the two parameters can be viewed at http://airsea.jpl.nasa.gov/movie/sa.qt, in animation form). In austral spring (October/November), positive values of dM/dt and high values of P occur over the western end of Amazon Basin, followed by the intensification of positive/high pattern in the south Amazon Basin and eastern Brazilian Highland south of the equator. This positive/high pattern has a maximum in austral summer (January and February), when it reaches the equator at the mouth of the Amazon. The positive/high center moves westward and northward to the Caribbean coast, where it peaks in June (boreal summer). Both parameters show this apparent coun-

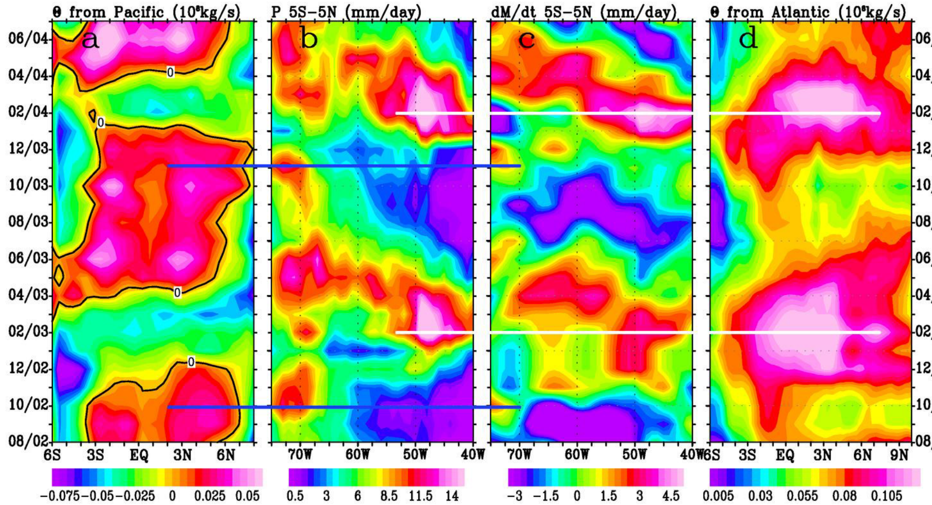

Figure 3. (a) Time-latitude variations of Θ across the Pacific coast, (b) time-longitude variation of P averaged between 5°S and 5°N, (c) same as Figure 3b, but of dM/dt, and (d) same as Figure 3a, but across the Atlantic coast.

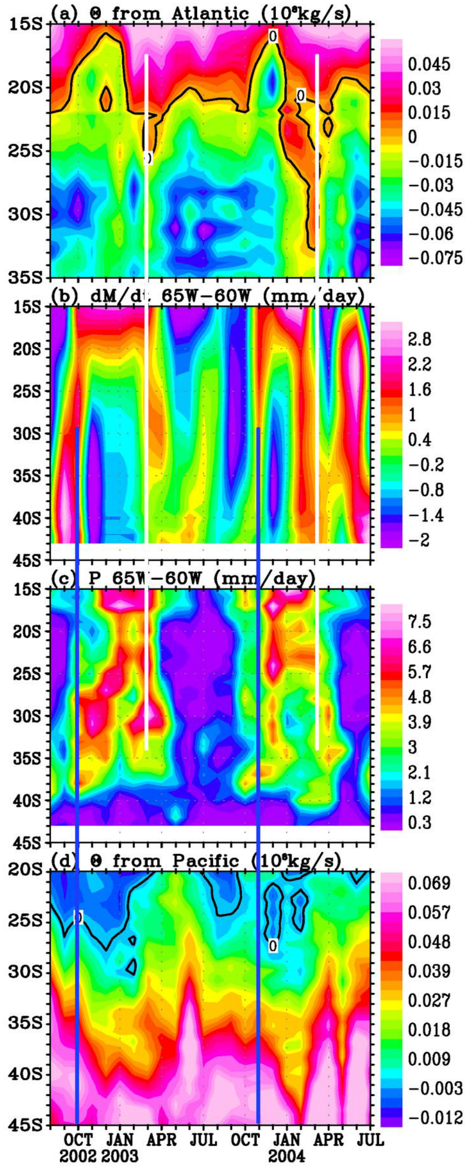

Figure 4. Latitude-time variations of (a) Θ across the Atlantic coast, (b) dM/dt averaged between 60°W and 65°W, (c) same as Figure 4b, but for P, and (d) same as Figure 4a, but for the Pacific coast.

terclockwise annual march. The landmass is narrower in the south and there is less agreement between the geographic patterns of dM/dt and P.

4. Regional Changes

[11] To relate the moisture influx from the ocean to regional P and dM/dt, time-longitude or time-latitude variations for selected cross sections of these regions are shown against similar variations of Θ across relevant coastlines (locations are denoted in the map of Figure 2).

4.1. Amazonia

[12] The Amazon is one of the largest drainage basins in the world. Several attempts have been made to examine the water balance (similar to equation (1)) over the Amazon basin. *Zeng* [1999] derived P-E, over the Amazon basin, by equating it to the divergence of Θ computed from atmospheric model outputs, and showed that E has small annual variation. Using climatological river discharge, they attempted to characterize the change of water storage, which is equivalent to dM/dt in Equation (1). Recently, *Syed et al.* [2005] used the same method to compute P-E over the same river basin, and by introducing GRACE data, attempted to estimate water discharge as residue.

[13] The annual cycles of both dM/dt and P in the equatorial Amazon have maxima in austral summer (February) at the mouth of Amazon, and coincide with the maximum influx of moisture from the Atlantic, as shown in Figure 3. There is a big reduction of Θ from the Atlantic across the northeast coast during the dry austral spring season in the eastern Amazon. The peaks of both P and dM/dt appear to propagate up the Amazon Basin and reach the west end in austral autumn (April–May). The annual march is consistent with earlier studies [e.g., *Marengo*, 1992]. In the western equatorial Amazon (Columbia and Peru), both TRMM and GRACE reveal a secondary peak in spring (October–November), which coincides with the only period of moisture influx from the Pacific.

4.2. La Plata Basin

[14] The drainage of the La Plata Basin is second only to the Amazon in SA, and the basin is most important to the economy and agriculture of SA. As shown in Figure 4, both P and dM/dt have maxima during summer (January–February) in the north end of La Plata Basin (Gran Chaco between the Andes and the Brazilian Highland). In the central valley, the high values apparently move south, perhaps transported by the South American Low Level Jet (SALLJ), and peak in autumn (April) in the Argentina Pampas (38°S) [e.g., *Berbery and Barros*, 2002]. This is the season of high moisture influx from the Atlantic anticyclone, which may contribute to the high rainfall. Another peak over the Pampas is observed in spring (October), which apparently propagates north. High influx of moisture from the Pacific across Southern Chile is observed at this time. Local transient convections and oceanic influx may join together to cause rainfall at this time.

4.3. Andes Cordillera

[15] The oceanic influence is most direct on the orographic rain [*Barros and Lettermaier*, 1994] or orography induced large-scale convection [*Xie et al.*, 2006]. Major rainfall periods in the northern Andes are found in austral spring and autumn (Figure 5, top), which correspond to major moisture influx from the tropical Pacific (Figure 3a). However, the peak moisture influx from the tropical Atlantic may also arrive in early austral autumn as discussed in Section 4.1. High rainfall periods in the southern Andes are found in June–October 2002, May–November 2003, April and June 2004 (Figure 5, bottom) and coincide with periods of high moisture influx from the Pacific at the same latitudes (Figure 4d).

5. Discussion

[16] The new data from GRACE provide the constraint and reduce the uncertainties in the estimation of other hydrologic parameters. The small differences between

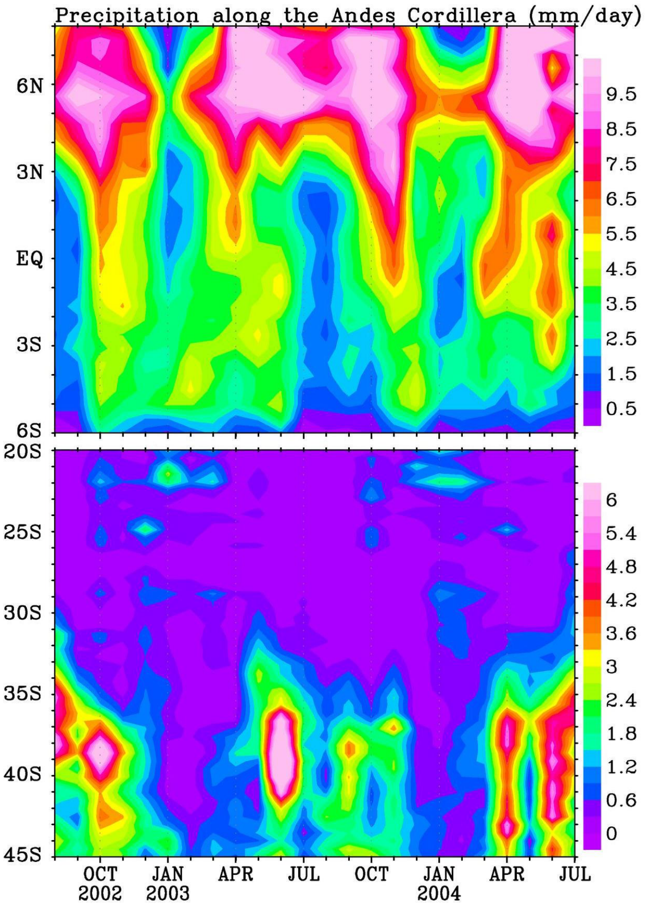

Figure 5. Latitude-time variations of precipitation, averaged for 3° longitude from the coast in the (top) northern Andes, and (bottom) southern Andes.

dM/dt and $\int\Theta$-R may be attributed to errors in dM/dt or $\int\Theta$, but is likely to be caused by errors in R or its interannual variability which is not represented. The agreement in the phase of the annual cycle, and the small bias, between dM/dt and $\int\Theta$-R, can be viewed as support on the credibility of the spacebased observation of $\int\Theta$ and dM/dt. The in-phase relation between the annual variation of P and dM/dt, for the whole continent and for each river basin, suggests the dominance of P among the hydrologic parameters in their annual variations. Although water balance over a river basin has been studied with in situ measurements, the satellite data allow us to ascertain ocean's influence on the entire continent.

[17] The prevalent postulate on rainfall variation is that the Bolivian High causes the onset of South American monsoon and the consequent transport of moisture from the Amazon to the La Plata Basin by the SALLJ through Gran Chaco [e.g., *Horel et al.*, 1989; *Zhou and Lau*, 1997]. The year-round positive $\int\Theta$ for the whole continent indicates clearly that water needs to be transported from the ocean to make up the excess of P over E in SA. Ocean's moisture influx is part of the monsoon system, and strong relations are observed with local rainfall in the Andes, the Amazon Basin and La Plata Basin. Moisture influx may destabilize the atmospheric boundary layer and cause local convective rainfall [*Fu et al.*, 1999] or large-scale convection may draw moisture influx from the ocean.

[18] Although clear demarcation between the Orinoco and Amazon watersheds across the equator was shown in the GRACE data, in agreement with TRMM data, the spatial resolution of GRACE data is too coarse to resolve the water balance of the Andes Cordillera. Reprocessing of GRACE data and a follow-on mission are needed to offer higher resolution and better accuracy. TRMM was designed mainly to measure over tropical and subtropical oceans, and the planned Global Precipitation Mission will improve measurements of light rain and snow over land and high latitudes. Retrieval of high-resolution coastal wind from QuikSCAT [*Tang et al.*, 2004] is being implemented. The European Space Agency's Soil Moisture and Salinity Sensor and National Aeronautics and Space Administration's (NASA) Aquarius promise unprecedented measurements of soil moisture and salinity. Spacebased studies of hydrologic balance lie very much in the near future; this is but an early demonstration.

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W. T. Liu, W. Tang, X. Xie, and V. Zlotnicki, Jet Propulsion Laboratory, Californian Institute of Technology, MS 300–323, 4800 Oak Grove Dr., Pasadena, CA 91109–8099, USA. (liu@pacific.jpl.nasa.gov)