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Global terrestrial water storage capacity and flood potential using GRACE

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[1] Terrestrial water storage anomaly from the Gravity Recovery and Climate Experiment (GRACE) and precipitation observations from the Global Precipitation Climatology Project (GPCP) are applied at the regional scale to show the usefulness of a remotely sensed, storage-based flood potential method. Over the GRACE record length, instances of repeated maxima in water storage anomaly that fall short of variable maxima in cumulative precipitation suggest an effective storage capacity for a given region, beyond which additional precipitation must be met by marked increases in runoff or evaporation. These saturation periods indicate the possible transition to a flood-prone situation. To investigate spatially and temporally variable storage overflow, a monthly storage deficit variable is created and a global map of effective storage capacity is presented for possible use in land surface models. To highlight a flood-potential application, we design a monthly global flood index and compare with Dartmouth Flood Observatory flood maps. Citation: Reager, J. T., and J. S. Famiglietti (2009). Global terrestrial water storage capacity and flood potential using GRACE, Geophys. Res. Lett., 36, L23402, doi:10.1029/2009GL040826.

1. Introduction

[2] Over the course of a year, many land ecosystems transition from a dry limit to a wet limit due to an annual cycle of precipitation. During the wet limit, each region can generally store and process only a finite amount of water before the saturated ground will force additional precipitation to run off. Globally, this response is highly heterogeneous and has implications for regional flooding, which, in a first-order approximation, depends on precipitation excesses and storage limitations [Kleinen and Petschel-Held, 2007]. In a changing climate, an intensification of the global water cycle may exacerbate this effect [Trenberth, 1999; Held and Soden, 2000; Huntington, 2006], and several studies [Allen and Ingram, 2002; Milly et al., 2005; Held and Soden, 2006] have shown that regional patterns of warming-induced changes in surface hydroclimate are complex and difficult to predict. There is some evidence however, that anthropogenic climate change and the resulting precipitation changes could increase the likelihood of floods in large basins [Milly et al., 2002; Parry et al., 2007].

[3] The opportunity to improve global operational flood forecasting with the use of satellite remote sensing is currently becoming a reality. The benefits of the future hydrology-specific altimetry mission, SWOT [Alsdorf et al., 2007; National Research Council, 2007], and the Global Precipitation Measurement satellite [Hossain and Lettenmaier, 2006] are clear, and pre-launch studies discuss the importance of not only precise precipitation data but also soil moisture [Entekhabi et al., 2008; Kerr et al., 2001] and surface discharge data as necessary components in an effective flood-forecasting algorithm. As these studies indicate, even the best precipitation monitoring will provide only short-term flood prediction. A true early warning system for flooding will need to be based not only on meteorological information, but also on the saturation conditions of the flood-prone region prior to rainfall.

[4] The Gravity Recovery And Climate Experiment (GRACE) satellite mission is currently helping to close the large gaps in in-situ global hydrological data sets and providing the opportunity to investigate the nature of the Earth’s water cycle from a true global perspective [Ramillien et al., 2004; Lettenmaier and Famiglietti, 2006; Syed et al., 2008; Ramillien et al., 2008; J. S. Famiglietti et al., manuscript in preparation, 2009]. GRACE data are well suited to act as a constraint on the hydrological processes of larger river basins since the amplitude of the annual storage signal reaches comfortably beyond the error range of the GRACE data set [Wahr et al., 2004]. This annual signal accounts for a majority of the storage variability in many regions (Figure 1) and in some places may indicate a persistent storage maximum [Crowley et al., 2006], which when exceeded is correlated with increased likelihood of flooding.

[5] In this study, we introduce a quantitative, effective terrestrial storage capacity and define a flood potential index to highlight the information contained within the GRACE data that is relevant for regional flooding. First, we use the GRACE time series of storage anomaly to calculate an effective maximum storage capacity in each region. Then we isolate, temporally and spatially, those months in which a high percentage of the storage capacity is achieved and high precipitation continues. This new data set is normalized to remove regional heterogeneity and create a global flood index. Finally, we map the occurrences in which this index approaches a threshold within a given year and compare with global maps of flood observations for validation. In an ideal situation with short data latency, GRACE observations could give a one-month window of maximum flood likelihood due to regional saturation that depends on both precipitation and storage.

2. Method and Data

[6] In the GRACE record, there are persistent annual maxima in GRACE terrestrial water storage time series that
are not exceeded under any observed conditions, even during a continued high rate of hydrological input (Figure 1). To investigate this threshold of storage, we start with a terrestrial water balance using 1-degree gridded time series of storage anomaly and precipitation data averaged at monthly intervals:

\[ P(t) = \frac{dS}{dt}(t) + R(t) + ET(t), \]  

(1)

where \( S \) represents storage anomaly from GRACE, \( P \) is precipitation from GPCP, and \( R \) and \( ET \) are runoff and evapotranspiration.

[7] We assume that regional storage capacity can be approximated by the historic record maximum of the repeated peaks in GRACE storage anomaly time series to give a quantitative estimate (in cm) of the saturation point of the regional land surface (Figure 1). We define the storage deficit for a grid cell, \( S_{DEF} \), as the water that can be held in storage before achieving the historic storage anomaly time series maximum, \( S_{MAX} \), or storage capacity:

\[ S_{DEF}(t) = S_{MAX} - S(t - 1) \]  

(2)

The use of the storage amount from the previous month, \( S(t - 1) \), allows us to be free from assumptions about the partitioning of precipitation during the current month. Thus, storage deficit (\( S_{DEF} \)) represents the highest allowable relative storage change (\( dS/dt \)) for the coming month, and indicates the amount of precipitation that must go to runoff or evapotranspiration in order to balance equation (1).

[8] The storage deficit increases during the drier part of the year and approaches zero during the wetter portion of the year. A low storage deficit combined with a high precipitation input indicates a high probability of flooding. For visualization, \( S_{DEF} \) can be normalized by \( S_{MAX} \) to yield the percentage of capacity remaining in each region as a function of time, thereby removing regional variation in hydrological processes (Figure 2).

[9] Continuing towards flood potential, we assume that flooding must imply an extreme in precipitation not matched by a similar increase in storage. GPCP monthly average precipitation anomalies are multiplied by the length of each month to estimate the amount of rainfall (in cm) that fell in the averaging interval:

\[ P_{MON}(t) = P(t) \times dt \]  

(3)

[10] In order to compare monthly precipitation excess with available storage capacity globally, we create a flood potential amount, \( F \), by subtracting the time series of storage deficit from monthly precipitation:

\[ F(t) = P_{MON}(t) - S_{DEF}(t) \]  

(4)

This flood potential amount is the quantity of incoming water that cannot enter storage for the current month based on the regionally observed storage anomaly maxima. Similar to a traditional ‘bucket model’, when this quantity exceeds zero, flooding may occur.

[11] The flood potential amount is normalized to create a flood potential index for two reasons: 1) since each region handles precipitation differently, we can normalize to account for regional hydrological variability and to make flood visualization graphically simpler; and 2) since a flooding month is an atypical case, normalizing removes the typical differences between precipitation and storage change that do not result in flooding (i.e. normal runoff and evapotranspiration). We normalize the flood potential amount by its historical maximum in each grid cell to create a flood potential index:

\[ F^*(t) = \frac{F(t)}{\max[F(t)]} \]  

(5)

[12] When normalized flood potential \( F^* \) nears 1, it indicates an abnormally high difference between precipita-
tion and regional storage ability, and therefore high flood likelihood.

[13] Time-variable gravity data are obtained from the latest and longest record GRACE product available (Release 04 through 2008 at writing), representing approximately monthly global values. GRACE data are averaged from 3 different releases (i.e. processing standards), from the three GRACE science data centers, University of Texas’ Center for Space Research, Germany’s Geo Forschungs Zentrum, and NASA’s Jet Propulsion Laboratory, each at 300km filtering. Tidal and non-tidal effects, including ocean, solid Earth and solid Earth pole tides, and atmospheric contributions are removed in the level-2 GRACE data processing [Ramillien et al., 2004; Tapley et al., 2004]. Chambers [2006] previously produced geocenter-corrected GRACE time series for global hydrology studies (Famiglietti et al., manuscript in preparation, 2009) and these data are used in the current research (http://grace.jpl.nasa.gov/data).

[14] The Global Precipitation Climatology Project (GPCP) blends various satellite and gauge-based precipitation estimates together to produce global gridded precipitation fields. The current operational procedure, as described by Adler et al. [2003], produced the GPCP Version 2 Combined Precipitation Data Set. For this study, monthly global maps at 2.5-degree resolution (approximately matching the 300km GRACE filter width) were re-gridded to 1-degree (as were the GRACE data) over the GRACE record length.

[15] Archived maps of reported floods were downloaded from the Dartmouth Flood Observatory (DFO). Their data set shows historic floods compiled from satellite observations and weather service reporting. Data and maps are available for public download from http://www.dartmouth.edu/~floods/.

3. Results and Discussion

[16] Figure 3 shows a global map of flood index for the year 2007, constructed by taking the maximum value of the flood index for each grid cell during the year. It is compared with the Dartmouth Flood Observatory map of reported floods, in which red areas indicate observed floods during 2007. While the flood index misses some flooded regions in Africa and Asia, it is generally successful at predicting large-scale flood-affected areas. The index captures the general shape of flooding on most continents, and captures some rather high spatial resolution structure, including events on the southernmost tip of Africa and the unique ‘T’ shape of Mississippi river flooding.

[17] Figure 4 shows the sum, from 2003–2008, of the flooded regions for the month of May, constructed by taking the maximum value of the flood index for each grid cell
during all of the May months within the GRACE record length. This map is compared with the DFO map of May floods from 1985–2008. While the coverage period is not identical, the data reliability and number of floods reported by DFO is significantly lower during years preceding the GRACE record (www.dartmouth.edu/~floods). The similarity in the two maps is clear, and demonstrates that the flood index matches observed flooding at monthly time resolution.

Regional flooding can be caused by a variety of factors, including brief torrential rain, monsoonal rain, tidal surge, and snowmelt. This index primarily sees flooding due to persistent strong rain, not matched by a correlated increase in storage, and provides a flood potential applicable only at the regional scales that are observable by GRACE. It estimates a critical range of allowable precipitation due to a climatological storage ceiling, which when exceeded indicates potential flooding. The validation of the method with DFO observed flood maps shows that while it may overpredict at times, its value lies in the ability to increase warning time by a few weeks.

The primary aim of this work is not the derivation of a flood index. Rather, it is the presentation of information in the GRACE record that is relevant to aid prediction, and the authors hope that this work can be applied for use in flood forecasting. Because the flood potential amount \( F \) is calculated from the previous month’s storage anomaly, it can be utilized by forecasters to indicate periods of potential danger based on a critical precipitation range. The method of GRACE storage deficit estimates should be used in combination with traditional methods of precipitation forecasting to help assess the likelihood for flooding during the coming weeks. The simple mathematics of the storage deficit quantity allow for recalculations as the GRACE record length increases, and this recalculations will be necessary as the storage deficit quantity is based on GRACE record-length time-series anomalies.

Several studies have cited the importance of soil moisture data in the accurate prediction of floods and general runoff [Alsdorf et al., 2007; Hossain and Lettenmaier, 2006]. One could argue that soil moisture primarily serves as a proxy in flood studies for the more critical water balance variable of storage [Rodell and Famiglietti, 1999] and for storage deficit [Beven and Kirkby, 1979; Famiglietti and Wood, 1991]. The terrestrial water storage signal defines the time-variable ability of the land surface to absorb and process water, and accounts for the water in plants, ground water and soil moisture. It has a strong annual signal in most regions, making it highly predictable. Because of this, the periodic GRACE signal may also have value for global modeling, where grid-based models require some measure of effective storage capacity. Assimilation of the GRACE-
based storage deficit could provide an additional benefit relative to current methods based on storage anomaly [Zaitchik et al., 2008].

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