Changes in land surface water dynamics since the 1990s and relation to population pressure

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[1] We developed a remote sensing approach based on multi-satellite observations, which provides an unprecedented estimate of monthly distribution and area of land-surface open water over the whole globe. Results for 1993 to 2007 exhibit a large seasonal and inter-annual variability of the inundation extent with an overall decline in global average maximum inundated area of 6% during the fifteen-year period, primarily in tropical and subtropical South America and South Asia. The largest declines of open water are found where large increases in population have occurred over the last two decades, suggesting a global scale effect of human activities on continental surface freshwater: denser population can impact local hydrology by reducing freshwater extent, by draining marshes and wetlands, and by increasing water withdrawals. **Citation:** Prigent, C., F. Papa, F. Aires, C. Jimenez, W. B. Rossow, and E. Matthews (2012), Changes in land surface water dynamics since the 1990s and relation to population pressure, *Geophys. Res. Lett.*, *39*, L08403, doi:10.1029/2012GL051276.

1. Introduction

[2] Among the different reservoirs in which continental waters are stored, surface freshwater, which covers only a few percent of the land surface [*Prigent et al.*, 2007; *Lehner and Doell*, 2004; *Downing et al.*, 2006], is a vital resource for human life and industrial and recreational activities and has a large impact on the biogeochemical and hydrological cycles with significant influence on the global climate. Consequently, monitoring surface freshwaters is a high priority in water management and climate research [*Solomon et al.*, 2007; *Vörösmarty et al.*, 2000; *Shindell et al.*, 2004]. However, the determination of the large-scale distribution and temporal evolution of inundation has been challenging due to the diversity of situations encountered from the Tropics to the Arctic [*Alsdorf et al.*, 2007]. We developed a remote sensing approach based on multi-satellite observations, which provides an unprecedented estimate of monthly distribution and area of land-surface open water over the whole globe. In this study, a global 15-year record of monthly surface-water extent at 0.25° spatial resolution has been completed for 1993–2007, and the inter-annual variability of the data set is analyzed (section 2). Section 3 examines the relationship between the wetland variability and the population density over 1993–2007. Conclusions are presented in section 4, insisting on the potential applications of the wetland dataset.

2. The Wetland Variability Over the 15-Year Period

[3] The detection and quantification of the land surface water extent is obtained from multi-satellite observations over a large spectral range, from visible to microwave wavelengths. The methodology has been described by *Prigent et al.* [2001, 2007] and *Papa et al.* [2010a]. It is summarized in the auxiliary material.[1]

[4] On the global map of the annual mean water extent averaged over the 15-year record (Figure 1, top) the river flooding of the major Tropical and sub-Tropical basins (e.g., Amazon, Orinoco, Congo, Niger, Mekong, or Ganges) are easily recognized, as well as the boreal wetlands (above 50°N, 20% of the total mean inundation extent over the year) and the region of rice paddies in South Asia (the region 0°–40°N; 60°E–140°E amounts to 30% of the global mean inundation extent over the year). The latitudinal distribution (Figure 1, top right) emphasizes the contributions of the Tropical and Boreal regions to the total surface water extent. The month-to-month variations also show a realistic seasonal cycle and modest inter-annual variability (Figure 1, bottom left), with a mean annual maximum extent over the record of 5.660×10^6 km^2 (StD = 286000 km^2) and 2.598×10^6 km^2 (StD = 199600 km^2) for the Tropics (30°S–30°N). Monthly anomalies, computed by subtracting the 15-yr mean monthly value from the monthly time series (Figure 1, bottom right), reveal recent changes in global inundated area. The magnitudes of these short-term changes are estimated by the slope of the least-square best-fit line. At global scale, a decrease in the surface water extent is evident from January 1993 to mid-2000 (−67700 km^2/yr, $p < 0.001$), followed by a moderate increasing trend (17800 km^2/yr, $p < 0.01$) through the end of the study period. The change for the entire period is a net reduction of 22100 km^2/yr (−331500 km^2/15-yr, $p < 0.001$) equal to a decline of 6% in 15 years in the mean annual maximum inundated area. Tropical and subtropical regions within 30° of the equator contribute 57% to the global net decline (−12700 km^2/yr, $p < 0.001$ or −7.3% in 15 years in the mean annual maximum inundated area), also marked by a sharp decrease from 1993 to mid-2000 (−38700 km^2/yr; $p < 0.001$), followed by an upward trend (21400 km^2/yr; $p < 0.001$) until 2007, with more limited variations after 2002.

[5] The results for six large river basins in a variety of environments are presented in Figure 2. In addition to large seasonal and interannual variability, a statistically significant decline in surface water extent is evident for the Amazon

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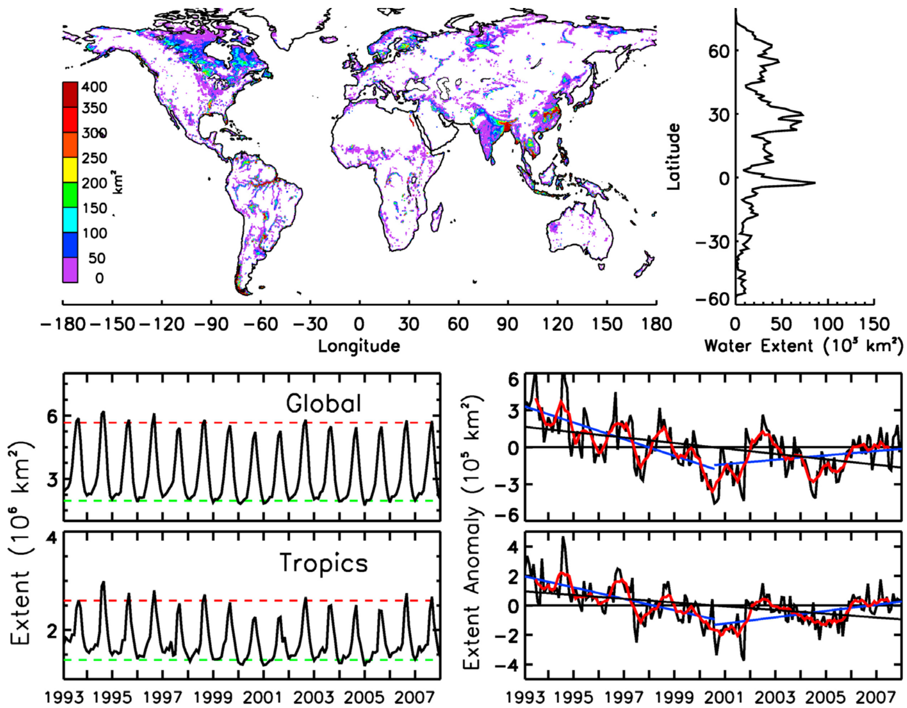

Figure 1. The surface water extent and their anomalies from 1993 to 2007. (top) Annual mean surface water extent averaged over 1993–2007, for each 773 km^2 pixel; also shown the latitudinal distribution of the surface water extent (by 1°). (bottom left) Monthly-mean surface-water extent for 1993–2007 in black, for the globe (top) and the Tropics (30°S–30°N, bottom); red and green lines for the 15-yr mean maximum and minimum respectively. (bottom right) Corresponding deseasonalized anomalies (black) with the 6-month running mean (red); statistically significant changes in surface water extent (black and blue) estimated using linear least-squares regression.

basin (−7.6% of the mean extent in 15 years, $p < 0.01$), the Orinoco basin (−30%/15-yr, $p < 0.001$), the Yangste River (−20.4%/15-yr, $p<0.01$), and the Mississippi River (−48.5%/15-yr, $p < 0.01$). Interestingly, neither the Ganges-Brahmaputra River system nor the Mackenzie River shows any significant changes for 1993–2007. Although loss of inland waters is well documented locally and has been reported for many parts of the world [*World Water Assessment Program*, 2006], no consistent, multi-year, global, or even regional datasets are currently available to represent and quantify these changes. In the absence of independent global estimates to evaluate our satellite-derived inundation results, the inter-annual variability is compared with related hydrological variables, namely in situ river discharge [*Global Runoff Data Centre*, 2009; *Papa et al.*, 2010b] (http://www.ore-hybam.org) and the total continental water mass change (soil and surface water, snow, and groundwater) derived from gravimetric satellite measurements from GRACE [*Ramillien et al.*, 2008]. The basin-averaged precipitation is also presented, as estimated from the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003]. For most river basins, variations of inundation extent show close agreement with fluctuations in river discharge, when available (Figure 2, left and middle), as well as with total continental water mass (Figure 2, right). For example, over the common period of availability of the data over the Amazon basin, the linear correlation between the water extent and in situ discharge is 0.93 ($p < 0.001$) for the raw data and 0.69 ($p < 0.001$) for the deseasonalized results. With GRACE-derived total water storage change, these correlations are respectively 0.93 ($p < 0.001$) and 0.67 ($p < 0.001$). They are 0.88 and 0.59 respectively with precipitation. However, the small negative trend of 3.2% observed in the mean Amazon River discharge for 1993–2007 was not found to be statistically significant. The trend in GPCP precipitation was not significant either. On the other hand, analysis of the changes in the Mississippi river discharge for 1993–2006 reveals a statistically significant decline of 28.7% of the mean value compared with the 48% decline of the mean inundated area. The corresponding trend in GPCP precipitation for the same area is −2.4 mm/month over the 15 years ($p < 0.001$).

[6] At global scale, Figures 3a and 3b show that the recent changes of the surface-water extent over these 15 years vary greatly among regions, including in some cases large increasing/decreasing patterns of changes within a single river catchment. River basins, such as the Parana or the Amazon, and large wetland complexes, such as the Pantanal, exhibit areal declines while some regions such as northern Scandinavia and east Africa show increased area. A significant decrease of the inundation extent over the 15-yr record is observed in a large majority of locations (inset of Figure 3a), but locations where surface water extent increased also exist (25% of the total number of pixel showing significant changes). For instance, the Indian Subcontinent shows opposite behavior with a large portion of the area exhibiting a large

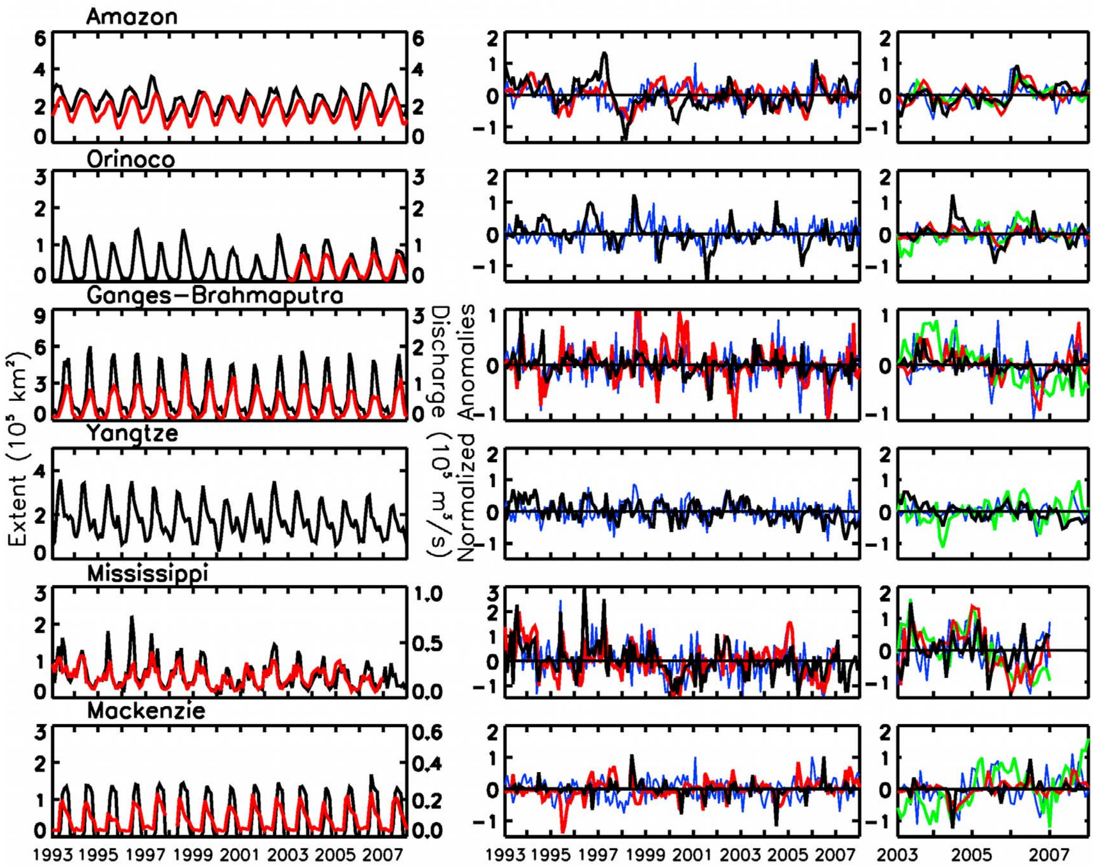

Figure 2. Variability of the wetland extent between 1993 and 2007 over 6 basins and corresponding river discharge, precipitation, and GRACE-derived water volume change. (left) Monthly-mean surface-water extent 1993–2007 (black), and comparison with in situ river discharge when available (red), for the in situ stations farthest downstream. (middle) Corresponding deseasonalized anomalies along with the deseasonalized anomalies of basin-averaged precipitation (GPCP) (blue). (right) Also the deseasonalized anomalies but for 2003–2007 with the GRACE-derived total water volume change anomalies (green).

decline located next to an area with a large increase. Tests of the spatial correlations did not suggest any direct link between changes in surface water extent and changes with related climatological variables such as precipitation (see for the latitudinal distribution of the change in precipitation on Figure 3b, along with the change in surface water extent).

3. Relationship Between the Wetland Change and the Population Pressure

[7] In general, the regions with the largest surface water decline (e.g., India, China) correspond to areas where the threat to water security is high [*Vörösmarty et al.*, 2010]. Our satellite-derived estimate of water extent shows substantial negative trends in heavily populated areas, particularly in Asia. The link between the changes in surface-water extent and population density is examined, using data on the distribution of human populations (http://sedac.ciesin.columbia.edu/gpw; also Figure 3). The linear correlation between the inundation and precipitation changes (as averaged by 1° latitude as on Figure 3b) is 0.31, to be compared with the correlation of 0.61 calculated between the inundation and population changes.

[8] To further explore the relationship between changes in surface-water extent and population density, Figures 3c and 3d show histograms of the changes in surface-water extent for regions with small and large population growths. The largest water extent reductions occur in regions of large population growth over the last two decades. This is consistent with an expected higher anthropogenic effect in these areas: human population growth and the expansion of economic activities are collectively placing great demands on local hydrology, including draining of marshes and wetlands for constructions and water withdrawals for agriculture and human needs. However, note that population increase in some regions actually contributes to an increase of the surface water extent, likely due to new irrigated areas or new constructions of dams and reservoirs (the secondary peak in the histograms for the curves related to population increases). The relationship between changes in surface-water extent and population density is illustrated for two specific coastal regions (Figure 4). Around Hanoi, Vietnam, there is a strong spatial correspondence between the population density increase and the decline of the surface water extent (Figure 4a). In order to evaluate the corresponding land-use

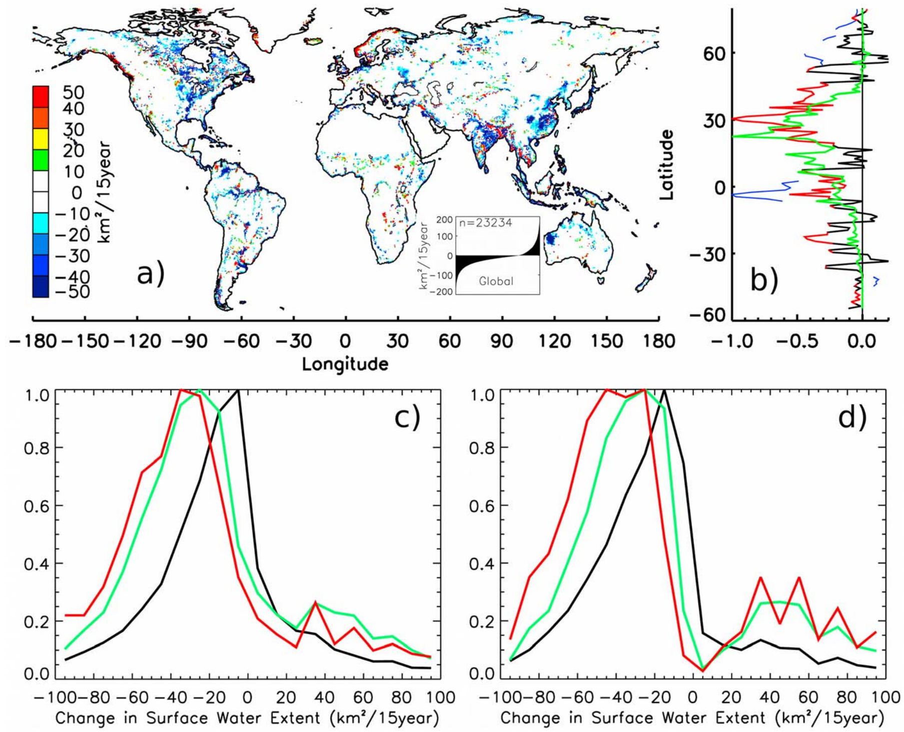

Figure 3. Changes in net surface-water extent 1993–2007. (a) Change estimated by linear fit (km^2/15-yr, only for pixels with significant changes with $|R| > 0.146$ for $p < 0.05$); inset figure shows the linear regression change (km^2/15-yr) ranked from most negative to most positive for all significant pixels. (b) Latitudinal distribution (by 1°) of the surface water extent change (normalized to 1) in black with red indicating significant trends; superimposed (normalized to 1 and multiply by −1) are changes in population density 1990–2005 (green) and statistically significant changes in the GPCP precipitation 1993–2007 (blue). (c, d) Histograms (normalized to 1) of changes in surface-water extent (km^2/15-yr) for 1993–2007 for the globe (Figure 3c) and for Asia (0°–40°N; 60°E–140°E) (Figure 3d); black line for all significant pixels, green for all significant pixels with large population growth (>50 inhabitants per km^2 for 1990–2005), red for all significant pixels with large population growth and located <100 km from the coasts.

change, visible and near-infrared satellite observations were also analyzed, using a Normalized Difference Vegetation Index, but this did not show any significant change during the same period, except very close to the coast, limiting the possibility of a spurious decrease of the satellite-derived surface water extent due to land-use changes only. In south Florida (Figure 4b), a decrease in the surface water extent is observed with an annual rate of −1.5%. The region of surface water decrease is located east and west of the cities of Naples and Miami and does not coincide with the region of increase in population density (>100 inhabitants per km^2). However, the areas of wetland drying do correspond to drainage of wetlands, to provide water for irrigation and for a tourist activity, agriculture, and sugar cane industry, and to sustain 6 million people (encompassing seven of the ten fastest-growing metropolitan areas in the US). With over half of the world's population living within 200 km of a coastline and with an accelerating population growth in the coastal region, it is expected that these areas will suffer from major anthropogenic effects, including significant changes in hydrology.

4. Conclusion

[9] A global dataset of surface water extent and dynamics has been derived from multi-satellite observations, for 1993–2007. It is available to the community upon request to the authors. Our analysis suggests a decline in global average maximum inundated area of 6% during the fifteen-year period. The largest changes of open water are generally observed where large increases in population density have occurred. Such observations can benefit the development and the improvement of models used to refine adaptation and mitigation strategies.

[10] This inundation data set also removes a crucial obstacle to progress on several other fundamental scientific questions. First, natural wetlands are the world's largest methane source and dominate the inter-annual variability of atmospheric methane concentrations [*Gedney et al.*, 2004; *Shindell et al.*, 2004; *Bousquet et al.*, 2006]. Our data set quantifying inundation dynamics throughout the world's natural wetlands provides a unique resource for reducing uncertainties in the role of natural wetlands in the inter-annual variability of the growth rate of atmospheric methane. Second, although progress has been made on quantifying the two primary contributors to sea-level rise - thermal expansion due to ocean warming and melting glaciers and ice sheets - uncertainties remain regarding the role of changes in continental water storage [e.g., *Ngo-Duc et al.*, 2005] despite recent results from gravimetric satellite missions [e.g., *Ramillien et al.*, 2008]. The combination of altimetric continental water height and our multi-satellite surface-water extent is underway [e.g., *Papa et al.*, 2008] to estimate variations in global surface-water volumes, quantify fluctuations

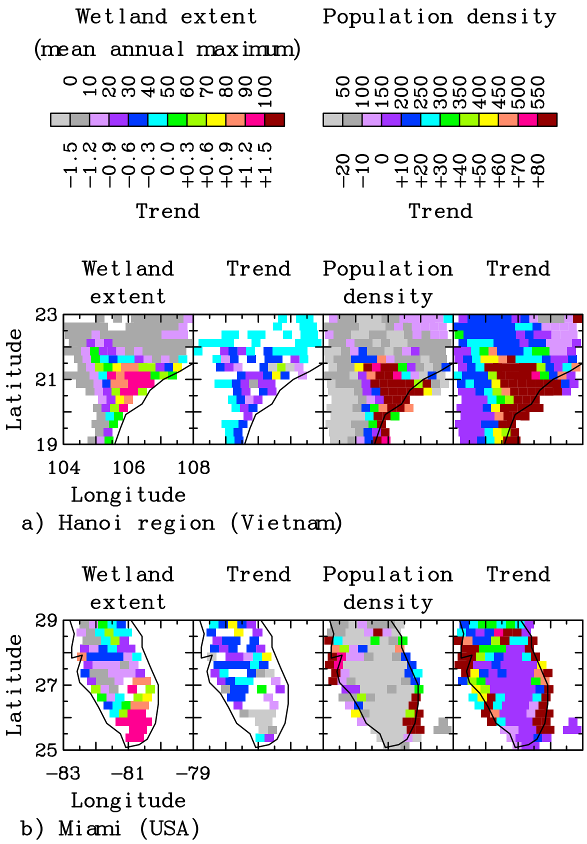

Figure 4. Relationship between changes in surface-water extent and population density in coastal regions near (a) Hanoi, Vietnam, and (b) Miami, USA. From left to right: mean annual maximum surface-water extent for 1993–2004 (% of the pixel per year), change in surface-water extent 1993–2007 in % of pixels per year (only for pixels with <50% uncertainty in the trend), population density in 1990, and change in population density1990–2005 (both in inhabitant per km^2).

of river discharge into the ocean, and understand the role of terrestrial water in sea -level rise.

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[12] The Editor thanks the anonymous reviewers.

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