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Additional information

Supplementary information is available in the online version of the paper. Correspondence and requests for materials should be addressed to R.A.B.

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COMMENTARY:

Earth's surface water change over the past 30 years

Gennadii Donchyts, Fedor Baart, Hessel Winsemius, Noel Gorelick, Jaap Kwadijk and Nick van de Giesen

Earth's surface gained 115,000 km^2 of water and 173,000 km^2 of land over the past 30 years, including 20,135 km^2 of water and 33,700 km^2 of land in coastal areas. Here, we analyse the gains and losses through the Deltares Aqua Monitor — an open tool that detects land and water changes around the globe.

Changes from land to water and vice versa are extremely relevant as witnessed by many recent news items: the President of Kiribati declared that his people would need to move to new grounds to prevent them from dying from the effects of sea-level rise on the atoll[1]; the impoundment of the Three Gorges Dam in China is causing massive inundations, forcing about 1.3 million people to resettle[2]; new islands along the coast of Dubai are created to provide new secluded areas for leisure and residence for the wealthy; and finally, the Mississippi Delta is losing thousands of hectares of land per year due to soil subsidence and lack of sediments[3], further aggravated by sea-level rise.

The causality of appearing or disappearing water surfaces may strongly depend on the case-specific context. Although atolls, such as Kiribati, are under severe threat, the exact effects of sea-level rise on coastal erosion, globally, may strongly depend on biophysical interactions as well, particularly in coastal marshes[4], as atolls may increase accretion rates as sea-level rise progresses[5]. The impoundment of the Three Gorges Dam has resulted in a reduction in sediment concentrations in the downstream Yangtze River of about 70%. Unexpectedly, this reduction has not led to a retreat of the downstream submerged Yangtze River Delta so far[6], contrasting what happens in the Mississippi Delta.

These examples demonstrate that conversions — and the stories and reasons behind them — can vary widely and are often the result of compounding causes. Therefore, general conclusions cannot be drawn from a limited sample of case studies. Instead, planetary-scale monitoring is needed to understand (and disentangle) the causes of detected changes and their attribution to natural variability, climate change or man-made change. Until now, such monitoring and estimates of land–water conversions were not feasible.

The massive growth in satellite data has resulted in a severe demand in storage, computation and smart analytics to enable analysis of planetary-scale data. Until recently, such analyses were performed by highly specialized scientists and engineers, and on a case-by-case basis. New cloud platforms for large satellite data analysis, such as Google Earth Engine (http://earthengine.google.com), rapidly remove thresholds to use planetary-scale data[7,8]. These platforms provide access to a plethora of satellite information in three ways: (1) storage of satellite data in the cloud; (2) provision of computational resources; and (3) availability of analytical tools to process data into a clear end product.

The Deltares Aqua Monitor (http://aqua-monitor.deltares.nl) is the first global-scale tool that shows at 30-m resolution where water is converted to land and vice versa. With assistance from Google Earth Engine, it analyses satellite imagery from multiple Landsat missions, which observed Earth for more than three decades on the fly. The Aqua Monitor provides a much needed[9], fully planetary-scale view on

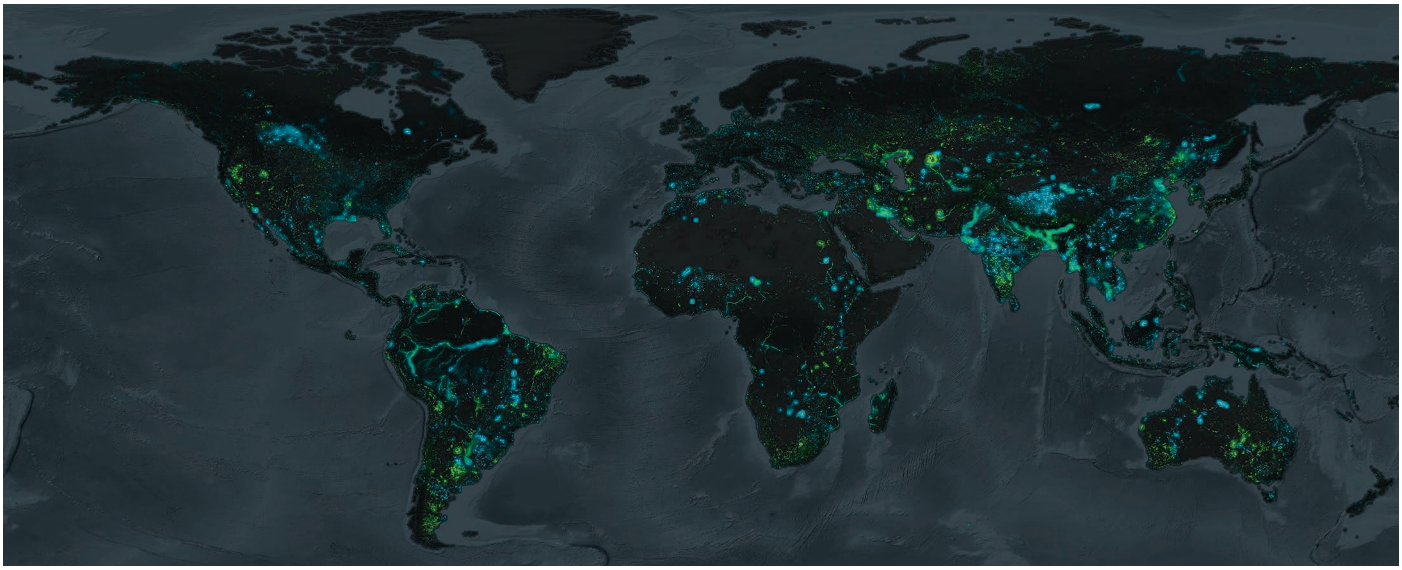

Figure 1 | Heat map of global surface water and land changes. Blue lighting shows where land was converted into water over the period 1985–2015. Green lighting shows where water was converted into land over the same period. The intensity of the colours highlights the spatial magnitude of the change.

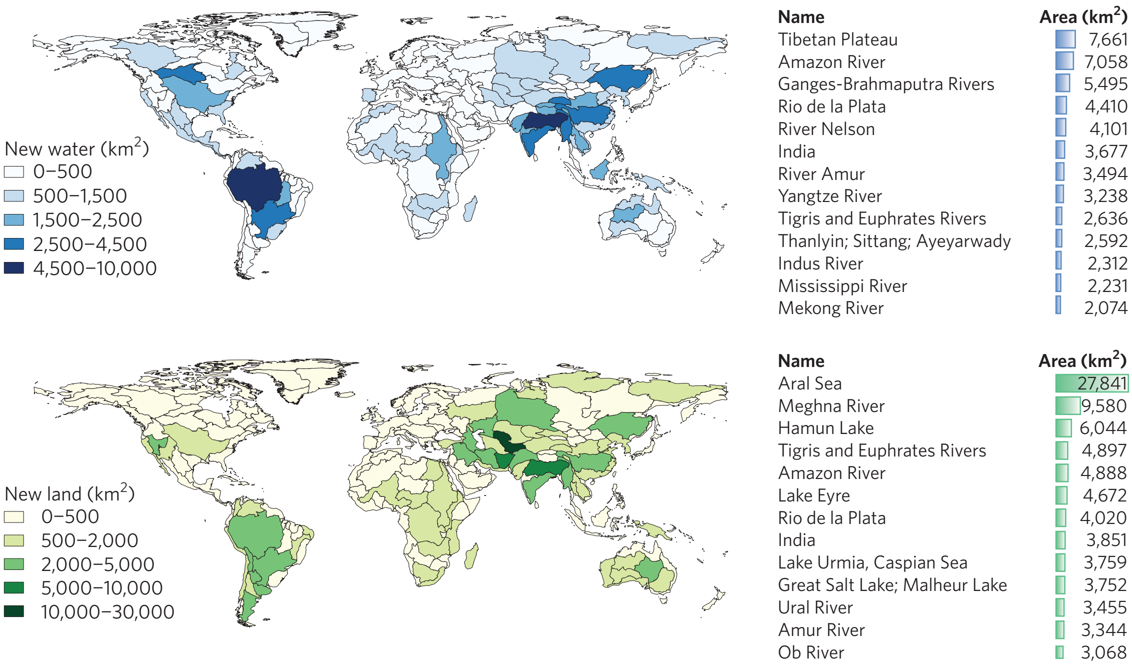

Figure 2 | Largest surface water and land changes from 1985 until 2015 grouped by drainage basins. Changes from land to water in blue and changes from water to land in green.

changes in land and water occurrence. Documented and undocumented changes due to man-made interventions, natural variability and climate change are revealed. It is possible to look at any area of interest and use the outcomes for scientific advances at planetary-scale, review large-scale statistics on land and water conversion, or open a discussion with stakeholders in a given area on the basis of unbiased information on water and land occurrence and change.

Here, we will demonstrate the planetary-scale ability of the Aqua Monitor by showing some significant and contrasting water–land conversions. We provide a perspective of what these abilities — which are now available to any researcher or stakeholder — mean for climate research.

First, we demonstrate the planetary-scale changes in the occurrence of water and land (Fig. 1). We see that globally, between 1985 and 2015, an area of about 173,000 km^2 — about the size of Washington State — has been converted to land, and an area of 115,000 km^2 has been converted into water. An overview of the largest changes found globally, aggregated per drainage basin (Fig. 2) identifies the Tibetan Plateau and the Amazon River as the areas with the largest area conversion to water. The Aral Sea is the standout for conversion to land. As changes in surface water only affect people at a regional and local scale, we show some contrasting cases for different areas (Fig. 3) and describe these below.

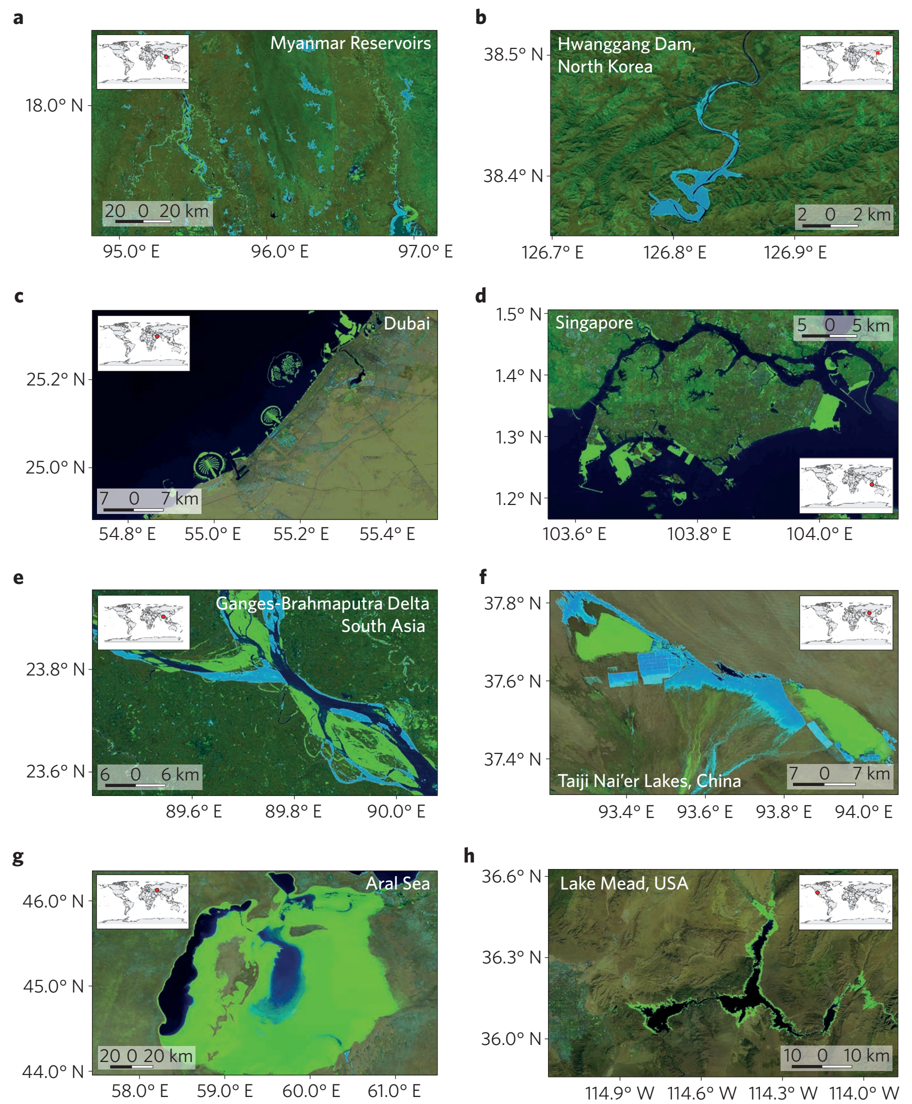

Figure 3 | Examples of surface water changes between 1985 and 2015, detected using the Aqua Monitor. Blue, conversion from land to water; green, conversion from water to land.

Known and unknown

Although many countries report on their dam construction, information in more remote or isolated areas is lacking. In Myanmar, the Global Reservoir and Dams database[10] shows an increase in water surface between 1985 and 2010 of about 400 km^2. Using the Aqua Monitor, we have counted the appearance of 1,180 km^2 of new water surface in this region over the same period (Fig. 3a). The previously unmapped damming of the Rimjin River in North Korea, close to the border with South Korea, resulted in a storage surface of 12.4 km^2 (Fig. 3b). This is, in fact, the Hwanggang Dam, at the time of writing mapped 35 km eastward. The dam was the topic of an international dispute between South and North Korea after the 2009 flash flood that killed six fisherman[11].

Luxury versus needs

The largest coastal water–land change is the construction of the Palm Island and adjacent islands along the coast of Dubai (80 km^2; Fig. 3c). Many countries have shaped and extended their coastlines by land reclamation. The motives to reclaim land are highly diverse. In Dubai, the main motivation was to increase the coast length, providing more room for recreation[12]. In contrast, reclamations in Singapore (76 km^2; Fig. 3d) are necessary to support its economic growth (http://www.mnd.gov.sg/landuseplan).

Nature versus man-made

Results of the Aqua Monitor only show compound impacts of natural and human change or variability. It is often hard to tell what the causes are for a change without looking at the details of the local water and sediment budget. Although changes in meanders in the Brahmaputra River Delta are clearly natural (Fig. 3e), the Mondrian-like shapes formed near Taiji Nai'er lakes in China, are clearly man-made (Fig. 3f).

Disruptive versus gradual

An example of disruptive change can be found at the Aral Sea, once the fourth-largest lake in the world. Since the 1960s, Soviet engineers diverted the rivers away from this endorheic lake to irrigate cotton and wheat agriculture[13]. The lake has almost entirely dried up, losing about 27,650 km^2 of surface water (Fig. 3g). The positive impacts of a recent restoration programme[14] in the northern part can be observed as well. A slower drying lake can be found near Las Vegas at Lake Mead, the largest freshwater supply in the United States. It lost 222 km^2 over the same period (Fig. 3h). The 10% probability scenario that the lake would have already dried out by 2013[15] did not come true, but the lack of inflow from the Colorado River will cause the lake to gradually disappear.

Big satellite data analytics at anyone's fingertips, may have strong implications on monitoring capacities and associated actions. At a very local scale, a civilian can now assess without any expert assistance, if coastal erosion threatens their house. At a regional scale, a downstream riparian state can monitor from year to year, if upstream neighbours are establishing new impoundments. Finally, at a global scale, agencies such as the United Nations International Strategy for Disaster Reduction can monitor the appearance of new, possibly flood hazard reducing, reservoir storage capacity.

Implications for climate research follow from the fact that the available time series are long enough to cover a climatologically relevant period. The period of 30 years allows distinction between noise of (multi) annual variations, such as the lake surface area of Lake Nasser, and long-term trends in land and water distribution, such as the vanishing of the Aral Sea. Feeding changes in land and water surfaces into regional climate models will lead to better representation of circulation patterns, as well as local climate, in particular in the vicinity of large wetlands[16]. Another example is the attribution to sea-level rise or other drivers of coastal erosion in soft sediment coastal areas[17]. Drivers such as sea-level rise, sediment delivery and subsidence, and the biophysical properties of the coastline, can cause highly nonlinear erosion and accretion. Quantifying the contribution of these drivers would benefit tremendously from information on multiscale patterns of erosion and accretion from low (global) to very high (local) resolution. We present the climate community with the capacity to take into account these new planetary-scale observation abilities. ❒

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Additional information
Supplementary information is available in the online version of the paper.

COMMENTARY:

The attribution question

Friederike E. L. Otto, Geert Jan van Oldenborgh, Jonathan Eden, Peter A. Stott, David J. Karoly and Myles R. Allen

Understanding how the overall risks of extreme events are changing in a warming world requires both a thermodynamic perspective and an understanding of changes in the atmospheric circulation.

Whenever an extreme weather or climate-related event occurs, the extent to which human-induced climate change has played a role is routinely questioned. Increasingly, scientists are able to give robust quantitative answers. In 2012, the *Bulletin of the American Meteorological Society* published the first of an annual series of special issues looking at how climate change may have affected the strength and likelihood of individual extreme events that took place during the previous year — with this first issue containing just six papers[1]. Since then the science of event attribution has developed rapidly, with an increasing number of research groups applying a wider range of methodologies (for example, ref. 2). The US National Academy of Sciences has recently completed a report into the issue, concluding that "in many cases, it is now often possible to make and defend quantitative statements about the extent to which human-induced climate change (or another causal factor, such as a specific mode of natural variability) has influenced either the magnitude or probability of occurrence of specific types of events or event classes"[3].

Although the thermodynamic consequences of a warming world, namely an increased likelihood of more heat and high-precipitation extremes are predictable, on average, in any specific location or circumstances, thermodynamic influences may be either amplified or counteracted by anthropogenically induced changes in circulation[4–7] and/or other local forcings. As far as impacts are concerned, the mechanism whereby human influence on global climate is manifest in a particular weather event is immaterial, so to understand how the risks of extreme events are changing requires both a thermodynamic and dynamic perspective. The emerging science of probabilistic event attribution provides the tools needed to assess such risks at the spatial scales people care about.

Multiple approaches

Overall, there is great strength in using different approaches to assess the role of anthropogenic climate change in extreme weather events as it allows estimates of the uncertainty in attribution statements beyond sampling uncertainty, thereby increasing confidence in the result[3]. However, differences in how the attribution question is framed can lead to apparently contradictory attribution statements that provide a challenge in communication, often reinforced by high media attention. An example where seemingly contradictory results are in fact complementary is provided by the studies of the Russian heat wave in 2010, where the magnitude of the event was mainly due to natural variability[8], whereas the likelihood of occurrence of an event of this magnitude had changed considerably due to anthropogenic drivers[9]. More subtle differences in analysing changes in the likelihood of occurrence can still lead to large discrepancies in results[2,10].

Other approaches to attribution have been suggested that allow improvements to our understanding of the event itself, but do not allow for an assessment of whether (or how) the risk of such an event has changed[11]. Such studies ask the following question: conditional on the large-scale circulation patterns, what was the role of anthropogenic climate change in, for example, the solar dimming observed over India?[7] Such studies allow for assessing whether climate change altered known relationships between large-scale drivers and local events. One such example investigated whether anthropogenic climate change affected the relationship between the El Niño–Southern Oscillation and extreme rainfall in Southeast Australia[12]. Although this method does not analyse the overall change in risk of an event occurring, isolating specific drivers can still be invaluable in improving understanding