**Author’s responses to**

Review of: Improving Understanding of the Global Hydrologic Cycle

By: P.H. Gleick, H. Cooley, J. Famiglietti, D. Lettenmaier, T. Oki, C. Vörösmarty, E. Wood

With that title I had hopes of a comprehensive paper. Instead I read something that deals with only a small fraction of the water cycle: the terrestrial component. In fact, most of the water cycle is within and over the oceans and less than 10 percent of global ocean evaporation is cycled back through rivers (Schanze et al, 2010). So there is a glaring lack of discussion of the bulk of the water cycle. Why call it global when you really mean the 10% that is terrestrial? And the main emphasis is on the small fraction of that 10% that is affected by mankind! If you want to keep the term “global” then please give the ocean its due. They have missed seeing the forest for a bush. I cannot agree with their current priorities. Perhaps they should rename it “Improving understanding of the terrestrial water cycle”.

There is also a curious paucity in discussion of predictions and predictability, just passing mention under modeling. Surely there is nothing more a water system manager needs than accurate predictions of future rainfall. Seasonal and longer term predictions of rainfall are the focus of much research yet there is barely a mention of it. We know that basic modes of ocean-atmosphere variability (ENSO, NAO) have huge impacts on regional rainfall, yet there is no mention of these phenomena. Lamb and many others have been using SSTs since the 70’s (e.g. Zhang and Delworth, 2006; Shanahan et al, 2009; Ummenhofer, 2009a, b) to understand and predict rainfall variations yet there is no mention of such standard empirical methods. Is finer resolution in terrestrial models really all that useful? Wouldn’t you rather have an accurate seasonal forecast of dry or wet conditions for a region rather than a high resolution map (to 350m!) of which valley gets more rainfall from a given storm? Such emphasis on micro-climates misses the big picture issue of long-term regional drought or flooding. We know that the multiyear drought in Texas can be ascribed to tropical Pacific SST patterns (La Nina).

[We acknowledge the large and diverse literature that shows the lack of skill by seasonal climate models and have made some adjustments of the text to reflect this, but also addressed recent improvements. The pretty weak ability of climate models to simulate the 20th C terrestrial water cycle is equally well documented.]

Doesn’t nearly all the rain come from the ocean? The headwaters of “atmospheric rivers” that

cause so much US flooding are in the tropical Pacific and Gulf of Mexico, that’s where you should be putting observational and modeling resources. [Edits made to incorporate this point.]

Similarly, the issue of the magnitude of long-term trends in the water cycle induced by global warming is of paramount importance, yet the emerging evidence for strong change in the water cycle is completely absent.

I think a really important topic would be the dramatic contrast between the standard model prediction of a 2% per degree intensification of the water cycle with global warming and the accumulating data that it is actually much stronger than this. Specifically, Clausius-Clapeyron

(C-C) thermodynamics would suggest an increase in the vapor-carrying capacity of the atmosphere of ~7% per oC of surface warming. However, all the IPCC climate models show a response of the water cycle at a rate that is much less than this, having only 1-3% intensification of the water cycle per degree of warming. Held and Soden (2006) term this weak sensitivity of the water cycle to warming a “robust response” of all the models. Land based data on the water cycle shows variability but no clear trends in water fluxes (Huntington, 2006; Dai et al, 2009).

[While observations show that absolute humidity is increasing, relative humidity is decreasing. This suggests that (at least over land) the land-vegetation system isn’t fully responding. We’ve expanded on this.]

ENSO and volcanoes are the primary contributors to inter-annual variability in the hydrologic cycle, with the 1991 Pinatubo eruption causing the most severe droughts on record in many places (Trenberth and Dai, 2007). However, the terrestrial water cycle is actually a small portion of the global water cycle, the vast majority involves exchange between ocean and atmosphere. For instance, the total discharge of all rivers is less than 10% of the evaporation from the surface of the global ocean (Schanze, Schmitt and Yu, 2010). This vast preponderance of water flux over the oceans suggests that it is where we should expect to detect evidence for a changing water cycle. And a new analysis of ocean salinity trends by Durack et al (2012) has provided decisive evidence for a surprisingly rapidly acceleration of the global water cycle. The implications of this for the future state of the water supply for civilization are disturbing, i.e. 16-24% intensification of the water cycle with 2-3 degrees of warming!

**[We have incorporated much of the following sections into the paper. Thank you for this comment.]**

Syed et al., (2010) used multiple remotely-sensed datasets to analyze the global ocean water balance for changes in water cycle strength. Over the 13-year (1994-2006) study period, they observed significant accelerations in oceanic precipitation (240 km3/yr2), oceanic evaporation (768 km3/yr2), and continental discharge (540 km3/yr2), which included ice sheet melting. Implications for a currently accelerating water cycle were duly noted.

Four independent data sets all indicate that the water cycle is indeed intensifying at the C-C rate, rather than the much reduced model rate. They include:

(1) Atmospheric water content (precipitable water). While not directly indicative of fluxes, it is widely recognized that the humidity of the atmosphere has been increasing at close to the CC rate, especially over the oceans (Trenberth et al, 2005; Wentz et al, 2007). This is a feature of the models even though evaporation and precipitation rates change little. This difference in the models is rationalized with a longer water residence time in a slower moving atmosphere, due to the reduced meridional temperature gradient (Held and Soden, 2006; Schneider et al, 2010).

(2) Oceanic evaporation rates. Yu and Weller (2007) find evaporation increasing over the global ocean at 1.3%/decade since the mid-70s. This is well above the model predictions and close to expectations from C-C. In their climatology this trend is due to both warming and to intensifying winds, in direct contradiction to model predictions of a slowing atmosphere (see also Weimerskirch et al, 2012 on winds).

(3) Precipitation rates. Wentz et al (2007) report that global precipitation rates from satellites have been increasing with SST at a rate of about 9% /oC in the last two decades, slightly above C-C. While the satellite based precipitation estimates comprise a short record, and natural variability cannot be ruled out, the basic response to SST changes seems reliable. [We note conflicting observations/comments, however, such as the GPCP.]

(4) Salinity trends. Sea surface salinity differences have increased by ~8% over the 5 decades from 1950 to 2000, according to Durack and Wijffels (2010) and the new analysis by Durack et al (2012). The oceanographic data is unequivocal (see also Boyer et al, 2005), with a very consistent pattern found in both the mean salinity and the long term salinity trends. Salty areas have gotten saltier, and fresh areas fresher over the last 50 years. The ocean has no internal sources or sinks of salinity, all the variations are introduced at the surface by evaporation, precipitation and runoff. Durack et al (2012) note that the salinity change would imply at least an 8% per degree of warming response, well above that projected by the current generation of climate models.

While the differences between modeled and observed evaporation and precipitation may be due in part to inadequate data (Allan and Soden, 2007) and short time series, the pronounced oceanic salinity trends seem consistent only with a strong response of the water cycle to warming. The models may rely too much on an assumption of equilibrium, where it should be recognized that the vast heat capacity of the ocean precludes an equilibrium climate on any timescale less than several centuries. Society is very vulnerable to drought and flood, so an intensification of the water cycle, or a rearrangement of precipitation patterns, of the magnitude suggested by the Durack et al (2012) analysis will have dramatic consequences.

Specific comments:

Lines 109-116: A lot of important but neglected high priority work is hidden in items 1 and 2, whereas items 3 and 4 seem to over-emphasize extraneous issues that the scientific community will never be able to resolve. Will this not siphon off support from the essential work that needs to get done to properly understand the water cycle? These things may be important policy issues but are decidedly not going to improve understanding of the water cycle; rather they seem to be here for political correctness. [We don’t agree – these human-related factors both influence, and are influenced by, the hydrologic cycle. We prefer to leave this list.]

Line 166: add “ocean” after “land” [Done]

Line 167: add “ocean evaporation,” after “predictions of” [Done]

Line 190: add Durack et al, 2012 to reference list. [Done]

Line 195: add “originating from the ocean” after “atmospheric rivers”. [Modified]

Lines-200-230: Somewhere in here add a discussion of the rapidly diminishing Arctic sea ice and how that adds a significant new source of moisture at high latitudes. [Done]

Line 214: Replace “ocean-moisture flux” with “ocean salinity and moisture flux”. [Done]

Line 216: add “Efforts should be made to strengthen ocean salinity measurements as an integral measure of water cycle changes through the new salinity satellites Aquarius and SMOS, the ARGO float program and the Global Drifter program.” [Done]

Line 278: add “ocean salinity” after “winds fields”. [done]

Box 3, GRACE: You should add some text about Aquarius measurements of ocean salinity for monitoring the oceanic water cycle as a complement to GRACE monitoring of the terrestrial water cycle. Actually, it may deserve its own box.

[We have chosen not to include a box on Aquarius – paper is too long, and we don’t feel this is critical here.]

Table 1: Add a separate row for Aquarius. Sea surface salinity is a direct indicator of the oceanic water cycle.

Modeling section (4): The “grand challenge” seems like more of a micro challenge to me. It

may advance local scale hydrologic modeling but a true grand challenge should be looking at big picture issues, such as the rate of intensification of the water cycle, or the oceanic SST patterns controlling drought or floods. Lines 770-782 advocate a grand challenge of determining human impacts on the water cycle. This is perhaps 10% of 10% or 1% of the water cycle. It seems that a focus on the details is distracting from where more dramatic progress can be made in terms of developing reliable predictions. Isn’t the real grand challenge to make a start on understanding the 90% of the water cycle over the oceans? This has been long neglected. The oceans are the source of atmospheric rivers and the driver of extended droughts. Please be more ambitious when issuing a “grand challenge”.

[We have made modifications to this and have expanded discussion of the critical role of the oceans.]