The observed sensitivity of the global hydrological cycle to changes in surface temperature

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Abstract
Climate models project large changes in global surface temperature in coming decades that are expected to be accompanied by significant changes in the global hydrological cycle. Validation of model simulations is essential to support their use in decision making, but observing the elements of the hydrological cycle is challenging, and model-independent global data sets exist only for precipitation. We compute the sensitivity of the global hydrological cycle to changes in surface temperature using available global precipitation data sets and compare the results against the sensitivities derived from model simulations of 20th century climate. The implications of the results for the global climate observing system are discussed.

Keywords: global change hydrological cycle

1. Introduction and background

Observations indicate that the global average annual mean surface air temperature has increased roughly 0.8 °C since 1900 (e.g., Trenberth et al 2007b). Climate modelling results indicate that this warming will continue in the future (Randall et al 2007), and significant impacts on the global hydrological cycle, including precipitation, are hypothesized. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) summarized the results of coupled ocean–atmosphere GCMs used to simulate past climate changes and to make projections of future conditions (Randall et al 2007). The results of AR4 coupled climate model simulations indicate that increases in global mean surface temperature are accompanied by consistent changes in certain aspects of the hydrological cycle. In particular, total atmospheric water vapour increases at about 7% K\textsuperscript{−1} as surface temperature increases, while precipitation increases at about 2.2% K\textsuperscript{−1} (Held and Soden 2006).

Given the significance of potential changes to the global climate, it is important to investigate the ability of our current climate observing system and resulting data sets to confirm these model results. While the impacts on humans and society will depend upon the spatial and temporal details of future variations, it is important to examine our ability to observe and simulate the globally averaged properties of the climate system, particularly the hydrological cycle. The elements of the globally averaged hydrological cycle are total atmospheric water vapour, evaporation and precipitation, and all are extremely challenging to observe. Most global diagnostic studies in recent years are based upon atmospheric observations derived from reanalyses, which are the products of data assimilation systems applied to an extended collection of relevant observations (Kalnay et al 1996, Uppala et al 2005, Onogi et al 2007). Reanalyses have become generally accepted as the most appropriate source for studies investigating the mass and motion fields of the atmosphere (see, for example, Trenberth et al 2008). However, their accuracy in depicting the
hydrological cycle is less certain, and so many investigators choose to rely more on data sets based on the merging of observations and estimates that are not filtered through a model/data assimilation system (Trenberth et al. 2007a) as a recent illustrative example). While data sets of oceanic evaporation (Yu and Weller 2007, Chou et al. 2003, Grassl et al. 2000, Wentz et al. 2007) and total atmospheric water vapour (Randel et al. 1996, Trenberth et al. 2005) largely independent of data assimilation products are available, we will focus here on precipitation due to the greater availability of data and our familiarity with the related issues. It is important to note that precipitation is not expected to increase in concert with surface temperature in the manner of atmospheric water vapour due to energetic considerations as discussed by Held and Soden (2006), among others.

The goal of this note is to determine whether currently available global data sets that are based on primarily on observations permit the confident calculation of the sensitivity of the global hydrological cycle to global surface temperature. The use of ‘climate sensitivity’ as a concept dates at least to the Charney report (NRC 1979), which examined the change in global mean surface temperature expected from a doubling of atmospheric CO₂. The several IPCC reports have used estimates of the ‘equilibrium climate sensitivity’ so defined as their consensus for projected climate change (see, e.g., IPCC 2007). Currently accepted usage defines the climate sensitivity as the projected change in global mean surface air temperature following a unit change in radiative forcing, and thus by analogy we can speak of the sensitivity of other globally averaged climate parameters to, for example, surface temperature changes (Held and Soden 2006). Here we will define the ratio of the relative change in global mean precipitation to the change in surface temperature as the sensitivity of the global hydrological cycle.

A number of recent studies (e.g., Hulme et al. 1998, Held and Soden 2006, Allan and Soden 2008) have begun to examine the sensitivity of the global hydrological cycle to climate change. At least two studies have attempted to evaluate the sensitivity of global mean precipitation to long-term changes in surface temperature from observations. Wentz et al. (2007) used oceanic satellite estimates of precipitation for the period since 1987 together with Global Precipitation Climatology Project (GPCP—Huffman et al. 1997) precipitation over land and found an increase of about 7% K⁻¹, considerably greater than expected from model results (Held and Soden 2006), but supported by a comparable change in oceanic evaporation. Adler et al. (2008), using the global GPCP data set for a somewhat longer period (1979–2007), found an increase in global precipitation of about 2.5% K⁻¹, more consistent with the AR4 model results. In both cases, confidence in the trend calculation is limited due to the short record, the presence of shorter-term variability of uncertain origin, and the underlying sampling and algorithm errors inherent in the observations and estimates used. Liepert and Previdi (2009) examined the sensitivity of the hydrological cycle during the 20-year period beginning in 1987 when precipitation estimates based on microwave observations permitted relatively accurate oceanic precipitation data sets and discussed the relative significance of greenhouse gas and atmospheric aerosol forcing for changes in global precipitation. They concluded that the period was too short to permit robust conclusions about the disagreements between models and observations.

In this article, we will use several observed global precipitation data sets to calculate the sensitivity of the hydrological cycle, as indicated by changes in global mean precipitation, to changes in global mean temperature. Our goal is to provide a straightforward assessment of the confidence with which available observation-based data sets can be used to verify or falsify this aspect of the current generation of climate models, and to indicate where improved observed data sets are essential.

2. Observed globally averaged precipitation

Three global precipitation products, GPCP (Huffman et al. 1997, 2009, Adler et al. 2003), CMAP (Xie and Arkin 1997) and MSAP (Sapiano et al. 2008), each provide a several decade long (1979–present) record of global precipitation based on observations. The precipitation data sets are all based on the combination of rain gauge observations over land with estimates derived from satellite data. In addition, MSAP uses precipitation forecasts from ERA-interim and ERA-40 to improve the analyses in higher latitudes. The satellite inputs used differ to some degree among the various products, as do the methodologies used to produce the combined analyses. We compare variability in the time series of precipitation to the global temperature time series produced by the Climate Research Unit (CRU) of the University of East Anglia (Jones et al. 1999, Jones and Moberg 2003) to determine the degree to which observed global temperature changes are accompanied by changes in precipitation. The CRU global mean surface air temperature time series is derived from a combination of land surface and sea surface temperature analyses. While it differs to some degree from other available surface air temperature data sets (Hansen et al. 1999, 2006, Smith and Reynolds 2005, Smith et al. 2008a) the differences are quite small compared to the differences among the precipitation products. In the following discussion, we will use P to represent global (or near-global) mean precipitation, T₆ to represent global mean surface air temperature, and S to indicate the sensitivity of the global hydrological cycle to changes in global mean surface air temperature. The index S is calculated as follows:

\[ S = 100 \times (\Delta P / (P \times \Delta T_S)) \]

where the changes in P and T₆ are taken over some common period, generally the longest available for the phenomenon under discussion.

Figure 1 shows the anomalies in the three P time series together with anomalies in T₆. The substantial increase in global mean surface temperature during the past few decades has been extensively discussed (Randall et al. 2007) and is clear here. A simple linear trend computed over the period 1979–2006 gives a T₆ change of 0.027 K/year. The trends calculated from GPCP, CMAP and MSAP are 0.0011, −0.0029 and
physical mechanisms controlling the relation between surface temperature and precipitation during the annual cycle may well differ from those operating on longer timescales, it seems reasonable to compare the available observational data to model calculations to determine whether observations and models agree on this aspect of the global climate.

The annual cycles of monthly mean $P$ and $T_S$ over the 30-year period (figure 2—the mean annual cycle is repeated six times) do show signs of a connection, although certainly not a simple one. $T_S$ exhibits a very clear annual cycle, and spectral decomposition (not shown) shows no indication of any semiannual influence. The maximum is in July and the minimum in January, indicating that the principal influence is the sun angle relative to the distribution of land and ocean, and the range is about 3.7 K. The three $P$ time series all exhibit local maxima during Boreal summer, consistent with the peak in $T_S$, and all also present relative maxima during Austral summer. While CMAP and MSAP, can be interpreted as resulting from the superposition of annual and semiannual cycles, GPCP varies throughout the year so that clear annual and semiannual cycles are not evident. Calculating $S_H$ from these data is problematic, since it is clear that the variations in $P$ are not related to $T_S$ in a simple way. If we use the difference between maximum and minimum values through the year of each, then we get sensitivities of $0.6/1.3/1.9$% K$^{-1}$ for GPCP/MSAP/CMAP, respectively.

While it appears that the sensitivity of the annual cycles in $P$ and $T_S$ in climate models has not been calculated in this manner, we can compare the observed values to those calculated from reanalyses. $P$ and $T_S$ taken from three atmospheric reanalyses, ERA-40/interim (Uppala et al 2005), NCEP/NCAR-1 (Kalnay et al 1996) and JRA-25 (Onogi et al 2007), exhibit clear mean annual cycles (figure 3). All three reanalyses show seasonal mean variations in $T_S$ and $P$ that are similar to observations, although the annual harmonic in $P$ is stronger relative to the semiannual than seen in observations. $S_H$ calculated from ERA-interim, NCEP/NCAR-1 and JRA-25 are $1.9, 2.8$ and $3.1$% K$^{-1}$, respectively, somewhat larger than from observations.

The global mean temperature time series is available for the entire 20th century, and the recent publication of a reconstruction of near-global precipitation (Smith et al 2008b, 2009a, 2009b, 2010) has made it possible to compare the trends in $T_S$ and $P$ over the entire period (figure 4). The reconstruction process reduces or removes much of the noise and short-term variability from the data set (Smith et al 2009b), and thus it is unsurprising that the global mean $P$ shows a prominent trend that is visually similar to that in $T_S$. The visual impression is supported by the fact that the two time series are correlated at 0.56, yielding $S_H$ of 2.5% K$^{-1}$, a value that is quite close to the 2.2% K$^{-1}$ calculated by Held and Soden (2006) from AR4 simulations of the period 1860–2000.

3. Conclusions and implications

An acceleration of the global hydrological cycle in response to increasing surface air temperature has been hypothesized. The sensitivity of the hydrological cycle to temperature changes can be represented by an index calculated as the ratio of the
percentage change in global mean precipitation to the change in global mean surface air temperature over common periods. The sensitivity calculated from three global precipitation data sets for the period 1979–2008 is highly uncertain due to large non-trend variability in the precipitation data, but appears to be of the same sign although somewhat less than that obtained from model simulations for the historical period. Use of a reconstructed near-global precipitation data set for the entire 20th century yields a more confident estimate of 2.5% K\(^{-1}\) for the sensitivity, which is quite close to the value of 2.2% K\(^{-1}\) obtained from AR4 model simulations for a similar period.

Two main conclusions follow from our results.

1. The sensitivity of the global hydrological cycle to global temperature change calculated using the longest available observation-based data set is consistent with model results in indicating an acceleration of the hydrological cycle as surface temperatures increase. Note that this result cannot speak to the regional or local implications of global change. It is also important to note that uncertainties in the precipitation reconstruction related to sampling, algorithm error and inhomogeneity of the record have not been quantified in the present study, and may be substantial. These issues should be addressed in future work.

2. The sensitivity calculated using the global precipitation data sets currently used for most climate studies does not agree with that derived from model and reanalysis products. These disagreements presumably reflect deficiencies in both the models and the observations, as well as the short period when precipitation observations over the ocean are most accurate. However, our results...
Figure 4. Time series of surface temperature anomalies (solid line; scale on left; base period 1961–1990) and precipitation anomalies (dashed; scale on right in mm month$^{-1}$ units; base period 1981–1990). Temperature data are from Jones et al (1999) and precipitation data are reconstructed to provide estimates prior to 1979 (Smith et al 2009a, 2009b).

indicate that one factor is that state of the art precipitation data sets are not sufficiently robust to permit the accurate calculation of globally averaged properties, as indicated by the disagreements among GPCP, CMAP and MSAP in representing the global mean annual cycle and trends in globally averaged precipitation. Thus continued efforts to improve the accuracy and consistency of global precipitation data sets remain crucial to confirm climate model results and to lend confidence to diagnostic studies of climate variability and change.

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References

Adler R F, Gu G, Wang J-J, Huffman G J, Curtis S and Bolvin D 2008 Relationships between global precipitation and surface temperature on inter-annual and longer timescales (1979–2006) J. Geophys. Res. 113 D22104

Adler R F, Wang J.J and Huffman G J 2009 A ten-year tropical rainfall climatology based on a composite of TRMM products J. Meteorol. Soc. Japan A 87 281–93

Adler R F et al 2003 The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present) J. Hydromet. 4 1147–67

Allan R P and Soden B J 2008 Atmospheric warming and the amplification of precipitation extremes Science 321 1481–4

Chou S H, Nelkin E, Ardizzone J, Atlas R M and Shie C L 2003 Surface turbulent heat and momentum fluxes over global oceans based on the Goddard Satellite retrievals, version 2 (GSSTF2) J. Clim. 16 3256–73

Grassl H, Jost V, Kumar A, Schultz J R, Bauer P and Schlaussel P 2000 The Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data (HOAPS): A Climatological Atlas of Satellite-Derived Air–Sea-Interaction Parameters over the Oceans (Hamburg: Max Planck Institute for Meteorology)

Hansen J, Ruedy R, Glasscoe J and Sato M 1999 GISS analysis of surface temperature change J. Geophys. Res. 104 30997–1022

Hansen J, Sato M, Ruedy R, Lo K, Lea D W and Medina-Elizade M 2006 Global temperature change Proc. Natl Acad. Sci. 103 14288–93

Held I M and Soden B J 2006 Robust responses of the hydrological cycle to global warming J. Clim. 19 5686–99

Huffman G J, Adler R F, Bolvin D T and Gu G 2009 Improving the global precipitation record: GPCP version 2.1 Geophys. Res. Lett. 36 L17808

Huffman G J et al 1997 The Global Precipitation Climatology Project (GPCP) combined precipitation datasets Bull. Am. Meteorol. Soc. 78 5–20

Hulme M, Osborn T J and Johns T C 1998 Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulations Geophys. Res. Lett. 25 3379–82

IPCC 2007 Summary for policymakers Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averet, M Tignor and H L Miller (Cambridge: Cambridge University Press)

Jones P D and Moberg A 2003 Hemispheric and large-scale surface air temperature variations: an extensive revision and update to 2001 J. Clim. 16 206–23

Jones P D, New M, Parker D E, Martin S and Rigor I G 1999 Surface air temperature and its variations over the last 150 years Rev. Geophys. 37 173–99
Kalnay E et al 1996 The NCEP/NCAR 40-year reanalysis project Bull. Am. Meteorol. Soc. 77 437–72
Liepert B and Previdi M 2009 Do models and observations disagree on the rainfall response to global warming? J. Clim. 22 3156–66
National Research Council 1979 Carbon Dioxide and Climate: A Scientific Assessment (Washington, DC: National Academy of Sciences) p 22
Onogi K et al 2007 The JRA-25 reanalysis J. Meteorol. Soc. Japan 85 369–432
Randall D A et al 2007 Climate models and their evaluation Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averly, M Tignor and H L Miller (Cambridge: Cambridge University Press)
Randel D L, Greenwald T J, Vonder Haar T H, Stephens G L, Ringerud M A and Combs C L 1996 A new global water vapor dataset Bull. Am. Meteorol. Soc. 77 1233–46
Sapiano M R P, Smith T M and Arkin P A 2008 A new merged analysis of precipitation utilizing satellite and reanalysis data J. Geophys. Res. 113 D22103
Smith T M, Arkin P A and Sapiano M R P 2009a Reconstruction of near-global annual precipitation using correlations with sea surface temperature and sea level pressure J. Geophys. Res. 114 D12107
Smith T M, Arkin P A, Sapiano M R P and Chang C-Y 2010 Merged statistical analyses of historical monthly precipitation anomalies beginning 1900 J. Clim. in press
Smith T M and Reynolds R W 2005 A global merged land air and sea surface temperature reconstruction based on historical observations (1880–1997) J. Clim. 18 2021–36
Smith T M, Reynolds R W, Peterson T C and Lawrimore J 2008a Improvements to NOAA’s historical merged land–ocean surface temperature analysis (1880–2006) J. Clim. 21 2283–96
Smith T, Sapiano M and Arkin P 2009b Modes of multi-decadal oceanic precipitation variations from a reconstruction and AR4 model output for the 20th century Geophys. Res. Lett. 36 L14708
Smith T M, Sapiano M R P and Arkin P A 2008b Historical reconstruction of monthly oceanic precipitation (1900–2006) J. Geophys. Res. 113 D17115
Trenberth K E, Fasullo J and Smith L 2005 Trends and variability in column integrated atmospheric water vapor Clim. Dyn. 24 741–58
Trenberth K E, Koike T and Onogi K 2008 Progress and prospects in reanalysis Eos 89 234–5
Trenberth K E, Smith L, Qian T, Dai A and Fasullo J 2007a Estimates of the global water budget and its annual cycle using observational and model data J. Hydrometeorol. 8 758–69
Trenberth K E et al 2007b Observations: surface and atmospheric climate change Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averly, M Tignor and H L Miller (Cambridge: Cambridge University Press)
Uppala S M et al 2005 The ERA-40 reanalysis Q. J. R. Meteorol. Soc. 131 2961–3012
Wentz F J, Ricciardulli L, Hilburn K and Mears C 2007 How much more rain will global warming bring? Science 317 233–5
Xie P and Arkin P A 1996 Global monthly precipitation estimates from satellite-observed outgoing longwave radiation J. Clim. 11 137–64
Xie P and Arkin P A 1997 Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs Bull. Am. Meteorol. Soc. 78 2539–58
Yin X, Gruber A and Arkin P 2004 Comparison of the GPCP and CMAP merged gauge-satellite monthly precipitation products for the period 1979–2001 J. Hydrometeorol. 5 1207–22
Yu L S and Weller R A 2007 Objectively analyzed air–sea heat fluxes for the global ice-free oceans (1981–2005) Bull. Am. Meteorol. Soc. 88 527–39