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How Much Will Precipitation Increase With Global Warming?

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The advent of meteorological satellites during the 1970s made possible the observation of the seasonally shifting patterns of global precipitation. It was not until recently, however, that the record could be considered long enough to investigate longer-term trends and the relationship between global precipitation and global warming. Using data from the Special Sensor Microwave Imager (SSM/I) instrument, *Wentz et al.* [2007] reported that global mean precipitation increased at a rate of 7.4 ± 2.6% per °C between 1987 and 2006.

Meanwhile, general circulation models (GCMs) used to predict climate change simulate twentieth- and 21st-century mean precipitation increases of about 1–3% per °C [*Held and Soden*, 2006]. This difference seems surprising because some GCMs can adequately reproduce the much longer twentieth-century surface-based land-mean precipitation record [*Lambert et al.*, 2005]. Global precipitation changes are tied to the surface energy budget through evaporation and to the tropospheric energy budget through condensation. Thus, if GCMs do underestimate global precipitation changes, the simulation of other climate variables will be affected.

Should GCM results be reevaluated in light of *Wentz et al.*'s [2007] findings? We find that 20-year trends are not directly comparable to 100-year trends. Hence, observations are not directly comparable to century-long GCM simulations [see also *Previdi and Liepert*, this issue]. Proper consideration is necessary of the physical processes potentially behind changes in the water cycle.

Observation of Precipitation and Evaporation

Global precipitation observations derived from satellite radiance measurements were first available in 1979. Using SSM/I data, *Wentz et al.* [2007] found that global precipitation increased by 7.4 ± 2.6% per °C during 1987–2006. Trends in Global Precipitation Climatology Project (GPCP) data, which are derived from a mixture of satellite- and surface-based products, are comparable.

Wentz et al. [2007] estimated the relationship between precipitation and temperature by dividing 20-year precipitation trends by 20-year temperature trends. Their error calculation estimated observational uncertainty but did not account for natural variability or other factors that may control precipitation. As such, their analysis tells us how much precipitation actually increased but does not describe the full range of possible fundamental relationships between precipitation and temperature. Estimating variability by using the residual error from their regression, we found a total error of 4.6% per °C.

The precipitation-temperature relationship can be found more directly by regressing annual mean precipitation directly onto annual mean temperature. This preserves the relationship between precipitation and temperature in every year, allowing us to reduce the probable range of relationships. By doing this, the estimated relationship is less positive, but the error bars are narrower: 6.7 ± 3.5% per °C.

Because water vapor has a residence time in the atmosphere of about 10 days, precipitation and evaporation amounts are almost equal on monthly and longer timescales. Hence, global precipitation changes must agree with contemporaneous global evaporation changes. *Wentz et al.* [2007] calculated an evaporation trend based on an independent retrieval of wind speed. They assumed that land evaporation remained constant during 1987–2006 because it cannot be retrieved from SSM/I. Estimates of recent land evaporation change do vary greatly: Compare, for example, approximately +4.7% per °C for 1950–2000 from *Brutsaert* [2006] with −2.5 ± 1.0% per °C for 1960–1990 from *Wild et al.* [2004]. However, probable ocean evaporation changes taken from SSM/I data are large enough that the possible range of land evaporation changes does not significantly affect *Wentz et al.*'s [2007] conclusions. Simultaneously regressing SSM/I evaporation and precipitation measurements directly onto temperature reduces our best estimate but does not narrow the error bars: 6.0 ± 3.5% per °C.

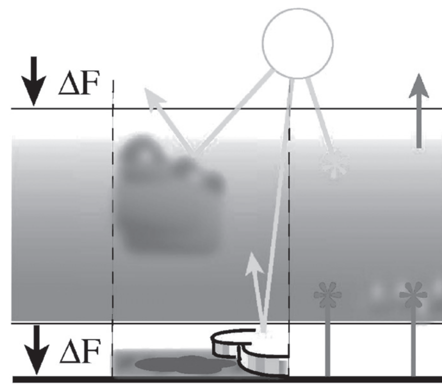

Fig. 1. Solar shortwave (yellow) and infrared longwave (red) radiation in the atmosphere. Fluxes ending in arrows are transmitted; fluxes ending in stars are absorbed. (left section) Global warming–independent adjustment to forcing eliminates net atmospheric energy absorption. Hence, net forcing (ΔF) is the same at the tropopause and surface. (middle section) Reflection of sunlight by clouds and the surface affects precipitation indirectly through surface temperature. (right section) Atmospheric absorption of sunlight and absorption and emission of infrared affect precipitation through surface temperature and directly through the tropospheric energy budget. Original color image appears at the back of this volume.

Overall, then, we find that the observed precipitation-temperature relationship may be weaker than reported by *Wentz et al.* [2007]. Nevertheless, we must conclude that increases in observed precipitation appear inconsistent with GCM values.

Understanding Precipitation Change and Its Link to Temperature

When tropospheric moisture condenses and precipitation falls, latent heat is released. Hence, increases in global mean precipitation are accompanied by increases in surface-to-troposphere latent heat transfer. Because the heat capacity of the troposphere is small on climatic timescales, energy conservation demands that increases in latent heating must be balanced by increased tropospheric

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radiative cooling and decreased sensible heating (conduction and dry convection) from below.

Global warming–driven increases in surface and tropospheric temperatures result in increases in tropospheric radiative cooling. To preserve energy balance, latent heating must increase to balance this cooling. Therefore, precipitation increases with global warming.

This is not the whole story, however, because climate forcings that cause global warming can directly affect precipitation independent of their effects through global surface temperature change. In GCMs, for example, the temperature-dependent precipitation increase due to a carbon dioxide (CO_2) increase is offset by about 25% through CO_2's ability to trap additional infrared radiation as heat [e.g., *Allen and Ingram,* 2002].

The climate system's response to external forcing can be separated into global warming–dependent and –independent feedbacks (see Figure 1). Global warming–independent feedbacks (Figure 1, left section) occur when the troposphere is made to absorb energy by forcing. Because of its small heat capacity, either the troposphere must export the additional absorbed energy, or it must decrease the import of some other form of energy. Relevant adjustments of surface and tropospheric energy fluxes occur over a few months. In the case of increased CO_2 in GCMs, the adjustment is largely a decrease in atmospheric latent heating (less precipitation). In the case of solar forcing in GCMs, a rapid tropospheric warming independent of surface warming causes the troposphere to cool to space and the surface, but with almost no effect on precipitation. After adjustment, no further net tropospheric energy absorption occurs. Hence, a net downward energetic forcing on climate, ΔF in Figure 1, has the same value at the tropopause and the surface.

Global warming–dependent feedbacks (Figure 1, middle and right sections) occur over a period of years as surface and tropospheric temperatures increase until equilibrium is reestablished. The net effect is to increase the rate of tropospheric radiative cooling, allowing latent heating and precipitation to increase. Global warming–dependent feedbacks depend primarily on the amount of warming and less on the type of forcing.

We now examine the modeling uncertainties that produce different GCM global precipitation responses to external forcing. Putting global warming–independent feedbacks (Figure 1, left section) aside for a moment, we consider the relationship between precipitation and temperature alone (Figure 1, middle and right sections).

The feedbacks in Figure 1 (middle section) control the reflection of solar shortwave radiation by clouds and the surface. These are highly uncertain and are key to producing the range of global temperature sensitivities to forcing seen in GCMs [*Webb et al.*, 2006]. However, most solar radiation is either absorbed by the surface or reflected back to space. Relatively little is absorbed in the troposphere. As a result, the Figure 1 (middle section) feedbacks primarily affect the tropospheric energy budget through their effects on surface temperature alone. Uncertainties in their formulation in GCMs lead to uncertainty in total surface temperature change to a given forcing and uncertainty in total precipitation change. To first order, however, these uncertainties do not affect the rate at which precipitation changes with temperature.

The feedbacks in Figure 1 (right section) are the clear-sky absorption of shortwave (yellow) and the clear-sky and cloudy absorption and emission of infrared longwave radiation (red). These not only influence surface temperature but also directly govern the rate at which tropospheric cooling changes per unit temperature. As a result, uncertainties in GCM formulation of these feedbacks introduce uncertainty not only in total temperature and precipitation change but also in the rate at which precipitation changes with temperature. With the exception of longwave cloud effects, however, such feedbacks are believed to be relatively well understood. The Figure 1 (right section) feedbacks are therefore quite similar in different GCMs, meaning that the relationship between precipitation and temperature is quite similar in different GCMs.

Could errors in longwave cloud feedbacks explain the difference between observed and modeled precipitation? Changing GCM tropopause longwave cloud feedbacks would mean significantly altering the sensitivity of GCM temperatures to forcing, unless other tropopause feedbacks are also changed. As *Wentz et al.* [2007] point out, however, this is probably undesirable because GCM temperature sensitivities are consistent with observed estimates.

We should focus instead on the surface. Currently, observations of surface longwave radiation are very limited. However, we note that a reduction of about 0.03 watts per square meter per year during the past 20 years would be sufficient to increase GCM precipitation from 1.3% per ºC to 5.7% per ºC, assuming that compensation occurs entirely through latent heating.

Global Brightening

We now return to global warming–independent feedbacks (Figure 1, left section). Given the dependence of these on forcing type, a natural question is whether it is fair to compare all twentieth- and 21st-century GCM results with 1987–2006 observed values. For example, a significant new component of climate change during the past 50 years is global dimming, which is the reduction in surface insolation caused by increasing concentrations of atmospheric aerosols. Because the aerosols absorb solar radiation, they can affect precipitation directly, independent of surface temperature change.

During the past 20 years, a reverse in global dimming, known as global brightening, has been observed as carbonaceous aerosol concentration has decreased. Has precipitation increased since 1987 because decreasing tropospheric aerosol concentration has decreased tropopause shortwave absorption? The 1987–2006 GCM values from the Intergovernmental Panel on Climate Change's Fourth Assessment Report are 0.8–4.4% per ºC, slightly more consistent with observations (Mat Collins, personal communication, 2008; see also *Previdi and Liepert* [this issue] for a more thorough examination of these data). However, many of these do not simulate the full effects of observed absorbing aerosol concentrations. We can only speculate, therefore, on the role of brightening during the past 20 years. The approximately 0.03 watts per square meter per year necessary to increase GCM precipitation values to 5.7% per ºC is certainly compatible with the 0.04 watts per square meter per year brightening trend estimated by *Romanou et al.* [2007]. We should remember, however, that not all global brightening is due to a reduction in atmospheric shortwave absorption and that not all reductions in absorption lead to increases in latent heat flux. GCM experiments that represent the full effects of dimming aerosol over the observed period are necessary.

Directions for Future Research

We urge caution in declaring that observed and GCM global mean precipitation changes and their relationship to temperature differ significantly. Relevant uncertainties in recent observations may be larger than originally thought. Those observations should also be compared only with GCM experiments that simulate the same period of time under the same forcings, because precipitation is not merely a function of temperature. Correct simulation of aerosols and global brightening may be important for 1987–2006. If a difference persists, then it is probable that interactions at the surface are responsible. Problems with GCM longwave cloud feedbacks are a candidate but may remain unresolved until better surface observations are available. In this article, we have concentrated on atmospheric processes. However, new developments in land surface modeling, such as fully coupled vegetation, could also significantly affect the modeled hydrologic cycle.

If global brightening is responsible for the high rate of precipitation increase during the past 20 years, then we should observe smaller increases in precipitation per degree of warming in the future as brightening subsides and greenhouse gas–driven changes take over. Alternatively, if significant relevant model errors remain, we could see precipitation changes 2 or 3 times larger than climate models predict.

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Interdecadal Variability of Rainfall on a Warming Planet

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How much will the global water cycle accelerate with global warming? In a recent study, *Wentz et al.* [2007] used satellite observations to show that global mean precipitation increased by 7% per °C increase in global mean surface temperature over the period between July 1987 and August 2006. This yields an absolute precipitation increase of 13.2 ± 4.8 millimeters per year per decade, a rate of increase that is 2–3 times greater than that simulated by general circulation models (GCMs). Century-long integrations of GCMs also yield much smaller global precipitation increases of about 1–3% per °C of global warming [*Held and Soden*, 2006]. Nonetheless, *Wentz et al.* [2007, p. 235] argue that the recent 20-year period may "be long enough to indicate that the observed scaling relations [e.g., between precipitation and temperature] will continue on a longer time scale," implying significant errors in climate model predictions.

We present evidence for large interdecadal variability in the global precipitation response to temperature changes, implying that the observed response during any given 20-year period may be unrepresentative of longer-term precipitation changes with global warming.

Further, we suggest that the rapid increase in global precipitation observed during 1987–2006 occurred because decreases in atmospheric aerosol loading accompanied increases in greenhouse gases. These decreases in natural and anthropogenic aerosol concentrations should have contributed to an increase in global rainfall that is in addition to the increase caused by rising greenhouse gas amounts. If the recent reduction in aerosol loading does not persist (e.g., if aerosol concentrations stabilize), then the scaling relation between precipitation and temperature observed during the past 20 years may not hold into the future.

Hydrological Sensitivity and Its Interdecadal Variability

Lambert et al. [this issue] seek to reconcile GCM and observed precipitation changes by performing a more thorough analysis of possible errors in *Wentz et al.*'s [2007] calculations. We use a different approach to show that Wentz et al.'s results are not inconsistent with GCMs if interdecadal variability in the rainfall response to global warming is taken into account.

The relationship between precipitation and temperature can be expressed as a hydrological sensitivity, which we define as the ratio of linear trends in global mean precipitation and surface air temperature. Figure 1 shows distributions of hydrological sensitivity for 20-year periods in the twentieth and 21st centuries based on output from eight coupled atmosphere-ocean GCMs. The median of both distributions is 1.4% per °C, in line with the modeling results cited above.

The hydrological sensitivity during a given 20-year period, however, can vary significantly from this average value. For example, 7% of the twentieth-century distribution is at or above the 7% per °C hydrological sensitivity observed during 1987–2006. Such relatively large sensitivities are therefore not outside the GCMs' range of interdecadal variability. The long-term (i.e., century-scale) hydrological sensitivity to global warming, however, which we approximate as the median of the distributions, is substantially smaller.

Why Does Global Warming Bring More Rainfall?

Solar radiation is the primary driver of the water and energy cycles on Earth. About half of the total incoming solar (or shortwave) radiation at the top of the atmosphere is absorbed by Earth's surface, and the surface heats up. In an effort to cool itself, the surface emits terrestrial (or longwave) radiation. The net longwave loss from the surface, however, does not entirely compensate for the solar gain, and thus when averaged globally and over the course of a year the surface has a net radiative energy gain.

To maintain total energy balance, there is a transfer of nonradiative energy from the surface to the troposphere. This nonradiative energy transfer takes primarily the form of latent and sensible heat fluxes, with the latent heat flux being about 5 times larger than the sensible heat flux in the global, annual mean. The latent heat flux from the surface to the troposphere is associated mainly with evaporation of surface water. When this water condenses in the troposphere to form clouds and eventually precipitation, the troposphere heats up and then radiates this energy gain out to space. The radiative energy loss from the troposphere is equal in magnitude to the radiative energy gain at the surface. The global water cycle is therefore fundamentally a part of the global energy cycle, and any changes in global mean precipitation and evaporation are consequently constrained by the energy budgets of the troposphere and surface.

With anthropogenic global warming, the troposphere loses more longwave radiation because the longwave emission is proportional to the fourth power of temperature according to the Stefan-Boltzmann radiation law. This additional loss of radiative energy from the troposphere is approximately balanced by an additional gain of energy from enhanced latent heating associated with greater precipitation [*Mitchell et al.*, 1987]. In other words, global warming brings more rainfall to satisfy the requirement of tropospheric energy balance. An important consideration is that the increasing loss of longwave energy from the troposphere with global warming is partially offset by a decreasing efficiency of longwave energy loss with higher atmospheric carbon dioxide (CO_2) levels [*Allen and Ingram*, 2002]. The result of this CO_2-induced reduction in longwave efficiency (or emissivity) is that a smaller increase in latent heating and thus

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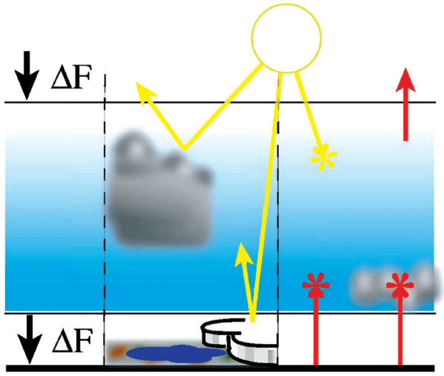

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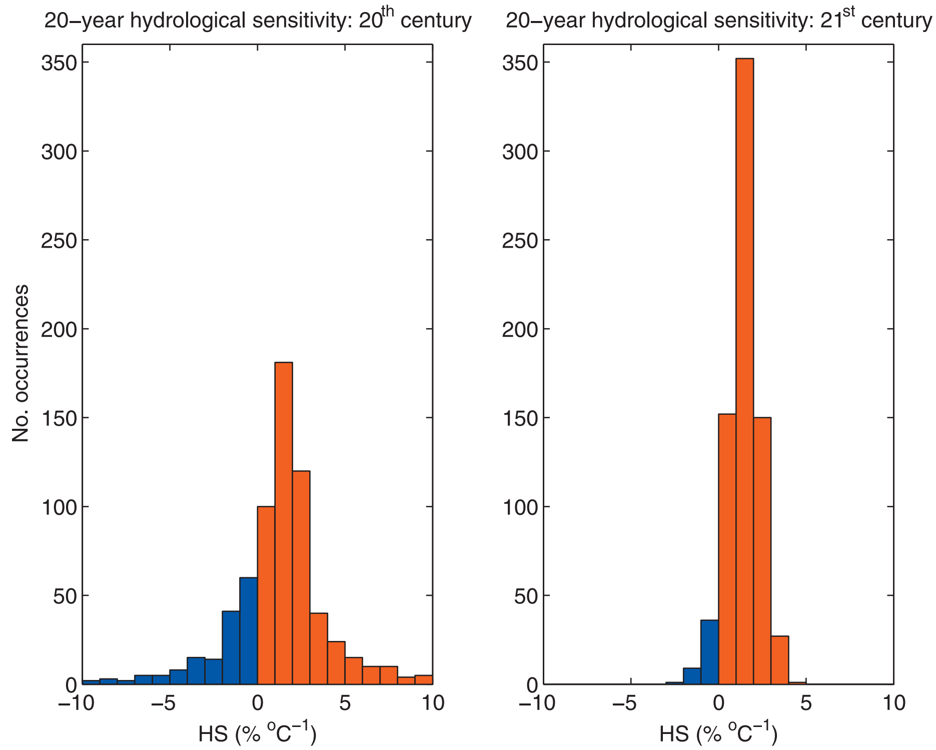

Fig. 1. Distributions of 20-year hydrological sensitivity (HS), defined as the 20-year linear trend in global mean precipitation divided by the 20-year linear trend in global mean surface air temperature. Negative HS values are shown in blue. Trends were calculated for overlapping 20-year periods in the twentieth and 21st centuries (e.g., 1900–1919, 1901–1920, and so forth) using output from the following eight climate models that participated in the Intergovernmental Panel on Climate Change Fourth Assessment Report: Geophysical Fluid Dynamics Laboratory (GFDL) CM2.0; GFDL CM2.1; Goddard Institute for Space Studies (GISS) EH; Institute for Numerical Mathematics CM3; Center for Climate System Research (MIROC) high resolution; MIROC medium resolution; Meteorological Institute of the University of Bonn (MIUB) ECHO; and National Center for Atmospheric Research (NCAR) CCSM3. Model data for the twentieth and 21st centuries are from the climate of the twentieth-century experiment and the A1B experiment, respectively. These HS distributions illustrate large interdecadal variability in the global precipitation response to temperature changes, suggesting that the precipitation response during any given 20-year period may be unrepresentative of the longer-term response. Adapted from Liepert and Previdi *[2008].*