EDITORIAL

The Earth radiation balance as driver of the global hydrological cycle

Martin Wild
Institute for Atmospheric and Climate Science, ETH Zurich, Universitätsstr. 16, CH-8092 Zurich, Switzerland

Beate Liepert
NorthWest Research Associates, 4118 148th Ave NE, Redmond, WA 98052, USA

Variations in the intensity of the global hydrological cycle can have far-reaching effects on living conditions on our planet. While climate change discussions often revolve around possible consequences of future temperature changes, the adaptation to changes in the hydrological cycle may pose a bigger challenge to societies and ecosystems. Floods and droughts are already today amongst the most damaging natural hazards, with floods being globally the most significant disaster type in terms of loss of human life (Jonkman 2005). From an economic perspective, changes in the hydrological cycle can impose great pressures and damages on a variety of industrial sectors, such as water management, urban planning, agricultural production and tourism. Despite their obvious environmental and societal importance, our understanding of the causes and magnitude of the variations of the hydrological cycle is still unsatisfactory (e.g., Ramanathan et al 2001, Ohmura and Wild 2002, Allen and Ingram 2002, Allan 2007, Wild et al 2008, Liepert and Previdi 2009).

The link between radiation balance and hydrological cycle

Globally, precipitation can be approximated by surface evaporation, since the variability of the atmospheric moisture storage is negligible. This is the case because the fluxes are an order of magnitude larger than the atmospheric storage (423 × 10^{12} m^3 year^{-1} versus 13 × 10^{12} m^3 according to Baumgartner and Reichel (1975)), the latter being determined by temperature (Clausius–Clapeyron). Hence the residence time of evaporated water in the atmosphere is not more than a few days, before it condenses and falls back to Earth in the form of precipitation. Any change in the globally averaged surface evaporation therefore implies an equivalent change in precipitation, and thus in the intensity of the global hydrological cycle. The process of evaporation requires energy, which it obtains from the surface radiation balance (also known as surface net radiation), composed of the absorbed solar and net thermal radiative exchanges at the Earth’s surface. Globally averaged, this surface radiation balance is positive, since radiative absorption, scattering and emission in the climate system act to generate an energy surplus at the surface and an energy deficit in the atmosphere (Liepert 2010).

Evaporation, or more precisely its energy equivalent, the latent heat flux, is the main process that compensates for this imbalance between surface and atmosphere, since the latent heat dominates the convective energy flux over sensible heating. The radiative energy surplus at the surface is thus mainly consumed by evaporation and moist convection and subsequently released in the atmosphere through condensation. This implies that any alterations in the available radiative energy will induce changes in the water fluxes. Our focus in this editorial is therefore on the surface radiation balance as the principal driver of the global hydrological cycle.

Note that this energetic view is in agreement with that of Richter and Xie (2008) who argue that the spatial and temporal behaviour of the process of evaporation is controlled by surface and atmospheric properties such as atmospheric stability, wind speed, moisture deficit and moisture availability.
From radiation theory it is expected that with increasing radiative absorption due to abundance of anthropogenic greenhouse gases in the atmosphere and consequent warming, the emission of thermal energy from the atmosphere towards the surface is increasing (known as downward thermal radiation). This enhances the radiative energy surplus at the surface, and, where surface water is not limited, fuels evaporation besides warming the Earth’s surface. The enhanced greenhouse effect therefore tends to accelerate the hydrological cycle, as also shown in many climate model simulations with increasing levels of greenhouse gases (e.g., IPCC 2007, but also see Yang et al 2003, Andrews et al 2009). We can assume that the increase in greenhouse gases since preindustrial times had already led to a substantial increase of downward thermal radiation during the 20th century, even though direct observational evidence is sparse and restricted to the latter part of the century (Philipona et al 2004, Wild et al 2008). Precipitation records averaged over global land surfaces indicate an overall, albeit not significant, increase in precipitation and intensification of the hydrological cycle over the 20th century (Trenberth et al 2007), in line with the aforementioned surface energy gain from the increased greenhouse gases and related downward thermal radiation. However, the observations show also that precipitation has not simply followed the increasing greenhouse gas forcing, but has undergone strong decadal variations, with extended periods of both increases and decreases. This is evident in figure 1(a), which shows global land precipitation over the 20th century as determined from the Global Historic Climate Network (GHCN; Peterson and Vose 1997, see also Trenberth et al 2007, figure 3.12). An increase in precipitation can be noted in the 1940s, followed by an overall decrease until the mid-1980s, and a renewed increase more recently.

![Figure 1](image_url)

**Figure 1.** Observed terrestrial precipitation anomalies (a) and the longest observational surface solar radiation record measured in Stockholm (b) covering the period 1923–2000 (annual means). The 11-year running means are given in blue. Precipitation data from GHCN, radiation data from GEBA.
However, not only greenhouse-gas-induced thermal radiation changes, but also solar radiation, as a result of changes in the atmospheric transmission, can alter the surface radiation balance and thus the amount of energy available to drive the hydrological cycle. Solar forcings may be even more efficient in modifying the intensity of the hydrological cycle than thermal forcings, as indicated by a higher hydrological sensitivity (e.g., Allen and Ingram 2002, Liepert et al 2004). The hydrological sensitivity, defined as change of precipitation per unit temperature change, is found to be 2–3 times larger under solar forcings than under thermal forcings (Liepert et al 2004, Andrews et al 2009). This is related to the fact that solar forcings apply at the surface directly because of the high solar transparency of the atmosphere compared to thermal radiation. Solar forcings thus effectively alter the surface radiation balance and the associated imbalance between the surface and atmospheric energy contents, which needs to be compensated for by convective fluxes and related evaporation/precipitation.

Greenhouse-gas-induced thermal forcings, on the other hand, heat the atmosphere directly through radiative absorption and the surface indirectly through downward thermal radiation. Thermal forcings are therefore less effective in strengthening the imbalance between the surface and atmospheric energy contents. Hence the required changes in the compensational convective fluxes and associated evaporation/precipitation are smaller (equation (4) in Liepert and Previdi 2009). The different effects of solar and thermal forcings become particularly evident in the direct (fast) response of the hydrological cycle to them, while the subsequent longer-term response of the hydrological cycle, including all feedbacks induced by these forcings, is similar between the two forcing mechanisms (Andrews et al 2009, Lambert and Webb 2008). The direct effect of doubling of CO₂ concentration reduces the precipitation increase in climate models by about 25% (Lambert and Webb 2008), while such compensational effects do not apply with solar forcings.

Recent evidence suggests that the amount of solar radiation incident at the Earth’s surface (hereafter referred to as downward solar radiation) has indeed not been stable over time but has undergone significant variations on decadal timescales. This evidence comes from the networks of surface radiation measurements taken around the globe which became operational on a widespread basis during the 1950s. Specifically, the measurements show a predominant decrease in downward solar radiation from the 1950s up to the 1980s (known as ‘global dimming’) and a partial recovery thereafter at many of the sites (known as ‘brightening’) (e.g., Gilgen et al 1998, Stanhill and Cohen 2001, Liepert 2002, Wild et al 2005, Wild 2009a). The consecutive downward and upward trends have at least to some extent been attributed to increasing and decreasing air pollution, respectively (Streets et al 2009), apart from the natural inter-decadal variability of cloudiness and volcanic eruptions. The longest observational records show in addition a tendency for an increase in downward solar radiation in the first part of the 20th century (‘early brightening’). An illustrative example is given in figure 1(b), which depicts the longest continuous record of downward solar radiation measured in Stockholm. This series, starting in 1923, shows an increase in the 1930s and 1940s, an overall decrease from the 1950s up to the 1980s and a more recent recovery. This evolution is, surprisingly, at least qualitatively similar to the global land precipitation record shown in figure 1(a). Although a comparison of a radiation time series measured at a single station with a global land-averaged precipitation time series is by no means representative, it may illustrate the above point of a potential close link between decadal variations of surface radiation and precipitation.

Attempts have been made to infer decadal changes in the surface radiation balance based on both modelling and observational approaches. Liepert et al (2004) analyzed equilibrium experiments with a climate model with greenhouse gas and aerosol concentrations representative for mid-1880s and mid-1980s
conditions, respectively. They noted a decrease in absorbed solar radiation at the surface of 3.8 Wm\(^{-2}\) globally, mainly due to the aerosol direct and indirect effects, which are larger than the increased greenhouse effect of 1.9 Wm\(^{-2}\). This resulted in a reduction of net surface radiation of 1.9 Wm\(^{-2}\) globally, and a related spin down of the simulated hydrological cycle. Wild et al (2004), based on observational evidence, estimated that the decrease in downward solar radiation between the 1950s and 1980s may have overcompensated the increase in the greenhouse-gas-induced downward thermal radiation during the same period, thus implying a decrease in the surface radiation balance over this period. This fits well with the overall decrease in global terrestrial precipitation between the 1950s and 1980s seen in figure 1(a). This decrease is on the order of 30–40 mm, which corresponds to roughly 3 Wm\(^{-2}\) latent heat equivalent, and which would imply a similar decrease in surface net radiation. Assuming further a decreasing net surface thermal cooling of \(-1\) W m\(^{-2}\) over this period (Wild et al 2004), this would require an overall decline of about 4 Wm\(^{-2}\) in surface solar radiation to balance it, which is not unrealistic.

Since the 1980s, however, there are indications that downward solar radiation overall has recovered and contributed to the increase in the radiative imbalance at the surface, which had increased already due to the increasing downward thermal radiation (Wild et al 2008, see also figure 1(b). This increase in the surface radiation balance, estimated at 2 Wm\(^{-2}\) decade\(^{-1}\) in Wild et al (2008), fits the observational evidence for a recent increase in terrestrial precipitation and associated intensification of the hydrological cycle (figure 1(a)).

Improved knowledge of variations of the components of the surface radiation balance is therefore a key to our understanding of past, present and future variations in the intensity of the hydrological cycle.

**Surface radiation balance and the hydrological cycle in climate models**

A number of recent studies have pointed out that climate models driven with all known historical forcings simulate smaller changes in precipitation than observed over recent decades (Zhang et al 2007, Wentz et al 2007, Allan and Soden 2007, Liepert and Previdi 2009, Wild et al 2008, Wild 2009a), and may underestimate the increase in precipitation extremes with global warming (Allan and Soden 2008).

For the present study, in figure 2 we compare precipitation changes during the 20th century over land surfaces as observed (blue lines, equivalent to figure 1(a)) and simulated by 18 individual coupled atmosphere-ocean models (CMIP3 models) used in the IPCC-AR4 report (in red). Shown are annual anomalies with respect to the 20th century means (dashed lines) as well as superimposed 11-year running means (solid lines) that highlight the decadal variations in both models and observations. None of the models captures the observed decadal variations during the 20th century. Particularly, none of the models qualitatively reproduces the sequence of increase in the 1930s/1940s, decrease from 1950s to the 1980s and renewed increase to 2000, and the correlations between observations and models are insignificant. Standard deviations of the 11-year running means, indicative of the amplitude of decadal variations in the 20th century annual precipitation, amount to 10.7 mm in the GHNC observations and 5.0 mm on average in the models (with a range from 2.6 mm to 10.6 mm). The closest standard deviation to the observations with 10.6 mm is found in the miroc_medres model simulation; however this simulation does not reproduce the main temporal characteristics of the observed time series either (figure 2). Thus, none of the models is capable of simulating the full extent and temporal evolution of decadal variations in 20th century terrestrial precipitation (see also Liepert and Previdi 2009).

Here we argue that, among other possibilities, inadequacies in the simulation of surface radiation balance may contribute to the poor simulation of decadal variations in precipitation during the 20th century seen in figure 2. A closer look
Environ. Res. Lett. 5 (2010) 025003

Editorial

Figure 2. Terrestrial precipitation anomalies during the 20th century as observed (in blue) and simulated by various models used in the IPCC 4th assessment report and in the Coupled Model Intercomparison Project (CMIP3) (in red). Annual mean time series given as dashed lines, 11-year running means as solid lines. Reference period is the entire 20th century. Annual precipitation observations from GHCN (Peterson and Vose 1997), units mm.

at the simulated evolution of the radiation balance over land surfaces during the 20th century seems to confirm this. Specifically, only half of the models qualitatively reproduce the decrease in the terrestrial surface radiation balance between the 1950s and 1980s and the subsequent recovery as indicated in estimates based on observations. Quantitatively, from 1950 to 1985, the linear change in the model-calculated surface radiation balance is on average almost zero, as opposed to the observational evidence for declining surface radiation balance over this period (Wild et al 2004). Over the period 1985–2000, the multi-model mean amounts to an increase of 0.22 Wm$^{-2}$ decade$^{-1}$ (with a range from −0.10 to 0.57 Wm$^{-2}$ decade$^{-1}$, which is an order of magnitude smaller than for example the estimate given in Wild et al (2008).
Truly global observational estimates of precipitation changes (covering both land and oceans) exist only since 1987 with the advent of satellite data from the Special Sensor Microwave Imager (SSM/I). Based on these observations, Wentz et al. (2007) determined an increase in global mean precipitation of $13.2 \pm 4.8$ mm yr$^{-1}$ decade$^{-1}$ over the period 1987–2006. To induce such an increase, which corresponds to a latent heat release of approximately 1 Wm$^{-2}$ per decade, an increase in the globally averaged surface radiation balance of at least the same amount would be required accordingly. We obtained this estimate under the assumption of (1) an unchanged sensible heat flux and (2) an unchanged top of atmosphere radiation balance and corresponding surface heat uptake by the ocean and landmasses, so that globally the change in surface net radiation is balanced by the change in latent heat flux. Regarding assumption (1), the global mean sensible heat flux is an order of magnitude smaller than the latent heat flux, and therefore even large relative changes in sensible heating would be small in absolute terms. Assumption (2) is a conservative assumption and can be considered an upper limit because ocean and land heat uptake has likely subtracted a portion of the radiative energy available for evaporation (see, e.g., Hansen et al. 2005) over recent decades. Therefore, if the Wentz et al. (2007) estimated precipitation increase is unbiased, this would likely require a global mean surface radiation increase of more than 1 Wm$^{-2}$ per decade (cf also the estimated 2 Wm$^{-2}$ per decade increase in surface net radiation over land surfaces in Wild et al. (2008)). Current climate models, on the other hand, show a much smaller average increase of less than 0.3 Wm$^{-2}$ per decade.

The underestimation of decadal scale variations in downward solar radiation and a lack of dimming and brightening in the models (Romanou et al. 2007, Bodas-Salcedo et al. 2008, Wild 2009b, Ruckstuhl and Norris 2009) could have affected the simulations of the surface radiation balance. While the response to the gradually increasing greenhouse gases in the thermal component of the surface energy balance is well understood and adequately simulated, much more uncertainties are apparent in the solar component. Since the hydrological cycle may respond particularly sensitive to non-homogeneous short-living types of solar forcings such as aerosols (see discussion above), the identification of the origins of the uncertainties in the solar forcings is of primary importance for predicting future changes. Uncertainties may be related to weaknesses in three areas: (1) Deficiencies in the parameterization of the relevant processes: aerosol–cloud interactions are still poorly understood and related model representations are subject to considerable uncertainties or entirely neglected. Note that only few models include the effects of aerosols on clouds, which dominate the hydrological response as shown in Romanou et al. (2007). Furthermore, many models only consider the temporal variations in scattering sulphur aerosol and neglect changes in other aerosol types such as absorbing black carbon or desert dust, which would enhance the degree of freedom of aerosol–cloud interactions and change the stability of the atmosphere. (2) Uncertainties in the highly variable spatial and temporal distributions of global aerosol fields used in the 20th century simulations as e.g. shown by Ruckstuhl and Norris (2009). Also, most models still prescribe fixed spatial aerosol burdens in the atmosphere, rather than aerosol and aerosol precursor emission fields, which could enhance the degree of freedom of the global aerosol system. (3) Shortcomings in the representation of the natural variability in atmosphere/ocean exchanges of energy and water that result in variations of convection and consequently in cloudiness and humidity. For example state-of-the-art climate models do not realistically reproduce decadal variations in the ocean atmosphere system such as Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) or El Nino–Southern Oscillation (ENSO) that may have significant effects.
Conclusions

To summarize, we emphasize the prominent role of the surface radiation balance as a key determinant of the intensity of the global hydrological cycle. There are indications that the surface radiation balance underwent significant decadal variations during the 20th century, which are reflected in the variations of the intensity of the global hydrological cycle. The current generation of climate models does not show such strong variability in either of these quantities. Here we point to the inadequate representation of surface solar dimming and brightening as a potential cause of these model deficiencies. This is further supported by the recent evidence that solar forcings are more effective in altering the intensity of the global hydrological cycle than their thermal (greenhouse-gas-forced) counterparts. Improved knowledge of variations of the components of the surface radiation balance as well as their underlying forcing factors are therefore key to our understanding of past, present and future variations in the intensity of the hydrological cycle.

The recent implementation of advanced space-borne and surface-based monitoring systems should allow for more rigorous constraints of the radiative drivers behind the hydrological cycle. Together with improved modelling capabilities, including sophisticated interactive aerosol and cloud microphysics schemes, these advances should result in more realistic simulations and predictions of the intensity of the hydrological cycle in the near future.

Acknowledgements

Particular thanks go to Professor Christoph Schär for his valuable input to the manuscript and for his support. Richard Allan’s comments on the manuscript were highly appreciated. This study is part of the National Centre for Competence in Climate Research (NCCR Climate) project HYCLIM (Intensification of the water cycle: scenarios, processes and extremes) supported by the Swiss National Science Foundation, and was further sponsored by National Aeronautics and Space Agency Modeling Analysis and Prediction Program NASA-MAP grant NNX09AV16G. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, US Department of Energy.

References

Allan R P 2007 Improved simulation of water vapour and clear-sky radiation using 24-hour forecasts from ERA40 Tellus A 59 336–43
Allan R P and Soden B J 2007 Large discrepancy between observed and simulated precipitation trends Geophys. Res. Lett. 34 L18705
Allan R P and Soden B J 2008 Precipitation extremes and the amplification of atmospheric warming Science 321 1481–4
Allen M R and Ingram W 2002 Constraints on future changes in climate and the hydrologic cycle Nature 419 224–32
Andrews T, Forster P M and Gregory J M 2009 A surface energy perspective on climate change J. Climate 22 2557–70
Baumgartner A and Reichel E 1975 The World Water Balance: Mean Annual Global, Continental and Maritime Precipitation, Evaporation and Runoff (Amsterdam: Elsevier) 179 pp
Bodas-Salcedo A, Ringer M A and Jones A 2008 Evaluation of the surface radiation budget in the atmospheric component of the Hadley Centre Global Environmental Model (HadGEM1) J. Climate 21 4723–48
Gilgen H, Wild M and Ohmura A 1998 Means and trends of shortwave irradiance at the surface estimated from GEBA J. Climate 11 2042–61
Hansen J et al 2005 Earth’s energy imbalance: confirmation and implications Science 308 1431–5
IPCC 2007 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 Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) 996 pp
Jonkman S N 2005 Global perspectives on loss of human life caused by floods Natural Hazards 34 151–75
Lambert F H and Webb M J 2008 Dependence of global mean precipitation on surface temperature Geophys. Res. Lett. 35 L16706
Liepert B G 2002 Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990 Geophys. Res. Lett. 29 1421
Liepert B G 2010 The physical concept of climate forcing Wiley Interdisciplinary Reviews—Climate Change submitted
Liepert B G, Feichter J, Lohmann U and Roeckner E 2004 Can aerosols spin down the water cycle in a warmer and moister world? Geophys. Res. Lett. 31 L06207
Liepert B G and Previdi M 2009 Do models and observations disagree on the rainfall response to global warming? J. Climate 22 3156–66
Ohmura A and Wild M 2002 Is the hydrological cycle accelerating? Science 298 1345–6
Ramanathan V, Crutzen P J, Kiehl J T and Rosenfeld D 2001 Aerosol, climate and the hydrological cycle Science 294 2119–24
Romanou A, Liepert B, Schmidt G A, Rossow W B, Ruedy R A and Zhang Y 2007 20th century changes in surface solar irradiance in simulations and observations Geophys. Res. Lett. 34 L05713
Peterson T C and Vose R S 1997 An overview of the Global Historical Climatology Network temperature database Bull. Am. Meteorol. Soc. 78 2837–49
Philipona R, Dürr B, Marty C, Ohmura A and Wild M 2004 Radiative forcing—measured at Earth’s surface—corroborate the increasing greenhouse effect Geophys. Res. Lett. 31 L03202
Richter I and Xie S-P 2008 Muted precipitation increase in global warming simulations: a surface evaporation perspective J. Geophys. Res. 113 D24118
Ruckstuhl C and Norris J 2009 How do aerosol histories affect solar ‘dimming’ and ‘brightening’ over Europe? IPCC-AR4 models versus observations J. Geophys. Res. 114 D00D04
Stanhill G and Cohen S 2001 Global dimming: a review of the evidence for a widespread and significant reduction in global radiation Agr. Forest Meteorol. 107 255–78
Streets D G, Yan F, Chin M, Diehl T, Mahowald N, Schultz M, Wild M, Wu Y and Yu C 2009 Discerning human and natural signatures in regional aerosol trends, 1980–2006 J. Geophys. Res. 114 D00D18
Trenberth K E et al 2007 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 Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press)
Wentz F J, Ricciardulli L, Hilburn K and Mears C 2007 How much more rain will global warming bring? Science 317 233–35
Wild M 2009a Global dimming and brightening: a review J. Geophys. Res. 114 D00D16
Wild M 2009b How well do IPCC-AR4/CMIP3 climate models simulate global dimming/brightening and twentieth-century daytime and nighttime warming? J. Geophys. Res. 114 D00D11
Wild M, Grieser J and Schär C 2008 Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological cycle Geophys. Res. Lett. 35 L17706
Wild M, Ohmura A, Gilgen H and Rosenfeld D 2004 On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle Geophys. Res. Lett. 31 L11201
Wild M et al 2005 From dimming to brightening: decadal changes in surface solar radiation Science 308 847–50
Yang F, Kumar A, Schlesinger M E and Wang W 2003 Intensity of hydrological cycles in warmer climates J. Climate 16 2419–23
Zhang X et al 2007 Detection of human influence on twentieth-century precipitation trends Nature 448 461–5