

# Vegetation-mediated impacts of trends in global radiation on land hydrology: a global sensitivity study

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## Abstract

Incident solar radiation has changed in the last 50 years, as an initial dimming trend from 1960 to approximately 1990 was followed by an ongoing brightening period, with concomitant changes in the partitioning between direct and diffuse fractions. Such radiation changes are expected to affect the global water cycle. In this study, we use the Community Land Model (CLM) to perform global offline simulations for the period 1948–2004 and study the effects of solar forcing changes on trends in evapotranspiration and runoff. The modeled components of the hydrologic cycle respond strongly to the imposed radiation changes in several regions, especially in the tropics. Exceptions are regions with soil moisture-limited evapotranspiration regime, such as the U.S. Great Plains. In Europe and the Eastern US, the imposed  $7 \text{ W m}^{-2}$  solar dimming for 1960–1990 leads to an evapotranspiration reduction of  $1.5 \text{ W m}^{-2}$  or approximately 5% of the mean and an enhancement of runoff by equal percentage. In these regions, the imposed  $6 \text{ W m}^{-2}$  solar brightening leads to a  $3 \text{ W m}^{-2}$  increase of evapotranspiration in 1990–2004, and a runoff reduction of between 7 and 10% of the mean. Additional simulations investigating the impact of higher diffuse radiation fraction during 1960–1990 suggest mostly an increase of evapotranspiration in the tropics of  $2.5 \text{ W m}^{-2}$  (3% of mean) due to increased photosynthesis from shaded leaves, but with smaller opposite effects elsewhere because of lower ground evaporation. The runoff trend resulting from the imposed radiation/aerosols effect is of the same sign and approximate relative magnitude (but larger absolute magnitude) as those calculated, in various studies, for other potential drivers of runoff change such as climate,  $\text{CO}_2$ , or land use. These results thus strengthen the claim that radiation effects on runoff are not to be neglected. Understanding the impacts of radiation on the water cycle will affect projections of river flow and freshwater availability for human consumption.

**Keywords:** diffuse radiation, evapotranspiration, global dimming, land-surface modeling, water cycle

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## Introduction

Incident global solar radiation (i.e. shortwave downward radiation, hereafter also referred to as 'SWdown') at the land surface has changed in the last 50 years, as an initial dimming trend approximately from 1960 to 1990 was followed by an ongoing period of widespread brightening (Wild *et al.*, 2005; Streets *et al.*, 2006; Wild, 2009). Indeed, observations since 1958 have revealed large, significant widespread reductions in incoming radiation, which, despite considerable spatial variation, amount to a global average of  $9 \text{ W m}^{-2}$  by 1985 (Stanhill & Moreshet, 1992). This phenomenon has been suggested to be limited to sites in urban areas and associated with human population density (Alpert & Kishcha, 2008), but other studies claim that it is widespread throughout the northern hemisphere (e.g. Liepert, 2002). Nonetheless, this pre-1990 dimming was

identified in observation records from ground stations (Stanhill & Cohen, 2001) as well as satellite measurements (Pinker *et al.*, 2005). In theory, causes for this dimming could include changes to orbital parameters or solar output, but these occur at geological time scales and have been estimated at an order of magnitude smaller than the observed values (Wild, 2009). Probably, dimming has anthropogenic causes due to an increase in atmospheric aerosol loading from fossil fuel emissions and associated increase in cloud formation, and is well correlated with pollution sources and vehicle traffic at latitudes of higher industrialization and population (Alpert & Kishcha, 2008; Wild, 2009). Since approximately 1990, more effective clean-air regulations, added to the decline in heavy-polluting eastern European economies, have probably contributed to a reversal from dimming to brightening, as noted in most global-wide observations (Wild *et al.*, 2005). This has been duly recognized by the research community and summarized in the latest IPCC report (IPCC 2007) whose accepted global average radiation change values

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have been adopted in this study. In addition, observations in recent decades from several locations across Europe, North America, and China have also hinted at changes in the partitioning of global solar radiation into its direct and diffuse components (Abakumova *et al.*, 1996; Li *et al.*, 1998; Liepert, 2002; Che *et al.*, 2005). Although aerosol loading trends and radiation partitioning have been noted to vary regionally and temporally in some of the above-mentioned regions during the dimming period (Liepert & Tegen, 2002), increased aerosol loadings can generally be assumed to contribute to a higher fraction of scattered light enhancing plant photosynthesis (e.g. Gu *et al.*, 2003), a mechanism possibly responsible for a quarter of the accumulated land carbon sink over the 20th century (Mercado *et al.*, 2009). Such effects are important in the context of volcanic eruptions (e.g. Gu *et al.*, 2003) as well as proposed geo-engineering options (e.g. Crutzen, 2006).

The reported changes in the amount and partitioning of SWdown in past decades are likely to have had important implications for trends in evapotranspiration (hereafter referred to as 'ET') and associated water cycle components in many regions, as net radiation is one of the factors limiting ET (e.g. Roderick & Farquhar, 2002; Teuling *et al.*, 2009; Pieruschka *et al.*, 2010; Seneviratne *et al.*, 2010), and the impact of the direct/diffuse partitioning on plant photosynthesis may be linked with impacts on ET. Terrestrial ET is a key component of the climate system, linking the hydrologic, energy and carbon cycles, amounting to up to 60% of the total land precipitation (Oki & Kanae, 2006), and using up over half of the net radiation on land in the process (Trenberth *et al.*, 2009), but observations are lacking at the global scale (Jung *et al.*, 2010; Seneviratne *et al.*, 2010). Runoff, a measure of water availability so important for human health, economic activity, ecosystem function, and geophysical processes, has also been found to be significantly impacted by external forcing in the 20th century, and larger changes are expected in the coming decades (Milly *et al.*, 2005).

Regarding the impact of changes in absolute SWdown on land hydrology, regional observational studies, e.g., based on soil moisture measurements in Russia and Ukraine (Robock & Li, 2006) or water-balance budgets and lysimeter data in Europe (Teuling *et al.*, 2009), have indeed suggested some effects. However, global analyses cannot be conducted based on observations alone. Indeed, available ET observations are insufficient to detect robust, long-term, regional to continental trends, given the short record length at most sites from the FLUXNET network (Baldocchi *et al.*, 2001) and the limited number of sites with long-term lysimeter measurements (Seneviratne *et al.*, 2010). Furthermore, linking information from pan evaporation

measurements with actual ET trends is not less difficult or uncertain (e.g. Teuling *et al.*, 2009). Also, runoff observations are often lacking or affected by human water use in many areas, and disagreements regarding the magnitude and even sign of trends in runoff on the continental scale persist (Labat *et al.*, 2004; Legates *et al.*, 2005; Dai *et al.*, 2009). In addition, the drivers for observed hydrologic changes cannot be easily attributed, as they are influenced by a large number of physical and biologic processes at the land surface.

Ultimately, the temporal and spatial coverage characteristics of hydrologic observations limit the ability to adequately represent the biophysical environment and land-surface hydrology fluxes in global-wide, multi-decadal studies. More importantly, observations incorporate all potential driving effects, making it more difficult to study specific mechanisms and separate causes. Thus, despite its documented shortcomings and oversimplifications, land-surface modeling is a suitable tool to investigate the sensitivity of land hydrology to forcing variables, and, in particular, to the reported changes in global radiation. Herein, we use the Community Land Model version 3.5 (CLM) to perform global offline simulations of land-surface processes, to study the effects of changes in amount and partitioning of global solar radiation on the hydrologic cycle. Specifically, we set out to ascertain whether and how the model and its output hydrologic variables are sensitive to changes in global radiation. In addition, we investigate modeled trends for regions of the northern hemisphere in the second half of the 20th century, the potential direct and indirect effects of radiation trends, and their relative importance. Lastly, we ask whether changes in the partitioning of solar radiation between direct and diffuse fractions can have a detectable effect on the water cycle.

## Methodology: model and numerical experiments

### *The Community Land Model*

The CLM is a numerical model that represents land-surface processes within the scope of global climate simulations (Oleson *et al.*, 2004, 2008; Stöckli *et al.*, 2008). Biophysical processes simulated by CLM include: solar radiation interactions with vegetation and soil; energy and mass fluxes between plant canopy, soil, and snow; plant photosynthesis; soil hydrology, including surface runoff, infiltration, and groundwater discharge; and a river routing scheme. Spatial heterogeneity is represented as a nested sub-grid hierarchy in which each grid cell is composed of various land units and multiple plant functional types. Furthermore, vertical profiles of water and energy are calculated for 10 soil layers and up to five snow layers. Biophysical processes are simulated for each sub-grid unit independently, and surface variables and fluxes are then averaged by area.

Photosynthesis varies non-linearly with solar radiation depending on the light response from stomata, which also depend on air humidity, CO<sub>2</sub> concentration, leaf temperature, and soil moisture stress (Collatz *et al.*, 1991; Oleson *et al.*, 2004). Leaf optical properties determine reflection and absorption of radiation, and so sunlit leaves at the top of the canopy are easily light-saturated whereas those in lower, shaded areas are usually unsaturated (Sellers *et al.*, 1992). Thus, CLM3.5 divides the canopy into sunlit (receiving both direct and diffuse light) and shaded (receiving only diffuse light) fractions (Oleson *et al.*, 2004; Thornton & Zimmermann, 2007), taking into account the link between stomatal conductance and photosynthetic activity through a formulation adapted from Collatz *et al.* (1991). Photosynthetic assimilation is calculated after Farquhar *et al.* (1980) and Collatz *et al.* (1991) for C3 plants, and Collatz *et al.* (1992) and Dougherty *et al.* (1994) for C4 plants. As clouds and other atmospheric particles can enhance the diffuse fraction of solar radiation, making photosynthetically active radiation more accessible throughout the canopy and rendering it more efficient (Roderick *et al.*, 2001), CLM3.5 computes, at each step, the direct and diffuse radiation fluxes absorbed by the vegetation using a two-stream canopy radiative transfer scheme that takes into account the optical depth and zenith angle of the direct beam and scattering (Oleson *et al.*, 2004). The default configuration of the model, used in particular for the whole control simulation, features a model standard 70%/30% global partitioning of SWdown radiation into its respective direct and diffuse fractions.

CLM3.5 has been thoroughly tested and compared with FLUXNET and GRDC data with respect to its simulation of hydrology and other fluxes of energy and nutrients, and was found to perform well for a wide variety of land biomes (Oleson *et al.*, 2008; Stöckli *et al.*, 2008). Known simulation limitations include low runoff in the Amazon as well as overall low amplitude of the annual cycle in terrestrial water storage throughout most tropical river basins (Oleson *et al.*, 2008).

#### Forcing data and experimental set-up

**Forcing trends.** The conducted simulations are performed at a resolution of 2.5° longitude by approximately 1.9° latitude (except runoff at 0.5° by 0.5°) driven by a 57-year (1948–2004) atmospheric forcing dataset composed of 6-hourly fields of meteorological data combining reanalysis and observational datasets (Qian *et al.*, 2006), after a previously spun equilibrium state and a subsequent run through a forcing data period of no less than 5 years to ensure negligible initialization drift. Atmospheric CO<sub>2</sub> concentration is kept constant at the 280 ppm level. Additional land-surface data for soil texture are derived from the FAO/UNESCO dataset, and vegetation cover parameters for the 17 chosen plant functional types are based on MODIS satellite measurements and other sources (Lawrence & Chase, 2007). All land-surface data are kept constant.

The Qian *et al.* (2006) forcing has been used in numerous applications (e.g. Qian *et al.* (2007); Dai *et al.* (2009); Randereson *et al.* (2009)), and shown to perform well with respect to the various components of the water cycle (Oleson *et al.*, 2008; Dai *et al.*, 2009). The NCEP/NCAR reanalysis product, on

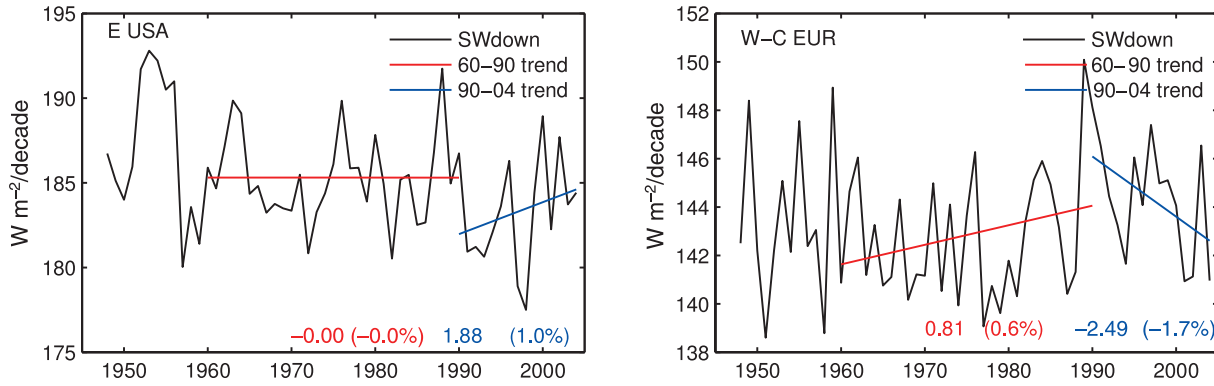
which the Qian *et al.* (2006) forcing is based, has been shown to match SWdown radiation observations poorly, especially in higher latitude regions such as northern Eurasia (Troy & Wood, 2009). After adjustment with observation datasets, in particular with cloud data, the used SWdown forcing showed reasonable performance (Qian *et al.*, 2006), at least on par with other forcing datasets with similar temporal characteristics available at the time of the simulations. However, SWdown is still overestimated especially during the observed dimming period, as seen from the absence of a dimming signal in either of the two regional averages shown for the control simulation in Fig. 1. Hence, it is necessary to impose additional forcing signals to simulate realistic SWdown radiation in Experiment 2 below. SWdown, as well as the other five forcing variables (precipitation, surface air temperature, specific humidity, wind speed, and surface pressure), have been tested and noted to perform reasonably well, in particular, the components of the water cycle (Qian *et al.*, 2006). However, known issues such as daily precipitation frequency and intensity remain, leading to possible erroneous trends in ET and runoff. To minimize this problem, analyses performed on all experiments focus only on anomalies after the subtraction of control.

**Experimental setup.** An overview of the conducted numerical experiments is provided hereafter and summarized in Table 1. Three sets of experiments were performed:

- Experiment 1 (Extreme sensitivity): idealized ‘extreme’ experiment over the 1950–1970 time period, investigating the impact of imposed extreme anomalies in incident global radiation.
  1. CTL: control simulation using Qian *et al.* (2006) forcing dataset for 1948–2004.
  2. XDim: ‘extreme dimming’ simulation, using Qian *et al.* (2006) forcing for 1950–1970, except for SWdown that includes an imposed (unrealistically large) decreasing trend of 1%/yr.
  3. XBri: ‘extreme brightening’ simulation, using Qian *et al.* (2006) forcing for 1950–1970, except for SWdown that includes an imposed (unrealistically large) increasing trend of 1%/yr.

Note that the trends imposed in XDim and XBri are two to five times larger than some of the highest estimates regarding trends in global radiation during the dimming and/or brightening phases (IPCC 2007), amounting to a total global mean change of 32 W m<sup>-2</sup> over the 20 years. The purpose of this first experiment is to provide an estimate of the absolute sensitivity of CLM to imposed extreme changes in global radiation.

- Experiment 2 (Realistic sensitivity): Experiments for the 1948–2004 time period, investigating the impact of imposed realistic forcing perturbations in incident global radiation.
  1. CTL: control simulation using Qian *et al.* (2006) forcing for 1948–2004.
  2. RealRad: ‘realistic radiation’ simulation, using Qian *et al.* (2006) forcing for 1948–2004 for all other variables



**Fig. 1** Time series of shortwave downward radiation from the Qian *et al.* (2006) forcing dataset, averaged for two regions: eastern US (left) and West-Central Europe (right). Decadal trends are shown for the dimming and brightening periods, both in absolute value and as the percentage of the mean.

except SWdown, which is modified to include ‘realistic’ perturbations over the dimming and brightening periods (superimposed on the Qian *et al.* (2006) 1948–2004 time series): Decrease of 7 W m<sup>-2</sup> in total, i.e. 0.23 (W m<sup>-2</sup>)/yr, over the time period 1960–1990 globally (dimming period), followed by an increase of 6 W m<sup>-2</sup> in total, i.e. 0.43 (W m<sup>-2</sup>)/yr, over time period 1990–2004 globally (brightening period).

The imposed trends in the RealRad simulation are chosen to match published estimates (IPCC 2007). However, it should be noted that trends in global radiation probably have not been globally uniform, contrary to what is assumed in the RealRad experiment (in particular because the aerosol loading has varied between regions). Due to lack of corresponding radiation observations in many regions (Wild *et al.*, 2005), exact trends cannot be inferred everywhere. Hence, in those regions without SWdown observations, the RealRad experi-

ment simply provides a sensitivity analysis of the potential impact of global radiation trends.

- Experiment 3 (Real direct/diffuse partitioning): Experiments for the 1960–1990 time period, investigating the impact of imposed forcing perturbations in direct/diffuse global radiation partitioning.
  1. CTL: control simulation using Qian *et al.* (2006) forcing for 1948–2004.
  2. DirDif: increased diffuse fraction simulation, using Qian *et al.* (2006) forcing for 1960–1990 except for SWdown, with modified SWdown partitioning changed globally at a rate of increased diffuse of 1.5% of total global radiation per decade, reaching 65.5% direct/34.5% diffuse at the end of the 30-year period (instead of model standard fixed 70%/30% partitioning as in all previous simulations).

**Table 1** Summary of performed simulations and imposed radiation changes

Simulation	Period					
	1948	1950	1960	1970	1990	2004
1. Control (CTL)	Qian forcing*					
2. Extreme sensitivity (XDim/XBri)	Extreme dimming/ extreme brightening†					
3. Realistic sensitivity (RealRad)	Realistic dimming‡      Realistic brightening‡					
4. Real direct/diffuse (DirDif)	Increased diffuse§					

\*1948–2004 forcing from Qian *et al.* (2006) dataset.

†Qian *et al.* (2006) forcing except SWdown: 1%/yr is subtracted (added) globally to a repeated sequence of the 1948–2004 climatology in annual steps.

‡Qian *et al.* (2006) forcing except SWdown: 7 W m<sup>-2</sup> dimming followed by 6 W m<sup>-2</sup> brightening signals are imposed to equal published estimations (IPCC 2007): globally, 0.23 (W m<sup>-2</sup>)/yr are subtracted for dimming 1960–1990 (0.43 (W m<sup>-2</sup>)/yr added for brightening 1990–2004).

§Qian *et al.* (2006) forcing except SWdown: 1960–1990 diffuse fraction increased to match reports from former Soviet Union 1955–1993 (Abakumova *et al.*, 1996): diffuse fraction added by 1.5% per decade starting from 70% direct/30% diffuse default reaching 65.5% direct/34.5% diffuse at end of 30 years, globally.

DirDif simulates an extreme increase in the diffuse fraction of total radiation similar to that reported for the Soviet Union and China in recent decades (Abakumova *et al.*, 1996; Che *et al.*, 2005).

This particular experimental setup, where we impose changes only to radiation, keeping other factors (atmospheric forcing fields including CO<sub>2</sub> and land cover) constant, and then analyze the anomalies after subtraction of the control values, allows for a better separation between possible concurring effects of existing forcing trends while maintaining the temporal variability as close to reality as possible.

## Results

### *Experiment 1: 'Extreme' global radiation experiments*

Analysis of the results of the CTL simulation (not shown) used in all three experiments shows some differences in noted trends in hydrologic variables. In Europe and eastern US, the ET trend compared with the half-century mean is either zero or slightly positive (~1% per decade) during the dimming phase and ~2–3% per decade during the brightening period. Runoff results show considerably larger regional and temporal variation, as Europe sees a shift from a negative ~2–4% per decade during the dimming period to a positive ~7–15% per decade, whereas in the eastern US, they go from a positive 7% per decade to a negative 18% per decade in the same periods.

We first present the results of the extreme global radiation experiments, i.e. extreme dimming (XDim) and extreme brightening (XBri) compared with CTL. The analysis focuses on differences in simulated ET (including transpiration and ground evaporation components) and runoff between the sensitivity and control experiments.

Figure 2 reveals that Experiment 1 exhibits a strong simulated response of the analyzed water cycle components to the imposed solar radiation anomalies in large parts of the globe. Overall, trends are regionally consistent, and dimming is shown to decrease ET and increase runoff, with the opposite behavior observed for brightening. ET change is largest in tropical forests, where the imposed decadal trend (hereby defined as 10 times the annual trend obtained from the slope of the linear regression line) is often in excess of 6 W m<sup>-2</sup>, as the annually imposed 1%-change impacts radiation more strongly in absolute terms in regions with already high SWdown (Fig. 2a and b). In these regions, most of the signal in total ET comes from the impact of the imposed radiation changes on plant transpiration, responsible for more than 70% of the total ET trend (Fig. 2c and d). Elsewhere, however, ground evaporation is found to play an equally important role (Fig. 2e

and f). Note that changes to canopy interception evaporation have a negligible contribution to overall ET changes in all regions (not shown). Runoff is affected in similar regions as ET, with decadal changes of approximately 10% of the half-century mean in the Amazon basin trend, and other strong response areas throughout the tropics and extending to southeast South America, southeast Asia, and eastern US (Fig. 2g and h). Furthermore, we assess the simulated sensitivity of ET and sensible heat flux to radiation changes, expressed in W m<sup>-2</sup> for each W m<sup>-2</sup> of imposed SWdown radiation. The sensitivity of total ET to radiation changes in the model is found to be higher in Europe, eastern US, eastern China, and in the tropics (Fig. 3a and b). These regions are expected to have a radiation or energy-limited ET regime according to several analyses of observational and modeling data (Seneviratne *et al.*, 2006, 2010; Teuling *et al.*, 2009), which is consistent with this outcome. Indeed, a wet regime characterized by high correlation with radiation, but low correlation with precipitation should show increased sensitivity to the imposed SWdown changes, as opposed to what would be expected in arid, water-limited regions. Sensible heat flux appears to be particularly sensitive to the imposition of extreme radiation trends (Fig. 3c and d), which is probably caused by limitations of this offline setup, as radiation is made to change while surface temperature is unrealistically kept unaltered. An analysis of the yearly correlation of simulated ET with the imposed SWdown and precipitation (P), forcing in the XDim and XBri runs (Fig. 3e–h), reveals similar patterns of ET regimes as those identified in previous studies (see above), indicating that regions most sensitive to the imposed radiation anomalies are indeed characterized by humid climate regimes, whereas more arid regions are instead better correlated with precipitation. It is noteworthy that the CLM ET regime distribution assessed from these correlation analyses matches multimodel analyses and eddy-covariance observation results well (Teuling *et al.*, 2009), and thus appears to be realistic.

### *Experiment 2: 'Realistic' global radiation experiments*

Figure 4 displays the CLM response to the imposed 'realistic' dimming and brightening signals in Experiment 2 (for time period 1948–2004). The net impact on the water cycle components is smaller than that produced by the extreme radiation experiment, but is nonetheless non-negligible, especially in several areas of the northern hemisphere, where solar radiation changes have been observed. Anomalies in West-central Europe (35°–55°N latitude, 10°W–10°E longitude),

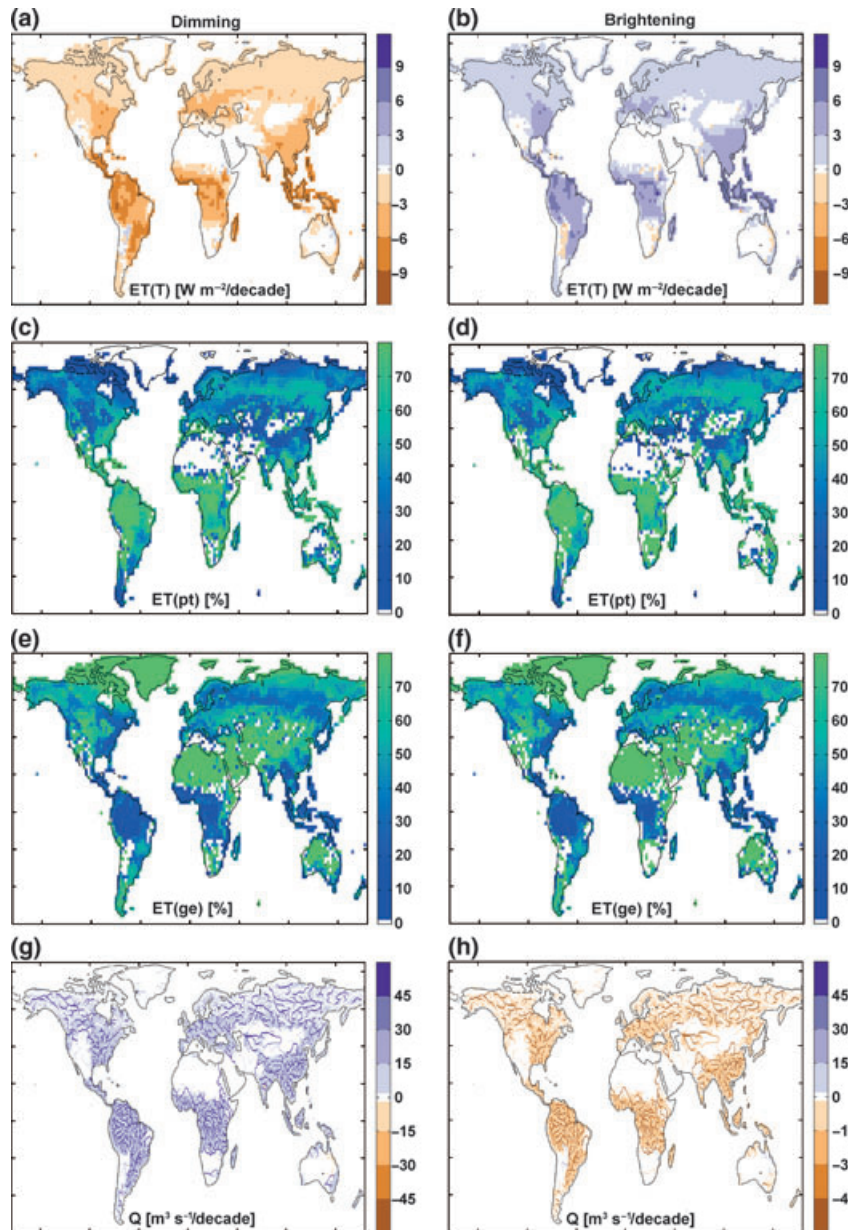
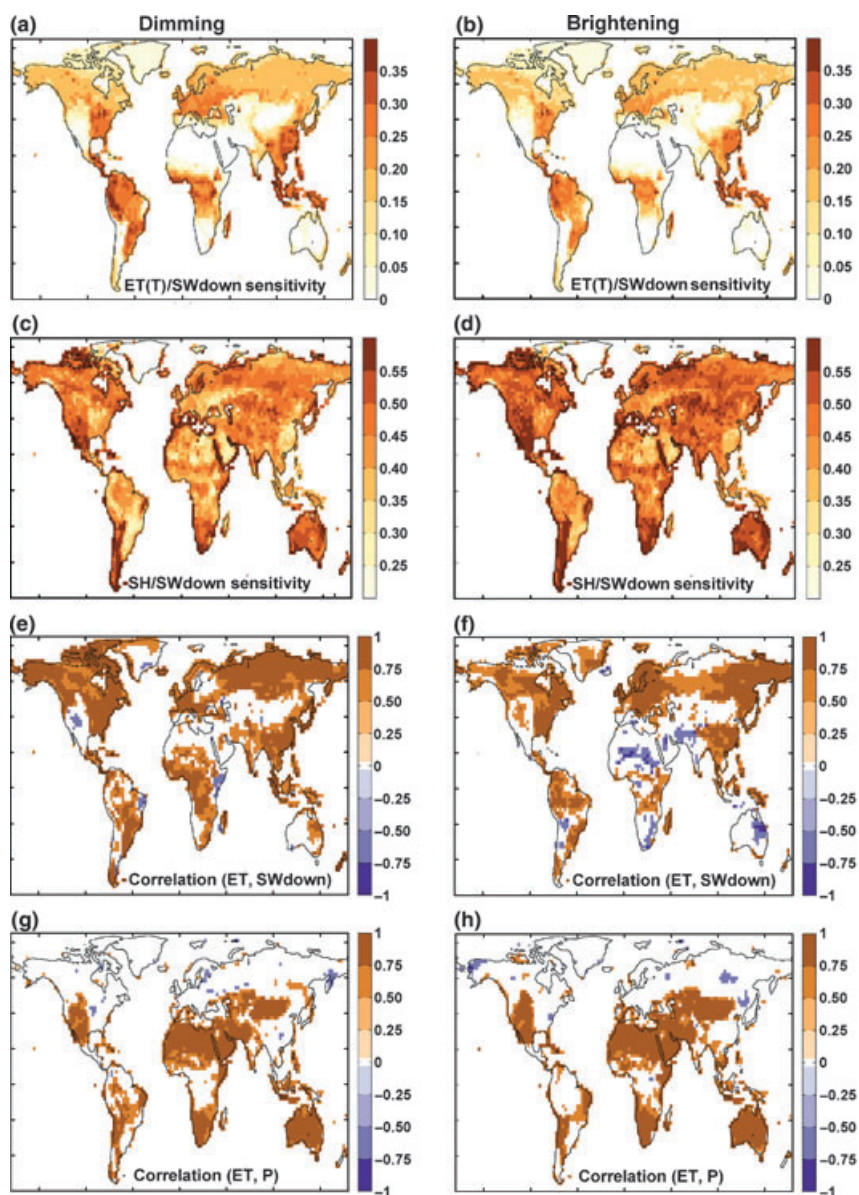


Fig. 2 Experiment 1: sensitivity to extreme dimming (brightening) signals, with global maps of the difference between decadal trends of XDim, left column (XBri, right), and CTL simulations for: (a, b) total evapotranspiration ( $W m^{-2}$ ); (c, d) plant transpiration, and (e, f) ground evaporation (% of change in total evapotranspiration); and (g, h) river runoff ( $m^3 s^{-1}$ ).

in particular, show a decadal ET reduction in excess of  $0.5 W m^{-2}$  during the dimming period, and an increase of over  $2 W m^{-2}$  per decade during the brightening (Fig. 4a and b). Conversely, runoff rises in this region during the dimming period by approximately  $3 m^3 s^{-1}$  per decade or 1.4% of the half-century mean, whereas the brightening causes a decadal drop equivalent to 7% of the mean (Fig. 4g and h). Results of similar magnitude and relative proportion are found for ET in East-central Europe ( $45^{\circ}$ – $65^{\circ}$ N latitude,  $10^{\circ}$ E– $45^{\circ}$ E longi-

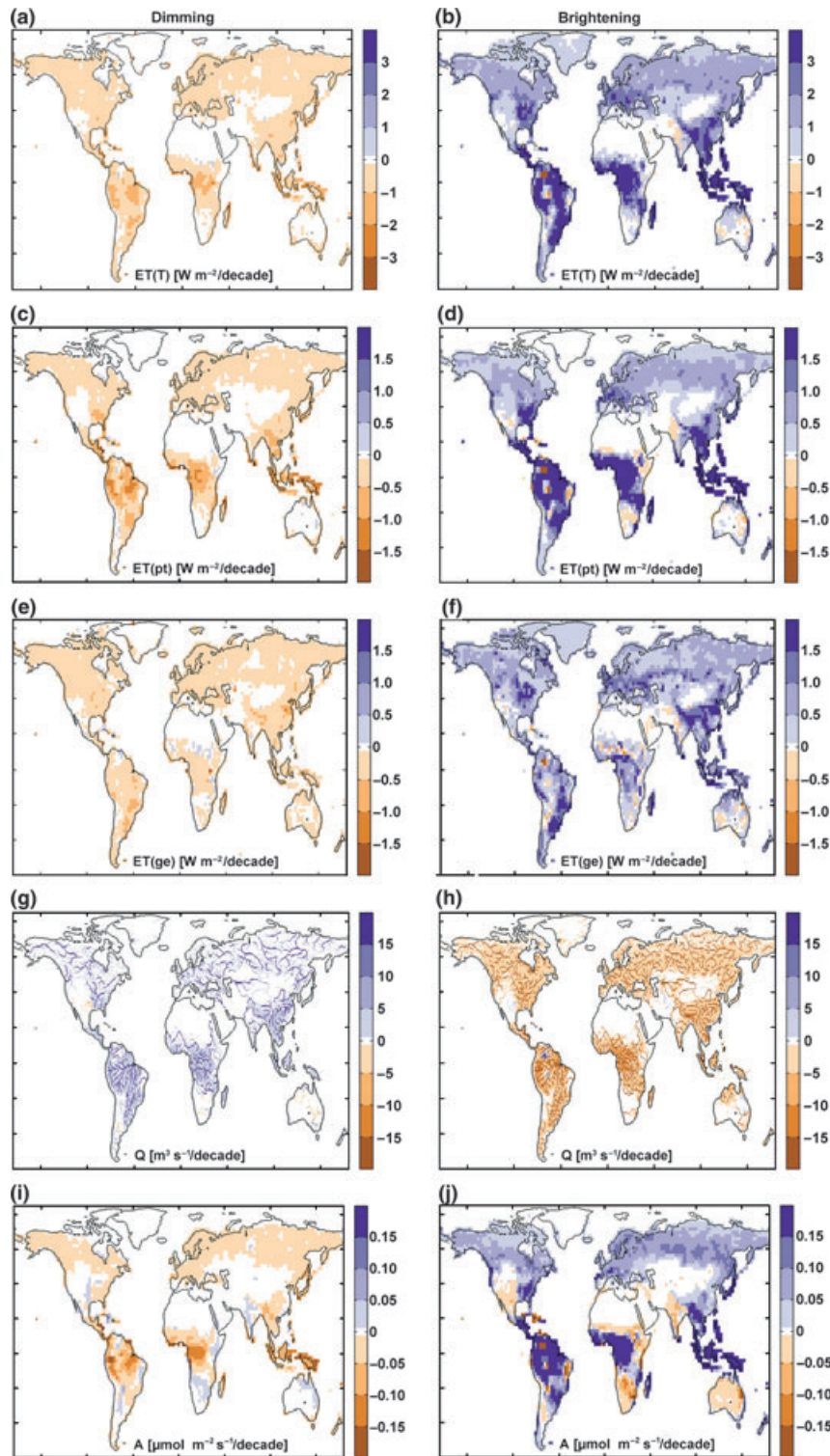
tude), where decadal runoff decreases by  $18 m^3 s^{-1}$  during the brightening period. For the Eastern US ( $25^{\circ}$ – $50^{\circ}$ N latitude,  $90^{\circ}$ – $60^{\circ}$ W longitude), the 'realistic' simulation shows a decadal ET decrease of  $0.5 W m^{-2}$  during the dimming phase or 1% of the half-century mean value, and an increase in excess of  $2 W m^{-2}$  or 4% of the mean during the brightening phase. ET changes in all above regions for either period come mostly from equal contributions from plant transpiration and ground evaporation (Fig. 4c–f). Similar to



**Fig. 3** Sensitivity of decadal trends of total evapotranspiration (a, b) and sensible heat (c, d) for each  $\text{W m}^{-2}$  of shortwave downward radiation increase for XDim (left) and XBri (right), subtracted by CTL; (e–h): analysis of evapotranspiration drivers in CLM3.5, i.e. correlation ET/SWdown and corr ET/P on yearly time scales (only grid cells significant at 5% level are shown).

Experiment 1, tropical forests exhibit a strong response of the water cycle to the imposed radiation signals, coming mostly from plant transpiration changes that match photosynthesis activity well, both spatially and quantitatively (Fig. 4i and j). The relative magnitudes of runoff decadal trends in RealRad with respect to control are approximately the same, for either time period, as those for the above European regions. Photosynthesis decadal trend behavior follows that of plant transpiration for both time periods in all regions, but its magnitude relative to its half-century mean was only

approximately 1/3rd the percentage of the latter. The sensitivity of the components of the hydrologic cycle to each  $\text{W m}^{-2}$  of radiation changes shows regional variations, but differs only slightly between dimming and brightening periods (Fig. 5). ET sensitivity to radiation change is higher in the Amazon, at almost three times the global average, with mid-latitude regions falling somewhere around  $0.2 (\text{W m}^{-2})^{-1}$ . With the exception of the tropical Amazon basin, where vegetation-mediated processes exert a substantial impact on all components of the water cycle, river runoff



**Fig. 4** Experiment 2: impact of 1960–1990 solar dimming, left column (1990–2004 solar brightening, right) on the water cycle: global maps of difference between decadal trends of RealRad and control (CTL) simulations for: total evapotranspiration (a, b), plant transpiration (c, d), ground evaporation (e, f), and river runoff (g, h); similarly for plant photosynthesis (i, j).

sensitivity to radiation is modest everywhere else. Sensible heat, however, shows a consistent 0.4–0.5

$(W m^{-2}) (W m^{-2})^{-1}$  sensitivity to radiation in all regions, for both periods.



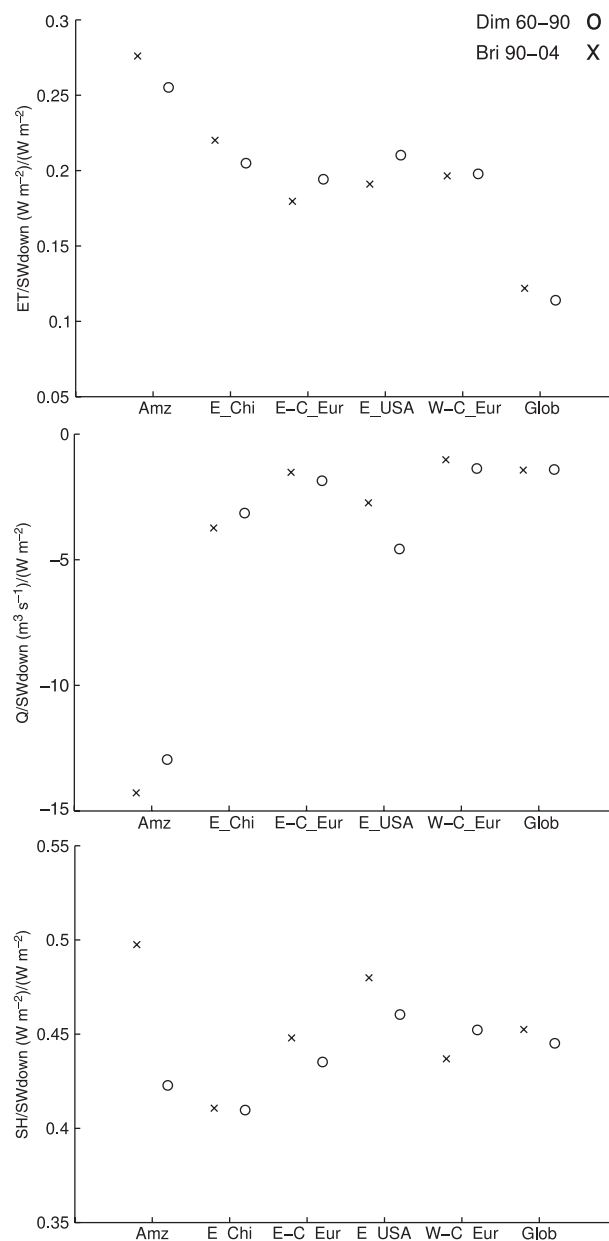
### Experiment 3: impact of direct/diffuse partitioning

Figures 6 and 7 display the impact of changes in direct/diffuse radiation partitioning in Experiment 3 compared with CTL. These show significant effects on land hydrology. A relative increase in the diffuse fraction, with total radiation remaining constant, produces increases in ET that reach  $0.5 \text{ W m}^{-2}$  per decade in some tropical regions (Figs 6 and 7). Smaller increases are also noted in other tropical regions, in northern and eastern North America, and across northern Eurasia (Fig. 7). With the exception of the latter region, ET rises almost exclusively due to plant transpiration, which more than offsets a faint contrary signal from ground evaporation. Overall, ET changes coincide with increased photosynthesis and decreased stomatal resistance from shaded leaves, both in terms of spatial distribution and relative intensity. Reductions to river runoff are largely negligible.

### Radiation effect comparison: dimming vs. direct/diffuse partitioning

As radiation changes simulated in subchapters 3.2 and 3.3 above were both observed during the period 1960–1990, we set out to compare regional patterns of the relative contribution and magnitude of their effects on biophysical and hydrologic variables. Thus, increased diffuse radiation fraction was found to cause a rise in total ET in all regions, an effect of opposite sign, but smaller absolute value than that resulting from global dimming (Fig. 6). Decadal trend anomalies for increased diffuse radiation range from an approximate  $0.2 \text{ W m}^{-2}$  rise in eastern US and the Amazon basin ( $10.5^{\circ}\text{S}$ – $3^{\circ}\text{N}$  latitude,  $72.5^{\circ}$ – $50^{\circ}\text{W}$  longitude) or about 25–30% the absolute magnitude of that from the dimming, to  $<0.1 \text{ W m}^{-2}$  in Europe and eastern China ( $21.5^{\circ}$ – $40.5^{\circ}\text{N}$  latitude,  $100^{\circ}$ – $120^{\circ}\text{E}$  longitude), equivalent to an effect of four to eight times smaller than that from dimming. The drop in runoff as a result of increased diffuse radiation is very modest compared with the increase from solar dimming, with the only noticeable exception found in the Amazon region.

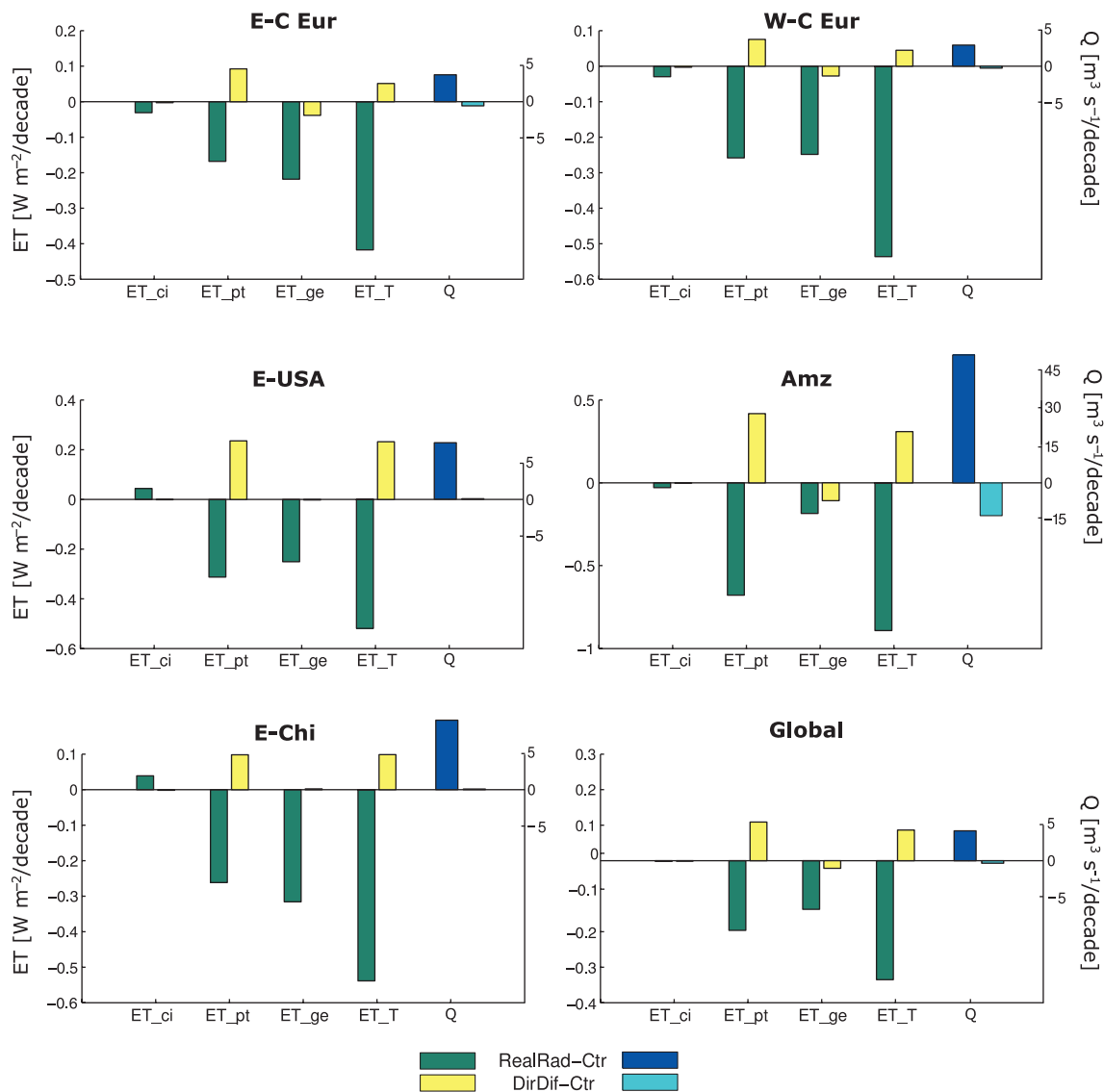
To investigate the potential role of soil moisture in the noted changes to the water cycle during the dimming phase, we calculate its anomalies for both the ‘realistic’ dimming and the increased diffuse fraction experiments. Results (not shown) indicate that decadal trends in soil moisture, both at the surface (top 6 cm) and deeper (top 104 cm) soil columns, rarely reach 0.5% of the mean for non-arid regions, and are therefore assumed to play a minor part in the noted radiation-induced hydrologic changes.



**Fig. 5** Sensitivity of decadal trends of total evapotranspiration (a), runoff (b), and sensible heat (c) to each  $\text{W m}^{-2}$  of shortwave downward radiation increase, for the dimming and brightening periods.

## Discussion

The CLM land-surface model responds to incoming solar radiation rise with increased ET and decreased runoff in regions with energy-limited ET regime, and the opposite behavior is found when radiation decreases. In the case of extreme radiation change, the water cycle response is strong, especially in regions where the heat and water fluxes are higher, such as



**Fig. 6** Comparison of decadal trends of RealRad (dimming) and DirD, if simulations are subtracted by control trend, for runoff (Q), total evapotranspiration [ET(T)], and its three components [canopy interception (ET<sub>ci</sub>), plant transpiration (ET<sub>pt</sub>), and ground evaporation (ET<sub>ge</sub>)], at the global and various regional scales (East-Central Europe, West-Central Europe, eastern US, Amazon, and eastern China).

tropical forests. Areas where ET is mostly water limited (Fig. 3g and h) show that it is insignificantly or weakly correlated with SW<sub>down</sub>, as radiation-induced evaporation changes depend on moisture availability. Although a coupled system may also experience concomitant changes in atmospheric water availability and air temperature as a result of ET variation, the offline nature of these experiments limits our ability to capture the behavior of the entire system in a more realistic fashion, in what constitutes one of the caveats of the study. Nonetheless, with extreme brightening, plant transpiration is enhanced to a point where it

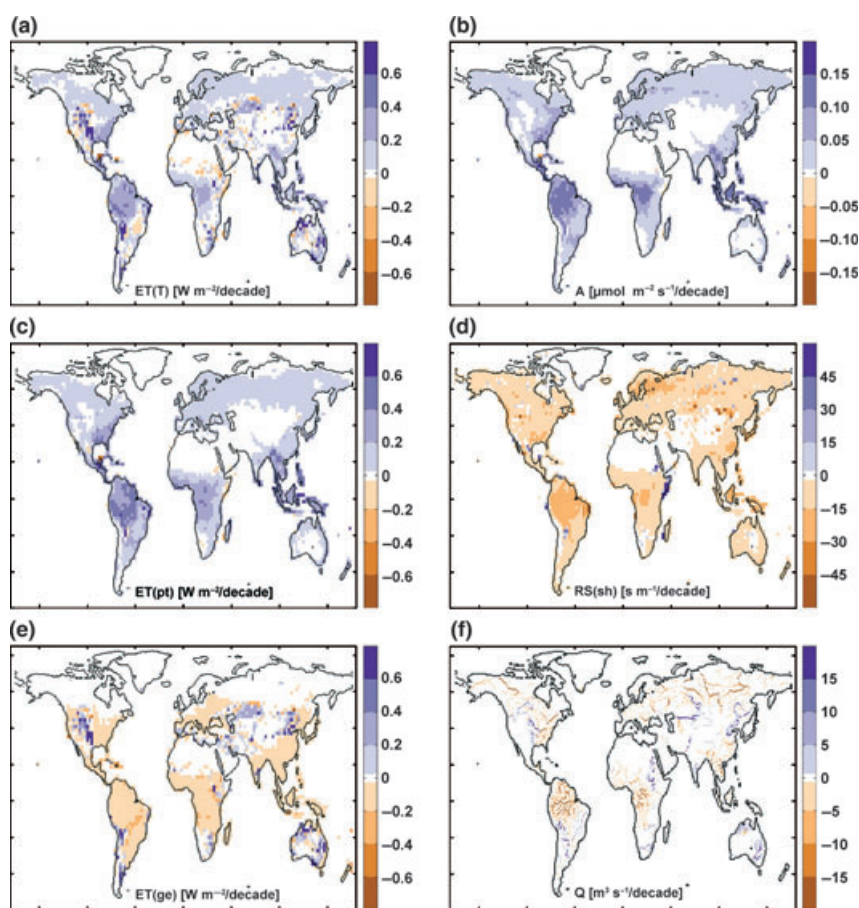
may return as much as half the additional energy in the form of latent heat, leaving less water on the surface to flow into rivers, with the opposite being true for extreme dimming. However, extreme radiation signals imposed offline on the global scale are physically unrealistic, and the response is only an indication of general model behavior. Indeed, they are, in particular, large artificial radiation changes uncoupled from a possible response of atmospheric temperature.

The implementation of 'realistic' solar radiation signals, observed in recent decades in regions such as

Europe and the eastern US, but missing in forcing datasets, produces substantial impacts on ET and runoff. Therefore, for the dimming period of 1960–1990, the modeled response is a decadal decrease in ET of about  $0.5 \text{ W m}^{-2}$  (mostly due to changes to its plant transpiration and ground evaporation components in approximately equal proportions) and a concurrent decadal increase in runoff of nearly 1.5% of the half-century mean. The runoff trends estimated from our study are larger than those in previous studies (Table 2). However, in relative terms, the runoff annual trends as a result of the radiation/aerosols effect ( $-23\%$  and  $-108\%$  relative to the magnitude of the climate-induced trends for Europe and globally, respectively) are similar to those from Gedney *et al.* (2006) obtained for an analogous experiment ( $-21\%$  and  $-93\%$ ), and are approximately of the same order of magnitude as those calculated, in various studies, for other potential drivers of runoff change such as climate,  $\text{CO}_2$ , or land use (Table 2), thus strengthening the claim that radiation effects on runoff trends are not to be neglected. Simi-

larly, the 0.6% decrease in ET obtained as a result of dimming radiation is of exactly the same magnitude as the effect of climate forcing alone (not shown), and larger than the 0.2% drop from a double- $\text{CO}_2$  effect on plant physiology from a 50-year coupled simulation (Cao *et al.*, 2009). The application of a reverse signal of similar magnitude to a period twice as small such as the 1990–2004 solar brightening elicits a qualitatively similar, but proportionally stronger response, as ET rises by  $2 \text{ W m}^{-2}$  per decade, whereas runoff has a decadal drop of almost 7% of its mean value.

Some noted discrepancies between global runoff trends from different modeling studies shown in Table 2, in particular, the larger trends found in our study, are probably a result of differences in model performance, forcing datasets, and considered time periods. Indeed, Gerten *et al.* (2008) found a high decadal variability in runoff with the LPJ model, suggesting that assessed trends strongly depend on the considered period (with variations of up to one order of magnitude on the global scale for 30-year periods), thus making



**Fig. 7** Experiment 3: sensitivity of land-surface processes to direct/diffuse radiation partitioning, with global maps of difference between decadal trends of DirDif and CTL simulations for total evapotranspiration and its plant transpiration and ground evaporation components (a, c, e); photosynthesis (b); shaded leaf stomatal resistance (d); and runoff (f).

Table 2 Comparison of modeled runoff trends (mm/yr<sup>2</sup>) from various studies

Land-surface model	Forcing data	Publication	Time period	Domain	Climate* (P + T + Hu + Wi)	Other drivers <sup>†</sup>			
						Radiation/aerosols	Diffuse radiation	CO <sub>2</sub>	Land use
CLM3.5	NCEP/NCAR Reanalysis	This study <sup>‡</sup>	1960–1990	Europe	-1.82	+0.41 <sup>§</sup> (-23%)	-0.09 <sup>¶</sup> (5%)	-	-
				Global	-0.40	+0.43 <sup>§</sup> (-108%)	-0.07 <sup>¶</sup> (18%)	-	-
ORCHIDEE	[IPSL CM4 output]	Alkama <i>et al.</i> (2010)	1951–2002	Europe	-0.30	-	-	-	-
				Global	-0.30	-	-	-	-
LPJml	CRU TS 2.1	Gerten <i>et al.</i> (2008)	1951–2002	Global	-0.12	-	-	+0.03 (-23%)	+0.02 (-14%)
				Global	+0.16	-	-	+0.03 (21%)	+0.04 (28%)
ORCHIDEE	CRU TS 2.1	Piao <i>et al.</i> (2007)	1901–1999	Global	+0.15	-	-	-0.04 (-27%)	+0.08 (53%)
				Europe	+0.19	-	-	-0.01 (-5%)	+0.10 (53%)
HadCM3	CRU05	Gedney <i>et al.</i> (2006)	1960–1994	Europe	-0.19	+0.04 (-21%)	-	+0.25** (-132%)	-0.02 (11%)
				Global	-0.14	+0.13 (-93%)	-	+0.25** (-179%)	0.00 (0%)

\*Includes trends intrinsic to atmospheric forcing datasets: precipitation, temperature, humidity, wind.

<sup>†</sup>Values in brackets show percentage relative to climate trend.

<sup>‡</sup>Domains: Europe latitude 37°N–72°N, longitude 11°W–30°E; Global latitude 60°S–90°N.

<sup>§</sup>1960–1990 runoff trend only from imposed additional shortwave radiation forcing trend equivalent to -2.94 mm yr<sup>-2</sup>.

<sup>¶</sup>1960–1990 runoff trend only from increased diffuse fraction by 1.5% per decade starting from the 70%/30% direct/diffuse model default, reaching 65.5%/34.5% at end of 30 years, globally.

\*\*Unlike other studies investigating sensitivity to CO<sub>2</sub>, Gedney *et al.* (2006) does not take the CO<sub>2</sub> fertilization (LAI) effect into account.

relative effects of the investigated drivers (indicated in percent in Table 2) more relevant than the absolute trends for the comparisons across studies.

Some of the analyzed variables of the climate system behave differently with respect to sensitivity to each  $\text{W m}^{-2}$  of radiation change. In mid-latitude regions, vegetation-mediated processes respond more strongly to radiation, whereas river runoff is less sensitive, both for dimming and brightening. Sensible heat, however, shows a consistently high sensitivity to radiation changes, which may question some beliefs from previous accounts that stated the opposite (Wild *et al.*, 2008). Part of this behavior may nonetheless be due to the uncoupled nature of the experiments (see above).

One caveat to this simulation might be that the observed dimming and brightening signals were limited to locations of observation sites in regions of the northern hemisphere that conducted such measurements, whereas the 'realistic' signals were imposed globally. However, the fact that the experiment is off-line ensures the removal of teleconnection effects. In addition, the selection of 1990 as the break point between periods of inverse radiation signals, although generally acceptable globally, might be inadequate for some regions, which may impact the results. Also, changes in aerosol loadings affect variables other than radiation, such as precipitation (Ramanathan *et al.*, 2001) and temperature, which may also play important roles for resulting hydrologic trends. Some regions, in particular, are still undergoing significant aerosol loading presently, e.g. India (Padma Kumari & Goswami, 2010). This problem is partly accounted for, as most of the analysis is done based on the anomalies resulting from subtracting the control simulation results. Nonetheless, further studies should attempt to validate the modeled runoff output with observed data from anthropogenically intact watersheds, in which case, the break point selection issue should be further addressed. Lastly, despite the model standard interpolation function, the employed 6-hourly forcing data does not fully capture the daily and annual cycles for important fields such as incoming solar radiation, which might lead to an underestimation of the variability. Future investigations should attempt to quantify the effect of the temporal resolution of the forcing on similar simulation results.

The reported increase in the diffuse fraction of total radiation also impacts the hydrologic cycle by increasing ET – over  $0.5 \text{ W m}^{-2}$  per decade in tropical regions due to plant transpiration. A concomitant increase in photosynthesis, mostly due to a rise in shaded leaf stomatal conductance, was noted, which is consistent with the notion that as sunlit leaves are often light-saturated, more incoming diffuse radiation will have a positive

net effect on shaded leaf photosynthesis (Mercado *et al.*, 2009). Conversely, the opposite, albeit smaller, effect on ground evaporation is a result of less total radiation reaching the ground in vegetated areas, as a greater direct and diffuse total is now captured by the canopy.

Comparing the effects on ET of an increase in diffuse fraction with those resulting from global dimming shows that, although the former tend to be almost one order of magnitude smaller and of opposite sign, they can play relevant roles in the energy and water balances in such regions as the Eastern US or the tropics. Outside the arid regions, the effect of soil moisture does not seem to play a significant role in either radiation-induced water cycle changes during the dimming period.

## Conclusions

Observed changes in solar radiation in recent decades have been shown to affect photosynthesis and the carbon balance, and should also impact key components of the hydrologic cycle such as ET and runoff. To clearly understand the mechanisms driving global, multi-decadal hydrologic changes by relying solely on hydrologic observation data is a challenging task, as such datasets often have large associated uncertainties and inadequate spatio-temporal coverage, and typically incorporate possible confounding effects. This makes land-surface modeling a useful tool to study the effects of modifications in the solar forcing on land hydrology. Modeled components of the water cycle respond strongly to extreme radiation change, especially in the tropics. A more realistic 1960–1990 solar dimming may have caused, in regions of Europe and the Eastern US, a decadal decrease in ET of about  $0.5 \text{ W m}^{-2}$ , mostly as a result of equal changes to plant transpiration and ground evaporation, and a concurrent decadal increase in runoff of nearly 1.5% of the half-century mean. Conversely, an imposed 1990–2004 solar brightening signal for those regions may have raised ET in  $2 \text{ W m}^{-2}$  per decade, lowering decadal runoff by about 7% of its mean. Reported increases in the diffuse fraction of solar radiation may have also impacted ET, raising it up to  $1 \text{ W m}^{-2}$  per decade in the tropics. Higher plant transpiration, which accompanies increases in photosynthesis from more shaded leaf stomatal conductance, appears to be the responsible mechanism. Conversely, less direct radiation reduced ground evaporation responsible for a drop in ET of similar magnitude in some marginally arid regions. Additional studies should seek to validate the modeled runoff output with observed streamflow data from non-impacted watersheds, and further analyze the hydrologic impacts of direct/diffuse radiation by implementing better

radiation partitioning. Furthermore, global, two-dimensional data on the partitioning of solar radiation between its direct and diffuse fractions is scarce, and further studies are necessary to implement appropriate radiation forcing and analyze the impacts on the various components of the water cycle. Ultimately, a more complete understanding of the mechanisms and processes driving the impacts of solar radiation on the hydrologic system is fundamental for the development and parameterization of land-surface schemes and the improvement of predictions of climate and water resources.

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