On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle

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[1] Several studies indicate that incident shortwave radiation at land surfaces has significantly decreased between 1960 and 1990. Despite this, land temperature has increased by 0.4°C over the same period. From a surface energy balance perspective, this counterintuitive behaviour can be resolved either 1) through an increase in the downward longwave radiation which outweighs the decreased insolation or 2) through a decrease of surface evaporation and associated reduced evaporative surface cooling. It is suggested that 1) may not be large enough, so that the available energy for evaporation may rather have decreased than increased over the period considered. This is in line with an analysis of observed surface net radiation records. The inferred decrease of evaporation would further imply that the observed intensification of the hydrological cycle over extratropical land has been more likely due to increased moisture advection from the oceans than due to increased local moisture release through evaporation. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 1655 Global Change: Water cycles (1836); 1836 Hydrology: Hydrologic budget (1655); 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Wild, M., A. Ohmura, H. Gilgen, and D. Rosenfeld (2004), On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle, *Geophys. Res. Lett.*, *31*, L11201, doi:10.1029/2003GL019188.

1. Introduction

[2] The climate of the 20th century has undergone significant changes of natural and anthropogenic origin [*IPCC*, 2001]. Many studies document the changes in surface temperature over the past decades. Only few studies concentrated on the surface energy balance components, which are the processes that govern the evolution of surface temperature. In the present study we are particularly interested to clarify how observed changes in surface radiation relate to observed changes in surface temperature and hydrology. This interest has been evoked by apparently counterintuitive reports of decrease in surface insolation and increase in surface temperature over the same period.

[3] We address this issue making use of the information available from observational records as contained in the Global Energy Balance Archive [GEBA, *Ohmura et al.*, 1989], located at the authors institute. GEBA is a comprehensive database of worldwide measured surface energy fluxes at currently more than 2000 sites.

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2. The Concept of Surface Energy Balance and Radiative Heating

[4] The law of energy conservation requires that the sum of the changes of the surface energy balance components adds up to zero, i.e.,

$$\Delta SW_{absorbed} + \Delta LW_{down} + \Delta LW_{up} + \Delta SH + \Delta LH + \Delta GH + \Delta M = 0 \qquad (1)$$

where $SW_{absorbed}$, LW_{down} and LW_{up} refer to the absorbed shortwave, and downward and upward longwave radiative fluxes, respectively, SH and LH to the sensible and latent heat fluxes, GH to the ground heat flux and M to the energy flux used for melt.

[5] We define here the surface radiative heating as the sum of the absorbed shortwave and downward longwave radiation (the first two terms in Equation (1)). This can also be interpreted as radiative input provided to the surface. The surface responds to this imposed change in surface radiative heating by redistributing the altered energy content amongst the nonradiative fluxes of the surface energy balance and the surface longwave emission (the third to seventh term in Equation (1)).

[6] Further, the sum of the first three terms in Equation (1) (the changes in the net shortwave and longwave radiation) determines the change in available energy at the surface for the nonradiative fluxes and is referred to as surface net radiation change.

3. Estimated Changes in Surface Radiative Heating and Surface Net Radiation

[7] In the following we derive estimates for the change in the surface radiative heating and surface net radiation over the past decades. We focus on the period 1960–1990 where quality controlled irradiance data are available and evaluated in several studies [*Gilgen et al.*, 1998; *Liepert*, 2002; *Ohmura et al.*, 1989; *Stanhill and Cohen*, 2001, and references therein]. All these studies report a decreasing trend in insolation between 1958 and 1990, based on worldwide long-term records of solar irradiance at the surface. *Gilgen et al.* [1998] give a reduction of solar irradiance of 2% per decade based on the comprehensive dataset contained in the

GEBA database. This corresponds to 3.4 Wm^{-2} per decade, or 3.0 Wm^{-2} per decade when the absorbed fraction of irradiance is considered. This is equivalent to 9 Wm^{-2} decrease in absorbed shortwave radiation at the surface over the period 1960–1990 (Table 1). The reduction of solar irradiance given in *Stanhill and Cohen* [2001] is 10 W m^{-2} over the 27 years 1958–1985, while *Liepert* [2002] estimated a decrease of 7 Wm^{-2} over the period 1961–1990. The estimates by *Stanhill and Cohen* [2001] and *Liepert* [2002] translated into the absorbed part of the incident irradiance at the surface correspond to −9 Wm^{-2} and −6 Wm^{-2}, respectively, assuming constant surface albedo (Table 1).

[8] At the same time, the temperature at the Earth's surface has significantly increased [*IPCC*, 2001]. From the dataset provided by *Jones et al.* [1999] we determine an increase of 0.4°C for global mean land temperature over the period 1960–1990, based on a linear regression of the annual mean values over this period. Opposing trends in insolation and temperature were also found on more local scales by comparing the insolation trends [*Gilgen et al.*, 1998, their Figure 8] with collocated temperature trends as e.g., given in *IPCC* [2001]. This temperature change can be translated into surface longwave emission (upward longwave radiation) using the Stefan-Boltzmann law. The increase of 0.4°C corresponds to an increase of surface longwave emission of 2 Wm^{-2} over land (Table 1).

[9] To obtain an estimate for the change in downward longwave radiation over the same period, we have to rely on Global Climate Model (GCM) experiments, since only few stations are available with longterm records of downward longwave observation. The transient experiments analyzed for the present study were performed with the ECHAM4 GCM and include greenhouse gas and direct and indirect sulphur aerosol forcings as described in *Roeckner et al.* [1999]. The downward longwave radiation is very accurately simulated in ECHAM4 as demonstrated in *Wild et al.* [1998] and therefore well suited to estimate the evolution of this quantity. The simulated change in downward longwave radiation associated with the simulated temperature change of 0.4°C (closely covering the modelling period 1960–1990) amounts to 3 Wm^{-2} over land surfaces (Table 1). A general increase of this flux is expected due to the increased level of greenhouses gas concentration and associated temperature and water vapour feedbacks. Similar estimates were derived from other models and experiments published in *Wild et al.* [1997] and *Garratt et al.* [1999], as well as from a simulation we recently completed in Switzerland with ECHAM5 and prescribed SSTs for the period 1960–1990. Reliable records of continuous downward longwave radiation measurements are hardly available prior to the 1990ies and thus do not cover the period 1960–1990 investigated here. *Philipona et al.* [2004] found a significant increase in downward longwave radiation observed at several stations in the Swiss Alps between 1995 and 2002. In a preliminary analysis of worldwide observations from the Baseline Surface Radiation Network starting in the early 1990's [BSRN, *Ohmura et al.*, 1998], we note a worldwide increase of downward longwave radiation, in quantitative agreement with estimates obtained from GCMs.

[10] The change in radiative heating over land surfaces as defined in Section 2 can then be inferred from the above estimates of shortwave and longwave changes for the period 1960–1990: The downward longwave flux has been estimated to increase by 3 Wm^{-2}, while the absorbed shortwave radiation decreased by 6–9 Wm^{-2} (cf. Table 1). This results in a reduced radiative heating of approximately −3 to −6 Wm^{-2} (Table 1) and suggests that the decrease in absorbed solar radiation may not have been fully balanced by the increase in downward longwave radiation over this period. The main point here is that, if the reported decrease in insolation has indeed been genuine and representative, the radiative heating over land surfaces has decreased between 1960 and 1990. A potential underestimation of water vapour and cloud changes in the GCM-determined downward longwave radiation changes unlikely affects this conclusion. Sensitivity studies with a radiation code show that a water vapour increase of more than 10% would be necessary to obtain downward longwave flux increases large enough to compensate for the reported shortwave decreases [*Wild*, 1997]. Such an increase of water vapour, however, is not expected before the time of doubling of CO_2 [cf. e.g., *Wild et al.*, 1997]. Further, changes in cloud cover affect the downward longwave flux much less than the downward shortwave flux, since the longwave cloud radiative forcing at the surface is only about one third of the shortwave [*Wild et al.*, 1998].

[11] An independent observational assessment of the above conclusion, i.e., the decrease in insolation may not have been outweighed by the increase in downward longwave radiation, may be obtained from measurements of the surface net radiation. Such observational records are available at selected sites from GEBA. The net radiation at the surface is determined by the balance between the surface radiative heating (as defined in Section 2) and the surface radiative cooling due to longwave surface emission. According to the estimates derived above the change in net radiation amounts to −5 to −8 Wm^{-2} (Table 1). Surface net radiation observations are not as widely distributed as the global radiation observations, which have been used for the determination of trends in solar radiation [cf. *Wild et al.*, 1995]. Nevertheless we could retrieve 66 stations from GEBA, located predominantly over northern extratropical land, which contain observational records of net radiation over at least a decade. Linear trends of the annual mean time series have been determined for each of these stations and were averaged over 4 regions, as given in Table 2. A slight

Table 1. Estimated Changes in Energy Fluxes Over Global Land Surfaces for the Period 1960–1990 (Energy Gain for the Surface is Signed Positive)

a) Change in absorbed shortwave radiation	−6 to −9 Wm^{-2} [abc]
b) Change in downward longwave radiation	+3 Wm^{-2} [def]
a) + b) = surface radiative heating	−3 to −6 Wm^{-2}
c) Change in upward longwave radiation	−2 Wm^{-2} [d]
d) Change in net radiation a) + b) + c)	−5 to −8 Wm^{-2}
e) Change in ground heat flux	−0.01 Wm^{-2} [g]
f) Change in melt	−0.2 Wm^{-2} [g]
=> inferred change in turbulent (latent and sensible heat) fluxes:	+5 to +8 Wm^{-2}

[a] *Gilgen et al.* [1998].
[b] *Liepert* [2002].
[c] *Stanhill and Cohen* [2001].
[d] Present Study.
[e] *Wild et al.* [1997].
[f] *Garratt et al.* [1999].
[g] *Ohmura* [2004].

Table 2. Changes in Time Series of Annual Mean Net Radiation Observed at 66 Sites From the Global Energy Balance Archive Covering at Least One Decade of the Period 1960–1990

Region	No. of Stations	Mean Change (Wm^{-2} per Decade)
Europe	16	−1.0
Canada	21	−0.1
Former Soviet Union	28	−0.5
Australia	1	−2.8

tendency for a decrease of surface net radiation is found over Europe and for the site in Australia. Also over the area of the former Soviet Union, a slight tendency for a decrease of surface net radiation is found. Over Canada, the picture is rather mixed with no clear sign for a tendency. Overall, however, we can note that at least no clear indication for an increase of available energy at the surface is evident in the observations, as e.g., typically found in GCM simulations. Rather, a slight decrease may be inferred from the observations. This is in line with the findings in Table 1, and is therefore not in conflict with the above conclusion that the decrease in insolation might have been at least as large as the increase in downward longwave radiation over the period 1960–1990.

4. Consequences for the Nonradiative Components of the Surface Energy Balance

[12] The changes in surface net radiation have to be balanced by the changes in the nonradiative fluxes of the surface energy balance (i.e., the last four terms in Equation (1)). Of those, the changes in ground heat flux and melt [*Ohmura*, 2004] are small compared to the estimated change in the radiative heating over the period and can be neglected in this context (cf. Table 1). The estimated reduction of available energy therefore has to be compensated predominantly by the turbulent fluxes. Since the majority of the turbulent energy transport over land is due to latent heat (the energy equivalent of evaporation), this flux is primarily affected by the reduction in surface net radiation [e.g., *Ramanathan et al.*, 2001].

[13] It is therefore the reduced evaporative cooling at the land surface, which resolves the apparent inconsistency between reduced surface radiative heating and increased temperature. The reduced evaporative cooling seems to overcompensate the reduced surface radiative heating, resulting in an increase in surface temperature. A reduced cooling due to reduced sensible heat flux may further play a role particularly in dry areas. From the above considerations on the consistency between surface radiative heating and temperature records we therefore infer, that the turbulent fluxes over land may rather have decreased than increased over the period 1960–1990. Several observational studies indeed report a worldwide reduction in pan evaporation over the past decades [*Roderick and Farquhar*, 2002, and references therein; *Ohmura and Wild*, 2002], although its interpretation in terms of actual evaporation is currently disputed [*Brutsaert and Parlange*, 1998; *Lawrimore and Peterson*, 2000; *Golubev et al.*, 2001; *Roderick and Farquhar*, 2002]. There are also observational studies that report increases in actual evaporation over specific regions [e.g., *Milly and Dunne*, 2001]. Direct measurements therefore do not yet provide a conclusive picture of actual evaporation trends. Estimates of changes in the radiative fluxes as derived in the present study may be able to put additional constraints on estimates of the past evolution of evaporation.

5. Summary and Implications for the Hydrological Cycle

[14] In this study, observational estimates of changes in surface radiative fluxes over land for the period 1960–1990 were brought together. These estimates indicate that the reported reduction in insolation over global land surfaces, if real and representative, may have exceeded the greenhouse induced increase in downward longwave radiation. This would imply a reduction in radiative heating at the surface on the order of 1–2 Wm^{-2} per decade between 1960 and 1990. This is in line with an independent analysis of long-term records of 66 surface net radiation stations, which also suggest a slight decrease rather than an increase in radiative energy available at the surface. If the decrease in surface radiative heating over the period 1960–1990 has indeed been genuine, the observed temperature increase of 0.4°C at global land surfaces over the same period has only become possible through a reduced surface cooling by the turbulent fluxes, particularly evaporation.

[15] Reduction of the land surface evaporation and associated moisture release into the atmosphere implies a reduction of precipitation, if no changes in the large scale moisture convergence take place. Reduced precipitation has also been suggested to result from increased aerosol loading in the atmosphere in observational studies [*Rosenfeld*, 2000]. Increased aerosol loading (both absorbing and scattering aerosol) lead to a reduced insolation at the surface, known as direct aerosol effect. In addition, the increased number of cloud condensation nuclei with increased aerosol loading lead to both brighter and less precipitating clouds, with thus longer cloud lifetime (indirect aerosol effect), again reducing surface insolation [*Albrecht*, 1989]. On the other hand, the downward longwave radiation is much less affected by these effects, which could explain why the downward longwave radiation, despite its greenhouse gas induced enhancement, may not have exceeded the shortwave loss over the period considered. The enhancement of both direct and indirect aerosol effects due to increased air pollution may therefore have led to a reduction of the surface radiative heating and surface net radiation over the investigated period, in line with the trends found in the observational records from GEBA. The increase of absorbing aerosol (such as organic carbon) over the past decades in addition may have lead to a stabilisation of the atmosphere due to the increased absorption of solar radiation within the atmosphere and reduced absorption at the ground [e.g., *Ramanathan et al.*, 2001]. This may also contribute to a suppression of the turbulent fluxes and further reduce surface insolation, net radiation and evaporation, as estimated in the present study.

[16] High loading of absorbing aerosols can lower the surface fluxes to the extent of preventing the formation of boundary layer clouds, and so actually prevent the cooling effect that these clouds would have induced by their reflectance [*Koren et al.*, 2004]. The solar radiation that is

absorbed in the smoke clouds that have suppressed and replaced the water clouds is fully converted to sensible heat, potentially explaining part of the warming in spite of the decreasing solar radiation reaching the surface.

[17] Recent global climate modelling studies which take into account a comprehensive representation of aerosol effects are in line with the above estimates [*Liepert et al.*, 2004; *Feichter et al.*, 2004]. These equilibrium experiments use detailed aerosol and greenhouse gas compositions representative for pre-industrial and present day conditions and show a decrease in surface net radiation and evaporation between the pre-industrial and present state, in contrast to GCM experiments which consider only the effect of greenhouse gases [*Liepert et al.*, 2004; *Feichter et al.*, 2004]. A decrease in insolation, evaporation and precipitation together with increasing surface temperature was also noted by *Roeckner et al.* [1999] in the transient GCM experiment referred to in Section 3.

[18] To summarize, our examination of various observational records gave no indications for an enhancement of the radiative heating and thus evaporation over land surfaces over the period 1960–1990. The increase in the intensity of the global hydrological cycle over extratropical land areas reported in *IPCC* [2001] may therefore not have been due to increased local moisture release from evaporation, but rather due to an increase of moist air advection into the land areas [cf. *Schär et al.*, 1999]. This might have been favoured by an increase of the Arctic Oscillation and of monsoon-like flow due to the stronger warming over land than over oceans [*Doherty et al.*, 1999; *New et al.*, 2001].

[19] Future investigations, including a seasonal and station-wise analysis as well as an extension from 1990 up to present, may provide additional insights into the interplay between changes in radiation, surface temperature, evaporation and the hydrological cycle.

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