Radiative forcing - measured at Earth's surface - corroborate the increasing greenhouse effect

Rolf Philipona, Bruno Dürr, Christoph Marty, Atsumu Ohmura* and Martin Wild*

Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland.

**Institute for Atmospheric and Climate Science, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland.*

RADIATIVE FORCING AT EARTH'S SURFACE

Abstract. The Intergovernmental Panel of Climate Change (IPCC) confirmed concentrations of atmospheric greenhouse gases and radiative forcing to increase as a result of human activities. Nevertheless, changes in radiative forcing related to increasing greenhouse gas concentrations could not be experimentally detected at Earth's surface so far. Here we show that atmospheric longwave downward radiation significantly increased (+5.2(2.2) Wm^{-2}) partly due to increased cloud amount (+1.0(2.8) Wm^{-2}) over eight years of measurements at eight radiation stations distributed over the central Alps. Model calculations show the cloud-free longwave flux increase (+4.2(1.9) Wm^{-2}) to be in due proportion with temperature (+ 0.82(0.41) °C) and absolute humidity (+0.21(0.10) g m^{-3}) increases, but three times larger than expected from anthropogenic greenhouse gases. However, after subtracting for two thirds of temperature and humidity rises, the increase of cloud-free longwave downward radiation (+1.8(0.8) Wm^{-2}) remains statistically significant and demonstrates radiative forcing due to an enhanced greenhouse effect.

Introduction

In the early 19th century *Fourier* (1827) found the atmosphere to be acting like a glass of a hothouse, letting through light rays of the sun but retaining the dark rays from the ground. That dark thermal radiation is absorbed by atmospheric trace gases, now called greenhouse gases (GHGs), was observed by *Tyndall* (1861). To him water vapour had the greatest influence, and it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. The importance of carbon dioxide however, and the influence of artificial CO_2 production on temperature at Earth's surface, was pointed out by *Arrhenius* (1896) by the end of the 19th century.

Accurate and highly resolved laboratory measurements have since improved the knowledge on spectral absorption of gases (*Goody*, 1964). The amount of heat energy added to the atmosphere is mainly controlled by the concentration of greenhouse gases and their ability to absorb solar shortwave and thermal longwave radiation. This natural control, known as the greenhouse effect, and its feedback on the climate has been explored by many theoretical and model studies suggesting that increased concentrations of greenhouse gases result in increased radiative forcing and hence increasing temperatures at the surface (*Callendar,* 1938*; Houghton et al.,* 1990). Meanwhile, increasing greenhouse gas concentrations have been widely reported and related radiative forcing is predicted with high level of scientific understanding (*Houghton et al*., 2001). Satellite radiation-budget measurements (*Raval and Ramanathan,* 1989*; Inamdar and Ramanathan,* 1997) have been used to examine the radiative feedbacks in the climate system. Changes of the Earth's outgoing longwave radiation (*Harries et al.,* 2001; Wielicki et al., 2002) have been reported also from satellite measurements. Yet to our knowledge, radiative forcing and its direct relation to surface temperature and humidity changes, has not been observationally examined in depth and over long time periods with radiation budget measurements at Earth's surface.

Here we present the changes and trends of radiative fluxes at the surface and their relation to greenhouse gas increases and temperature and humidity changes measured from 1995 to 2002 at eight stations of the Alpine Surface Radiation Budget (ASRB) network. ASRB stations (Table 1) are located between 370 and 3580 m a.s.l., and over an area of about 200 by 200 km square in the Alps (central Europe, latitude ≈ 46° N). Surface radiation budget measurements (*Marty et al.,* 2002) rely on accurate measurements of downward and upward shortwave and longwave radiation at the meteorological screen level height. Longwave radiation instrumentation has been largely improved in recent years (*Philipona et al.,* 1995*; Marty et al.,* 2003) and is now related to an absolute reference standard instrument (*Philipona*, 2001).

Temperature, humidity and radiative flux changes

Over the last two decades temperature and humidity increases in central Europe are considerably larger than global average (*Jones and Moberg,* 2003). According to measurements at six MeteoSwiss stations, temperature and absolute humidity in the Alps increased from 1980 to 2002 by +1.32 (0.5) °C and +0.51 (0.2) g m^{-3} (values in parenthesis represent 1σ standard deviation of residuals to the linear regression trend line) respectively (Fig.1). At those six and two additional stations ASRB radiation measurements were initiated in 1994. Although very warm years were recorded in the early 1990s, an even stronger average surface temperature increase of +0.82 (0.4) °C is found between 1995 and 2002 at the eight stations, with an absolute humidity increase of +0.21 (0.1) g m^{-3} or 4.4 %.

During these eight years, longwave downward radiation (*LDR*) measurements show increases (Fig. 2a) of about 5 to 8 Wm^{-2} for most of the stations north of the Alps except

Davos (Da), and a more modest increase for the stations south of the Alps. Solar or shortwave downward radiation (*SDR*) on the contrary decreased at all ASRB stations by 0.5 and 6 Wm^{-2}, except at the station Weissfluhjoch (Wf) (Fig. 2b). Hence, temperature and absolute humidity increases in the Alps are likely to be related to the +5.2 (2.2) Wm^{-2} average increase of longwave radiative flux, which is considerably greater than the average decrease of -2.0 (3.7) Wm^{-2} of solar shortwave radiation at the surface.

Longwave downward radiation is expected to increase with increasing greenhouse gas concentrations, but also with the increase in temperature and cloud amount. Cloud amount is determined with the clear-sky index method (*Marty and Philipona,* 2000), and the longwave cloud effect (*LCE*) is calculated by subtracting longwave net radiation (downward minus upward) of cloud-free from all-sky situations (*Charlock and Ramanathan,* 1985). *LCE* (Fig. 2c) increased over the eight years at all stations north of the Alps, except Davos (Da). Although south of the Alps at Locarno-Monti (Lo) and Cimetta (Ci) the cloud amount decreased, an overall increase of +1.0 (2.8) Wm^{-2} of *LCE* is measured. Subtracting *LCE* from *LDR* results in the cloud-free longwave downward radiation LDR_{cf} (Fig. 3a), which shows an average increase of +4.2 (1.9) Wm^{-2}. The reduced stdev of LDR_{cf}, which is the average of the stdev of all stations, results from the fact that *LCE* is part and not independent of *LDR* (note the correlation between the two variables in Fig.2a and 2c). The rather homogeneous LDR_{cf} increase is a result of increasing greenhouse gas concentrations and temperature in the surface-atmosphere system. The increasing cloud amount adds to the reduction of solar shortwave radiation. Subtracting the shortwave cloud effect (similar definition as *LCE*) from *SDR* reduces the SDR_{cf} decrease to –1.0 (3.7) Wm^{-2}. This reduction is mainly due to increased water vapour absorption.

Larger forcings observed than expected by GCMs

Coupled atmosphere-ocean General Circulation Models (GCMs) were used to predict changes of radiative forcings and their impact on surface temperature and humidity, for given variations of greenhouse gases in the atmosphere (*Wild et al., 1997*). For a 10 % increase of CO_2, including respective increases of other greenhouse gases and water vapour feedback, the ECHAM-4 GCM calculates an increase over land in the northern hemisphere of LDR_{cf} of +4.6 Wm^{-2} and a SDR_{cf} decrease of –1.4 Wm^{-2}. These flux changes induce temperature and absolute humidity increases of +0.74°C and +4.4 % respectively. Table 2 shows that these model predicted flux and climate parameter changes are in good agreement with ASRB measured variations over the eight years time period.

However, the CO_2 increase from 1995 to 2002 was not 10 %, but only 12 ppm or 3.3 % in central Europe. Hence, although changes of radiative fluxes and subsequent climatic changes observed at the surface are in due proportion with model predicted variations, they are about three times larger than expected from greenhouse gas increases. A 10 % CO_2 increase was actually measured from 1980 to 2002 (337 to 372 ppm) in central Europe at the station Schauinsland, Germany. During this time period temperature increased by +1.32 (0.5) °C and absolute humidity by +0.51 (0.2) g m^{-3} or 10 % over the central Alps (see Fig.1). Hence, even for the 22 years time period, measured temperature and humidity increases are still twice as large than models predict for anthropogenic greenhouse gas increases. At least half of the increases may therefore not be explicable by direct effects of increased GHGs and associated feedbacks on temperature and humidity, but are rather due to circulation changes over central Europe. On the northern hemisphere, non-uniform warming with differing decadal and marked seasonal and regional variations is often related to changes of the North Atlantic Oscillation (NAO) (*Hurrell,* 1995).

Radiative forcing due to enhanced greenhouse effect

To isolate and detect enhanced radiative forcings that are solely due to increased greenhouse gas concentrations and their feedbacks, temperature changes as well as humidity changes that are due to external warm air advection, must be subtracted from LDR_{cf}. Temperature (Fig.1a) and cloud free longwave downward radiation (Fig. 3a) are highly correlated showing correlation coefficients r between 0.88 and 0.97 at all stations. Since average temperatures as well as residuals to the linear regression and temperature increases at the stations are known, year-to-year variations as well as temperature trends over the measurement period can be corrected. From LDR_{cf} values we subtract the respective temperature driven changes of longwave downward radiation (ΔLDR_t), which is the first derivative of the Stefan-Boltzmann equation multiplied by the cloud-free apparent sky emittance (ε_{Acf}) (see Table 1).

$$\Delta LDR_t = 4\,\sigma T_a^3\,\Delta t_a\;\varepsilon_{Acf}\,. \tag{1}$$

σ is the Stefan-Boltzmann constant, T_a the average temperature at the station and Δt_a is on the one hand the residual of the temperature to the linear regression for the year-to-year correction, and on the other hand two thirds of the temperature trend that is due to warm air advection. The resulting temperature corrected cloud-free longwave downward radiation ($LDR_{cf,tc}$) shown in figure 3b) has, due to the high correlation, now much less variability and a quite uniform increase between 2.1 and 2.9 Wm^{-2} over all stations. The average $LDR_{cf,tc}$ increase is +2.4 (0.9) Wm^{-2} and most of the stations show a trend at the 95% significance level.

Stand-alone radiative transfer calculations with the MODTRAN model predict a +0.26 Wm^{-2} LDR increase for 12 ppm CO_2 and other greenhouse gas increases apart from water vapour. For water vapour, MODTRAN calculations show sensitivities of 0.56 and

1.73 Wm^{-2} at 500 respectively 3000 meters a.s.l., for a 0.1 g m^{-3} change of water vapour (gradual decrease assumed in the first 4 km). According to the GCM calculations only one third of the measured water vapour increase (Fig. 1b) is due to feedbacks of anthropogenic greenhouse gas increases. Measurements further show that for cloud free situations the water vapour increase is about half of that measured for all sky situations. Accordingly, the expected increase of LDR_{cf} due to water vapour feedback is +0.44 Wm^{-2}. The LDR_{cf} increase due to one third of the temperature increase over the measurement period is 0.88 Wm^{-2}. Overall, model calculations predict anthropogenic greenhouse gases and feedbacks to increase LDR_{cf} by a total of +1.58 Wm^{-2} on average over the eight years.

Since part of the increased $LDR_{cf,tc}$ flux shown in figure 3b) is due to water vapour that stems from external warm air advection, we correct for two thirds of the humidity increase applying the same sensitivities as in the preceding paragraph. Good correlation is also found between $LDR_{cf,tc}$ and absolute humidity ($r = 0.89$ for the average values), which allows further correcting year-to-year variability. Figure 3c) shows the cloud and external temperature and humidity corrected longwave downward radiation ($LDR_{cf,tc,uc}$), uniformely increasing by 1.4 to 2.5 Wm^{-2} over the eight years. No clear sign of altitude dependence is observed. On average the final corrected $LDR_{cf,tc,uc}$ measurements show an increase of +1.8 (0.8) Wm^{-2} with a 95% significance level at almost all stations. This remaining increase of longwave downward radiation demonstrates radiative forcing that is due to enhanced greenhouse gas concentrations and feedbacks, and is in reasonably good agreement with the expected +1.58 Wm^{-2} increase predicted by MODTRAN radiative transfer model calculations.

Conclusions

We have shown that longwave downward radiation flux increases at Earth's surface can be accurately measured, subdivided and explicitly explained and backed with model calculations as cloud-, temperature-, water vapour- and enhanced greenhouse gas radiative forcing effect. Large differences on uncorrected longwave downward radiation measurements, which are caused by local effects such as cloud variability and temperature and humidity variations can be properly accounted for. The resulting uniform increase of longwave downward radiation manifests radiative forcing that is induced by increased greenhouse gas concentrations and water vapor feedback, and proves the 'theory' of greenhouse warming with direct observations.

Acknowledgements. This investigation was financed by the Swiss National Science Foundation (Grant No. 21-58746.99).

Received, 3 October 2003

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Figure captions

Figure 1. Large increases of a) temperature (*t*) and b) absolute humidity (*u*) measured in the Alps from 1980 to 2002 at six MeteoSwiss stations, and from 1995 to 2002 at eight stations. Annual mean values of temperature [°C] and absolute humidity [g m^{-3}], with increases over the measuring period and stdev are shown from 1980 to 2002 (center), and from 1995 to 2002 (right). Stations south of the Alps are shown in red, all station average in green.

Figure 2. Annual mean values of a) Longwave Downward Radiation (*LDR*), b) Shortwave Downward Radiation (*SDR*) and c) Longwave Cloud Effect (*LCE*) measured at eight stations from 1995 to 2002. Radiative flux changes over the eight years and stdev are given in [Wm^{-2}] on the right.

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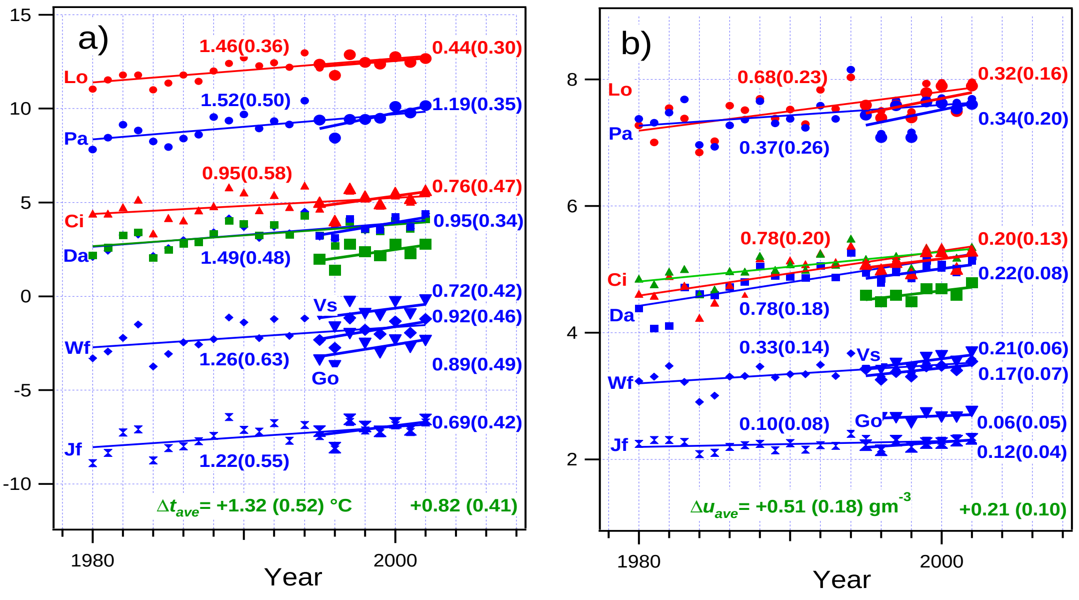
Figure 3. Annual mean values of a) cloud-free Longwave Downward Radiation (LDR_{cf}), b) temperature corrected Longwave Downward Radiation ($LDR_{cf,tc}$) and c) humidity corrected Longwave Downward Radiation ($LDR_{cf,tc,uc}$) measured at eight stations. Increases over the eight years and stdev are shown.

Table 1. ASRB radiation stations parameters

ASRB station	Abr	Altitude [m a.s.l.]	t [°C]	u [g m^{-3}]	ε_{Acf}
Locarno-Monti	Lo	370	12.5	7.6	0.743
Payerne	Pa	490	9.6	7.5	0.762
Davos	Da	1610	3.8	5.0	0.709
Cimetta	Ci	1670	5.2	5.1	0.704
Versuchsfeld	Vs	2540	-0.8	3.5	0.677
Weissfluhjoch	Wf	2690	-1.8	3.4	0.648
Gornergrat	Go	3110	-2.7	2.7	0.613
Jungfraujoch	Jf	3580	-7.0	2.3	0.600

Table 2. Measured and calculated flux, temperature and humidity changes

	ASRB All stations	ECHAM-4 10 % CO_2 change
ΔLDR_{cf} [Wm^{-2}]	+ 4.2	+ 4.6
ΔSDR_{cf} [Wm^{-2}]	- 1	- 1.4
Δt [°C]	+ 0.82	+ 0.74
Δu [%]	+ 4.4	+ 4.4



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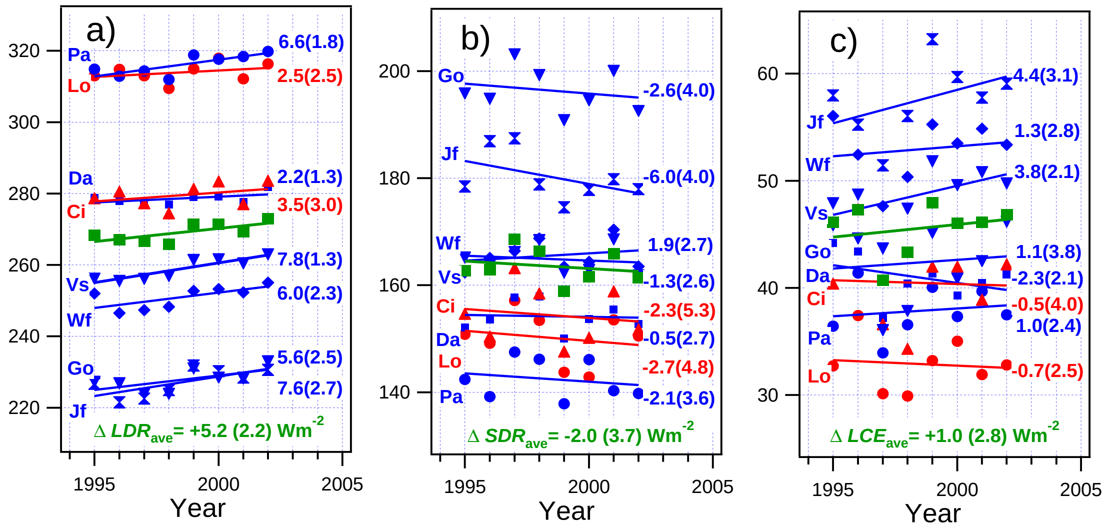

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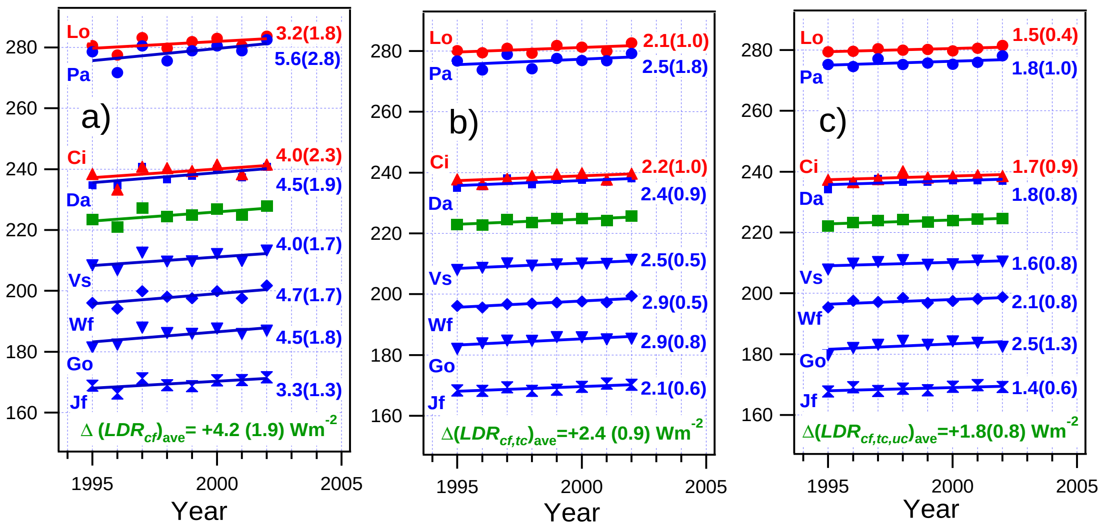

Figure 3. Annual mean values of a) cloud-free Longwave Downward Radiation (LDR_{cf}), b) temperature corrected Longwave Downward Radiation ($LDR_{cf,tc}$) and c) humidity corrected Longwave Downward Radiation ($LDR_{cf,tc,uc}$) measured at eight radiation stations. Increases over the eight years and stdev are shown.