GCM-Simulated Surface Energy Fluxes in Climate Change Experiments

MARTIN WILD AND ATSUMU OHMURA
Department of Geography, Swiss Federal Institute of Technology, Zurich, Switzerland

ULRICH CUBASCH
Deutsches Klima Rechenzentrum GmbH, Hamburg, Germany

(Manuscript received 13 June 1996, in final form 9 September 1996)

ABSTRACT

The changes in the surface energy fluxes calculated with a general circulation model under increased levels of carbon dioxide concentration are analyzed and related to the simulation of these fluxes under present-day conditions. It is shown that the errors in the simulated fluxes under present climate are often of similar or larger magnitude than the simulated changes of these quantities. A similar relationship may be found in climate change experiments of many GCMs. Although this does not imply that the projected changes of the fluxes are wrong, more accurate absolute values would improve confidence in GCM-simulated climate change scenarios.

The global mean increase in the downward component of the longwave radiation, which is the direct greenhouse forcing at the surface, is on the order of 10 W m\(^{-2}\) at the time of doubled carbon dioxide in a transient coupled atmosphere-ocean scenario experiment. This is an amount similar to the underestimation of this quantity in the present-day simulations compared to surface observations. Thus, it is only with doubled carbon dioxide concentration that the simulated greenhouse forcing at the surface reaches the values observed at present.

The simulated shortwave radiation budget at the surface is less affected by the increased levels of carbon dioxide than the longwave budget on the global scale. Regionally and seasonally, the changes in the incoming shortwave radiation at the surface can exceed 20 W m\(^{-2}\), mainly due to changes in cloud amounts. The projected changes, however, are generally of smaller magnitude than the systematic errors in the control run at the majority of 720 observation sites.

The positive feedback between excessive radiation and surface processes leading to excessive summer dryness and temperatures over continental surfaces in the control run is enhanced in the doubled carbon dioxide experiment, resulting in a massive increase in the projected surface temperature.

In the high-resolution T106 time-slice scenario experiment performed in this study the global mean latent heat flux and associated intensity of the hydrological cycle is slightly decreased rather than increased with doubled carbon dioxide. A reduction in surface wind speed in the T106 scenario is suggested as a major factor for the reverse of sign.

The improved representation of the orography with T106 resolution allows a better estimate of the projected changes of surface energy fluxes in mountain areas, as demonstrated for the European Alps.

1. Introduction

The possibility of global climate changes due to modifications of atmospheric composition by human activities has attracted much scientific and public attention in past years. Particularly the increased concentration of greenhouse gases has raised much concern. General circulation models (GCMs) have become the primary tools to study the reaction of the climate system to these perturbations, and a large number of experiments have been performed with increased levels of greenhouse gases, particularly carbon dioxide (e.g., IPCC 1990).

To get an estimate of the reliability of these climate change scenarios, the usual procedure is to test the model performance under present-day conditions, where the simulations can be verified against observations. This has been done extensively for standard parameters like temperature or precipitation. Other quantities have been verified to a lesser extent, mainly due to the lack of adequate observational datasets. Among these are the surface energy fluxes, which are of primary importance for climate, as they determine the surface temperature and the energy available for the hydrological processes. Of particular interest in the context of greenhouse gas-induced climate change is the incoming longwave radiation at the surface—that is, the thermal emission of the atmosphere directed toward the earth’s surface. This flux is most directly affected by the increase in atmospheric greenhouse gas concentration and is one of the primary effects of climate change experienced at the
surface. It is a fundamental question in the context of climate change to understand how the additional energy from the increased incoming longwave flux will be redistributed within the components of the surface energy balance.

Not many studies have specifically focused on the changes in surface energy fluxes in climate change experiments. Gutowski et al. (1991) found substantial differences in the sensitivity of the simulated surface energy fluxes in three GCMs to a doubling of carbon dioxide. Randall et al. (1992) noted in a sensitivity experiment with an imposed global increase in sea surface temperature of 4 K significant differences in the simulated surface energy fluxes of 19 GCMs. More recently, Watterson and Dix (1996) discussed the changes in the surface energy fluxes in a doubled carbon dioxide experiment with the CSIRO9 GCM.

Little is known about the absolute accuracy of these simulated fluxes, due to the lack of an adequate observational reference, and the above studies do not discuss in detail how realistic they are in the unperturbed state of the 1×CO2 control experiment.

Recently it has become easier to validate the GCM-calculated surface energy fluxes due to a new dataset of the worldwide measured surface energy fluxes compiled in the Global Energy Balance Archive (GEBA, World Climate Program, Water Project A7). This dataset has been used in a number of studies to assess the ability of GCMs to simulate the surface energy fluxes under present-day conditions (Garratt 1994; Wild et al. 1995a,b, 1996a; Garratt and Prata 1996). Using this experience, the present study examines the flux changes in GCM simulations with increased levels of greenhouse gases and relates them to the systematic errors found in the simulation under present-day climate.

GCM-projected changes in surface energy fluxes, such as changes in surface insolation, are more and more frequently used as input parameters in climate impact studies. A critical discussion of GCM-projected changes of surface energy fluxes is therefore an aim of this study.

2. Models and experiments

This study is based on simulations with the ECHAM GCM developed at the Max-Planck Institute for Meteorology in Hamburg, Germany. This GCM has evolved from the spectral numerical weather forecasting model of the European Centre for Medium-Range Weather Forecasts (ECMWF) and has been modified extensively in Hamburg for climate applications (Roeckner et al. 1992). The modifications include an additional prognostic equation for cloud water (Roeckner et al. 1991), a new surface parameterization scheme (Dümenil and Todini 1992), and the radiation scheme of Hense et al. (1982).

The parameterizations of relevance to the surface energy fluxes are shortly referenced below, valid for the model versions ECHAM1–3. A detailed description of the model can be found in Roeckner et al. (1992).

The radiation scheme is based on a two-stream approximation described by Kerschgens et al. (1978) and Zdunkowski et al. (1980). The longwave spectrum is divided into six spectral intervals taking into account absorption due to water vapor, carbon dioxide, and ozone, while scattering is neglected. The shortwave spectrum is divided into four intervals with the same gaseous absorbers as above. Additionally, scattering due to molecules, aerosols, and clouds is included. The surface fluxes of momentum, heat, and moisture are calculated from Monin–Obukhov theory with the transfer coefficients depending on roughness length and Richardson number (Louis 1979). The surface hydrology scheme, of importance for the latent heat flux over land, consists of a single reservoir for soil moisture, which evolves with time using infiltration of rainwater, snowmelt, and evaporation as input (bucket-type model). The depth of the soil moisture reservoir (field capacity) is 200 mm at all land points.

Two scenario experiments are analyzed in this study, involving the model versions ECHAM1 and ECHAM3: with ECHAM1, coupled to the global ocean model (LSG, Maier-Reimer et al. 1993), transient climate change experiments with gradual increase of carbon dioxide have been performed (Cubasch et al. 1992). Thereby the coupled model was integrated for 100 yr with carbon dioxide increase according to the Intergovernmental Panel on Climate Change (IPCC) scenario A. These integrations were performed using a comparatively coarse horizontal resolution for the atmospheric model (T21, corresponding to a 5.6° grid spacing).

With the ECHAM3 model, simulations with high horizontal resolution (T106, corresponding to a 1.1° grid spacing) of present and future climates have been performed in a joint project between the Max-Planck Institute for Meteorology, Hamburg, and the Swiss Federal Institute of Technology, Zurich. The ECHAM3 T106 has been integrated for 5½ yr for present-day conditions, with prescribed sea surface temperatures (SST) and sea ice distributions from the Atmospheric Intercomparison Project (AMIP) SST and sea-ice dataset (Gates 1992), averaged over the 10-yr period 1979–88 on a monthly basis (“control run”). Since it is not feasible with today’s supercomputing resources to run such a high-resolution GCM over several decades as required in transient climate change experiments, a “time-slice” experiment was performed. Thereby the T106 atmospheric model was run with prescribed boundary conditions of SST and sea ice at the time of doubled carbon dioxide inferred from the low resolution, coupled atmosphere–ocean ECHAM1–LSG experiment. These boundary conditions were created in the following way: changes in SST and sea ice with doubled carbon dioxide were determined as differences between the respective distributions projected by the coupled transient run for the period when the carbon dioxide is expected to double
(2040–50), and the first 10 yr of an associated control run of the same coupled model. These changes were then averaged on a monthly basis and superimposed on the climatological AMIP SST and sea ice dataset used in the ECHAM3 T106 control run, to serve as boundary conditions for the T106 scenario run. Forced with these boundary conditions and a doubled carbon dioxide concentration the T106 model was then rerun for 5½ yr ("time-slice scenario").

In the present study, the changes of the surface energy fluxes in the T106 time-slice simulation with respect to the T106 control run are discussed. The first 6 months of both integrations were not used in the analysis to allow the model to adjust to the boundary conditions, leaving five complete years of model data. The surface energy fluxes of the T106 control run have been evaluated in Wild et al. (1995a, 1995b, 1996a). A major advantage of the high T106 resolution is the more realistic representation of coastlines and orography. This allowed in the aforementioned studies a more appropriate point-by-point comparison of the observed and calculated fluxes than in models of lower resolution. For many mountain ranges, such as the European Alps, a resolution as high as T106 is needed for an adequate representation. This allows a better assessment of changes in the surface flux fields associated with orography, as illustrated in section 7 for the European Alps. The results of this climate change experiment of unprecedented high resolution have been used in two other studies that focus on GCM-projected changes in the frequency of tropical cyclones (Bengtsson et al. 1995; Bengtsson et al. 1996) and the mass balance of the polar ice sheets (Ohmura et al. 1996). Both aspects were realistically simulated in the T106 control run, thus providing more confidence in the changes projected by the T106 experiments than by lower resolution experiments. Time-slice experiments have also been performed with a T42 (2.8° grid spacing) version of the ECHAM3 GCM using the identical boundary conditions from the ECHAM1 T21–LSG transient experiment (Cubasch et al. 1995a).

Further, the same SST boundary conditions have been used to study the response of the Météo-France climate model to doubled carbon dioxide in a time-slice experiment (Mahfouf et al. 1994; Timbal et al. 1995).

Note that the superposition of different resolutions for the construction of the SST–sea ice boundary conditions may lead to local inconsistencies near sharp SST gradients or ice boundaries. Changes in these areas, which are not the focus of this study, should therefore be interpreted with caution.

3. Observational data

The observational data used as the baseline in this study are taken from a database developed at the Swiss Federal Institute of Technology for the worldwide instrumentally measured energy fluxes at the earth’s surface, the Global Energy Balance Archive (GEBA) (Ohmura et al. 1989; Gilgen et al. 1997). This database currently possesses 220 000 monthly mean data entries for about 1600 sites and is continuously updated and expanded. The main sources of data are periodicals, monographs, data reports, and unpublished data.

The data underwent a number of quality control procedures, described in detail in Gilgen et al. (1997, manuscript submitted to J. Climate). The accuracy of the radiation measurements is estimated at 2% for the incoming shortwave radiation and 5% for the incoming longwave and net radiation (Ohmura and Gilgen 1993; Gilgen et al. 1997, manuscript submitted to J. Climate). The stations of incoming shortwave and longwave radiation as well as latent heat flux are representative for their larger scale setting as outlined in Wild et al. (1995b, 1996).

4. Longwave radiation

The exchange of energy between the atmosphere and the surface in the longwave spectrum is based on the thermal emission of the earth’s surface (outgoing longwave radiation) and the atmospheric emission directed toward the surface (incoming longwave radiation). The incoming longwave radiation is one of the largest terms in the equation of the surface energy balance and a crucial element in the discussion of climate change: the most direct consequence of an enhanced concentration of atmospheric greenhouse gases experienced at the surface is an increased flux of incoming longwave radiation.

The temporal evolution of the global mean incoming longwave radiation at the surface with gradual increase of carbon dioxide simulated with the ECHAM1–LSG coupled atmosphere–ocean model is shown in Fig. 1. The increase of carbon dioxide is prescribed in this run according to the IPCC scenario A (Cubasch et al. 1992). In this scenario, the carbon dioxide concentration is doubled after 60 yr of model integration (year 2045). This is the period at which the time-slice experiment with the high-resolution T106 model has been performed. The global annual mean increase in the incoming longwave flux in the year 2045 amounts to 8 W m⁻² in the coupled ECHAM1–LSG atmosphere–ocean model (Fig. 1). The enhanced flux is directly related to the increased carbon dioxide concentration and indirectly to the positive water vapor feedback with more water vapor concentration in a warmer atmosphere. The calculated increase in the incoming longwave radiation is relatively slow in the first 35 yr of the coupled experiment at approximately 1 W m⁻² per decade but then accelerates to approximately 2.3 W m⁻² per decade in the following decades (Fig. 1). The delayed increase is related to the "cold start problem" in this coupled atmosphere–ocean experiment; that is, the experiment was started at year 1985 from an initial equilibrium state rather than from an already warming state (Hasselmann et al. 1993; Cu-
basch et al. 1995b). Thus, the greenhouse gas–induced forcing prior to 1985 is not included in this experiment. The magnitude of the cold start effect is further dependent on the exact state of the coupled system at the beginning of the transient experiment as shown in “Monte Carlo” type simulations with different initial conditions (Cubasch et al. 1994). Extrapolating the largely linear increase found in the final decades over the first 60 yr of the experiment would result in a global mean increase of approximately 14 W m$^{-2}$ rather than the 8 W m$^{-2}$ given in Fig. 1 for the year 2045, which may be a more appropriate value to be expected at the time of doubled carbon dioxide. This value is still considerably lower than the values given in Gutowski et al. (1991) and Watterson and Dix (1996) for the changes of the incoming longwave radiation with doubled carbon dioxide in four other GCMs (NCAR: 23.9 W m$^{-2}$, GFDL: 27.5 W m$^{-2}$, GISS: 27.2 W m$^{-2}$, CSIRO: 30.2 W m$^{-2}$).

These values, however, stem from equilibrium $2 \times \text{CO}_2$ experiments, while in the transient ECHAM1–LSG experiment the retarding effects of the oceans with large heat capacities substantially damp the increase of atmospheric temperature and water vapor, and accordingly, of incoming longwave radiation. In the ECHAM1–LSG experiment the amplitude of the equilibrium $2 \times \text{CO}_2$ response is obtained only at the end of the 100-yr integration, when the transient forcing has reached the tripped carbon dioxide mark (Cubasch et al. 1995a), corresponding to 17 W m$^{-2}$ increase of the incoming longwave radiation (Fig. 1). This increase is still smaller than in the above-mentioned models and associated with a lower equilibrium $2 \times \text{CO}_2$ temperature sensitivity of the ECHAM model (2.6°C) compared to the four other models with $2 \times \text{CO}_2$ sensitivities exceeding 4°C (Gutowski et al. 1991; Watterson and Dix 1996). The incoming longwave radiation is most directly affected by an increase of radiatively active gases in the atmosphere and shows substantially larger changes in the $2 \times \text{CO}_2$ scenario than other surface energy fluxes (cf. Table 1). The incoming longwave radiation is therefore a potential candidate for an early detection of the greenhouse signal. This is supported by recent improvements in the instruments measuring incoming longwave radiation (pyrgeometers), which reach an accuracy near 3 W m$^{-2}$. This may provide an estimate for the time frame when this greenhouse signal is expected to exceed the measurement uncertainties. The long-term monitoring of the incoming longwave radiation is one of the objectives of the Baseline Surface Radiation Network (BSRN), (WCRP 1991).

The ECHAM1–LSG-calculated increase over land is larger by 2.5 W m$^{-2}$ than over sea at the time of doubled carbon dioxide (Fig. 1). This is consistent with a faster surface air temperature increase over land than over sea due to the retarding effect of the oceans in this transient run, while the increase in atmospheric water vapor is similar over land and sea. The surface temperature increase over land at the time of doubled carbon dioxide is 2.3°C, while 1.1°C over sea, resulting in a global mean surface temperature increase of 1.4°C.

The latitudinal changes in the incoming longwave
Table 1. Global annual mean values of different quantities calculated with ECHAM3 T106 in the experiment for present-day conditions (Control), in the time-slice experiment with doubled carbon dioxide (2 × CO₂), and differences between the two experiments (Diff).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>2 × CO₂</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface incoming LW (W m⁻²)</td>
<td>335</td>
<td>345</td>
<td>10</td>
</tr>
<tr>
<td>Net surface LW (W m⁻²)</td>
<td>−63</td>
<td>−60</td>
<td>3</td>
</tr>
<tr>
<td>Surface incoming SW (W m⁻²)</td>
<td>189</td>
<td>187</td>
<td>−2</td>
</tr>
<tr>
<td>Surface absorbed SW (W m⁻²)</td>
<td>164</td>
<td>163</td>
<td>−1</td>
</tr>
<tr>
<td>Atmospheric absorbed SW (W m⁻²)</td>
<td>71</td>
<td>72</td>
<td>1</td>
</tr>
<tr>
<td>TOA absorbed SW (W m⁻²)</td>
<td>235</td>
<td>235</td>
<td>0</td>
</tr>
<tr>
<td>TOA cooling LW (W m⁻²)</td>
<td>−238</td>
<td>−235</td>
<td>3</td>
</tr>
<tr>
<td>Surface albedo (%)</td>
<td>16.2</td>
<td>15.4</td>
<td>−0.8</td>
</tr>
<tr>
<td>Cloud amount (%)</td>
<td>50</td>
<td>51</td>
<td>−1</td>
</tr>
<tr>
<td>Integrated water vapor (kg m⁻²)</td>
<td>25.4</td>
<td>28.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Integrated cloudwater (g m⁻²)</td>
<td>85.1</td>
<td>89.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Surface temperature (°C)</td>
<td>14.5</td>
<td>15.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Sensible heat flux (W m⁻²)</td>
<td>13.5</td>
<td>12.5</td>
<td>−1.0</td>
</tr>
<tr>
<td>Latent heat flux (W m⁻²)</td>
<td>84.1</td>
<td>83.5</td>
<td>−0.6</td>
</tr>
<tr>
<td>Evaporation (mm yr⁻¹)</td>
<td>1061</td>
<td>1053</td>
<td>−8</td>
</tr>
<tr>
<td>Precipitation (mm yr⁻¹)</td>
<td>1061</td>
<td>1053</td>
<td>−8</td>
</tr>
<tr>
<td>10-m wind speed (m s⁻¹)</td>
<td>6.09</td>
<td>6.03</td>
<td>−0.06</td>
</tr>
</tbody>
</table>

The global mean change in the incoming longwave radiation in the ECHAM3 T106 time-slice experiment together with other global mean values of several quantities of the ECHAM3 T106 control and scenario runs are given in Table 1. Due to the cold-start problem mentioned above, the values given in Table 1 may be representative of a state prior to the time of doubled carbon dioxide.

Wild et al. (1995a) suggested that ECHAM3 and other GCMs underestimate the incoming longwave radiation at the surface for present-day conditions. The underestimation of incoming longwave radiation, on the order of 10–15 W m⁻² in ECHAM3, is of very similar magnitude to the GCM-projected increase of this flux at the time of doubled carbon dioxide. Thus, it is only in an atmosphere with doubled carbon dioxide that the GCM-calculated incoming longwave radiation approaches the values measured under present-day conditions.

The underestimation of incoming longwave radiation in the ECHAM3 control run has been demonstrated by Wild et al. (1995a) in a comparison of calculated annual cycles with observations at a number of sites available from GEBI. In Fig. 4, annual cycles of the T106 time-slice simulation with doubled carbon dioxide at these sites are shown together with the annual cycles of the control run and the observations. The increase in the incoming longwave radiation in the doubled carbon dioxide simulation is clearly visible at all sites. However, the increased fluxes are still usually below the present-day observations: the annual mean over the nine sites shown is 280 W m⁻² for the control run, 290 W m⁻² for the doubled carbon dioxide experiment, and 295 W m⁻² for the observations.

Other GCMs may show a similar or larger underes-
Fig. 3. (a) Geographical distribution of annual mean changes in surface incoming longwave radiation calculated in the ECHAM3 T106 scenario experiment with doubled carbon dioxide (units: W m$^{-2}$). (b) As in (a) but for surface air temperature (units: °C).

It is important to emphasize that these findings do not necessarily put into question the GCM-projected magnitude of the changes. Assuming a quantity shows a closely linear response to an imposed forcing, its exact absolute magnitude may not be of primary importance. Nevertheless, modeling efforts should aim at reducing these systematic errors in the control run in order to increase the confidence in the simulated changes.

Progress in this direction was made with the latest version of the ECHAM model series, the ECHAM4 GCM. In this model, the global mean incoming longwave flux in the control run is increased by 10 W m$^{-2}$ compared to ECHAM3, which brings the calculated fluxes in better agreement with the observations from GEBA (Wild et al. 1996b). The underestimation was removed mainly by an increase of the incoming longwave radiation of the cloud-free atmosphere due to modifications in the parameterization of the water vapor continuum (Giorgetta and Wild 1995) in the new ECHAM4 model.
INCOMING LONGWAVE RADIATION

FIG. 4. Annual cycles of model-calculated and observed surface incoming longwave radiation at a number of sites from the Global Energy Balance Archive. Model calculations from the ECHAM3 T106 control run and the scenario run with doubled carbon dioxide (units: W m\(^{-2}\)).
radiation scheme of Morcrette (1991). Transient climate change experiments using this new model are currently in progress. In these experiments, the ratio between projected changes in the incoming longwave radiation and its systematic errors in the control run is expected to improve substantially, and the projected flux changes may consequently be more reliable.

5. Shortwave and net radiation

a. Global changes

The shortwave radiation balance changes only marginally with time in the transient ECHAM1–LSG experiment in the global mean. A slight decrease of \(-2\ W\ m^{-2}\) is found in the incoming shortwave radiation at the surface in the T106 time-slice scenario for doubled carbon dioxide. This is consistent with a small increase in the cloud amount and atmospheric water vapor (Table 1). The small decrease of incoming shortwave radiation is partly compensated at the surface by a decreased surface albedo due to the reduced extension of snow and ice in the warmer scenario, resulting in an only slightly reduced surface shortwave absorption \((-1\ W\ m^{-2})\). A very similar decrease in the surface shortwave absorption \((-0.6\ W\ m^{-2})\) was found in the time-slice scenario simulation with the Météo-France model using the same SST boundary conditions (Timbal et al. 1995). The total shortwave absorption in the climate system (net solar flux at the top of atmosphere) in the ECHAM scenario is not changed, thus the global mean atmospheric absorption of solar radiation is slightly increased with doubled carbon dioxide, due to the increase in the vertically integrated atmospheric water vapor (Table 1).

At the surface, however, the increase in atmospheric water vapor enhances the incoming longwave flux much more effectively than it reduces the incoming shortwave flux. Therefore, the reduced absorption of solar energy at the surface does not compensate for the increased incoming longwave flux. Thus, the radiative forcing at the surface is enhanced and responsible for the surface temperature increase in the greenhouse scenario.

On the zonal and regional scales the changes in the incoming shortwave radiation are closely linked to changes in cloud amount. The zonal mean change of annual incoming shortwave radiation in the T106 time-slice experiment is shown in Fig. 5. A slight increase is found in the midlatitudes, while a decrease is noted in the Tropics and high latitudes, consistent with an increase in cloud amount in these areas, and a decrease around 40°N/S (cf. Fig. 2c, section 4). The reduced insolation in the Tropics leads to a minimum temperature increase in these areas (Fig. 2b), despite an enhanced incoming longwave flux in the Tropics (Fig. 2a).

The regional distribution of annual mean changes in the incoming shortwave radiation is shown in Fig. 6b. It closely follows the regional changes in cloud amount depicted in Fig. 6b. Insolation changes of up to 20 W m\(^{-2}\) can be found locally, which may significantly affect the regional-scale climate. During summer, the surface insolation is enhanced and cloud amount reduced over large areas of the midlatitude continents (cf. section 5b).

It is instructive, for specific locations, to compare the GCM-projected changes with the systematic errors in the control simulation at these location. Such an analysis can provide a guidance for the reliability of the projected changes. In Fig. 7, the GCM-projected changes of incoming shortwave radiation are related to the errors in the control run at sites where observations are available. The incoming shortwave radiation calculated for present-day conditions in the control run has been compared in Wild et al. (1995a) with long-term observations at 720 sites from GEBA. In Fig. 7a the changes in the incoming shortwave radiation projected in the time-slice experiment for the 720 sites from GEBA are shown as a function of latitude. The changes reflect the zonal mean changes of Fig. 5, with a decreased insolation at tropical and high-latitude sites, and an increased insolation at midlatitude sites.

Differences between calculated and observed annual mean fluxes at the same GEBA sites in the control run are reproduced from Wild et al. (1995a) in Fig. 7b and show the characteristic behavior of large overestimation in the Tropics and some underestimation at higher latitudes. The ratio between the flux changes in the scenario run and the systematic errors in the control run at each site is depicted in Fig. 7c in terms of absolute values. The ratio is larger than one at only 89 of the 730 sites; that is, the annual mean changes projected by the model are only at a few sites larger than the errors in the present climate simulation.

For the surface net radiation, as for the incoming shortwave radiation, the magnitudes of projected changes at the majority of the 113 available sites from GEBA are smaller than the systematic errors found in the control run (not shown). Again, this does not imply that the projected changes must be wrong. But it may serve as a caveat not to overestimate the significance of GCM-projected flux changes, for example, when using them as scenarios for climate impact studies, particularly on the regional scale.
The reliability of the flux changes may not be estimated only by the magnitude of the biases of the control-run fluxes alone, but also by investigating the types of mechanisms responsible for these biases. When the biases are caused by largely nonlinear feedbacks, the reliability of the projections may be restricted. This is illustrated in the section below and in section 6b.

b. Changes over Europe

The European region is particularly well suited to compare the changes of the surface energy fluxes with the systematic errors in their absolute values, since the dense observational network allows an accurate assessment of the present climate simulation.

Using these observations from GEBA, Wild et al. (1995b) found an overestimation in the incoming shortwave radiation calculated in the ECHAM3 T106 control run of 46 W m$^{-2}$ for the summer months. This was caused by an overestimated clear-sky flux of the radiation scheme and too little cloud amount related to an excessive summer dryness over Europe (Wild et al. 1995b, 1996a).

In the doubled carbon dioxide experiment, the summer insolation over Europe is increased (Fig. 8a). This is due to the fact that the summer dryness found in the
Fig. 7. Incoming shortwave radiation at the surface: (a) annual mean changes of the incoming shortwave radiation calculated in the ECHAM3 T106 scenario experiment with doubled carbon dioxide at 720 sites from the Global Energy Balance Archive as function of latitude (units: W m\(^{-2}\)); (b) annual mean differences between observed and calculated incoming shortwave radiation in the ECHAM3 T106 control run at the same sites (taken from Wild et al. 1995a; units: W m\(^{-2}\)); (c) ratio between changes of the fluxes in the scenario run (shown in a) and their systematic errors in the control run (shown in b) at the same sites (absolute values).

The annual cycles of incoming shortwave radiation calculated in the scenario experiment and in the control run at a number of European stations are shown together with the observed values in Fig. 9. The summer insolation averaged over the 12 stations in Fig. 9 is 202 W m\(^{-2}\) observed, 248 W m\(^{-2}\) in the control run, and 264 W m\(^{-2}\) in the doubled carbon dioxide experiment. The model-projected increase of 16 W m\(^{-2}\) is small relative to the systematic overestimation of 46 W m\(^{-2}\) in the control run. It is doubtful, whether the response to a perturbation can be considered as independent of the base state, when the base states differ by almost 25% and largely nonlinear feedbacks are involved as in this example of European summer dryness (cf. section 6b).

The same applies for the surface net radiation during summer over Europe, where the calculated control run fluxes deviate by 25% from the observations due to the excessive insolation, compared to a change of 4% with doubled carbon dioxide.

6. Latent heat flux

a. Global changes

The change in the global mean latent heat flux is close to zero, showing a slight decrease of \(-0.6\) W m\(^{-2}\) in the T106 time-slice simulation with doubled carbon dioxide (Table 1). This is equivalent to a slight reduction in the strength of the global hydrological cycle (\(-8\) mm
Fig. 9. Annual cycles of model-calculated and observed surface incoming shortwave radiation at a number of sites from the Global Energy Balance Archive. Model calculations from the ECHAM3 T106 control run and scenario experiment with doubled carbon dioxide (units: W m\(^{-2}\)).
yr\(^{-1}\), cf. Table 1), since the latent heat flux is the energy equivalent of evaporation, which in turn balances precipitation in the global annual mean. Therefore a decreased latent heat flux/evaporation is equivalent to decreased global mean precipitation. The decrease in the global latent heat flux is persistent in all of the five simulated years of the T106 time-slice experiment. ECHAM1–LSG and also the identical time-slice experiments with the lower-resolution models ECHAM3 T42 and T21 predict, unlike the T106 model, a strengthened rather than a weakened hydrological cycle. Thus, the reverse of sign is specific to the experiment with T106 resolution. So far, there are no other climate change simulations at this high resolution available that would allow to judge whether this is a general finding in high resolution GCMs or specific to the ECHAM3 model. The decrease of evaporation in a warmer atmosphere is not in contradiction with evidence from observational studies. These studies indicate that the warmer summer hemisphere exhibits a smaller evaporation than the winter hemisphere (Budyko 1974; Oki et al. 1993). This is due to a less intense general circulation in the summer hemisphere and associated weaker surface winds. Zhang (1996) and Zhang and McPhadden (1995) pointed out that wind speed rather than the humidity gradient between surface and atmosphere is the determinant factor for evaporation. A decrease in velocity of the surface winds may compensate or overcompensate for a possible increase in the water vapor gradient in a greenhouse scenario. In the T106 scenario experiment, the 10-m wind speed is reduced by 1% in the global annual mean (Table 1). This factor alone reduces the evaporation by roughly 1% in a first-order approximation assuming proportionality between wind speed and latent heat flux (the latent heat flux is parameterized by a bulk transfer model), an amount consistent with the actual reduction of evaporation of 0.7%.

The most significant reduction of evaporation in the scenario experiment is found over the oceans. Zonal mean changes in the latent heat flux over sea are shown in Fig. 10a for the June–August mean (JJA) and in Fig. 11a for the December–February mean (DJF). Additionally, changes in the zonal mean 10-m wind speed are shown for JJA and DJF in Figs. 10b and 11b, respectively. The largest reductions of 10-m wind speed are found in the storm track areas of the Northern Hemisphere midlatitudes, associated with the zones of largest reduction of evaporation.

This experiment points out that it may not be a priori certain that the hydrological cycle intensifies with increased levels of greenhouse gases. A sufficient reduction of the turbulent surface–atmosphere exchange due to, for example, decelerated surface wind speeds, may even lead to a slight reduction in the strength of the global hydrological cycle in a greenhouse scenario. 

### b. Changes over Europe

On the regional scale, the T106-simulated latent heat fluxes in the control run have been compared with observations at a number of sites over Europe in Wild et al. (1996a). Systematically too high latent heat fluxes...
were calculated in early summer, leading to an excessive depletion of the soil moisture reservoirs and eventually too little evaporation in late summer due to the lack of available soil water (cf. Fig. 12). An important factor was thereby shown to be the excessive surface insolation, which favours the too high evaporation and excessive soil moisture depletion in early summer. The excessive surface insolation is further enhanced in a positive feedback loop where the dry soils cause reduced moist convection, decreased cloud amounts and atmospheric relative humidity, which further increases insolation.

In the scenario experiment with doubled carbon dioxide, the flux changes are pursuing the tendencies of the biases in the control run. This is shown in Fig. 12, where T106-calculated annual cycles of latent heat of the scenario experiment and the control run are displayed together with the observed fluxes from GEBA at a number of European sites. The calculated latent heat flux is further increased in the doubled carbon dioxide experiment in the first half of the year. The increase in both incoming longwave and shortwave radiation provides additional energy for the latent heat flux, as shown in sections 4 and 5, respectively. Thereby, the excessive available energy at the surface in the control run is further increased in the scenario experiment leading to an enhanced latent heat flux, and thus to an even more rapid depletion of soil moisture than in the control run. In the doubled carbon dioxide experiment, the soil water becomes a limiting factor already in May/June, 1–2 months earlier than in the control run (July). The subsequent lack of available soil water restricts the latent heat flux, so that in the scenario experiment most of the available radiative energy at the surface is transferred into sensible heat during the whole summer period. This reduces the moist convection, atmospheric relative humidity, and related cloud amount, which further increases the surface insolation in the positive feedback loop outlined above. The nonlinear feedback mechanisms, which cause large deviations from the observed state in the control run, are strengthened in the scenario run.

The surface temperature response is largely nonlinear and enhanced as soon as the soil water becomes a limiting factor and the latent heat flux ceases. Thus, the summer temperature over Europe in the scenario run is massively increased, on the order of five and more degrees over western Europe (compared to a global annual mean increase of 1.4°C) (Fig. 13a). Similar effects can be found over large areas of the midlatitude continents during summer in the scenario run.

This positive feedback with associated large temperature increases is only fully effective when the latent heat flux is more restricted in the scenario run than in the control run. It is therefore critical, to what extent the soil water available for evaporation changes in the scenario experiment. The change in soil water in the scenario run during summer over Europe is shown in Fig. 13b in percentage of field capacity (constant at 0.2 m in ECHAM3). The largest reduction of soil water is found over the Alps and adjacent regions. These areas are linked through the positive feedback with the areas of largest temperature increase (cf. Figs. 13a and 13b). They also coincide with the areas where a certain amount of soil water is still available for evaporation in the control run, despite the simulated excessive summer dryness (cf. Wild et al. 1996a, Fig. 7). In the surrounding areas the soil moisture content is already so excessively depleted during summer in the control run that no substantial further depletion is possible in the scenario run. In these areas the positive feedback involving excessive insolation, soil moisture depletion, and cloud reduction can no longer fully develop and, accordingly, the temperature response is more moderate (Fig. 13a), insolation is less enhanced, and cloud amount less reduced (Figs. 8a,b).

An accurate simulation of the processes that determine the soil moisture conditions in the control run is therefore a prerequisite to get reliable estimates of the projected flux and temperature changes. Since the excessive insolation has been shown to be an important contributor to the problem of excessive summer dryness and soil moisture depletion (Wild et al. 1996a), it is evident that the projected insolation changes are not unaffected by the insolation errors in the control run as noted in section 5b.

Therefore, the projected changes in the surface fluxes and temperature for a particular region should be interpreted with caution, taking into account their deficiencies in the control simulation.

7. Changes in surface flux gradients associated with orography

An advantage of high-resolution GCM simulations, such as the T106 experiment, is the improved representation of orography. In the context of climate change it is of importance how the surface energy fluxes in mountainous regions may change, since the ecosystems in mountain areas are particularly sensitive to environmental changes (IPCC 1996). In the following, the focus is on the projected changes in the European Alps. This area is particularly well suited for this purpose since there exists only for the European Alps an adequate level of information on the distribution of radiation in mountain regions (Barry 1992) to assess the model performance in the control run. Using such observations, Wild et al. (1995b) showed that the ECHAM3 T106 model is capable of realistically capturing gradients in the surface radiation fields related to orography for present-day conditions, even so the absolute values may show substantial systematic errors. This justifies a discussion of projected changes in the flux gradients associated with the Alps in the scenario experiment. The high T106 resolution is inevitable for such a study since only at this resolution do the Alps start to get resolved.
Fig. 12. Annual cycles of model-calculated and observed latent heat fluxes at a number of sites from the Global Energy Balance Archive. Model calculations from the ECHAM3 T106 control run and the experiment with doubled carbon dioxide (units: W m$^{-2}$).
Fig. 13. (a) Change in summer (June–July–August mean) surface air temperature over Europe as projected in the ECHAM3 T106 scenario experiment with doubled carbon dioxide (units: °C). (b) As in (a) but for soil water content (units are percentage of field capacity).

The altitudinal distribution of T106-calculated annual mean incoming longwave radiation at grid points on the northern slope of the model Alps is shown in Fig. 14 for both control and scenario experiments. The incoming longwave radiation is increased in the scenario experiment at these grid points by 10–12 W m⁻², an amount close to the global and zonal mean increase at this latitude (Table 1 and Fig. 2a). For comparison, the observed Alpine gradient taken from Wild et al. (1995b) is shown in the Fig. 14. This highlights not only the adequacy of the simulated vertical flux gradient in the control run found in Wild et al. (1995b), but shows also that the absolute values of incoming longwave radiation in the scenario run, despite the doubled concentration of carbon dioxide and increased water vapor, still do not reach the currently observed values (cf. section 4).

The incoming longwave radiation shows a general decrease with altitude in both control and scenario experiments (Fig. 14). The decrease is slightly stronger in the scenario experiment, thereby somewhat reducing the projected change in incoming longwave radiation at higher elevations (by approximately −1.5 W m⁻²/km altitude). Thus, there is a small reduction with altitude in the direct greenhouse gas–induced climate change signal at the surface.

Nevertheless, the surface temperature increase is slightly enhanced at higher elevations, as shown in Fig. 15 for annual mean values at the same grid points on the northern Alpine slope: the annual mean warming in the greenhouse scenario is enhanced with altitude in the Alps by approximately one quarter degree per kilometer. This is related to the altitudinal changes in the incoming shortwave radiation at these grid points (Fig. 16). These changes show a general increase in insolation in the annual mean, which is enhanced with altitude, related to a reduction in cloud amounts (cf. Fig. 8b for the summer months).

The enhanced increase of insolation with altitude of approximately 4 W m⁻²/km (Fig. 16) dominates the slightly reduced increase in incoming longwave radiation (Fig. 14), consistent with the enhanced warming at higher elevations in Fig. 15.

A further feature accurately captured in the T106 control run is the horizontal north–south gradient of insolation across the Alps, with more insolation received at...
sites situated on the southern than on the northern Alpine slopes on the order of 20 W m\(^{-2}\) \cite{Wild95b}.

To estimate the GCM-projected changes of this gradient in the scenario run, insolation changes at grid points on the southern slope of the Alps are further displayed in Fig. 16. The changes show a similar enhancement with altitude as on the northern slope, but the absolute increases are smaller by approximately 5 W m\(^{-2}\). This reduces the north–south insolation gradient by 25\%, since the smaller absolute values on the northern slope are more increased than the larger values on the southern slope.

These results indicate the potentials inherent in high-resolution climate change experiments to provide estimates of changes in orography dependent quantities for a wide range of impact studies. Again, confidence in such estimates grows with the progress made in the accurate simulation of the present climate.

8. Conclusions

The changes in surface energy fluxes simulated in a low-resolution (T21) transient GCM experiment and an associated high-resolution (T106) time-slice experiment have been analyzed and related to their performance under present-day conditions. The analysis was focusing on global, continental (Europe), and subcontinental (Alpine areas) scales.

The projected change in the global mean incoming longwave radiation, which is the most direct consequence of increased atmospheric carbon dioxide experienced at the surface, is of similar magnitude to its systematic underestimation in the control run (10–15 W m\(^{-2}\)). Thus, the simulated downward longwave emission of the atmosphere with doubled carbon dioxide comes closer to the observations than with present-day carbon dioxide concentration. This is expected to be the case in other GCM climate change scenarios as well.

Although systematic errors in the energy fluxes in the control run do not a priori imply that their predicted changes are unrealistic, it is important to minimize the errors to increase confidence in climate change scenarios provided by GCMs.

The simulated shortwave radiation budget at the surface is much less affected by the increased levels of carbon dioxide than the longwave budget on the global scale. The regional change pattern of incoming shortwave radiation closely follows the pattern of changes in cloud amount. Locally, the projected annual mean changes in the shortwave and net radiation at the surface are mostly substantially smaller than their deviations from observations in the control run.

Systematic biases in the control run tend to be strengthened in the doubled carbon dioxide experiment. The positive feedback between excessive radiative fluxes and surface processes leading to excessive summer dryness and temperatures over midlatitude continents in the control run is enhanced in the doubled carbon dioxide experiment, resulting in a massive increase in the surface temperature.

The global mean latent heat flux and associated intensity of the hydrological cycle is slightly decreased rather than increased in the high-resolution T106 time-slice scenario experiment. This indicates that an-
creased level of greenhouse gases may not necessarily imply an intensified global hydrological cycle. Even a slight reduction may be possible in a climate change scenario if the turbulent surface–atmosphere exchange is sufficiently reduced—for example, by decreasing surface wind speed.

The realistic simulation of flux gradients associated with orography in the high-resolution T106 control run provides a basis for the analysis of changes in these gradients under increased levels of carbon dioxide, which was illustrated for the European Alps. Features noted include a slightly smaller increase in incoming longwave radiation at higher elevations, a decrease in the north–south Alpine insolation gradient, and an enhanced temperature and insolation increase at higher altitudes.

Acknowledgments. The authors are grateful to Prof. L. Bengtsson for the stimulating cooperation in the joint MPI–ETHZ project and for the possibility given to the first author to frequently visit the MPI. Thanks to Drs. M. Beniston and M. Rotach for reviewing the manuscripts and their valuable comments. We thank Jan Perlwitz from MPI for providing the SST and sea ice data. P. Tschucks’ efforts in the T106 data processing are highly acknowledged. The Swiss Scientific Computing Center CSCS generously provided the computer resources, which allowed climatic change simulations of unprecedented high resolution. U. Schlese, M. Esch, and Dr. A. Bernasconi installed the ECHAM3 model at CSCS and supported the T106 experiments. The present work was supported by the following Swiss National Science Foundation Grants: National Research Program 31, Climate Change and Natural Hazards (Grant 4031-033250); Swiss Priority Program for the Environment (SPP, Grant 5001-35179); ETH Grant 020-043-95; and EU Grants EV5V-CT92-0123 and ENV4-CT95-0102.

REFERENCES


Roeckner, E., M. Riehl, and E. Keup, 1991: Modelling of cloud
and radiation in the ECHAM model. ECMWF/WCRP Workshop on clouds, radiative transfer and the hydrological cycle. Reading, United Kingdom, ECMWF, 199–222.


