Validation of General Circulation Model Radiative Fluxes Using Surface Observations

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(Manuscript received 2 May 1994, in final form 3 October 1994)

ABSTRACT

The surface radiative fluxes of the ECHAM3 General Circulation Model (GCM) with T21, T42, and T106 resolutions have been validated using observations from the Global Energy Balance Archive (Geba, World Climate Program—Water Project A7). GEBA contains the most comprehensive dataset now available for worldwide instrumentally measured surface energy fluxes.

The GCM incoming shortwave radiation at the surface has been compared with more than 700 long-term monitoring stations. The ECHAM3 models show a clear tendency to overestimate the global annual-mean incoming shortwave radiation at the surface due to an underestimation of atmospheric absorption. The model-calculated global-mean surface shortwave absorption around 165 W m^-2 is estimated to be too high by 10-15 W m^-2. A similar or higher overestimate is present in several other GCMs. Deficiencies in the clear-sky absorption of the ECHAM3 radiation scheme are proposed as a contributor to the flux discrepancies. A stand-alone validation of the radiation scheme under clear-sky conditions revealed overestimates of up to 50 W m^-2 for daily maximum values of incoming shortwave fluxes. Further, the lack of shortwave absorption by the model clouds is suggested to contribute to the overestimated surface shortwave radiation.

There are indications that the incoming longwave radiation at the surface is underestimated in ECHAM3 and other GCMs. This largely offsets the overestimated shortwave flux in the global mean, so that the 102 W m^-2 calculated in ECHAM3 for the surface net radiation is considered to be a realistic value. A common feature of several GCMs is, therefore, a superficially correct simulation of global mean net radiation, as the overestimate in the shortwave balance is compensated by an underestimate in the longwave balance.

Seasonal and zonal analyses show that the largest overestimate in the incoming shortwave radiation of ECHAM3 is found at low latitudes year round and in midlatitude summer, while at high latitudes and in midlatitude winter the solar input is underestimated. As a result, the meridional gradient of incoming shortwave radiation becomes too large. The zonal discrepancies of the fluxes are consistent with differences between the simulated cloud amount and a cloud climatology based on surface observations. The shortwave discrepancies are further visible in the net radiation where the differences show a similar latitudinal dependency including the too strong meridional gradient.

On the global and zonal scale, the simulated fluxes are rather insensitive to changes in horizontal resolution. The systematic large-scale model deviations dominate the effects of increased horizontal resolution.

1. Introduction

Within the climate system the surface of the earth is the place where the most active energy exchange takes place. The geographic distribution of the individual components of the surface energy balance determines the distribution of surface temperature and the intensity of the hydrological cycle and atmospheric circulation. It is therefore essential that numerical models attempting to simulate present, past, and future climates be able to reproduce the surface energy fluxes accurately.

Previous studies have shown that large uncertainties exist in the simulation of surface energy budgets within General Circulation Models (GCM). Gutowski et al. (1991) found substantial differences in the surface energy balance in three GCMs under present-day conditions and in the sensitivity of the fluxes to a doubling of carbon dioxide on all spatial scales. 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 budgets of 19 GCMs.

Few studies have attempted to compare the simulated fluxes with observations. The uncertainties inherent in the semiempirical climatologies (e.g., Budyko 1974) and the difficult access to the original measurements have prevented the surface fluxes from becoming a standard quantity in the validation process of GCMs.
Satellite-based estimates of surface radiative fluxes are now becoming available, but still span a relatively short observation period and their accuracy has yet to be fully assessed (e.g., Darnell et al. 1992; Li et al. 1995). A few studies have used surface measurements for GCM validation: Shuttleworth and Dickinson (1989) compared surface energy fluxes measured at the Manaus site in Amazonia to a version of the National Center for Atmospheric Research (NCAR) GCM and found a significant overestimate of net radiation caused by excessive surface solar radiation. Garratt et al. (1993) used direct surface observations and climatological maps to demonstrate the excess of surface net radiation and evaporation over selected land areas in a number of GCMs. Garratt (1994) ascribes the overestimation of net radiation to excessive incoming shortwave radiation in the models. Betts et al. (1993) compared 48-h forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) model with measurements from the FIFE field experiment and identified, among other things, a too high clear-sky surface shortwave flux of 5%–10% at noon.

The availability of surface-energy flux observations has recently been improved, since the most comprehensive compilation of flux measurements, which have been performed worldwide over the past few decades, is currently under preparation at the authors’ institute (World Climate Program—Water Project A7).

The aim of this study is to show what can be inferred from direct flux measurements with respect to GCM-simulated surface fluxes. The use of any empirically derived climatologies for comparison was consciously avoided. This approach is complementary to efforts using satellite-derived climatologies with the advantage of providing more reliable point values at the cost of full area coverage.

The analysis is based on simulations with the ECHAM3 GCM of the Max Planck Institute for Meteorology, which have been performed in a joint project of the Max Planck Institute for Meteorology and the Swiss Federal Institute of Technology. Further emphasis is put on the dependency of the results on spatial resolution. So far only one study (Gleckler and Taylor 1993) has looked into the effects of resolution on the surface fluxes. Using the ECMWF model, Gleckler and Taylor focused on the surface fluxes over sea and used the atlas of Oberhuber (1988) as reference. In the present work, the emphasis is given for land surfaces where observations are more frequently available. While accurate modeling of the energy fluxes over sea is a prerequisite for a successful coupling of an ocean to an atmospheric model, reliable surface fluxes over land are essential at the interface between the atmospheric model and the schemes describing the land surface processes.

The analysis of the surface energy fluxes is guided by the number of direct measurements available and restricted in a first step to the radiative fluxes. Emphasis is put on incoming shortwave radiation, where most observations are reported. The radiative components are the dominant components of the surface energy budget in absolute values and therefore need particular attention.

In section 2 the models and experimental setup are presented. A short description of the observational dataset used in this study is given in section 3. This is followed by the discussion of the surface shortwave, longwave, and net radiation balances in sections 4, 5, and 6, respectively. Section 7 summarizes the principal findings of this study.

2. Model description and experimental design

The model used in this study is the ECHAM3 GCM of the Max Planck Institute for Meteorology, Hamburg. It has evolved from the spectral-numerical weather forecasting model of the European Centre for Medium-Range Weather Forecasts and has been modified extensively in Hamburg for climate applications (ECHAM, described in Roeckner et al. 1992). These modifications include an additional prognostic equation for cloud water (Roeckner et al. 1991), a new surface scheme (Dümenil and Todini 1992), and the radiation scheme of Hense et al. (1982).

The radiation scheme is based on a two-stream approximation described by Kerschgens et al. (1978) and Zdunkowski et al. (1980) with delta-Eddington approximation for clouds. The longwave spectrum is divided into six spectral intervals, taking into account absorption due to water vapor, carbon dioxide, ozone, and aerosol. An inversion procedure is employed to define the relevant optical properties by matching the two-stream solutions to more accurate model solutions obtained by a line-by-line model (Hense et al. 1982). For cloud droplet absorption, an emissivity formulation is used (Stephens 1978). Scattering of longwave radiation is neglected.

The shortwave spectrum is divided into four intervals with the same gaseous absorbers as above. The optical thickness for gas absorption is a function of the effective absorber amount and is determined similar to the longwave part. Scattering due to molecules, aerosols, and clouds is included. Cloud optical depth and single scattering albedo are derived from the cloud water path (Stephens 1978).

Profiles of temperature and water vapor, cloud cover, and cloud water content are model-predicted inputs to the radiation scheme, while carbon dioxide, ozone, and aerosols are specified. The surface albedo is derived from satellite data for snow-free land (Geley and Preuss 1983), a function of solar zenith angle for ocean areas, and depends on temperature and fractional forest area for snow.

Three control runs with climatologically prescribed sea surface temperatures have been performed with ECHAM3: two multidecadal integrations at a hori-
horizontal resolution of T21 and T42 (corresponding to a grid of 5.6° and 2.8°, respectively) performed at the German Climate Computing Center, Hamburg, and a 51/2-yr integration at T106 resolution (corresponding to a 1.1° grid) performed at the Swiss Scientific Computing Center.

The model formulation and parameters are identical for the three different resolutions with two exceptions: the horizontal diffusion coefficients were set resolution dependent, such that the slope of the spectral kinetic energy comes close to observations. Furthermore, a rain efficiency parameter in the cloud scheme was set resolution dependent, which influences the cloud lifetime and thereby the associated planetary albedo in order to match the global annual-mean top-of-the-atmosphere radiative fluxes with Earth Radiation Budget Experiment (ERBE) satellite observations (Roeckner et al. 1992).

The simulations have included the diurnal cycle of insolation, and time steps of 40 (T21), 24 (T42), and 12 min (T106) were used for the integration. Full radiative calculations were performed every two hours and approximated in between. Sea surface temperatures and sea ice were prescribed daily by linear interpolation between monthly mean climatologies from the Atmospheric Model Intercomparison Project SST and sea–ice dataset (Gates 1992).

From the T106 run, the first three months were ignored, leaving five complete years for the analysis. From the multidecadal T21 and T42 runs, one decade (years 21–30) has been chosen since interdecadal variances in the simulated surface radiative components are considered to be small.

3. Observational data

The observational data used in this study have been retrieved 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; Ohmura and Gilgen 1991). The database currently possesses 200 000 monthly mean data entries for about 1600 sites and is continuously updated and expanded.

The quality control of the dataset is under progress. So far the data have been checked to lie within the range of physically possible values. For the incoming shortwave radiation, this range was further restricted through an empirical relation between cloud cover and the ratio of the surface irradiance to the irradiance at the top of the atmosphere. Further quality checks will include difference plots among neighboring stations to detect possible inhomogeneities in the time series.

Nevertheless, the authors believe that the conclusions drawn in this study are not significantly affected by the quality of the database at this stage.

The focus throughout this study is on the global and zonal behavior of the radiative fluxes. An analysis of specific regions will be carried out after the completion of the station-specific quality control of the GEBA data.

4. Shortwave radiation

a. Comparison with observations

The global annual-mean value of the solar radiation absorbed at the surface of the three ECHAM3 resolutions is shown in Table 1, together with values of several other GCMs from the literature and personal communications, and two values derived from observations. The values calculated by ECHAM3 at the three resolutions do not differ much in their global mean owing to the identical physics and the resolution-dependent adjustments to match their top-of-the-atmosphere fluxes with global mean ERBE data. The differences among the various GCMs are, however, considerable. Still all model values are systematically higher than the values derived from observations.

The GEBA value (Ohmura and Gilgen 1993) is an estimate based on the surface measurements contained in the GEBA dataset over land areas, while over the oceans the sparse measurements had to be complemented with empirical estimates. Inherent in all estimates of absorbed radiation are further uncertainties related to the albedo of the earth’s surface. The ERBE value (Li and Leighton 1993) is based on satellite observations, and a simple parameterization has been used to derive the shortwave surface radiation from the irradiance reflected from the top of the atmosphere. This satellite-based estimate has been compared with selected data from GEBA and showed a bias error near zero (Li et al. 1995).

To obtain more insight into the discrepancies between simulated and observed values, GCM fluxes are...
compared point by point to the GEBA sites with direct surface measurements in the following. For the comparison, the model data were interpolated to the measurement sites using the four surrounding grid points weighted by their inverse spherical distance. It can be argued that a comparison of GCM results with point observations may not be representative due to the subgrid variability. However, it is not the aim of this work to concentrate on specific locations, but on the general trend at a large number of sites that should not be systematically affected by local deviations.

The analysis of the shortwave surface fluxes is focused on the incoming shortwave radiation (also referred to as global radiation or surface insolation), which is by far the most frequently measured component of all surface energy fluxes. The accuracy of the incoming shortwave radiation measurements is estimated to be within 2%.

For this analysis, 720 stations have been selected from GEBA, where at least several years of continuous records are available (595 of them with more than 10 years). The global distribution of the observation sites is shown in Fig. 1. The sites are predominantly over land and the highest density is found over Europe and North America.

The observed and calculated annual incoming shortwave radiation for the 720 sites is presented in Fig. 2 as a function of the sites' latitudes. The increase of the insolation from the poles to the equator and its reduction in the intertropical convergence zone can be clearly identified in the GEBA data. The T106, T42, and T21 results interpolated to the stations reproduce the qualitative pattern of the observations reasonably well.

A direct pointwise comparison of simulated against observed annual-mean incoming shortwave radiation at the stations as a function of latitude is shown in Fig. 3 for the three resolutions. A strong latitudinal dependence of the differences between calculated and observed fluxes can be identified. At all three resolutions, the incoming shortwave radiation is overestimated at low latitudes and underestimated at higher latitudes in both hemispheres, while in polar regions the model comes close to the observed values. This results in a too large meridional gradient of insolation between 60°N/S and the equator with a maximum around 45°N and 30°S. Between 60°N/S and the poles, the calculated meridional gradient is too small. The excess solar input at low latitudes contributes to a too high surface air temperature of 1°–2° over the continents (Fig. 4), while at higher latitudes with too low solar input the model-calculated land surface temperature is underestimated. Observational air temperature data were taken from Legates and Willmott (1990b).

The excess solar input in equatorial regions and the lack of insolation at higher latitudes also appear in all seasons, including winter (Fig. 5) and summer (Fig. 6). The transition zone from over- to underestimates

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**Fig. 1.** Global distribution of the 720 sites with long-term incoming shortwave radiation measurements selected for this analysis from the Global Energy Balance Archive.
is, however, shifted poleward from winter to summer. In this manner the midlatitudes around 45°N receive too much insolation in summer and too little in winter. For these areas, the sign of the differences, therefore, depends not only on the latitude but also on the season. Evidence for an overestimate of incoming shortwave radiation in tropical areas and in the extratropical summer in four other GCMs is given in Garrett (1994). This analysis is based on a subset of our GEBAB dataset for selected regions.

The above findings seem to be rather insensitive to the resolution. In the annual mean, the most significant difference can be found at midlatitudes in the Northern Hemisphere, where the bulk of the sites show an overestimation at T106 and an underestimation at T21, while the T42 values lie in between. This can be related to differences in cloud amount (cf., section 4b). A similar behavior can be seen in the winter and summer simulations at midlatitudes (Figs. 5 and 6).

To facilitate the comparison of the performance at the different resolutions, the modeled and observed annual-mean point values have been grouped into 5° latitudinal belts. The number of stations within each segment is depicted in Fig. 7a. The highest number of stations is found in the segments between 40° and 55°N, while only few stations are found in the segments south of 35°S. Average annual-mean differences between modeled and observed fluxes at the sites within each segment have been calculated in Fig. 7b. The model overestimation reaches up to 40 W m⁻² for the segments near the equator compared with a maximum underestimation of 20 W m⁻² in the segment near 60°N and 50°S. There is no particular evidence that the simulations improve with increasing resolution in their overall latitudinal representation.

To assess the significance of the differences between the observed and simulated fluxes shown in Fig. 7b, standard deviations of the time series of observed and model-calculated yearly shortwave fluxes at the GEBAB sites have been determined. The standard deviations averaged over the sites within each segment are shown in Fig. 7c. The segment-mean standard deviations of
the T106 model-calculated time series are below 7 W m\(^{-2}\) throughout, mostly between 3 and 5 W m\(^{-2}\). This indicates that sampling errors due to the limited time span of the model runs are small and do not affect any conclusions drawn. The segment-mean standard deviations of the observed time series are between 10 and 14 W m\(^{-2}\) in the low-latitude segments from 40\(^\circ\)N to 30\(^\circ\)S, and below 10 W m\(^{-2}\) at higher latitudes. We expect a reduction of the standard deviations of the observed time series with the further progress of the GEEBA quality control. Given these results, the differences of the calculated and observed fluxes in Fig. 7b are significant: in low latitudes they are twice as large as the sum of the simulated and observed segment-mean standard deviations, and in high latitudes still larger than this sum.

To assess the ability of the different model resolutions to capture regional features, correlation coefficients between the calculated and observed fluxes have been determined within each zonal segment (Fig. 7d). The values vary substantially with latitude. In general, the T106 resolution shows a slightly better correlation than the other two resolutions, indicating some improvements in the description of regional patterns. A global correlation coefficient between all 727 measured and calculated points has been computed as well (T21 = 0.93, T42 = 0.94, T106 = 0.95), but the high correlation mainly reflects the dominant dependence of both model and observational data on the meridional gradient of the extraterrestrial insolation. A partial correlation coefficient, where the meridional trend is eliminated, is therefore more representative. The trend has been eliminated by subtracting from each station value the mean over all stations in the corresponding segment. The partial correlation including all stations is 0.60 for T106, 0.58 for T42, and 0.57 for T21. Only a marginal improvement with higher resolution can be noted. This may indicate that, on regional scales too, systematic model deviations common in all resolutions mask possible merits gained by increasing the horizontal resolution. This was already supposed by Gutowski et al. (1991) and is now experimentally confirmed here.

Finally, an overall estimate of the differences between observed and simulated annual surface incoming shortwave radiation has been calculated from the areally weighted segment-mean values in Fig. 7b. This

![Image](image_url)

**Fig. 4.** Zonal annual-mean 2-m temperature over land calculated at T21, T42, and T106 resolutions and observations from Legates and Willmott (1990b).

![Image](image_url)

**Fig. 5.** As in Fig. 3 but for the December–January–February mean.
wave radiation incident at the surface is substantially overestimated in many current GCMs.

The solar radiation absorbed by the surface depends additionally to the incoming shortwave radiation on the surface albedo. There are only a small number of long-term measurements of absorbed solar radiation available. They are also unlikely to be representative for a larger area as they strongly depend on the local surface albedo at the measurement site (predominantly short grass). A recent reevaluation of the albedo of the earth’s surface suggests a surface albedo near 0.16 (Ohmura and Gilgen 1993), while ECHAM3 has a value of 0.13. A 3% albedo increase corresponds to a reduction in the absorbed shortwave radiation of approximately 5 W m$^{-2}$. Differences in the incident solar radiation at the surface can therefore be further reinforced in the absorbed shortwave radiation by up to 5 W m$^{-2}$, depending on the surface albedo.

![Fig. 6. As in Fig. 3 but for the June-July-August mean.](image)

![Fig. 7. (a) Number of GEEA observation sites within latitudinal belts of 5°. (b) Differences between calculated and observed annual mean surface incoming shortwave fluxes averaged over the stations within the latitudinal belts for the three model resolutions. Units in W m$^{-2}$. (c) Mean standard deviations of observed and T106 model-calculated time series of yearly surface shortwave fluxes at the GEEA sites within the latitudinal belts. Units in W m$^{-2}$. (d) Correlations between calculated and observed annual mean surface incoming shortwave fluxes within the latitudinal belts for the three model resolutions.](image)
b. Discussion of the differences

In general, deficiencies in the modeled radiative fluxes can either stem from inaccurate prescribed or model-predicted input to the radiation scheme (water vapor, ozone, aerosols, cloud amount, and cloud radiative properties) or from deficiencies in the radiation scheme itself. In a first step, the cloud cover as a relevant input to the radiative scheme and the performance of the scheme under clear-sky conditions are analyzed.

1) CLOUD COVER

The distribution and the optical properties of clouds can largely modify the surface radiation fields. Clouds are therefore a key quantity in the explanation of the differences between modeled and observed surface fluxes. To obtain an estimate of the model's ability to represent cloud cover, comparisons have been made with the global dataset of Warren et al. (1986, 1988). This dataset is based on a compilation of surface-based synoptic observations.

To assess the impact of cloud cover on the shortwave radiation fields, an "effective cloud amount" has been defined, where for each month and latitude the cloud amount is weighted by the corresponding top-of-the-atmosphere incident solar irradiance. The effective cloud amount allows a representative comparison of modeled and observed cloud amounts with respect to their influence on the surface insolation (e.g., goes to zero at high latitudes in winter, where the cloud distribution becomes irrelevant for solar radiation).

The zonal annual-mean effective cloud amount over land for the three models is shown in Fig. 8 together with the effective cloud amount calculated from the Warren et al. (1986) observations. The focus is on the cloud distribution over land where most radiative fluxes are measured. All three resolutions substantially underestimate the low-latitude cloud amount in the annual mean. This is consistent with the excessive amount of calculated incoming shortwave radiation in these areas (cf. Fig. 3). The differences in cloud amount are reduced toward high latitudes and finally change sign at northern high latitudes, in agreement with the latitudinal differences in the shortwave fluxes discussed in section 4a. For the winter and summer season, the differences in cloud amount can be related to differences in the radiative fluxes in a similar way (cf. Fig. 8 with Figs. 5 and 6). The underestimate of cloud amount in low latitudes is a permanent feature in the summer and winter simulations except in December–January–February (DJF) around 20°S, where the models come close to the observations. Accordingly no clear overestimation in the DJF surface shortwave fluxes is found at these latitudes. The excessive incoming shortwave radiation during summer at midlatitudes around 45°N coincides with a too low cloud amount, while the underestimated fluxes in wintertime at the same latitudes are accompanied by a too high cloud amount.

FIG. 8. Fractional cloud amount, zonal mean over land, weighted for each month with the corresponding extraterrestrial insolation. Simulations of the T106, T42, and T21 resolutions and observations (Warren et al. 1986) for the annual mean, winter, and summer season, respectively.

The above findings suggest that a considerable part of the zonal differences in the shortwave surface fluxes can be attributed to deficiencies in the simulation of cloud amount.

Over ocean areas (Fig. 9), the model-calculated effective cloud amount is again substantially lower than the effective cloud amount calculated from Warren et al. (1988). This implies that the above conclusion concerning excessive surface shortwave radiation in the global mean biased toward land points should not be altered fundamentally when including the ocean areas.

Between the different resolutions of ECHAM3, the overall behavior of the modeled cloud amount is similar. The global mean cloud amount does not vary strongly with resolution; only a small decrease with increasing resolution can be noted (fractional cloud amount T21 = 0.55, T42 = 0.52, T106 = 0.50). A similar insensitivity to resolution is found for the ECMWF model in the study of Gleckler and Taylor (1993), while Kiehl and Williamson (1991) report a massive decrease in cloud amount with increasing resolution in the NCAR Community Climate Model. The largest differences in the zonal effective cloud amount over land can be seen in the Northern Hemisphere midlatitudes with the highest cloud fraction in the T21 model (Fig. 8). This leads to the underestimation of the T21 shortwave fluxes at the bulk of the midlatitude stations discussed above, while the reduced midlatitude
cloud amount at T42 and T106 resolution induces substantially higher fluxes at these stations (cf. Fig. 3). The cloud-induced reduction of solar input in the T21 northern midlatitudes is further consistent with a lower surface temperature in these areas compared with T42 and T106 (Fig. 4).

The global mean cloud fraction in the different model resolutions between 0.55 and 0.50 is underestimated compared with both the Warren et al. (1986) climatology, from where we deduced a global mean value of 0.61, and the satellite-derived ISCCP value of 0.63 (Rossow and Gardner 1993). Since the calculated global mean top-of-the-atmosphere shortwave reflectance is nevertheless in close agreement with ERBE satellite measurements, this suggests that the too low model cloud amount is compensated by too high cloud water content, which results in a too high cloud albedo. The model clouds, therefore, seem to contribute to the overestimation of the incoming shortwave fluxes at the surface, predominantly through a too small cloud absorption rather than through a too small cloud reflectivity. This is supported by recent observational evidence that clouds absorb substantially more shortwave radiation than assumed from theory (Cess et al. 1995; Ramanathan et al. 1995). These studies suggest that the ratio of shortwave cloud radiative forcing at the surface and the top of the atmosphere is near 1.5, while ECHAM3 shows a ratio of 1.1.

2) RADIATION SCHEME

For clear-sky conditions, an isolated validation of the GCM radiation code was performed. A stand-alone version of the radiation scheme was run with atmospheric profiles of temperature and humidity provided by radiosonde observations. The calculated surface fluxes could then be compared with radiation measurements made simultaneously at the site of the radiosonde launches. This gives an estimate of the uncertainties inherent in the clear-sky surface flux calculations of the radiation code. This method is a complementary approach to validations against line-by-line codes as followed in the Intercomparison of Radiation Codes used in Climate Models (ICRCCM) Study (Fouquart et al. 1991; Ellingson et al. 1991). It delivers not only a relative estimate but also an absolute estimate of the simulation error within the accuracy of the measurements.

The radiosonde data and radiation measurements were taken from the Swiss Aerological Station at Payerne. Ten clear-sky cases at noon were selected for the year 1988. In Table 2, the calculated surface fluxes are compared with the measured fluxes published in Ohmura and Gilgen (1993). Differences of more than 50 W m$^{-2}$ can be found, corresponding to an error larger than 5%. These differences are in line with the large uncertainties found in the simulated clear-sky surface fluxes during ICRCCM. The differences show large model overestimates in summer and some underestimates in winter. Note that these are differences under daily maximum insolation at noon and should not be mixed up with mean climatological differences, which are smaller. Still, the results suggest that deficiencies in the simulation of clear-sky radiative transfer contribute significantly to the differences in the simulated and observed surface flux climatologies. These deficiencies are possibly related to inaccuracies.

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in the parameterization of water vapor absorption, which may underestimate absorption in atmospheres with high water vapor concentrations. In ICRCCM, the ECHAM3 radiation scheme showed a tendency to underestimate the shortwave atmospheric absorption in calculations with water vapor only (B. Rockel 1994, personal communication). However, the reference line-by-line and narrowband models revealed a considerable spread among themselves (Fouquart et al. 1991). Further work with more case studies under different climatic regimes is needed to confirm this hypothesis.

5. 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 to the surface (incoming longwave radiation). These fluxes are the two largest components of the surface energy balance in absolute values and are therefore very sensitive to deficiencies in their parameterizations. While the modeling of the longwave outgoing surface radiation is straightforward according to Planck’s law, the incoming longwave radiation is a complex function of the vertical distribution of temperature and absorbers in the atmosphere. The incoming longwave radiation is, in addition, a crucial element in the discussion of climate change as it is most directly affected by an increase in radiatively active gases. Accurate modeling of this quantity is therefore a fundamental prerequisite for reliable climate predictions.

The incoming longwave radiation is very difficult to measure and is only available at a few sites with relatively low accuracy. In GEBAG there are currently 20 stations with at least one year of measurements, the longest being Hamburg, Germany, with 36 years, and Bergen, Norway, with 25 years of continuous observations.

Annual cycles of the most reliable stations from GEBAG are shown in Fig. 10. These include the two long-term stations in Hamburg and Bergen together with the Swiss stations of Payerne, Reckenholz, Rietholzbach, and Arosa; the German stations of Stuttgart and Weiherstephan; and the U.S. station at the South Pole. The accuracy of the measurements at these stations is estimated to be within ±5 W m⁻². Where substantial height differences between model and real topography exist, a height correction of 2.8 W m⁻² (100 m)⁻¹ was applied. This height gradient was derived from the Swiss radiation network with three stations for longwave downward radiation at different heights in the Alps. The observed height gradient comes very close to the gradient found in the T106 model for the Alps [3 W m⁻² (100 m⁻¹)].

At most sites the incoming longwave radiation is substantially underestimated in the models, indepen-
TABLE 3. Incoming longwave radiation at the surface under clear-sky conditions at noon. ECHAM3 are stand alone calculations with the GCM radiation scheme with atmospheric profiles prescribed from radiosonde data, LOWTRAN are calculations with a narrowband model, OBS_{conv} are synchronous surface measurements with a conventional pyradiator, and OBS_{shaded} are measurements with a pyradiator with shading disk and ventilation. Radiosonde data and measurements from Payerne, Switzerland (Müller and Ohmura 1993). Units: W m^{-2}.

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<tr>
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</tr>
<tr>
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<td>3.11.1988</td>
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<tr>
<td>Mean</td>
<td>267</td>
<td>273</td>
<td>278</td>
<td>244</td>
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</tbody>
</table>

ECHAM3 models tend to simulate a too small amount of low-level clouds, especially at low latitudes. This affects the distribution of longwave downward radiation leading to a substantial underestimate, particularly at low latitudes.

To obtain an estimate of the accuracy of the longwave scheme under clear-sky conditions, an analysis similar to the shortwave scheme was carried out. The radiosonde data from Payerne for clear-sky days were again used as input to the radiation scheme. The calculated longwave surface fluxes using radiosonde launches at noon are reproduced in Table 3 and compared with the observed fluxes and model calculations given in Ohmura and Gilgen (1993). The fluxes have been measured in parallel with two different methods: on one hand with a conventionally installed pyradiator, which underestimates fluxes when exposed to direct solar radiation as mentioned above and, on the other hand, with a more sophisticated measurement method, where the filter dome is ventilated and shaded from direct solar radiation by a shading disc to prevent convective heat loss from the sensor (Ohmura and Gilgen 1993). Further calculations with the narrowband code LOWTRAN7 (Kneizys et al. 1988) using the same atmospheric profiles have been added. The ECHAM3 incoming longwave fluxes are lower than both the measurements with shading disc and the calculated fluxes from the narrowband model. The low value of the conventional measurements cannot be considered as reliable (Ohmura and Schroff 1983). For the same dates, additional calculations have been performed for clear-sky conditions at midnight (Table 4). Without the impact of direct solar radiation, the two measurement methods come very close. The ECHAM3 value is again lower than the narrowband model and the observations, on the order of 10 W m^{-2}. This is in line with results from ICRCCM, where the ECHAM3 radiation scheme showed an underestimated incoming longwave flux of about 10–15 W m^{-2} with respect to the reference line-by-line codes (B. Rockel 1994, personal communication).

These results, together with the lack of low-level clouds over a large portion of the globe and the comparison with the observations from GEBA, lead to the supposition that the incoming longwave radiation is underestimated in ECHAM3 by 10–20 W m^{-2}.

In Table 5 global mean values of the incoming longwave radiation at the surface for the three ECHAM3 models are listed together with a number of other GCMs from the literature and personal communications. The ECHAM3 models are already at the high end of the range, which indicates a similar or larger underestimate of the incoming longwave radiation in other GCMs as well.

The zonal annual-mean outgoing longwave flux from the land surfaces for the three model resolutions is shown in Fig. 11. The “observed” flux is derived from the zonal mean observed screen-level temperatures over land (Legates and Willmott 1990b) using the Stefan-Boltzmann law. The models overestimate the longwave outgoing radiation from low-latitude land surfaces by 5–15 W m^{-2} as a consequence of the excessive surface temperature in these areas (Fig. 4). At high latitudes the model fluxes are somewhat too small. A comparison for ocean areas was not made, since the sea surface temperatures are prescribed from observations in the model (cf. section 2).

TABLE 4. As in Table 3 but for midnight situations. Units W m^{-2}.

<table>
<thead>
<tr>
<th>Date</th>
<th>ECHAM3</th>
<th>LOWTRAN</th>
<th>OBS_{shaded}</th>
<th>OBS_{conv}</th>
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<td>22.4.1988</td>
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<td>25.7.1988</td>
<td>298</td>
<td>298</td>
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<tr>
<td>Mean</td>
<td>266</td>
<td>270</td>
<td>274</td>
<td>277</td>
</tr>
</tbody>
</table>

TABLE 5. As in Table 1 but for incoming longwave radiation at the surface.

<table>
<thead>
<tr>
<th>Incoming longwave radiation</th>
<th>W m^{-2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHAM T21</td>
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<tr>
<td>ECHAM T42</td>
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<tr>
<td>ECHAM T106</td>
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<td>GISS</td>
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<td>CCC</td>
<td>315</td>
</tr>
<tr>
<td>LMD</td>
<td>342</td>
</tr>
</tbody>
</table>
6. Surface net radiation

The surface net radiation is the sum of the net shortwave and the net longwave fluxes. It determines the level of energy available for the nonradiative components of the surface energy balance and is therefore the driving force behind the hydrological cycle.

For a direct comparison of the net radiation, 113 stations are available from GEBA with at least several years of continuous monitoring (72 of them with more than 10 years). Their global distribution is shown in Fig. 12. The largest number of stations is found in mid- and high latitudes in the Northern Hemisphere.

Annual-mean measured net radiation at the observation sites as a function of latitude and model-calculated values interpolated to the same sites for the three different resolutions are shown in Fig. 13. The observations show a steady increase from zero or slightly negative values near the poles to more than 100 W m\(^{-2}\) in equatorial regions. This general behavior is well reproduced in the models. Differences between calculated and observed net radiation at the sites are shown as a function of latitude in Fig. 14. The overall behavior at all three resolutions is very similar to the incoming shortwave radiation discussed earlier with an underestimation at high latitudes and an overestimation at low latitudes. In particular, the excessive meridional gradient at the northern midlatitudes is clearly seen. Furthermore, an overestimate of net radiation in summer and an underestimate in winter is

Fig. 11. Surface outgoing longwave radiation, zonal annual mean over land, calculated at T21, T42, and T106 resolutions and derived from observed surface air temperature (Legates and Wilmott 1990b) using the Stefan-Boltzmann law. Units: W m\(^{-2}\).

The above results lead to the hypothesis that the simulated net longwave cooling at the surface may be too strong, particularly at low latitudes but probably not at high latitudes.

Fig. 12. Global distribution of the 113 sites with long-term surface net radiation measurements selected for this analysis from the Global Energy Balance Archive.
found in the Northern Hemisphere midlatitudes as well (not shown). This suggests that much of the deviations in the net radiation can be attributed to the shortwave discrepancies, in accordance with Garratt (1994) and Shuttleworth and Dickinson (1989). Some caution regarding the measured values of net radiation, however, is necessary. The quality of net radiometers is affected by the exposure to direct solar radiation very much like pyrheliometers, resulting in an underestimate particularly in low latitudes with strong insolation [up to 10–15 W m$^{-2}$ in monthly means according to Ohmura and Gilgen (1993)]. This effect can substantially reduce the differences between calculated and observed net radiation at low latitudes.

Nevertheless, after taking into account the systematic biases in the measurements, the observations still suggest that the model tends to overestimate, or at least not to underestimate, the net radiation in the global mean. The ECHAM3-calculated global mean value of 102 W m$^{-2}$ (average value of the three resolutions) is therefore likely to pose an upper limit to the range of possible values for the net radiation.

An independent estimate of the net radiation can be obtained from the global hydrological cycle. Observed global mean precipitation estimates lie in the range 80–100 mm mo$^{-1}$ (Jaeger 1976; Legates and Willmott 1990a; Spencer 1993) with the more recent estimates closer to the upper limit. This closely corresponds to a global mean latent heat flux of 80–100 W m$^{-2}$. The net radiation, which is the sum of latent and sensible heat flux in the global annual mean, should therefore not be much below the value of 102 W m$^{-2}$ presently found in ECHAM3 to ensure sufficient energy for a realistic model hydrological cycle. This argumentation tends to put the 102 W m$^{-2}$ as a lower limit to the range of possible values for the net radiation.

The direct comparison with GEA data and the indirect estimate via the hydrological budget help to restrict the range of net radiation estimates and indicate that the net radiation around 102 W m$^{-2}$ calculated by the ECHAM3 models is a realistic value. A correct simulation of the net radiation is in line with the above discussion of the single components that form the net radiation. In section 4 evidence has been presented that

FIG. 13. Annual-mean surface net radiation at the observation sites as a function of latitude. Observations from GEA, model results interpolated to observation sites at T106, T42, and T21 resolutions. Units in W m$^{-2}$.

FIG. 14. Differences between observed and simulated annual mean surface net radiation at the observation sites for T106, T42, and T21 resolutions as a function of latitude. Units in W m$^{-2}$.
the model overestimates the absorbed shortwave radiation by 10–15 W m⁻² in the global mean. The necessary underestimate in the net longwave balance of 10–15 W m⁻² needed to offset the excess of shortwave radiation seems to be realistic in light of the discussion in section 5. The value 102 W m⁻² was also given by Ohmura and Gilgen (1993) as the most likely global annual-mean value for net radiation.

Table 6 shows that several of the GCMs come close to the 102 W m⁻² in their net radiation. GCMs with substantially higher values are likely to overestimate the net radiation with respect to the GEBAt data.

However, the point to make here is that a realistic value of global mean net radiation does not necessarily imply a correct simulation of the longwave and shortwave balances.

7. Summary and conclusions

Surface radiative fluxes calculated with the ECHAM3 GCM at T21, T42, and T106 spectral resolution have been compared with the observed data in the Global Energy Balance Archive (GEBAt). GEBAt is a new comprehensive compilation of surface energy balance measurements that have been performed worldwide over the past decades. This observational dataset has proved to be a valuable tool for the validation of surface fluxes in GCMs.

On the global scale, the model atmospheres absorb a too small amount of solar radiation resulting in an overestimation of the incoming shortwave radiation at the surface. The absorbed global mean shortwave radiation of 164–167 W m⁻² in the ECHAM3 models is estimated to be too high by 10–15 W m⁻². Since the absorbed shortwave radiation in ECHAM3 is already comparatively small with respect to other GCMs, similar or higher overestimates must be found in many current GCMs.

As one source of the flux differences, an inadequate performance of the radiation scheme under clear-sky conditions is supposed. A stand-alone validation of the shortwave scheme showed daily maximum overestimates up to 50 W m⁻² for clear-sky cases, which may be related to the underestimation in the water vapor absorption. As a further source, an insufficient shortwave absorption by the model clouds has been suggested.

The surface incoming longwave radiation in the ECHAM3 models (330–335 W m⁻²) is underestimated by 10–20 W m⁻², an amount similar to the shortwave overestimate. This was concluded from comparisons with the measurements available in GEBAt, from the analysis of the low cloud distribution, which showed a lack of calculated low clouds, and from an isolated validation of the radiation scheme, which showed an underestimation of the incoming longwave radiation under cloud-free conditions on the order of 10 W m⁻². Underestimates of the global mean incoming longwave radiation are present in other GCMs as well.

<table>
<thead>
<tr>
<th>Table 6. As in Table 1 but for surface net radiation.</th>
</tr>
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<tbody>
<tr>
<td>ECHAM T21</td>
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<tr>
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<td>ECMWF</td>
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</table>

The net radiation measurements in GEBAt suggest that the global mean surface net radiation is unlikely to be higher than the 102 W m⁻² calculated in ECHAM3. A value near 102 W m⁻² is further supported from the analysis of the longwave and shortwave components of the net radiation and from independent considerations on the global hydrological cycle.

A common feature of ECHAM3 and other GCMs is a superficially realistic simulation of surface net radiation, as the overestimate in the shortwave balance is compensated by an underestimate in the longwave balance.

From a zonal and seasonal perspective, the incoming shortwave radiation in ECHAM3 is overestimated in low latitudes year-round and in midlatitudes in summer but underestimated in high latitudes year-round and in midlatitudes in winter. This results in a too strong meridional gradient of surface solar insolation in midlatitudes. This behavior is found in all simulations independent of horizontal resolution. The same tendency is found in the net radiation and temperature, so that too much net energy and too high surface temperatures are found in latitudes with excessive solar radiation, while a too small amount of energy is available for the nonradiative fluxes of the surface energy balance at higher latitudes. This may have major consequences on the model’s dynamics and hydrological cycle. The latitudinal discrepancies in the incoming shortwave radiation are consistent with differences between simulated cloud amount and the surface-based cloud climatology of Warren et al. (1986).

The large-scale simulation of radiative surface fluxes is largely independent of changes in horizontal resolution. The systematic model deviations seem to dominate the effects of an increase in resolution.

Acknowledgments. The authors are indebted to Prof. L. Bengtsson for his leadership in the development of ECHAM3 and valuable comments during the preparation of the manuscript. He kindly enabled one of the authors (M.W.) several stays at the Max Planck Institute. We are grateful to the Swiss Scientific Computing Center CSCS (Dr. A. Scheidegger, Dr. R. Gruber) for generously providing the computer resources needed for the T106 simulations. Dr. M. Beniston’s efforts during the early phase of the T106 project are greatly acknowledged. U. Schlese, M. Esch, and Dr. A. Ber-
nasconi installed the ECHAM3 model at CSCS and supported the T106 experiments. Thanks as well to P. Tschuck for his efforts in the T106 data processing and visualization, and for many stimulating discussions on the T106 results. We appreciate the proofreading of Mrs. Ohmura, S. Kälin, and C. Ammann. The present work was financed through the following Swiss National Science Foundation Grants: National Research Program 31, Climate Change and Natural Hazards (Grant 4031-033250); Priority Program Environment (SPP, Grant 5001-35179); Rerevaluation of the Global Surface Energy Balance (Grant 2.307-0.86, 20-25271.88, and 20-29826.90).

REFERENCES


Boer, G. J., 1993: Climate change and the regulation of the surface moisture and energy budgets. Climate Dyn., 8, 225–239.


—, and Coauthors, 1992: Simulation of the present day climate with the ECHAM model: Impact of model physics and resolution. Max Planck Institute for Meteorology Rep. No. 93, 171 pp. [Available at MPI für Meteorologie, Bundesstr. 55, D-20146 Hamburg, Germany.]


