

Excessive transmission of solar radiation through the cloud-free atmosphere in GCMs

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Abstract. Large uncertainties exist in the distribution of solar radiation in the global climate system and its representation in General Circulation Models (GCMs). The present paper assesses the transmission of solar radiation through cloud-free atmosphere in three GCMs using information from direct observations at the surface. Clear-sky insolation climatologies have been constructed from hourly radiation data through composites of clear-sky episodes for seven sites in Germany with ten years of accurate measurements. The results suggest that GCMs overestimate clear-sky insolation at the surface, indicating that the cloud-free atmosphere is overly transparent to solar radiation in the models. Quantitatively, the annual mean overestimation for the German sites is on the order of 10 Wm^{-2} in the models which include an aerosol climatology and 30 Wm^{-2} in the models without aerosol. The GCM-predicted atmospheric water vapor content is abundant compared to the ECMWF Re-Analysis and therefore not considered responsible for the missing absorption in the model atmosphere. Rather, underestimated water vapor absorption in the GCM radiation codes is implied.

1. Introduction

The distribution of solar radiation within the climate system is a key determinant for the thermo-dynamic conditions of our planet. A number of authors (eg., Garratt 1994, Wild et al. 1995, 1996, Cess et al. 1995, Li et al. 1997) have presented evidence that large uncertainties still exist in this respect in current GCMs.

For all-sky conditions Wild et al. (1995) found that GCM atmospheres do not absorb enough solar energy and thus are overly transparent to solar radiation, based on long-term measurements at more than 700 observation sites from the Global Energy Balance Archive (GEBA, Gilgen et al. 1997). Cess et al. (1995) among others, pointed to a possible underestimation of solar absorption within clouds, which may explain this

bias. Wild et al. (1995, 1996), on the other hand, presented evidence that also the cloud-free GCM atmosphere might be too transparent to solar radiation. This was concluded from biases in stand-alone calculations with the GCM radiation scheme. Barker and Li (1995) and Li et al. (1997) also reported an underestimation of solar absorption in the cloud-free GCM atmosphere compared to estimates derived from satellite observations. However, no attempts have so far been made to directly validate GCM-calculated clear-sky solar climatologies with surface observations, due to the lack of appropriate reference data. We are currently preparing such a data set of clear-sky irradiance climatologies measured at selected sites all over the world. This paper presents the first, newly extracted observation records from seven German sites available for the analysis of GCM clear-sky climatologies.

2. Observational Data

The clear-sky solar radiation climatologies were constructed from records of the Radiation Network of the German Weather Service (DWD) which are among the most reliable long-term networks in the world. The stations are described in detail by Liepert et al. (1994) and their geographic coordinates are given in Table 1. Hourly values of irradiances were available along with hourly synoptic data from 1964 to 1990. According to the methodology described in Liepert (1997), clear-sky values were identified by including information on cloudiness and sunshine duration available at the sites. From the clear-sky hourly episodes, climatologies have been calculated on a mean monthly basis for the time period of the model simulations from 1979 to 1988.

The respective observational estimates of vertically integrated water vapor content have been selected from the ECMWF Re-Analysis (ERA) data base (Gibson et al. 1997). These estimates are based on 6 hourly assimilation and physical interpolation of the worldwide radiosonde observations. They currently form the best available estimates of water vapor distribution within the atmosphere, particularly over the European continent considered in this study which has a dense observational network.

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Table 1. Decadal means of solar clear-sky irradiance at the surface in Wm^{-2} , calculated with the three GCMs (ARPEGE, HadAM2b, ECHAM3) and observed at seven radiation sites in Germany.

Site	Latitude	Longitude	Altitude	ARPEGE	ECHAM3	HadAM2b	OBS
Norderney	53.72°N	7.15°E	13 m	187	187	211	180
Hamburg	53.63°N	10.00°E	14 m	188	188	212	177
Braunschweig	52.30°N	10.45°E	81 m	193	192	219	175
Braunlage	51.72°N	10.53°E	601 m	194	193	220	187
Trier	49.75°N	6.67°E	265 m	204	202	229	192
Wurzberg	49.89°N	11.73°E	259 m	212	209	235	189
Weihenstephan	48.40°N	11.73°E	467 m	212	209	235	199
mean				199	197	223	185

3. Model Data

Clear-sky climatologies from a number of GCMs were available to us for this study. This includes the ECHAM3 model (Roeckner et al. 1992) from the Max Planck Institute for Meteorology, Hamburg, the ARPEGE model (Déqué et al. 1994) from Météo-France, Toulouse, and the HadAM2b model (Stratton 1998) from the Hadley Center for Climate Prediction and Research, Bracknell. These model data stem from AMIP type simulations with prescribed SST and sea ice for the period 1979 to 1988. The simulations have been analyzed at various resolutions, ranging from T21 (5.6°) to T106 (1.1°) for the spectral models ARPEGE and ECHAM3, and the standard ($2.5^\circ \times 3.75^\circ$) and high ($0.833^\circ \times 1.25^\circ$) resolution of the HadAM2b gridpoint model. The horizontal resolution turned out to have little impact on the calculated clear-sky fluxes (less than 2 Wm^{-2} for most seasonal and annual values). Therefore, results are shown only for the T42 (2.8°) or standard resolution. All models include broad-band radiation schemes with two-stream approximation as typically used in GCMs. The ECHAM3 and ARPEGE models further include simple aerosol climatologies, while HadAM2b does not include any aerosol effects. From the Hadley Center, two additional simulations were available with the next generation model version HadAM3, one including aerosol and the other without any aerosol (Cusack et al. 1998). These simulations are used to estimate the impact of aerosols on the irradiances.

For the comparison of model-calculated and observed data, the model fluxes were interpolated to the mea-

surement sites using the four surrounding grid points weighted by their inverse spherical distances.

4. Results of the comparisons

The annual means of the observed and the GCM calculated clear-sky surface insolation fluxes at the seven German sites for the time period from 1979 to 1988 are listed in Table 1. All three models ARPEGE, ECHAM3 and HadAM2b calculate substantially too high irradiances. This indicates that the cloud-free GCM atmospheres are generally too transparent to solar radiation in comparison with the observations. The annual mean model overestimation is 12 Wm^{-2} , or 6% for the two models with aerosol (ARPEGE, ECHAM3) and 37 Wm^{-2} , or 20% for HadAM2b which does not include any aerosol effects. The interannual variability has been determined for the HadAM2b model and is less than 2 Wm^{-2} , as it depends only on the changing water vapor content in the model atmosphere. The observations, however, show larger interannual variability with a standard deviation of about 4 Wm^{-2} . The ten year mean annual cycles of the model-calculated and observed clear-sky insolation for the seven sites are shown in Figure 1. The overestimations in the models are largest during summer, while small during winter. The overestimation in fall is comparable to spring.

5. Discussion

Aerosol and water vapor are the primary constituents in the cloud-free atmosphere that attenuate the transfer of solar radiation.

5.1. Aerosol Effect

According to Table 1 and Figure 1 the HadAM2b model without aerosol has a 13% higher long-term mean surface irradiance than the two GCMs with aerosol (ECHAM3 and ARPEGE) and a substantially larger overestimate compared to the observations. To estimate the magnitude of the effect of aerosols on the surface insolation we used the two additional GCM experiments

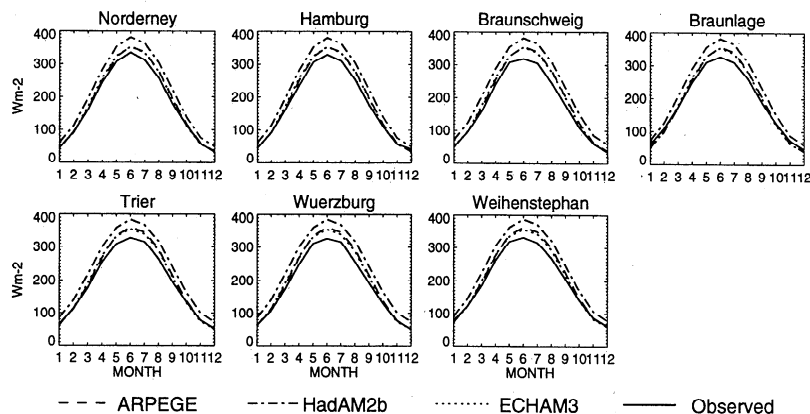


Figure 1. Annual cycles of clear-sky insolation at the surface, calculated by the three GCMs (HadAM2b, ARPEGE, ECHAM3) and observed at seven radiation stations in Germany.

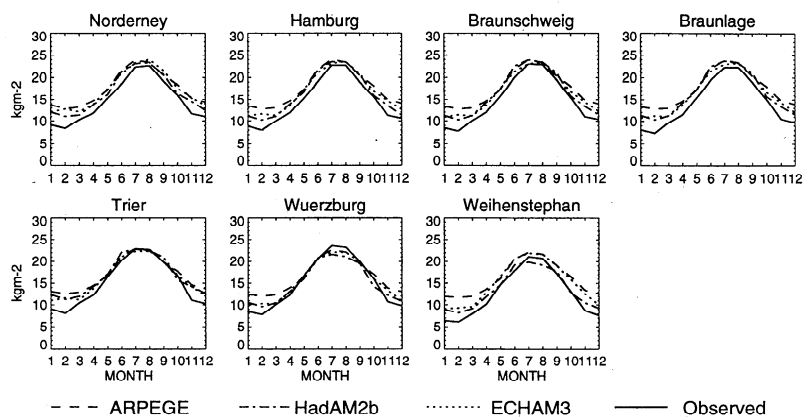


Figure 2. Annual cycles of vertically integrated water vapor content, calculated by the three GCMs (HadAM2b, ARPEGE, ECHAM3) and observed at seven radiation stations in Germany. Observed climatology from ECMWF Re-Analysis.

with the HadAM3 model (Cusack et al. 1998). One experiment was run without any aerosol effects and the other one included an aerosol climatology (WMO 1983) similar to ECHAM3 and ARPEGE. The inclusion of the aerosol climatology resulted in a mean decrease in solar irradiance of 18 Wm^{-2} at the seven German sites (Table 2). The seasonal cycle decreased respectively, showing a 12 Wm^{-2} decline in winter (DJF) and 23 Wm^{-2} in summer (JJA) due to the aerosol effect. This reduces the overestimate with respect to the observations considerably and underlines the necessity to incorporate aerosol effects into GCMs. However, the modeled clear sky solar flux is still 10 Wm^{-2} higher than the observations, as in both ECHAM3 and ARPEGE. Detailed calculations with a radiation model in combination with a global aerosol transport model and various types of aerosol (absorbing and non absorbing) gave an aerosol attenuation of very similar magnitude for the same region (Höllrigl 1997). Thus, about one half of the overestimation in the models without aerosol may be attributed to the missing aerosol effect itself. However, more information on aerosol type and optical depth at radiation sites are urgently needed to reduce the uncertainty in that respect.

5.2. Water Vapor Effect

While the distribution of aerosols is prescribed in the GCMs, water vapor concentration is a model-predicted quantity. Thus, a possible underpredicted water vapor content could also contribute to the overestimated irradiance. Therefore, the GCM-predicted water vapor content has been compared with the observational esti-

mates of the ERA data set. The annual cycles of vertically integrated water vapor content as calculated in the three GCMs and in the ERA at the German sites are shown in Figure 2 and the annual and seasonal means averaged over the sites are given in Table 3. The mean annual integrated water vapor of the GCMs exceeds the ERA values on the order of 10% in this region. Thus, the model irradiances are too high despite abundant presence of water vapor. Seasonally, the overestimate in water vapor is particularly large in winter with about 3 kgm^{-2} or 34%, while much closer to the ERA estimate in summer with only about 0.8 kgm^{-2} or 4% for the German sites. In winter the GCM overestimates are related to a too pronounced zonal large-scale flow over the European/Atlantic sector with excessive advection of moist air into the European continent (Marinucci et al. 1995, Déqué et al. 1995). Despite the 34% excess of water vapor, the calculated surface insolation is not too small in winter (Figure 1). Accordingly, in summer, with realistically simulated water vapor content, the overestimation in insolation is substantial. This indicates that the overestimates in the GCMs are not due to the predicted atmospheric composition but rather related to the GCM radiation schemes, with a possible underestimation of water vapor absorption. This is in line with the findings of Wild et al. (1995, 1996) based on stand-alone calculations with the GCM radiation scheme in off-line mode. These calculations were

Table 2. Decadal and seasonal means of solar clear-sky irradiance at the surface in Wm^{-2} calculated with the HadAM3 GCM in experiments with and without aerosol averaged over seven radiation sites in Germany.

	Annual	DJF	MAM	JJA	SON
HadAM3 without aerosol	213	82	278	341	150
HadAM3 with aerosol	195	70	257	318	134
Observed	185	69	243	300	137

Table 3. Vertically integrated water vapor content in kgm^{-2} averaged over the German radiation sites as calculated with the three GCMs (ARPEGE, HadAM2b, ECHAM3) and observed in the ECMWF Re-Analysis for annual, winter (DJF), spring (MAM), summer (JJA) and fall (SON)

	Annual	DJF	MAM	JJA	SON
ARPEGE	16.9	13.1	14.7	22.5	17.4
HadAM2b	15.7	10.9	13.7	22.1	16.2
ECHAM3	16.1	11.3	13.9	22.2	17.1
Observed	14.4	8.7	12.4	21.5	15.1

performed using observed atmospheric profiles of temperature and humidity, which allowed a direct comparison with collocated synchronous surface observations. Daily maximum solar irradiances calculated with the ECHAM3 radiation code showed an overestimation of up to 50 Wm^{-2} for typical clear-sky midlatitude conditions, corresponding to approximately $10\text{-}15 \text{ Wm}^{-2}$ in the daily mean. Thus, the overestimates found in the stand-alone radiative transfer calculations are consistent and in quantitative agreement with the overestimates on climatological timescales at the German sites in Table 1.

6. Conclusions

Clear-sky solar flux climatologies calculated in the ECHAM3, ARPEGE and HadAM2b GCMs have been analyzed using direct observations at the surface. Observed clear-sky insolation climatologies have been constructed from composites of clear-sky episodes at seven radiation stations in Germany with long-term records of high quality measurements. The comparisons show that the GCM clear-sky insolation climatologies are significantly too high, i.e. the cloud-free atmospheres in the GCMs are overly transparent to solar radiation at these sites. Including aerosol effects improves the agreement between models and observations, but is not likely to be the only reason for the pronounced overestimation of the GCM irradiance. An overestimate of 10 Wm^{-2} remains in models including aerosol and abundant water vapor. This points to a probably inaccurate representation of aerosols in the models and / or the possibility of an underestimation of water vapor absorption calculated in the radiation codes of the GCMs, as formerly suggested by Wild et al. (1995). While they showed an overestimation of the irradiances calculated by the isolated radiation code for specific clear-sky cases, the present study documents the propagation of such overestimates on climatological timescales. Thus, the analysis provides additional evidence for an overly transparent atmosphere in GCMs under clear-sky conditions without involving clouds.

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