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How accurate did GCMs compute the insolation at TOA for AMIP-2?

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[1] Monthly averages of solar radiation reaching the Top of the Atmosphere (TOA) as simulated by 20 General Circulation Models (GCMs) during the period 1985–1988 are compared. They were part of submissions to AMIP-2 (Atmospheric Model Intercomparison Project). Monthly averages of ISCCP-FD (International Satellite Cloud Climatology Project – Flux Data) are considered as reference. Considerable discrepancies are found: Most models reproduce the prescribed Total Solar Irradiance (TSI) value within ±0.7 Wm^{-2}. Monthly zonal averages disagree between ±2 to ±7 Wm^{-2}, depending on latitude and season. The largest model diversity occurs near polar regions. Some models display a zonally symmetric insolation, while others and ISCCP show longitudinal deviations of the order of ±1 Wm^{-2}. With such differences in meridional gradients impacts in multi-annual simulations cannot be excluded. Sensitivity studies are recommended. **Citation:** Raschke, E., M. A. Giorgetta, S. Kinne, and M. Wild (2005), How accurate did GCMs compute the insolation at TOA for AMIP-2?, *Geophys. Res. Lett.*, *32*, L23707, doi:10.1029/2005GL024411.

1. Introduction

[2] Numerical models of the climate system are excellent tools to analyze the past and present state of the climate and to gain further insight into the large cascades of nonlinearly interacting processes forming it. They are tools to estimate future states of the climate system under a variety of forcing scenarios. Such projections gained extremely wide importance in far reaching political decisions concerning the maintenance of life on our planet. However, such models are not perfect. Therefore within the World Climate Research Program (WCRP) in various projects the performance of models or model components is investigated, when operated with the same boundary conditions and forcing scenarios. One of those projects is the Atmospheric Model Intercomparison Project [*Gates et al.*, 1999; *Phillips*, 1996; *AMIP Project Office*, 1996], where in its second phase (AMIP-2) the output computed by more than 20 models for essentially the same forcings are inter-compared. Other results on cloud and radiation fields or on the soil moisture, computed within the AMIP, are discussed, e.g., by *Potter and Cess* [2004], *Robock et al.* [1998], or *Wild* [2005]. A more recent project, the Coupled Model Intercomparison Project (CMIP [e.g., *Covey et al.*, 2003; *Meehl et al.*, 2005]) investigates the performance of models coupling the atmosphere with oceans. Many GCM-groups use their models for the purposes of the next IPCC Technical Review (International Panel of Climate Change). All models should reproduce the known major state and related fluxes of energy, mass and momentum with high accuracy. But quite large disagreement was found in various quantities, in particular at higher latitudes over both hemispheres [*Gates et al.*, 1999]. They are not subject of this paper.

[3] We concentrate on the major forcing for all climate processes [e.g., *Lean*, 2005]: the incoming solar radiation reaching the top of the atmosphere (TOA). This quantity has not yet been identified as an important object to be investigated within the frame of AMIP-2. Its total amount, the TSI at TOA, is now assumed to be 1366.5 Wm^{-2} on the basis of recent measurements from satellites [e.g., *Fröhlich and Lean*, 2004] and varies slightly (less than 0.1%) during the 11-year sunspot cycle. In most GCMs of AMIP-2 the value of 1365 Wm^{-2} has been used. The amount of radiation reaching the TOA at all regions of the Earth and during each time step is computed on the basis of the well-established (and for the AMIP for the period 1980 to 1996 redefined) facts of the Earth's astro-mechanics and their temporal variations. No information has been provided on the lowest possible sun-elevation in each model defining sunrise and sunset.

[4] Computations of the solar radiation reaching the TOA are also done for the purpose of establishing an accurate radiation climatology of our planet. The ISCCP [*Rossow and Duenas*, 2004; *Zhang et al.*, 2004; *Raschke et al.*, 2005] provides at present a data series on cloud characteristics and on various radiation products covering the period from mid-1983 to October 2001. In this data set, sunrise and sunset are defined by a value of 0.0005 for the cosine of the solar zenith angle. Its (and also of other similar projects) insolation should completely agree with that of the models, when computed with the same value of the TSI. *Zhang et al.* [2004] estimate their inaccuracy with about ±10 to 15 Wm^{-2}, while the plans for a global climate monitoring system call for an absolute accuracy of about 1–2 Wm^{-2} with a multi-year stability of about 1/5 of this range or better [*Ohring et al.*, 2004]. This obvious discrepancy between reality and demand needs further consideration.

2. The AMIP-2 Data Set

[5] Several details of the 20 models, given in Table 1 are described on the Web site http://www-pcmdi.llnl.gov/projects/amip. Most modeling groups participating in AMIP-2 followed the recommendations by the AMIP project team [*AMIP Project Office*, 1996] to simulate an elliptical orbit of the earth and also to use the realistic calendar for the period between 1980 and 1996. They compute the incoming solar radiation with different time steps ranging between 30′ and 6h, where 2 models provide also some adjustment between two discrete time steps

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Table 1. AMIP-2 Models, Used in This Study[a]

Model Names in Figures 1–3	Organization
ccc	CCCMA, Victoria
ccs	CCSR, Tokyo
cnr	CNRM, Toulouse
col	COALS, Calverton
dnm	DNM, Moscow
ecm	ECMWF, Reading
gis	GISS, New York
gla	GLA, Greenbelt
jma	JMA, Tokyo
mgo	MGO, St. Petersburg
mpi	MPI-M, Hamburg
mri	MRI, Tsukuba
nca	NCAR Boulder
nce	NCEP, La Joia
pnn	PNN, Richland
sun	SUNY, Albany
uga	UGAMP, Reading
uiu	University Illinois, Urbana
ukm	UK Met Office
yon	Yonsei University, Seoul
isc	ISCCP

[a] No leap year for ccc, gis, nca, nce, pnn, sun, uiu.

according to the cosine of the Sun's zenith angle. In almost all models the value for the TSI of 1365 Wm^{-2} has been used. Unfortunately none of the models, except the procedure for the ISCCP-FD data-set, offers information on the lowest possible height angle defining sunrise and sunset. This limit is of importance for computations over all areas being dominantly illuminated by a low Sun, like over both polar regions.

[6] According to the AMIP Newsletter No. 8, many models are using "realistic" calendar years with leap years from 1980 to 1996. But the MRI does not consider the shift of the vernal equinox and the PNN uses 365 days within each year without an additional day during the leap year. Most models use an elliptic time dependent orbit of the earth around the Sun with the following parameters: obliquity: 23,441; eccentricity: 0.016715; longitude of perihelion: 102,7°. Realistic calendar means inclusion of leap years from 1980 to 1996 with the equation for the time of vernal equinox at March, X,: X = 20,41 –0,0078 (Y – 1987) + 25xY(Modulo4); where Y = year; Modulo4 = remainder of Y/4, and with a vernal equinox of 282,7 degrees.

[7] Since all models used a different horizontal resolution, we transformed the data on the insolation at TOA with a linear interpolation scheme into a 1 × 1 degree grid. Here very small errors might be generated in the shadow zone. One of the models (JMA) was adjusted by its users from an earlier low resolution (8 degrees) version to a higher horizontal resolution (4 degrees) without a new calculation of the incident solar radiation, thus identical values of the insolation are found in two neighboring latitudinal zones causing then the strong oscillations to be seen in Figure 2 in section 3.3.

3. Some Results of This Intercomparison

3.1. Annual Averages of the Insolation at TOA

[8] For the models ecm and mri values of 1376.,2 and 1356,7 Wm^{-2} were obtained apparently due to errors in their codes. The ISCCP used TSI = 1367 Wm^{-2}. Values of all other models deviate from the prescribed value of 1365 Wm^{-2} within ±0.7 Wm^{-2}.

3.2. Zonal Means

[9] Meridional profiles of zonal averages of the net radiation fluxes at TOA determine the total poleward energy transports by the atmosphere and oceans [e.g., *Trenberth and Caron*, 2001]. The incoming solar radiation is one component. In Figure 1 we show a section of profiles computed by each of the models and by the ISCCP-FD to illustrate that quite large deviations occur over the high-latitude regions and also over the subtropics with associated different meridional gradients, which may affect the atmospheric circulation. During the end of the main seasons in February (and August), respectively, when both polar regions still obtain large amounts of solar radiation they reach values of up to 10–12 Wm^{-2}. These deviations over the polar regions and near the shadow zone might be a consequence of the model resolution. Another reason could be the use of different angles of the Sun's height above horizon defining sunset or sunrise. But also over the regions of highest possible insolation the model results (except the two extremes provided by the ecm and mri) deviate within the range of ±2 to 5 Wm^{-2}. In November, as an example, we also can observe, that the meridional profiles for the MRI and JMA models alternate their location with respect to the other curves, which also means a change of their meridional gradient. The ISCCP values coincide with those model results near the median of this ensemble. These differences may explain parts of the discrepancies in model results [*Gates et al.*, 1999].

3.3. Do the Models Produce Different Meridional Gradients of the Insolation at TOA?

[10] Since the expected changes in the slope of meridional profiles are small in comparison to the average meridional gradient, we computed the deviation of individual meridional profiles from that of the ISCCP [*Zhang et al.*, 2004]. The ISCCP has been used as a "reference", since its procedures seem to be best documented [e.g., *Rossow and Duenas*, 2004]. It uses a mean constant TSI of 1367 Wm^{-2} and computes the insolation at TOA with realistic astro-mechanical assumptions [*Nautical Almanac Office*, 1987]. During the leap year an extra day is added at the end of

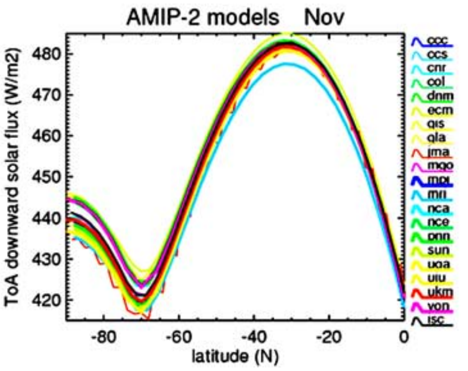

Figure 1. Monthly (November) zonal averages of incoming solar radiation at TOA, computed for the period 1985 to 1988 and plotted with original meridional resolution. N = North. ISCCP: black curve.

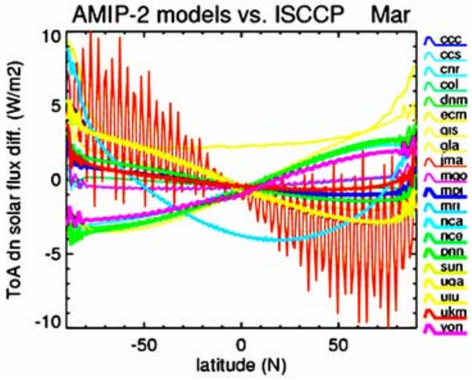

Figure 2. Deviations of monthly zonal averages (1985 to 1988) of the downward solar radiation at TOA, as computed by 20 GCMs, from the ISCCP during March (example for transitional season). Meridional resolution: 1 degree. N = North.

February, all following months are shifted by this day. This meridional profile coincides narrowly with most of the other profiles. Results in Figures 2 and 3 are all based on data interpolated onto the finer grid of 1 × 1 degrees.

[11] The deviations of the profiles from the ISCCP-FD produced by the models ecm and mri cannot be explained entirely by the choices of different values for the TSI. The gis-model, computes for the month February over the South Pole up to 7 Wm^{-2} less solar radiation than the ISCCP. The patterns of the monthly curves during all 12 months indicate that all models have some difficulties to compute the insolation poleward of about 65 degrees latitude. During the transitional seasons the differences between some the individual zonal profiles and the ISCCP are most pronounced. They are getting smaller towards the main seasons (July and January). The "fading" in the results of the jma model is caused by the expansion of the horizontal resolution from originally 8 degrees to 4 degrees. We expect that in long-term integrations such systematic differences in the monthly insolation will have a pronounced effect on the computed climate components. The higher frequency patterns with very small amplitude of less than 0.2 Wm^{-2} in several curves is possibly caused by the originally coarse resolution of such models. In an annual average over this 4-year period, most anomalies are smaller than ±2 Wm^{-2}, but climate develops on seasonal or even daily variations of the insolation.

3.4. Deviations From Individual Zonal Means

[12] Differences between the actual monthly maps and their zonal profiles should identify other longitudinal and latitudinal variations. The resulting global maps (Figure 3) show various longitudinal structures occurring in particular during the transitional seasons. The structures with zonal wave-numbers 8 (in the dnm model) and 24 (in 9 others) are due to the use of constant radiation values for the full length of time intervals of 3 and 1 hour, respectively. Computations of convective processes near the surface should be affected. These structures do not occur in models where either the radiation time step is equal to the dynamical time step or adjustments were made to take the change in the Sun's zenith angle into account.

[13] During the transitional seasons we see in 14 of the 21 seasonal maps some kind of a quadrupole pattern with a maximum amplitude of about ±1 Wm^{-2}, where however the extremes are located over the same areas in 12 of them, while in two others they are shifted by 90 and 180 degrees in longitude. These anomalies move by 12 hours or 180 degrees with the season. Their location is stationary throughout each season. They change regionally the zonal and meridional gradients of insolation at TOA thus influencing the forcing of the general circulation. This quadrupole patterns can be expected since during the equinox seasons the orbital parameters show the most pronounced daily changes in the annual cycle. In these seasons a region of the Earth can receive more irradiation at the TOA than the region mirrored at the equator or that rotated by 180 degree longitude in the monthly average. In the solstice seasons (December and June), the daily changes of the orbital parameters are smallest so that deviations from the zonal mean are much smaller, and may disappear if the time average were centered on the aphelion or perihelion time. So it appears, that this quadrupole patterns should be considered to be correct. In seven models (gis, mgo, mri, uga, uiu, ukm and yon) no trace of the above-mentioned anomalies are found. The quadrupole-like pattern in Figure 3 averages almost completely out in the annual means. However this result is insignificant for the development of climate that is a result of the daily (or here monthly) forcing by the Sun.

4. Conclusion

[14] In the spatial and temporal variations of the insolation at TOA as computed by 20 models participating in the AMIP-2 project and for the ISCCP data-set we discover that none of the models reproduced accurately the prescribed TSI value of 1365 Wm^{-2}. Some models ignore leap years. Moreover, leap years are included in different ways either leading to a small increase (0.34 Wm^{-2}) or decrease (0.92

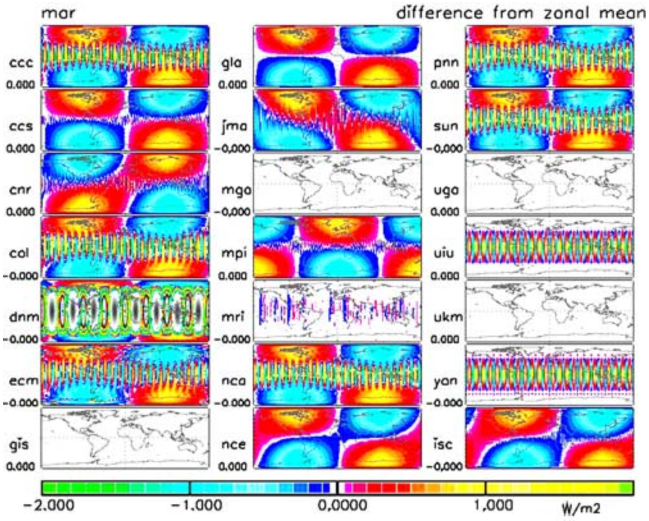

Figure 3. Dezonalized anomalies of the insolation at TOA during March (1985 to 1988) computed in 20 models and for the ISCCP products. Spatial resolution: 1 degree (long, lat).

Wm^{-2}) of the annual mean of insolation at TOA. Most models produce seasonal insolation fields at TOA that deviate from their zonal means. More importantly, the corresponding latitudinal profiles (of zonal averages) differ, as illustrated by deviations to a "reference profile" (here: ISCCP data set). These different latitudinal gradients of insolation are expected to affect the atmospheric circulation in integrations over multiple years. The largest deviations exceed ±5 Wm^{-2} (in conjunction with extended low sun-elevation times) at high latitudes and polar regions. These discrepancies compare unfavorably to an absolute accuracy requirement for all radiation quantities at the TOA of 1.5 Wm^{-2} [*Ohring et al.*, 2004].

[15] Not all of the observed features in Figures 2 and 3 are completely understood. The quadrupole-like spatial patterns of insolation anomalies (Figure 3) might be linked to the eccentricity of the Earth's orbit around the Sun. The differences for the latitudinal gradients mainly at high/polar latitudes (Figure 2) seem inherent to individual model assumptions. These different meridional gradients of the insolation are expected to affect the model results in integrations over multiple years. Based on our comparison already an error source has been identified in the MRI model (A. Kitoh, MRI, private communication, 2005).

[16] We recommend that in all climate models and in all "radiation climatologies" the incoming solar radiation at TOA must be identical for any given time period and area on the globe. Modelers should use the real length of the tropical year. Since a similar analysis of IPCC AR4 simulations shows qualitatively the same deficiencies as described here for the AMIP simulations, we think, that there is a need for sensitivity tests that investigate impacts of detected differences in the TOA insolation on circulation structures developing in the model's climate system.

[17] **Acknowledgments.** The authors thank G. Potter and R. Cess for initial data and W. Rossow and Y. Zhang for discussing ISCCP. E.R. began this work as Visiting Professor (2004–05) at NIPR in Tokyo.

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