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Downward longwave radiation in general circulation models: a case study at a semi-arid continental site

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ABSTRACT

The present case study evaluates the downward longwave radiation at the surface (DLR) in several high-resolution ($\approx 1°$) general circulation models (GCMs) using surface observations from a semiarid continental site in New South Wales, Australia (Uardry, 34.39°S, 142.30°E). This site is located on a large grassland plain uniform in both its land use and landcover type, and is therefore particularly well suited for a comparison with GCM grid mean values. Monthly averages of newly constructed clear-sky and all-sky DLR climatologies and the resulting cloud-radiative forcing are compared. It is shown that the GCMs exceed the observed DLR under cloud-free conditions by 10–20 W m^{-2} at this semiarid site on an annual basis, with a strong seasonal dependence. The calculated clear-sky fluxes are overestimated during the warmer summer season, with large absolute values of DLR, while the biases are reduced in the colder and dryer winter season with smaller fluxes. This gives direct support for recent evidence that the DLR model biases depend systematically on the thermal and humidity structure of the cloudless atmosphere. Fluxes from strongly emitting atmospheres tend to be overestimated, but may be underestimated from atmospheres with smaller emission. This points to common problems inherent in the simulation of the emission from the cloudless atmosphere in current longwave radiation codes.

The comparisons of the all-sky climatologies at Uardry show that the clear-sky biases are partly masked in the models with an insufficient cloud-radiative forcing, thereby counterbalancing the excessive DLR of the cloud-free atmosphere. On the other hand, when the cloud-radiative forcing is improved, the biases in the cloud-free atmosphere become fully apparent in the all-sky fluxes.

1. Introduction

The longwave radiation emitted to space by the climate system to balance the net solar absorption is well established through satellite measurements. The longwave exchange between the earth's surface and the atmosphere, however, is known with much lesser confidence. In particular, the downwelling atmospheric emission towards the surface (downward longwave radiation, DLR) is only poorly known on global scales. Accordingly, considerable differences exist in the simulated DLR amongst various General Circulation Models (GCM) (Wild et al., 1995; 1998a,b; 2001; Garratt and Prata, 1996).

Wild et al. (1995) and Garratt and Prata (1996) showed that DLR is typically underestimated in GCMs when compared to observation sites available at the time from the Global Energy Balance Archive (GEBA; Ohmura et al., 1989; Gilgen et al., 1998). Similar conclusions were drawn in the studies of Gupta et al. (1999) for GCMs in

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comparison with satellite-derived estimates and in Chevallier and Morcrette (2000) for the ECMWF operational forecast system.

First evidence that the biases in the GCM climatologies of DLR are not globally uniform, but systematically differ at low latitude sites, with a tendency towards overestimation rather than an underestimation, was presented in Wild et al. (1998a,b; 2001) using new data material from a total of 45 globally distributed observation sites. Consistent results are given in Allan (2000) for the fluxes of the ECMWF reanalysis at a tropical and a polar site.

Based on stand-alone calculations with the radiation scheme in isolation, Wild et al. (1998a; 2001) further suggested that the biases found in the GCM climatologies are predominantly related to problems under cloud-free conditions, in line with Dutton (1993). However, so far no direct assessment of the cloud-free GCM flux climatologies has been done which could support the above findings. This was due to the lack of adequate observational records of sufficient length and quality to allow for the construction of representative clear-sky climatologies for comparison with the respective GCM climatologies. However, the situation is changing rapidly, as in the near future extended observational records will become increasingly available from programs such as the Baseline Surface Radiation Network (BSRN; Ohmura et al., 1998), the Atmospheric Radiation Measurement Program (ARM; Stokes and Schwartz, 1994) or the CSIRO Integrated Ground-truth Site Network (CIGSN; Prata, 1994). The present work is a pilot study which uses a 7 yr record from a semiarid site in Australia to demonstrate the significance of long-term state-of-the-art observational records for the separate assessment of GCM all-sky and clear sky climatologies.

In general, one should be cautious in attempting to diagnose model performance for variables such as precipitation or temperature based on data acquired at only one location. However, we believe that general conclusions are possible in this case because of the choice of site and the more fundamental nature of the quantity being considered. A measurement of DLR (flux density) at the earth's surface is the hemispherical integral of the atmospheric emission (i.e. longwave radiation from the whole atmosphere covering an area of tens of square kilometres received at that point). The emission of radiation from 'greenhouse gases' in the atmosphere occurs in a series of wavelength bands, and is strongly dependent on the vertical distributions of all the relevant gases. This is fundamentally a different quantity to validate and also less difficult than, say, point estimates of precipitation or temperature, due to the natural spatial amalgamation of DLR.

2. Observational data

2.1. Uardry site

The longwave irradiance observations are part of a new high-quality land surface radiation budget (SRB) data set from a large uniform site in Australia, located at Uardry, NSW (34.39°S, 145.30°E, elevation 94 m). This site is part of the CIGSN (CSIRO Integrated Ground-truth Site Network) and has been established chiefly for the validation of radiation-related products of satellite remote sensing (Prata, 1994; Grant et al., 2000a). The Uardry site is located on the vast Hay Plains, an area several hundred kilometres in extent that is extremely flat and largely uniform in its land use and landcover type (Prata et al., 1998; Prata, 1994). The daily mean albedo for a 5-yr period (ranging from 0.15 to 0.28) is shown in Fig. 2 of Prata et al. (1998), whilst the site albedo variability (three sites) is given in Grant et al. (2000b). The site generally lies under a relatively clear atmosphere. Aerosol optical depth measured at the site is consistently less than 0.05 at 0.5 μm. The landcover is semiarid grassland, which is typical of large sections of the Australian continent. Prata et al. (1998) show based on NOAA-AVHRR reflectances, that the coefficient of variation of the reflectance (standard deviation/mean) is 14% over a region $180 \times 220\ km^2$. Uardry has a high frequency of clear skies, with the atmosphere over the region generally containing low water vapor and aerosol amounts. The Uardry site is therefore an ideal location for providing long-term climatological data representative of a region on the scale of a GCM model grid box.

2.2. Instrumentation and measurements

The Eppley Precision Infrared Radiometer (PIR) pyrgeometer (Eppley, 1995) was used to measure the longwave irradiance. The Eppley pyrgeometer is well known to the solar and terrestrial radiation community. It is being used by the World Climate Research Program (WCRP) Baseline Surface Radiation Network (BSRN) (Ohmura et al., 1998) for monitoring long-term trends in radiation flux densities, and is generally considered the standard monitoring instrument for downwelling longwave irradiance. The instrument was not ventilated and shaded as recommended by the BSRN (Ohmura and Schroff, 1983), due to remote power considerations. During the first 2 yr of the pyrgeometer data record, the instrument was mounted on a stand 2 m above the ground. For the remainder of the data record, the pyrgeometer was located on a platform at the top of a 15 m tower. The relatively low drag of the surrounding grassland vegetation ensured excellent natural ventilation which significantly reduced errors due to frost/dew deposition.

The observed monthly climatologies for the all-sky and clear-sky DLR are based on 7 yr of data covering the period August 1992 to July 1999. Instantaneous measurements of DLR were initially obtained every 3–7 min; a major upgrade of datalogging instrumentation in July 1994 increased the sampling rate to every 30 s with averaged values stored every 2 min (Prata et al., 1998).

Clear-sky longwave irradiances were determined using cloud detection provided by shortwave irradiance measurements during the daylight period and the pyrgeometer data during the night-time period. For details, the reader is refered to Grant et al. (2000b). The pyrgeometer data employed a threshold test on the standard deviation of measurements within a 15-min period. The threshold was set at 10% above the standard deviation of that measured for the diurnal cycle of the clear-sky DLR data for days in the same month of the year that occured during long periods of fine cloudless conditions. The clear-sky monthly DLR climatology was obtained using only those days that were clear for all 24 h. Visual inspection of the diurnal cycle for all days used in the clear-sky monthly climatology (from about 20–30 d in the winter months to nearly 90 d in the summer months) was conducted as a final check.

2.3. *Calibration*

Laboratory calibrations were carried out against the Australian longwave standard (Collins, 1968) and field intercomparisons were carried out annually using a travelling standard which itself was calibrated annually using the Australian longwave standard. The Australian Bureau of Meteorology operates the Australian longwave standard. It consists of a hot (fixed temperature of approximately 400 K) downward-facing black-body radiation cavity constructed from 2.5 cm thick aluminium casting. The pyrgeometer is held in a blackened insulated chamber and a double shutter is provided which seals this chamber from the radiation source to obtain the zero reading for the instrument. Our results are based on this Australian National Standard Calibration Facility (in use for over 30 yr) which has a 95% confidence level uncertainty of 2.5% (as endorsed by the National Associations of Testing Authorities; NATA). The repeatability of the thermopile sensitivity constant determination was better than ±1%.

Instrument calibration was based on the results of a round-robin experiment undertaken by the World Radiation Center (Philipona et al., 1998), which involved the calibration of the same five pyrgeometers by 11 calibration institutes world-wide. Each laboratory conducted their calibrations independently (no knowledge of other results) using the same autonomous measurement system and a non-intrudable computer program. The pyrgeometer sensitivity factor C was determined by six of the 11 institutes to about 2% of the median for all five instruments being considered. Among these six laboratories, the absolute deviation around the median of the five instruments was less than 1%. The Australian National Standard Calibration was on average about 5% high compared to an average of these six laboratories. An allowance for what appears to be a 5% bias in the pyrgeometer sensitivity factor C has been made to the Uardry data.

3. Models

DLR fluxes from four atmospheric GCMs are analysed: the last two model versions of the Hadley Center for Climate Prediction and Research, version HadAM2b (Stratton, 1999) and HadAM3 (Pope et al., 2000), and the last two model versions of the Max-Planck Institute for Meteorology, the ECHAM3 (Roeckner et al., 1992) and the

ECHAM4 (Roeckner et al., 1996). The GCM data stem from AMIP type simulations with prescribed sea surface temperature and sea ice climatologies (Gates, 1992). The majority of the experiments were done at an exceptionally high horizontal resolution (T106 or 1.1° for ECHAM3, ECHAM4, 0.833° × 1.25° for HadAM2b). This facilitates the comparison with point observations and minimizes the differences in altitude between the GCM gridpoints and the observation site, on which the DLR is rather sensitive. HadAM3 is at standard resolution (2.5° × 3.75°).

All models include broad-band radiation schemes with two-stream approximation, as typically used in GCMs. The transition from the second-last to the last model versions in both the HadAM and ECHAM model series brought a replacement of the radiation schemes. Thus, the four GCMs used in this study include four independent radiation schemes which are described in detail in Slingo and Wilderspin (1986) for HadAM2b, Edwards and Slingo (1996) for HadAM3, Hense et al. (1982) for ECHAM3, and Morcrette et al. (1986) with modifications according to Giorgetta and Wild (1995) for ECHAM4.

For the comparison of model-calculated and observed fluxes, the model fluxes were interpolated to the coordinates of the Uardry site using the four surrounding grid points weighted by their inverse spherical distances.

4. Results

4.1. Emission from the cloud-free atmosphere

Annual mean DLR observed under cloud-free conditions at Uardry is compared with the different GCMs in Table 1. The models exceed the observed annual mean DLR under cloud-free atmosphere (300 W m^{-2}) by 10–20 W m^{-2}. The individual yearly means of observed DLR cover a range from 292.2 W m^{-2} (1993) to 311.8 W m^{-2} (1998). The interannual variability is thus small compared to the model biases, which underlines their statistical significance.

Comparisons between the GCM-calculated and observed annual cycle under cloud-free conditions are shown in Fig. 1. It is evident that all models

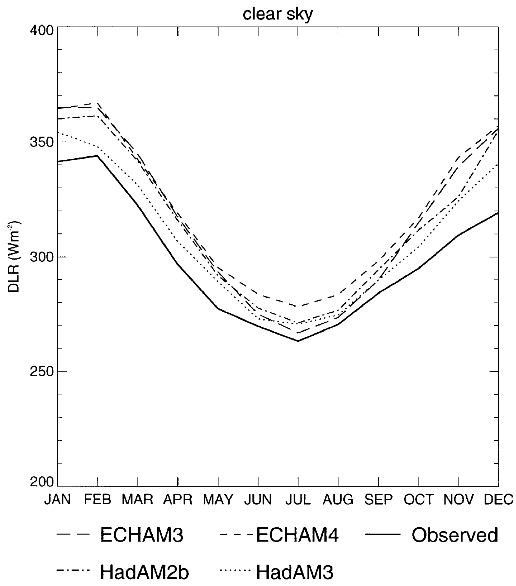

Fig. 1. Annual cycles of longwave downward radiation at the surface under clear-sky conditions, observed at Uardry, NSW, Australia, and calculated in the GCMs ECHAM3, ECHAM4, HadAM2b and HadAM3.

Table 1. *Annual, summer (DJF) and winter (JJA) means of downward longwave radiation at the surface under clear-sky and all-sky conditions and resulting surface longwave cloud radiative forcing (LW CRF), as observed at Uardry, NSW, Australia, and calculated in the GCMs ECHAM3, ECHAM4, HadAM2b and HadAM3. Units Wm^{-2}*

	Clear-sky			All-sky			LW CRF		
	Annual	DJF	JJA	Annual	DJF	JJA	Annual	DJF	JJA
ECHAM3	317	362	272	333	372	299	16	10	27
ECHAM4	321	363	282	342	386	303	21	23	21
HadAM2b	315	359	275	327	366	293	12	7	18
HadAM3	309	348	273	323	356	296	14	8	23
Observed	**300**	**335**	**268**	**325**	**359**	**295**	**25**	**24**	**27**

show a distinct signal in the seasonal biases of DLR under cloud-free conditions. A substantial overestimation is consistently found during the hot and more humid summer season in all models (on average 23 W m^{-2}, cf. Table 1). During the colder and drier winter season, on the other hand, the overestimation is substantially reduced (to 7 W m^{-2} on average). This tendency might be even somewhat more pronounced, since there may exist a small underestimation in the observed clear-sky DLR climatology in winter, due to the method of only considering totally clear days. This introduces a slight 'dry bias' due to the neglect of higher water vapor amounts prior and following cloudy conditions, which may only be relevant in the winter months when partly cloudy days are the norm.

The above tendencies are in line with the findings on more global scales in Wild et al. (1998a; 2001) based on all-sky data only, which indicated that the sign and magnitude of the biases systematically depend on the strength of the emission of the atmosphere. Sites with large fluxes of DLR tend to be overestimated, while sites with smaller DLR fluxes were found to be increasingly underestimated by the GCMs. Consistently, at Uardry during the summer months, the large DLR fluxes (335 W m^{-2} observed) are significantly overestimated in the GCMs considered here, whereas during the winter months the smaller fluxes are less biased. This suggests that the excessive DLR found in the GCM climatologies under all-sky conditions in Wild et al. (1998a; 2001) at low latitude sites with warm climates might be primarily a problem of the simulated emission from the cloud-free atmosphere. Additional insight can be expected from future studies planned at moist tropical sites which will be carried out as soon as enough data become available from BSRN to allow for the construction of clear-sky climatologies at these highly overcast sites.

On the other hand, the Uardry site cannot directly confirm the underestimated DLR in GCMs for small fluxes from cold, dry atmospheres found in the earlier studies, since the monthly means measured at Uardry do not cover this low range. However, the significant reduction of the overestimates in the cold season at Uardry supports the systematic dependence of the biases on the absolute magnitude of the fluxes noted in Wild et al. (1998a; 2001).

A comparison of the integrated water vapor content calculated in the GCMs with the observed estimates taken from the ECMWF reanalysis (Gibson et al., 1997) for Uardry is shown in Fig. 2. This gives an estimate of the extent to which the GCM biases may be related to problems in the simulated humidity. Except for ECHAM3, the models simulate the annual cycle of integrated water vapor realistically. It is evident that the biases in DLR are not dominated by water vapor biases in these models. For example, the overestimation in the ECHAM4 clear-sky DLR is present despite an accurately simulated seasonal cycle of water vapor. Sensitivity studies with standalone models showed that an increase of humidity by 10% results in an increase in DLR of the order of 5 W m^{-2} (Wild, 1997). This indicates that in the case of ECHAM3, the excessive simulated water-vapor abundance at Uardry may provide a significant contribution to the overestimated clear-sky DLR in summer. Nevertheless, even if the humidity is accurately simulated, as is the case in the other GCMs, the clear-sky DLR of strongly emitting atmospheres is biased. This points to problems in the longwave radiation codes them-

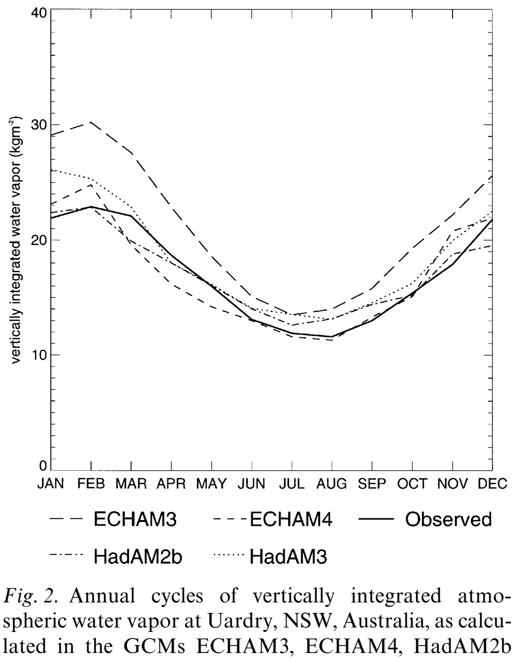

Fig. 2. Annual cycles of vertically integrated atmospheric water vapor at Uardry, NSW, Australia, as calculated in the GCMs ECHAM3, ECHAM4, HadAM2b and HadAM3 compared to the observational estimate taken from the ECMWF-reanalysis (Gibson et al., 1997).

selves, in line with the findings in Dutton (1993) and Wild et al. (1998a; 2001) based on stand-alone calculations with 'correct' atmospheric input, and the results in Chevallier and Morcrette (2000) and Allan (2000).

Of further importance for the DLR is the near-surface temperature. Comparisons with observed 2 m temperatures at Uardry showed a slight warm bias in the near surface temperature of the models which may contribute to the excessive DLR. The near-surface temperature, however, not only affects the DLR, but in turn is also affected by the DLR. I.e., excessive DLR causes excessive heating of the soil, resulting in turn in excessive near-surface temperature. An excessive DLR is therefore expected to be associated with an excessive 2 m temperature. We cannot exclude the possibility, however, that errors in advective temperature effects may also contribute to the excessive DLR.

4.2. *Cloudy atmosphere and cloud-radiative forcing*

The presence of clouds tends to increase DLR due to their high thermal emittance (cf. Table 1). The difference between the DLR emitted under cloudy and under cloud-free conditions is referred here as longwave cloud radiative forcing at the surface (LW CRF). In contrast to the shortwave cloud radiative forcing at the surface, the LW CRF is small, on the order of 25 W m^{-2} on an annual basis. This is due to the fact that the major fraction of DLR emission originates from the lowest part of the atmosphere below clouds. Nevertheless, errors in the simulation of low cloud properties can affect the simulation of DLR.

The LW CRF for the different GCMs and that observed at the Uardry site are shown in Fig. 3 and Table 1. All models underestimate the LW CRF on an annual basis (cf. Table 1). Accordingly, the overestimates in the clear-sky fluxes are partly compensated by a lack of LW CRF. As a result, the all-sky DLR climatologies are generally in better agreement with observations than the clear-sky climatology, as shown in Fig. 4 and Table 1. HadAM3, for example, shows excellent agreement with the observed climatology for all-sky fluxes, yet this is favored by an error cancellation between a too weak LW CRF and excessive DLR of the cloud-free atmosphere. Such findings only become apparent in a separate clear-sky and all-sky analysis of both model and observational records as

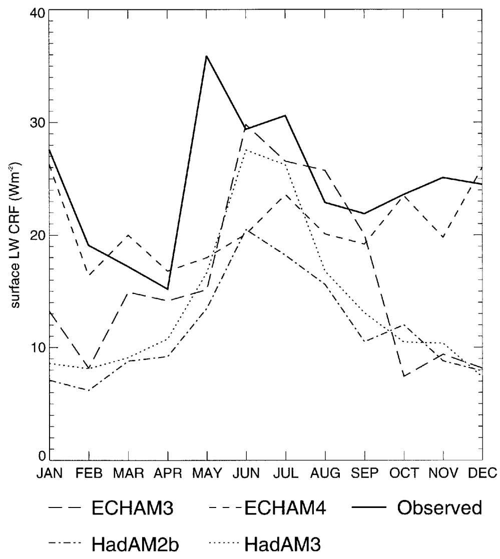

Fig. 3. Annual cycles of longwave cloud radiative forcing (LW CRF) at the surface, observed at Uardry, NSW, Australia, and calculated in the GCMs ECHAM3, ECHAM4, HadAM2b and HadAM3.

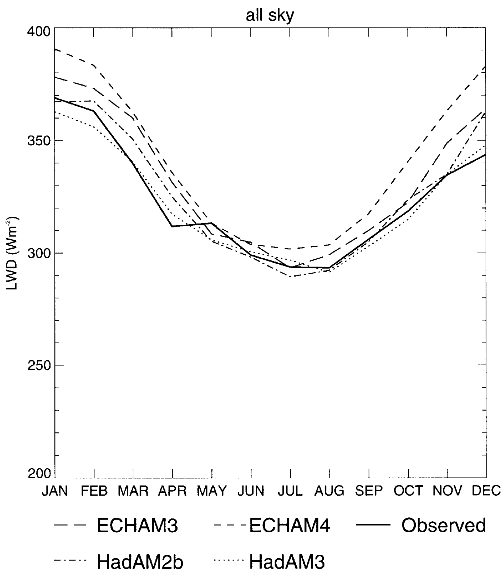

Fig. 4. As Fig. 1, but for all-sky conditions.

advocated in the present study. It should be noted, however, that HadAM3 still shows the smallest DLR biases under both clear-sky and all-sky conditions amongst the models considered here (cf. Table 1). In ECHAM4, on the other hand, the CRF in summer is fairly realistically simulated. Thus, the large summer biases in the all-sky fluxes of ECHAM4 are predominantly a reflection of the clear-sky biases, which are in this case not masked by compensating errors in the cloud radiative forcing.

5. Summary and conclusions

The longwave downward radiation at the surface (DLR) calculated in GCMs has been assessed using data from the CSIRO Uardry observation site, which allowed the construction of both clear-sky and all-sky monthly climatologies. Furthermore, both the extended uniformity of the site surroundings as well as the high horizontal resolution ($\approx 1^{\circ}$) of the studied models ensure a representative comparison of the model-calculated and observed fluxes.

The assessment of the all-sky and clear-sky GCM flux climatologies suggests that the simulated DLR is particularly biased under cloud-free conditions: the simulated longwave emission of the warm cloud-free atmosphere in summer is significantly too large (on average $23\ \mathrm{W\ m^{-2}}$), while the overestimation decreases with the cooling and drying of the atmosphere during the winter months (to $7\ \mathrm{W\ m^{-2}}$ on average). This gives direct support for recent evidence (Wild et al., 1998a,b; 2001; Allan, 2000) that the DLR biases in GCMs largely depend on the emission strength of the cloudless atmosphere, with overestimates under strongly emitting warm atmospheres and underestimates under cold atmospheres with weak emission. Inaccuracies in the simulated water vapor amount are thereby not large enough to explain the significant biases at Uardry, thus pointing to common deficiencies within the longwave radiation schemes. Advective temperature biases may further deteriorate the flux calculations. Biases in the DLR all-sky climatologies at Uardry reflect the biases found under cloud-free conditions as long as the longwave surface cloud radiative forcing is realistically simulated, whereas the excessive emission of the cloud-free atmosphere is partly masked in those models that calculate a cloud forcing that is too weak.

The strategy employed in this study, namely the separate evaluation of the emission from cloudless and cloudy atmospheres in both GCMs and observational records, may be extended in future studies to make use of the increasing number of long-term observational records of high quality, which are becoming increasingly available through new ground-based networks such as BSRN, ARM or CIGSN.

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