Diurnal cycles in the NCAR climate model

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ABSTRACT

The performance of two versions of the atmospheric component in the National Centre for Atmospheric Research (NCAR) community climate model, Community Earth System Model Version 1 (CESM1), in simulating near-surface parameters is evaluated. Many aspects of the model physics are different between the two model versions but here we focus on the boundary layer scheme. The Community Atmospheric Model Version 4 (CAM4) employs a non-local first order scheme, whereas CAM5 uses a diagnostic TKE scheme. Both boundary layer schemes are run for the first and second GABLS case where their performance is within the range of other models. Five-year simulations using climatological sea-surface temperatures and interaction with the same version of the community land model are performed with hourly output at certain locations. The evaluation focuses on the diurnal cycle and global observational and reanalysis datasets are used together with multi-year observations from flux tower sites. It is found that both model versions capture the timing of the diurnal cycle, but considerably overestimate the diurnal amplitude of near-surface temperature, wind and turbulent heat fluxes. The seasonal temperature range at mid- and high latitudes is also overestimated with too warm summer temperatures and too cold winter temperatures. The two model versions differ substantially in their representation of near-surface wind speeds over land. The low-level wind speed in CAM5 is about half as strong as in CAM4 except in areas where the sub-grid scale terrain is significant and the difference in wind speed is even larger. The reason for this is the applied turbulent mountain stress parameterization, which acts to increase the surface stress and thereby reduce the wind speed.

1 Introduction

Few studies that evaluate the performance of planetary boundary layer (PBL) parameters in GCMs are found in the literature. Some very early studies include Boer et al. (1991) and Randall et al. (1992). At the time of these intercomparisons, most models did not resolve the diurnal variation in solar insolation and only had a few vertical grid levels in the entire PBL (Garratt, 1993). The diurnal temperature amplitude has been evaluated in an earlier version of the NCAR community climate model (CCSM2) by Dai and Trenberth (2004). They found summer amplitudes to be in good agreement with synop station data evaluated in latitude bands but too small amplitude over the ocean. Commonly, evaluations of GCMs focus on mean fields at monthly, seasonal, and annual timescales. As pointed out by Lin et al. (2000), there are apparent limitations to this approach. It is possible for GCMs to produce realistic climate states for the wrong reasons, for instance, the mean near-surface temperature could be simulated correctly without any diurnal variation. Most evaluations of the diurnal cycle in global models consider precipitation (e.g. Lin et al., 2000; Betts and Jakob, 2002) and they usually contain some of the turbulent parameters, e.g. the surface heat fluxes. A more comprehensive study from the PBL point of view is reported in Garratt et al. (2002) where they compared 5-years of GCM results with detailed boundary-layer observations at six locations, two over the ocean and four over land. The observational data was limited to hourly data for a month or two at each site. They found overall good agreement between the observations and the model except for some unrealistic model mixed-layer temperature profiles over land in clear skies, which they related to the use of a simple local first-order turbulence closure. In this study, we utilize a selection of data from the FLUXNET (Baldocchi et al., 2001) network and the Coordinated Energy and Water Cycle Observation Project (CEOP) is utilized to study not only the diurnal amplitude in temperature but other near-surface parameters such as the turbulence fluxes of heat, moisture and momentum in CAM4 and CAM5. This report gives a short summary of the study which is fully documented in Lindvall et al. (2012).

2 NCAR climate model

The most recent version of the global climate model developed at NCAR is Community Earth System Model version 1 (CESM1) which has the option of two substantially different atmospheric components, CAM4 (Neale et al., 2010) or CAM5 (Neale et al., 2010). The land component of CESM1 is the Community Land Model Version 4 (CLM4, Oleson et al., 2010; Lawrence et al., 2011). The land surface fluxes are calculated in the land model using Monin-Obukhov similarity theory with the stability functions from Zeng et al. (1998) (Oleson et al., 2010). They are similar to the ones in CAM4 (Holtslag and Boville, 1993), but differ substantially from those in CAM5 (Bretherton and Park, 2009). CAM5 include the University of Washington (UW) boundary layer scheme (Bretherton and Park, 2009; Park and Bretherton, 2009). This scheme is a first order moist turbulence scheme in which the diagnostic TKE is explicitly calculated. The UW scheme was developed with focus on improving the representation of stratocumulus topped boundary layers (Grenier and Bretherton, 2001). The scheme allows for several decoupled turbulent layers in the atmospheric column. The turbulent layers are identified using a bulk moist Richardson number (Ri) and layers are considered non-turbulent if $\mathrm{Ri} > 0.19$. CAM4 employs a turbulence parameterization scheme based on Holtslag and Boville (1993), but with an updated formulation of the boundary layer height from Vogelezang and Holtslag (1996). It is a non-local diffusivity K-profile scheme developed for dry convective conditions. The PBL height is explicitly calculated using a bulk dry Richardson number and the height, together with a turbulent velocity scale, determines the eddy diffusivity profile. For turbulent layers above the PBL, a local first order closure scheme is used.

3 GABLS cases

The two PBL schemes have been run for GABLS1 and GABLS2. GABLS1 case is reasonably well represented by both schemes both in high resolution and operational versions (Bretherton and Park, 2009). Results for all participating models with a first model level above 5 m in the GABLS2 case is found in Figure 1 with CAM4 and CAM5 results highlighted. The simulations for the two CAM versions are performed with standard vertical resolution and time step and clearly the diurnal cycle in temperature is largest in CAM regardless of version. The diurnal cycle in the wind is peculiar with a marked increase when the PBL becomes convective in the morning and then a sudden drop to very low wind speeds. Further results and discussions from GABLS2 are presented in Svensson et al. (2011).

4 Experimental setup

The model results presented below are from simulations of the two versions of CAM coupled with CLM4 and using climatological sea-surface temperatures based on years 1982-2001. The horizontal resolution is 0.9° latitude $\times 1.25^\circ$ longitude and there are 26 or 30 vertical layers in CAM4 and CAM5, respectively. The lowest mass level is at about 60 m and the four extra model levels in CAM5 are all below 2500 m. Three five-year simulations are analysed, one with CAM4 and two versions of CAM5. In CAM5 there is a parameterization for the turbulent mountain stress (TMS) and we added one simulation with this effect turned off. The comparison of the models to the flux observations is done by choosing

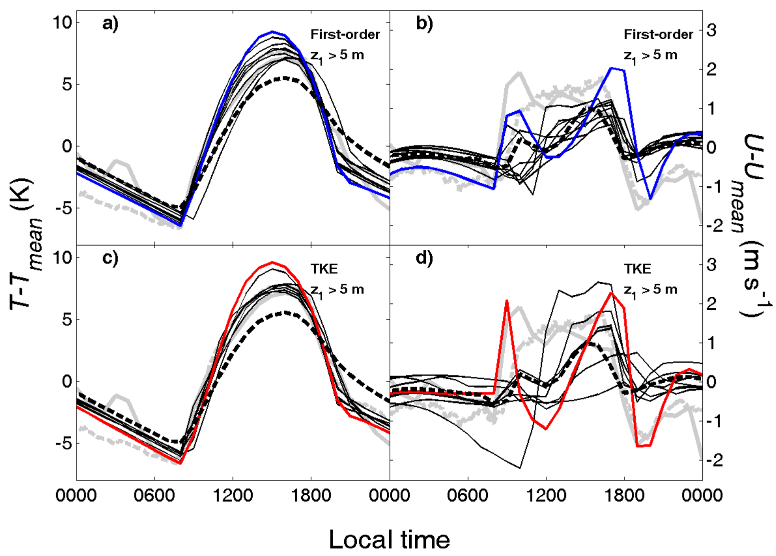

Figure 1: CAM4 (blue line) and CAM5 (red line) results for the GABLS2 case. The SCM results are presented in four categories based on model closure a, b first-order closures; c, d TKE-based schemes; and on height to the first model layer below (not shown) or above 5 m a.g.l. (shown here). Thick black dashed line is the LES result. Time series of observed and modelled temperature deviation (K) at 2 m a.g.l. (left panels) and observed and modeled mean wind speed deviation (ms^{-1}) at 10 m a.g.l. (right panels). The Light grey solid line is the selected experiment period, the light grey dashed line shows the average over the entire CASES-99 campaign.

the closest model land grid point for each study site. Hourly model output from the 5-year period is used to derive median diurnal cycles for each month and season, treating the data as climatological data and thus providing 12 monthly median diurnal cycles and four seasonal median diurnal cycles from the model.

5 Observational data

The flux sites used in this study are chosen to cover different climate zones and ecosystems (Figure 2 for locations). In total, 35 micrometeorological flux tower sites provide the observational data used in this study. The turbulent fluxes are measured in 30 or 60 minute intervals using the eddy-covariance technique (e.g. Aubinet et al., 2000; Baldocchi et al., 1988). In addition to the fluxes, the sites maintain measurements of standard meteorological variables, such as temperature, wind speed and pressure. All sites included in the study have at least two years and up to 16 years of eddy-correlation measurements.

6 Model results

The annual cycle is presented for three land areas in Figure 3. The annual temperature cycle is larger in CAM5 for both polar and midlatitudes though the annual average compare well with observations. The annual cycle in the tropical rainforest does resemble the observations but the annual mean is lower. The annual cycles in 10-m wind speeds are not strong in neither models nor reanalysis products (no observational data is presented) but the mean level varies substantially. The two versions of CAM5

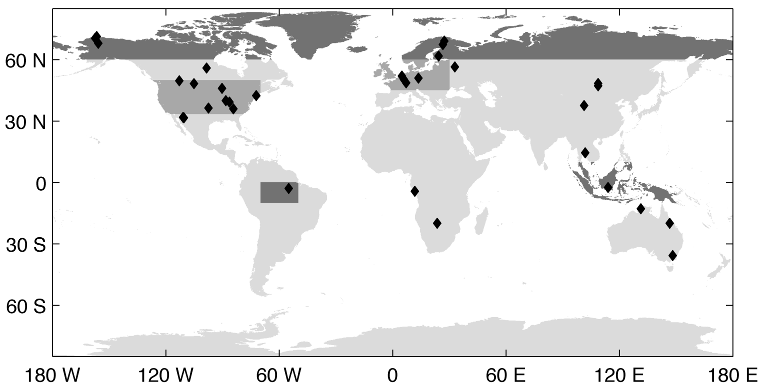

Figure 2: Map showing the locations of the flux tower sites used in this study. The darker grey areas show polar areas, midlatitude Europe and North America and tropical rainforest in South America and Indonesia.

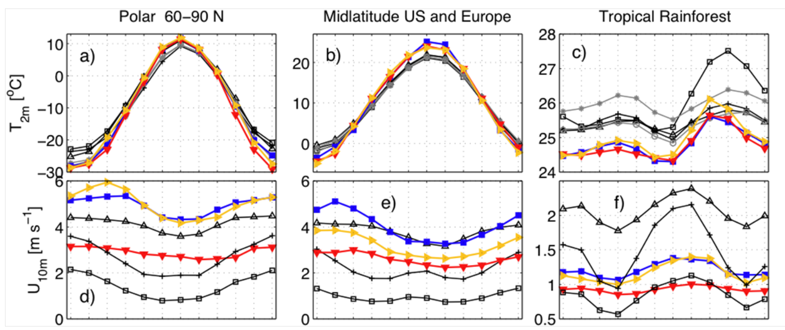

Figure 3: Averaged seasonal cycles of a-c) 2-m temperature, d-f) 10-m wind speed for CAM4 (blue and CAM5 (red and yellow without TMS) and observational (CRU and Wilmott and Matsura, grey lines with square and circle, respectively) and reanalysis datasets (JRA25, NCEP and ERA-Interim, black lines with square, plus and triangle, respectively). The left panels contain data for the polar areas (60°-90°N), the middle panels midlatitude Europe and North America (45°-60°N, 10°W-30°E and 30°-50°N, 130°-70°W), and the right panels tropical rainforest in South America and Asia (10°S-0°, 70°-50°W and 10°S-10°N, 90°-150°E) . All variables are shown for land areas only and are area averaged.

with and without TMS (red and yellow, respectively) differs substantially. This is because the enhanced surface roughness influences the surface stress that is used as boundary condition for the PBL scheme (Lindvall et al., 2012). For all fluxstations (Figure 2), the climatological diurnal cycle in many near-surface parameters are evaluated. Summary statistics for all variables show a too large diurnal cycle in all analysed variables and the largest deviation is found for wind speed where the correlation coefficient is also lowest (about 0.6). The simulated median monthly diurnal cycles of turbulent heat fluxes and temperature correlate with the observed ones with values of 0.75 or higher. The bias is largest for the latent heat flux. Many interesting details are revealed when examining the differences in seasonal mean diurnal cycles for the flux stations in each region presented in Figure 2. The effect of TMS is the most striking difference between CAM4 and CAM5 where the overall wind speed is much lower in CAM5 along with a much larger friction velocity, due to the enhanced surface roughness. The summer diurnal cycle in temperature, latent and sensible heat fluxes are simulated quite well for the polar region while the temperature is much overestimated for midlatitude forest sites. For a more detailed disucssion we refer to Lindvall et al. (2012).

7 Conclusions

The performance of near-surface parameters in the two versions of the atmospheric model in CESM are evaluated. There are substantial differences in the parameterization schemes between the two versions. The comparison between the two model versions with observed turbulent fluxes and near surface varaiables is performed with flux station data gathered at 35 sites in different climate zones. From this evaluation we find:

- Both CAM versions capture the timing of the diurnal cycles reasonably well, but substantially overestimate the diurnal amplitude in general. This is particularly true for temperature and wind speed, which consistently have too large simulated amplitudes, but also in most cases for the turbulent fluxes.
- The summer temperatures are too high in CAM4 and CAM5 compared to the global reanalysis and observational datasets as well as to the flux site observations. The flux tower observations show that the models are too warm primarily during daytime, with biases in the order of 5°C at the midlatitude, boreal forest and arid sites.
- Both models are too cold in winter at high latitudes and CAM5 underestimates the temperature more than CAM4.
- The wind speed is substantially lower in CAM5 than in CAM4 over land. CAM5 matches the flux observations and the NCEP dataset better than CAM4 does, but the spatial variation is underestimated in CAM5. CAM4, on the other hand, overestimates the wind speed, particularly in mountain regions. The model differences are explained by the TMS parameterization applied in CAM5, which decreases the wind speed. Its impact is large in unforested areas, where the roughness length otherwise would be low, and in mountain regions. The effect of TMS is enforced when the boundary layer is stably stratified.

It is apparent that the TMS parameterization in CAM5 has positive effects on the model simulations. Nevertheless, the implementation could be improved. By substantially increasing the roughness length even in relatively flat regions the spatial variation becomes too low. Also, the fact that TMS is only applied in the atmospheric component and not in the land component gives rise to inconsistencies in the model.

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