Sensitivity of Cloud and Radiation Parameterizations to Changes in Vertical Resolution

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ABSTRACT

The importance of vertical resolution to the parameterization of cloud–radiation processes in climate models is examined. Using a one-dimensional single-column model containing a typical suite of physical parameterizations, the authors test 12 different vertical resolutions, ranging from 16 to 60 layers. The model products are evaluated against observational data taken during three intensive observation periods from the Atmospheric Radiation Measurement Program. The simulated values of cloud–radiation variables display a marked sensitivity to changes in vertical resolution. This sensitivity is apparent in all the model variables examined. The cloud fraction varies typically by approximately 10% over the range of resolutions tested, a substantial amount when compared to the typical observed values of about 50%. The outgoing longwave radiation typically changes by approximately 10–20 W m$^{-2}$ as resolution is varied, which is of the order of 5%–10% of the observed value. The downwelling shortwave radiation change is somewhat smaller but is still significant. Furthermore, the model results have not converged even at a resolution of 60 layers, and there are systematic differences between model results and observations.

1. Introduction

Cloud height feedbacks are well known to be critically important in model simulations of the climatic response to enhanced atmospheric concentrations of carbon dioxide. The question naturally arises, therefore, as to what vertical resolution is adequate for the treatment of cloud–radiation interactions and other physical processes. For present-day general circulation models (GCMs), computer speed limitations are a serious practical restriction on vertical resolution. For example, all of the atmospheric GCMs used for the transient coupled atmosphere–ocean GCM experiments described in the 1995 Intergovernmental Panel on Climate Change Report (Houghton et al. 1996) contained 19 or fewer layers. As computational power increases, however, general circulation models with greatly increased vertical resolution will become readily affordable. Thus, it is of considerable interest to learn how the current generation of parameterizations will respond as limitations on vertical resolution are relaxed. In general, the sensitivity of modern GCM parameterizations to vertical resolution is a little-explored subject.

In this study, we use a one-dimensional single-column model (SCM) to investigate the performance of a particular suite of parameterizations as vertical resolution is varied. We focus on key cloud–radiation variables. Because of its computational efficiency, the SCM is an especially useful tool with which to develop and test parameterizations (Randall et al. 1996). For example, our SCM has recently been used, together with GCM tests, to evaluate several different cloud–radiation schemes and to compare them with observational data (Lee et al. 1997).

The SCM is a stand-alone diagnostic model that can be envisioned as a vertical stack of model layers above a single surface grid element of an atmospheric GCM, situated at a specific geographical location. Our model is identical in concept to that described by Iacobellis and Somerville (1991a,b) but with updated parameterizations. The SCM, as used in this study, contains a complete set of parameterizations of physical processes that are typical of those found in contemporary GCMs. The purpose of these parameterizations is to simulate the ensemble large-scale effects of processes that occur on smaller scales than the horizontal extent of the grid element. For all of the numerical experiments described in this paper, the following algorithms were used: the Morcrette (1990) longwave radiation routine, the Fouquart and Bonnel (1980) shortwave radiation routine, cloud–radiative properties prescribed according to Slingo (1989), the convection algorithms of Hack (1994) and Zhang and McFarlane (1995), and the cloud prediction scheme of Tiedtke (1993). The parameterization of processes occurring in the atmospheric boundary layer are based on routines developed for the Community...
Climate Model, version 3 (CCM3; Kiehl et al. 1998). For the results reported in this paper, the maximum cloud overlap assumption was employed in all integrations. As the Fouquart–Bonnel scheme assumes a random overlapping of clouds, we have made appropriate modifications to the SCM that ensure a maximal overlap of clouds in all layers, following the example of Morcrette and Fouquart (1986).

The SCM requires a set of initial values of prognostic variables such as temperature and humidity. This initial state, together with forcing data comprising the time evolution of wind and advection terms of state variables, is derived from data taken at the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurement (ARM) Program (Stokes and Schwartz 1994). Additional observations at the SGP site have been used to evaluate the results of the SCM.

For these simulations, observational soundings from the perimeter of the ARM SGP site have been used to calculate the necessary input data for the SCM. The vertical spacing of the forcing data, as provided by ARM data processing procedures, is 10 hPa. The time-dependent output of the SCM includes profiles of moisture and temperature, clouds, cloud–radiative properties, diabatic heating terms, surface energy balance terms, and hydrologic cycle components.

2. Experiment description

In these numerical experiments, the SCM was integrated with a model domain corresponding to the ARM SGP site during three intensive observation periods (IOPs). The SGP site is representative of one GCM grid cell: approximately 140 000 km² in horizontal extent. The first IOP took place from 26 October to 13 November 1994, the second from 17 July to 4 August 1995, and the third from 16 April to 7 May 1996. These IOPs will be referred to throughout this paper as fall 1994, summer 1995, and spring 1996, respectively.

In this research, we use 12 different SCM configurations, differing only in vertical resolution. Our lowest resolution is 16 layers, and our highest is 60 layers. Between these extremes, we test all vertical resolutions in which the numbers of layers are integer multiples of 4, that is, the 12 tested resolutions are 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, and 60 layers. In each version of the model, the layers are equally spaced in pressure with the surface pressure set by observational values and the top pressure level no higher than 100 hPa. At the highest resolution, 60 layers, the spacing between levels is 15 hPa. For each IOP, the same forcing dataset is used for all model resolutions. The time step is constant for all simulations.

Outgoing longwave radiation (OLR), downwelling shortwave radiation (DWSR), and cloud fraction (CF) modeled by the 12 different vertical resolutions of the SCM were time averaged for each IOP and compared to ARM observations averaged over the same period. For the fall 1994 IOP, observational values of OLR and CF were taken from the Geostationary Operational Environmental Satellite-7 (GOES-7) products of Minnis and Smith (1998). Measurements from the Oklahoma Mesonet (Brock et al. 1995) were used to specify the DWSR. For the summer 1995 and spring 1996 IOPs, the same data sources were used with the exception of the satellite, which changed from GOES-7 to GOES-8.

3. Results

a. Spring 1996

We first describe results from the spring 1996 IOP, which we shall use as a reference case. During this transition period from a cold season circulation regime to a warm season regime for the southern Great Plains, moist convection is greatly enhanced (Schmitz and Mullen 1996; Higgins et al. 1997). Figure 1 shows time-averaged values of DWSR, OLR, and CF (percentage of sky covered by cloud) for each of the tested SCM resolutions. The cloud fraction results are dominated by the striking monotonic increase in convective cloud fraction as resolution is increased from 16 to 60 layers. The radiative consequences of this increase appear most noticeably as a nearly monotonic decrease in OLR with increasing resolution. This decrease in OLR as resolution improves is attributable to the increase in convective cloud fraction, which in this case leads to an increase in mean cloud altitude (decreasing the mean cloud temperature) at resolutions beyond 20 layers, as shown in Fig. 2. Note that Fig. 2 depicts an average over times when cloud is present.

The effect of changing resolution on DWSR is smaller and less systematic, as shown in Fig. 1a. As resolution increases, DWSR first increases as mean cloud altitude increases and mean cloud albedo increases; and then at still finer vertical resolutions, DWSR decreases as the increasing fraction of convective cloud gradually dominates and increases the mean cloud albedo. Figure 3 shows that as resolution increases, the structure of the cloud shifts toward smaller spatial and temporal scales, the amount of low cloud increases, and the cloud population becomes more vertically coherent.

We may note also that, as shown in Fig. 1, the model at all resolutions has too small a cloud fraction, and correspondingly too high a value of DWSR, when compared to ARM observations. The systematic underestimation of OLR by the model, relative to measurements, may be due to errors in cloud amount, cloud altitude, cloud–radiative properties, cloud overlap, or some combination of these. Nevertheless, there is no apparent tendency for the model results to converge toward observations as resolution increases. Indeed, the model results are not converging toward any apparent limit at even the highest tested values of vertical resolution in these numerical experiments.
Fig. 1. Time-averaged values of (a) downwelling shortwave radiation, (b) outgoing longwave radiation, and (c) cloud fraction for the spring 1996 IOP, for each of the tested vertical resolutions of the single-column model, and as estimated from ARM observations. For cloud fraction, the total length of the bar depicts total cloud fraction, and the unshaded portion of the bar depicts the convective cloud fraction.

Fig. 2. Time-averaged values of cloud fraction and convective mass flux (kg m$^{-2}$ s$^{-1}$), shown as functions of pressure and SCM resolution, averaged over times when cloud is present during the spring 1996 IOP.

In an effort to further diagnose the reasons for the variability with resolution shown in these numerical experiments, we have evaluated the convective mass flux fields. The evolution of net convective mass flux as resolution changes is depicted as a function of pressure in a time-averaged sense in Fig. 2 and is shown time dependently in Fig. 4. Figure 2 shows that, at all resolutions, there is a relative maximum in convective mass flux at pressures between 400 and 500 hPa. Figure 2 also shows that the absolute value of convective mass flux decreases as resolution increases. Again, the correct interpretation of this figure requires recognition that the time average is taken only over times when cloud is present. The detrainment rate in updrafts (not shown) increases as vertical resolution is improved, especially at altitudes above 500 hPa. As shown in Fig. 4, as vertical resolution increases, the convective mass flux occurs over shorter timescales. The more frequent convective events at altitudes greater than 500 hPa are mostly due to convective events originating in the upper troposphere and having limited vertical extent, and are not due to increased deep convection. In the model, these events are produced by the Hack (1994) scheme. Thus, the dominance of convective over supersaturation cloud as vertical resolution improves is associated with more convective events, weaker mass flux, increased detrainment, and larger cloud amounts at both high and low altitudes.
Because the increase in high cloud amount with finer vertical resolution is not associated with more intense convection, we also investigated the influence of the boundary layer representation. The code for the CCM3 boundary layer scheme, which we used in the single-column model, contains an arbitrary upper limit of 9 on the number of permissible levels in the boundary layer. In the higher-resolution models, this restriction can sometimes decrease the height of the boundary layer during convective events. However, the effect of this constraint on cloud fraction is not as pronounced as on convective mass flux.
limit is negligible when the number of layers is smaller than 44. Even for the finest resolutions tested, the total amount of cloud is increased by only 3%–4%, while the tendency for the OLR to decrease with finer resolution is slightly reduced.

b. Fall 1994

The months of October and November are a time of increased convection and precipitation for Oklahoma as the North American monsoon decays and the cold season circulation returns (Schmitz and Mullen 1996; Higgins et al. 1997). Figure 5 shows the DWSR, OLR, and CF for the fall 1994 IOP. In general, model simulations of this IOP exhibit similar behavior to those of spring 1996. In particular, we note that higher vertical resolutions produce greater cloud fractions, a larger relative fraction of convective clouds, a decrease in OLR, and weaker and less monotonic changes in DWSR. Figure 5 also demonstrates that the SCM does not appear to have converged to any asymptotic limit at even the highest tested resolution and that it displays systematic differences in comparison to measurements.

Figure 6 shows that clouds are present at a much greater range of altitudes during fall 1994 than during spring 1996 and that as resolution improves, there is not a systematic tendency to converge toward a particular vertical structure of cloud fraction. Figure 6 also shows that again, as in spring 1996, improving the vertical resolution markedly decreases the magnitude of the
convective mass flux without substantially altering its vertical structure. In general, the similarity of the fall 1994 and spring 1996 simulations increases our confidence in the generality of the SCM results and suggests that they are not artifacts of a particular set of forcing data or a particular regime of meteorological events.

c. Summer 1995

The model simulations of the summer 1995 IOP exhibit somewhat different behavior from those of spring 1996 and fall 1994. Some differences may be attributed to the less convective regime present in the southern Great Plains during the months of July and August (Schmitz and Mullen 1996; Higgins et al. 1997). Figure 7 shows that at the three lowest resolutions (16, 20, and 24 layers), an anomalously large cloud fraction is obtained, in comparison with that found at the eight higher resolutions. Only at the highest tested resolution (60 layers) does the time-averaged cloud fraction again increase substantially enough to approach that obtained at the lowest resolutions. The vertical distribution of cloud undergoes a dramatic change when the vertical resolution is improved to 28 or more layers. At fewer than 28 layers, very little detrainment occurs at altitudes below 400 hPa, and so at these coarse vertical resolutions, the model produces large cloud amounts at altitudes of approximately 200–300 hPa. When vertical resolution is increased to 28 or more layers, substantial detrainment occurs between 600 hPa and the surface, so that the large amount of upper-tropospheric cloud is reduced. The result is the striking difference in cloud amount as resolution is increased, shown in Fig. 7c. We note that for all simulations the SCM underestimates total cloud fraction due to the maximum overlap assumption, which corresponds to the overestimation of downwelling shortwave radiation, demonstrated in Fig. 7. We may also note that the observational value of total cloud fraction is intermediate between the lowest and highest model values, but this parameter is notoriously difficult to observe accurately, or even to define precisely, so an observational validation using cloud fraction data alone would be problematic at best.

Figure 8 shows that the excessive cloud amounts at the three lowest resolutions are found at a pressure-altitude range of approximately 200 to 350 hPa. Furthermore, the convective mass also changes rapidly with resolution in this pressure region, for resolutions of 28 layers or less. We may conclude, therefore, that for the particular suite of parameterizations used in the SCM, especially the parameterization of convective cloudiness, under the conditions of the summer 1995 IOP at the ARM site, the model behaves qualitatively differently at coarse vertical resolution than at fine vertical resolution.

4. Summary and conclusions

This diagnostic study using a single-column model shows that simulated values of cloud–radiation variables display a marked sensitivity to changes in vertical resolution. This sensitivity is apparent in all the model variables examined. The cloud fraction varies typically by about 10% over the range of resolutions tested, a substantial amount when compared to the typical ob-
FIG. 8. Time-averaged values of cloud fraction and convective mass flux (kg m$^{-2}$s$^{-1}$), shown as functions of pressure and SCM resolution, averaged over times when cloud is present during the summer 1995 IOP.

served value of cloud fraction, which is about 50%. The OLR typically changes by approximately 10 or 20 W m$^{-2}$ as resolution is varied, which is of the order of 5% or 10% of the observed value. The DWSR variation is somewhat smaller than the OLR change but is still significant. Furthermore, the model results have not converged even at a resolution of 60 layers, and there are significant systematic differences between model results and observations.

It is unlikely that the strong sensitivity to vertical resolution apparent in these results is limited to the particular location, season, choice of parameterization, or other specific details of this study. Instead, it seems probable to us that contemporary general circulation models taken as a class contain physical process parameterizations that tend to display the characteristics shown in this study, including a strong sensitivity to vertical resolution, systematic errors relative to observations, and a failure to converge to a well-defined limit as vertical resolution is increased, at least within a range of typical resolutions. An objective of future research is to produce parameterizations that are physically more realistic and numerically better behaved than those of present-day climate models. In pursuing this objective, diagnostic tools such as the single-column model, in conjunction with observational programs such as ARM, will have an important role to play in developing and evaluating these parameterizations.

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