A Global Climate Simulation with Explicit Physics

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Abstract

Mean climate and intraseasonal to interannual variability of two versions of the Community Climate System Model (CCSM) coupled atmosphere-ocean general circulation model (CGCM) are analyzed. The first version is the standard CCSM, in which cloud effects on the large-scale circulation are represented via parameterizations. The second version includes “super-parameterization” (SP) of convective processes by replacing parameterized cloud processes with an explicit two-dimensional cloud-resolving model (CRM) at each CGCM grid column. The SP-CCSM improves several shortcomings of the CCSM simulation, including mean precipitation patterns, equatorial SST cold tongue structure and associated double intertropical convergence zone (ITCZ), the Asian monsoon, periodicity of the El Nino-Southern Oscillation, and the intraseasonal Madden-Julian Oscillation. These improvements were obtained without the retuning of the coupled model, which is surprising in view of previous experience with other coupled models.
For computational purposes, the horizontal resolution in current coupled ocean-atmosphere general circulation models (CGCMs) is truncated at a point in the energy spectrum that does not allow the explicit representation of important physical processes such as cloud formation, turbulent mixing in the boundary layer, eddy mixing in the ocean, and the floe-scale physics of sea-ice. The models include parameterizations of these processes, which lead to large errors and uncertainties in the results. The latest assessment of climate model simulations and projections using state-of-the-art CGCMs, issued by the Intergovernmental Panel on Climate Change (1), reiterates the conclusion of earlier reports that clouds still represent the largest source of uncertainty in climate simulations. While cloud parameterizations have been improved for over half of a century (2), the systematic errors associated with the shortcomings of the parameterizations remain large. These range from errors in the simulated background climate to errors in the frequency and intensity of internal fluctuations on various space and time scales (3).

We demonstrate that replacing the parameterization of cloud processes by explicit cloud resolving models improves coupled global climate simulation on a wide range of spatial and temporal scales.

We use a state-of-the-art version of the Community Climate System Model, version 3 (CCSM, 4), which we have modified to include an explicit cloud resolving model (CRM) in each CGCM atmospheric grid column, through a multi-scale modeling framework (MMF, 5-8). The MMF allows simultaneous representations of the large-scale atmospheric circulation on the coarse-resolution grid of the atmospheric component of
the CGCM and physical processes such as convection and stratiform cloudiness on the fine-resolution grid of the CRM. The embedded CRMs are sometimes referred to as super-parameterization (SP) of small-scale processes. The coupled model with a CRM embedded in each grid column of the atmospheric component will hereafter be referred to as SP-CCSM. While the CRM is a two-dimensional (2D) model described in (6, 9), the SP-CCSM includes a wide range of spatial and temporal scales and their interactions. Observational evidence suggests that such interactions play a key role in the spatiotemporal organization of tropical convection (10, 11).

We assessed the implication of the cloud processes representation by comparing the climate simulation produced by the SP-CCSM with the observations and also with a control simulation obtained from a version of the CCSM that uses parameterized cloud processes. Details of each model’s configuration are presented in table S1.

Figure 1 compares the monthly Niño-3.4 time series of the sea surface temperature (SST) anomalies associated with the El Niño-Southern Oscillation (ENSO) as simulated by the SP-CCSM (1B) and CCSM (1C), and as observed (1A) based on the Hadley Centre SST version 2 (HadSST2) data set (12). The SP-CCSM produces a sequence of ENSO events that is less regular than in the control simulation and with a more realistic asymmetry between the warm and cold phases. The irregularity of events is also notable in the broadening of the main peak of the power spectrum (fig. 1D). The amplitude of the signal is more realistic, but the period of the spectral peak in the oscillation is too short by 18 months when compared to the observations. However, the period of ENSO simulated by the SP-CCSM has improved compared to the CCSM simulation. We note that ENSO
is a coupled phenomenon driven by the interactions between the ocean and the atmosphere. The improvement in the period and irregularity in the SP-CCSM is solely due to a better representation of clouds in the atmospheric model. The resolution of the ocean model can also be a key factor (13); the resolution used in our simulation is known to be less ideal for ENSO simulation (14, 15).

We find that the improvement in ENSO simulation is consistent with the SP-CCSM’s ability to capture the correct structure of the equatorial cold tongue, which in the CCSM is too narrowly confined to the equator and extends too far into the western tropical Pacific (fig. S1). The SP-CCSM also simulates the opposite relation with the Niño-3.4 region across the central and western Pacific, although it is not as strong as observed. On the western side of the basin, the ocean acts like a “slab” and the SST responds mostly to the local wind anomalies. The complex system of islands in this region influences the wind-stress simulation. Increased resolution in all components of the CGCM will allow a better representation of the wind-stress acting at the air-sea interface and over the Maritime Continent (14, 15).

Rainfall is a key factor influencing the hydrological cycle, atmospheric circulation, and ocean salinity; as a result, the regional distribution has vital socioeconomic impacts. Realistic simulation of precipitation is one of the biggest challenges for the current generation of models. Comparing the global distribution of the seasonal mean rainfall simulated by SP-CCSM (fig. 2B) and CCSM (fig. 2C) with observations (fig. 2A) taken from the Climate Prediction Center (CPC) Merged Analysis Precipitation (CMAP) dataset (16), the superiority of SP-CCSM is apparent. In both boreal winter and summer
seasons, the distribution of rainfall along the inter-tropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) in the SP-CCSM reproduces the observed patterns, and does not produce the spurious double ITCZ present in the CCSM. However, the SP-CCSM’s rainfall east of the date line in the SPCZ, does not extend into the extratropics as in the observations. During the summer, the distribution of precipitation over the western part of the tropical ocean basin shows an improvement in the SP-CCSM, but it is still weak compared to the CMAP analysis. We find a significant improvement in the simulation of rainfall over the South Asian monsoon region, where large-scale model biases have been reduced. Two realistically simulated maxima, one west of the Indian peninsula and the other in the Bay of Bengal, are a response to moisture advection by the onshore flow. Compared to observations, the precipitation variation over India is less well simulated, possibly due to the inability of coarse resolution of the CGCM to resolve orography. However, compared with the CCSM, we see a significant improvement in the simulation of monsoon variability such as the interannual variability of the summer monsoon associated with the SST anomalies. The pattern of correlation between the Indian summer monsoon rainfall index and the subsequent winter season SST anomalies (fig. S2) shows that, in the SP-CCSM, a reduced Indian summer monsoon rainfall is associated with a warm eastern Pacific and western Indian Ocean, as in the observations.

During the northern winter, the CCSM has a deficit of rain in the storm track regions and excessive rain in the western Pacific. During the summer, the CCSM rains very often over the Arabian Peninsula. In the SP-CCSM these errors are reduced or
eliminated.

Recent research (21, 22) has shown that biases in the tropical SST simulations of coupled models impact the simulation of the rainfall distribution and its variability. The tropical atmosphere is very sensitive to changes in the SST, and small SST anomalies can lead to large changes in the distribution of convection (23). For comparison, a simulation with the atmospheric component of SP-CCSM (SP-CAM) using specified (observed) SST and sea-ice distributions as boundary conditions (8) was analyzed. Figures 2G and 2H show the winter and summer rainfall distributions simulated by SP-CAM. In both seasons, there are regions with excessive precipitation compared to observations. The most notable biases are found during the summer over the western Pacific Ocean and the Asian monsoon region. In the SP-CCSM, these biases are greatly alleviated, and as a result, the coupled model produces a better simulation of the geographical distribution and amplitude of precipitation than the uncoupled model does. This finding is gratifying but surprising, since coupling to an ocean model typically makes the results of an atmosphere model worse (24).

The impact of CRMs on the simulation of tropical variability discussed in connection with SST and precipitation can also be seen in the simulation of the dominant mode of intraseasonal variability of the tropical atmosphere, the Madden-Julian Oscillation (MJO), which is poorly simulated in most of the current generation of models (1). The phase composites of the dominant MJO oscillatory mode extracted using a multi-channel singular spectrum analysis (MSSA, 15, 25, 26) of outgoing longwave radiation (OLR) anomalies in observations and simulations are compared in fig. 3. The composites
are constructed by averaging the OLR MJO mode anomalies (reconstructed components) over several equal intervals in a \((0, 2\pi)\) phase cycle of the MJO oscillation for the entire analyzed period. The MJO-related mode of variability simulated by the SP-CCSM occurs at realistic period (56 days in SP-CCSM and 52 days in the observations) and propagates eastward with a realistic phase speed. The CCSM produces MJO-like variability but the period of oscillation is much longer (72 days) and the disturbance propagates more slowly. Analysis of the spatial structure of the MJO during its average lifecycle in CCSM (fig. 4) reveals that the parameterization of convection results in weak convective anomalies in the Indian Ocean that cannot propagate beyond the Maritime Continent and decay before reaching the central Pacific Ocean. In the SP-CCSM, the alternating “active” periods of enhanced convection and “break” periods of reduced convection over the Indian Ocean are in agreement with the observations, as are their eastward and meridional propagation.

Complementary to the MSSA analysis, we have also applied the CLIVAR (27) standardized set of MJO diagnostics (not shown). We find that the CCSM has additional shortcomings in representing MJO characteristics such as weak northward propagation during the boreal summer and poor representation of the lag of zonal wind anomaly behind (to the west of) the precipitation peak. The SP-CCSM improves the simulation of these processes.

Results reported here provide compelling evidence that replacing the cloud process parameterizations with embedded CRMs improves some of the known shortcomings of the CCSM. Since these shortcomings affect most of the current CGCMs
we argue that currently available parameterizations for representing the overall properties of clouds in a grid box have deficiencies that limit the model skill in simulating the observed characteristics of the Earth's climate and its variability.

Convection and cloud parameterizations of most atmospheric general circulation models (AGCMs) have been tuned in uncoupled simulations to improve the model results, which in some cases may be achieved by the cancellation of errors. For example, errors in a cloud microphysics parameterization can be tuned to cancel errors in the convection parameterization. When the AGCM is coupled to an ocean model, the errors do not cancel any more, and the AGCM results usually become less realistic. As shown above, when the SP-CAM is coupled to an ocean model, its results actually become more realistic, counter to expectations based on prior experience with parameterized models. This is both encouraging and intriguing. We might expect coupling with an ocean model to improve the SP-CAM results, without tuning, simply because ocean-atmosphere interaction on short time scales plays a role in determining the observed climate.

Conventional convective parameterizations are based on the assumption that collective effects of cloud ensembles are in quasi-equilibrium with the large-scale forcing (28). This approximation affects the model’s ability to simulate the stochastic variability of the observed climate that arises from internal high-frequency fluctuations. Observational studies show that ENSO is affected by the high-frequency variability of westerly wind anomalies in the western Pacific during MJO events (29–31). Our results suggest that improvements of the ENSO variability in the SP-CCSM could be linked, at least in part, to the model’s ability to simulate the MJO.
This experiment suggests that MMF approach should not be limited to the atmospheric model but extended to the other components of the climate model, which also use parameterizations of small-scale process. These results also bode well for the ability of the global cloud resolving models to simulate Earth’s climate.
References and Notes


15. Materials and methods are available as supporting material on *Science* Online.


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Fig. 1 Time series of the Niño3.4 index (SST anomaly averaged over 5°S-5°N, 170°W-120°W) and the associated power spectrum. (A) observations (HadSST; the SST anomaly is computed with respect to the 1959-2002 climatology and only the last 22 years are shown to be consistent with the length of the model time series.), (B) SP-CCSM and (C) CCSM simulations for 22 years. (D) Power spectra computed from the time-series (A)-(C). Shading denotes ±5% significance interval for the SP-CCSM and observations, and the dashed line represents the red noise power spectrum.
Fig. 2 Seasonal mean precipitation. (A) Observed December-January-February (DJF) 1979-2006 mean from CMAP. (B) As (A) but for June-July-August (JJA). (C) DJF mean from SP-CCSM. (D) As (C) but for JJA. (E) DJF CCSM. (F) As (E) but for JJA. (G) DJF mean for 1986-2003 from SP-CAM. (H) As (G) but for JJA. Units are in mm/day.
Fig. 3 Phase composites of OLR MJO mode reconstructed component (RC) for CCSM (blue), SP-CCSM (red), and NOAA observation (green). The composites are averages of RCs over phase intervals of length $\pi/36$, $\pi/28$, and $\pi/26$ of the MJO oscillations of CCSM, SP-CCSM and NOAA observation, respectively. The choice of the phase interval was based on the average period of the MJO oscillation in the models and observation (72, 56 and 52 days, respectively) such that each phase interval is 2 days long. The composites are plotted by averaging over (5°S–5°N) at 60°E (A) and 120°E (B). Day 0 corresponds to the composite over the phase interval 0– $\pi/36$, 0– $\pi/28$ and 0– $\pi/26$, respectively, for CCSM (blue), SP-CCSM (red), and NOAA observation (green), and represents the composites for the next two days of the average MJO oscillation. The sequence follows the phase intervals in the (0 – 2$\pi$) cycle of the oscillation’s phase. Units are in W m$^{-2}$. 
Fig. 4 Phase composites of the dominant OLR MJO mode reconstructed component for 2-day long phase intervals for (A) CCSM, (B) SP-CCSM, and (C) NOAA observation. Day 0 corresponds to the composite over the phase interval $0–\pi/36$, $0–\pi/28$ and $0–\pi/26$, respectively, for CCSM (A), SP-CCSM (B), and NOAA observation (C). The sequence follows the phase intervals in the $(0–2\pi)$ cycle of the oscillation’s phase. The average period of one cycle of these eight phase intervals is 72 days for CCSM, 56 days for SP-CCSM, and 52 days for NOAA observation. Units are in W m$^{-2}$. 
Supporting Online Material for

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Supporting Online Material

1. Materials and Methods

1.1 Models and Data Description

The coupled general circulation model (CGCM) is based on the CCSM version 3 (CCSM3.0.1 beta 14 source code released in 2006, S1). The atmospheric component, the Community Atmosphere Model (CAM, S2) version 3 uses a semi-Lagrangian configuration of the dynamical core (S3), with horizontal resolution T42 (approximately 2.8 degree) and 26 hybrid terrain-following levels in the vertical.

This model is also used as the host model for the SP-CCSM. In SP-CCSM the parameterized physics related to moist convection, large-scale condensation, and cloud fraction is replaced by an ensemble of 2D cloud-resolving models (CRMs, S4). The other parameterized processes of CAM remain unchanged. The radiation parameterization is the same in both models; in the SP-CCSM the interaction is at the CRM-scale hydrometeors. The cloud model includes prognostic variables for the wind components (zonal and vertical), liquid water/ice moist static energy, total non-precipitating water and, total precipitating water mixing ratio. The domain of the CRM is periodic and aligned in the east-west direction with a horizontal resolution of 4 km. The vertical levels in the cloud model are the same as the host atmospheric GCM. The number of vertical levels in SP-CCSM was increased from 26 to 30, by adding four more levels in the lower part of the atmosphere.

Table S1 summarizes the differences between the atmospheric components in the two models. The SP-CCSM is computationally demanding, being about 200 times more
expensive than the CCSM, which limits the choice of the resolution in the atmospheric model. Previous modeling studies strongly suggest that it is important for individual components of the coupled system to have comparable resolutions \(S5\). This argument influenced our choice for the ocean model resolution. The ocean grid is \(gx3v5\) for which the longitudinal resolution is 3.6 degree and the latitudinal resolution decreases monotonically equatorward to approximately 0.9 degrees near the equator.

Model simulations are compared with observations taken from different analysis datasets. Timeseries of observations are longer than the model simulations to assure a robust statistical significance of the phenomenon. Accordingly, statistical significance of the results is assessed in both observations and models based on their corresponding number of degrees of freedom.

The monthly mean sea surface temperature (SST) data were obtained from the Second Hadley Centre \(S6\) dataset on a \(1^\circ\) latitude \(\times\) \(1^\circ\) longitude grid. Monthly mean precipitation from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP, \(S7\)) dataset for the period 1979-2006 were used. Monthly mean anomalies were computed by subtracting the climatology from the total filed for both observations and model simulations.

Daily mean precipitation data over India are from the high-resolution gridded daily rainfall dataset developed by the India Meteorological Department \(S8\). The on \(1^\circ\) latitude \(\times 1^\circ\) longitude grid for 1951 – 2004 period were used.

The observed daily mean outgoing longwave radiation (OLR) data on a \(2.5^\circ\) longitude \(\times 2.5^\circ\) latitude grid were obtained from the National Oceanic and Atmospheric
Administration (NOAA) for the period 1979-2007 (S9). The daily climatologies of OLR and rainfall were calculated as the mean (for the length of the data set) of the total daily values for each calendar day. The daily anomalies are obtained by subtracting the climatology from the total field. The daily climatologies and anomalies of the model OLR and rainfall were also similarly determined with 20-year long simulations.

2. Supporting Text

Climate variability associated with El Niño-Southern Oscillation (ENSO) is not confined to only the tropics, and changes in the atmospheric circulation and SST are felt at global scale. The current generation of global models cannot capture global teleconnections associated with ENSO (S10). Extratropical- and monsoonal-response to tropical SST anomalies are two examples of relationships in the large-scale variability related to ENSO. In addition to improvements in the SST simulation we also see improvements in the simulation of space-time evolution of atmospheric and ocean variability in phase with the SST perturbations on ENSO timescales.

2.1 Linear regression of the global SST anomaly on the Niño3.4 index

Figure S1 compares the regression maps of the global SST anomaly on the Niño-3.4 index from models simulations and observations. The regression in the extra-tropical Pacific is more realistic in the model with finer representation of cloud processes, the SP-CCSM. This result suggests that replacing the parameterization of convection with cloud-scale models leads to a different distribution of deep convection in the tropics and associated heating, low- and high-level convergence. As a consequence, the atmospheric bridge (S11 – S13) between the tropics and extra-tropics identified in the observations is
captured in the SP-CCSM. The response of the Indian Ocean to ENSO forcing changes when the parameterized convection is replaced by the explicit convection, suggesting that the Walker circulation may be different in the SP-CCSM.

2.2 Correlation between the Indian summer monsoon and the following winter

In the observations, the Indian summer monsoon shows a maximum correlation with the SST anomalies in the eastern Pacific when the monsoon leads by a season (S10, S14, S15). Figure S2 shows the correlation between the Indian summer monsoon rainfall and the subsequent winter SST in the model simulations and observations. The SP-CCSM is able to capture the observed relationship well. Recent studies (S15, S16) show that Indian summer monsoon consists of two non-linear oscillations and two seasonally persistent large-scale patterns. One of the persistent patterns is related to ENSO. We have already noted that SP-CCSM captures some of the observed variability of ENSO (main text) and ENSO-monsoon teleconnection is another example of the impact of this improvement.

2.3 Multi-channel Single Spectra Analysis Method

To extract distinct space-time patterns of convection over the Indo-Pacific region, multi-channel singular spectrum analysis (MSSA) was applied to daily OLR anomalies. This data-adaptive method is an extension of empirical orthogonal function (EOF) analysis to delay-coordinate space and extracts oscillatory modes, persisting modes and trends present in the original data (S17). The application of MSSA to data at L grid points (or channels) specified at N discrete times using lags from 0 to $M-1$ yields $LM$ eigenvalues and $LM$ eigenvectors by diagonalizing the lag-covariance matrix of the
multi-channel time series. The eigenvectors are the space-time empirical orthogonal function (ST-EOF), each consisting of M sequence of maps. Each corresponding space-time principal component (ST-PC) is of time length $N' = N - M + 1$, and the eigenvalues describe the variance explained. The original time series is expressed as a sum of reconstructed components (RC) constructed from the corresponding ST-EOF and ST-PC. The RC corresponding to a particular eigenmode is a time series of maps on the same grid as the original field with its time length and sequence exactly as those of the original time series.

The MJO modes in the observation and model simulations were obtained by applying MSSA to daily OLR anomalies in the Indo-Pacific region (40°E-70°W, 35°S-35°N) for all days of the entire period of the respective data set and using a lag window of length 120 days at one day interval. The procedure followed is similar to that used in a recent study of the intraseasonal oscillations of the Indian monsoon (S16).

**References**


Table S1 Atmospheric components in the Community Climate System Model (CCSM) and super-parameterized CCSM (SP-CCSM).

<table>
<thead>
<tr>
<th>Model</th>
<th>CCSM</th>
<th>SP-CCSM</th>
</tr>
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<tbody>
<tr>
<td>Horizontal resolution</td>
<td>T42 (~300 km)</td>
<td>T42 (~300 km)</td>
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<tr>
<td></td>
<td>SLD*</td>
<td>SLD</td>
</tr>
<tr>
<td>Vertical levels</td>
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<td>Deep convection</td>
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<td>CRM (S4)</td>
</tr>
<tr>
<td>Shallow convection</td>
<td>Hack (S19)</td>
<td>CRM(S4)</td>
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* Semi-Lagrangian dynamical core
Figure S1 Regression map of sea surface temperature anomalies on the Nino-3.4 index (sea surface temperature anomaly averaged over 5°S-5°N, 170°W-120°W). (A) HadSST observations (1959-2002), (B) SP-CCSM, and (C) CCSM. Shading denotes regions where the regression coefficient is significant at the 95% level.
Figure S2 Correlation between the Indian monsoon rainfall index (June–September anomalies area averaged over India) and the following winter (December–February) SST anomalies. (A) The observed correlation between the IMD rainfall and HadSST (1951-2004). (B) SP-CCSM simulation. (C) CCSM simulation. Contour intervals encompass regions where the correlation coefficient is significant at the 95% level.