Southeast Pacific Stratocumulus in the Community Atmosphere Model

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(Manuscript received 8 September 2011, in final form 21 March 2012)

ABSTRACT

Forecasts of October 2006 are used to investigate southeast Pacific stratocumulus in the Community Atmosphere Model, versions 4 and 5 (CAM4 and CAM5). Both models quickly develop biases similar to their climatic biases, suggesting that parameterized physics are the root of the climate errors. An extensive cloud deck is produced in CAM4, but the cloud structure is unrealistic because the boundary layer is too shallow and moist. The boundary layer structure is improved in CAM5, but during the daytime the boundary layer decouples from the cloud layer, causing the cloud layer to break up and transition toward a more trade wind cumulus structure in the afternoon. The cloud liquid water budget shows how different parameterizations contribute to maintaining these different expressions of stratocumulus. Sensitivity experiments help elucidate the origins of the errors. The importance of the diurnal cycle of these clouds for climate simulations is emphasized.

1. Introduction

On synoptic spatial scales and averaged over seasons or longer, the subtropical stratocumulus decks are characterized by optically thick clouds capping a well-mixed boundary layer. These characteristics imply a strong albedo effect, and it follows that the stratocumulus decks exert a cooling influence on the climate system (Hartmann and Short 1980). The subtropical stratocumulus are found over the cool sea surface temperatures of eastern boundary currents, and the clouds break up and transition toward cumulus-topped boundary layers over warmer water (Albrecht et al. 1995). Therefore, a possibility exists for a positive feedback between the surface temperature and cloud cover, making representing stratocumulus important for coupled modeling (Duynkerke and Teixeira 2001). An underestimate in cloud cover could allow the sea surface to warm, further reducing cloudiness (e.g., Ma et al. 1996). Stratocumulus also undergo a pronounced diurnal cycle, and because their climatic impact is manifest mostly through the shortwave radiation budget, representing this diurnal variation is critical for capturing cloud effects on climate (see Rozendaal et al. 1995; Turton and Nicholls 1987).

Faithfully capturing subtropical stratocumulus—and other boundary layer clouds—in climate models is notoriously difficult and has been repeatedly pointed out as the largest source of uncertainty in projections of future climate (e.g., Randall et al. 2007). The prevailing difficulty is that climate models resolve scales much larger than individual clouds, necessitating parameterization. Parameterization methods are disparate, ranging from highly empirical to sophisticated cloud physics models. Evaluating these parameterizations has been hampered by incomplete observations, inappropriate comparisons, and the numerous nonlinear interactions connecting the clouds to other aspects of the simulation.

In this work, we evaluate subtropical stratocumulus in the Community Atmosphere Model versions 4 and 5 (CAM4 and CAM5). Our goal is to understand the fidelity of stratocumulus in these models compared with observations and expectations. To focus on the parameterized physics, a short-term, global forecast approach is used and we restrict our analysis to the southeast Pacific (section 2). Both models maintain stratocumulus, but show biases compared with observations. Sections 3 and 4 describe the simulated clouds, including decomposing the sources and sinks of cloud water by the parameterized processes. Model errors are discussed in section 5, including the role of the diurnal cycle in long-term climate
biases. Both models’ parameterizations contain loosely constrained adjustable constants that introduce a layer of empiricism to the model physics that may influence the resulting clouds and climate. Results of sensitivity experiments that alter two of these constants are presented in section 5. The changes impact the cloud fraction and liquid water path, but have little consequence for the processes controlling the stratocumulus. A summary and suggestions for future study are provided in section 6.

2. Methods and models

Stratocumulus are among the most intensely investigated cloud types, and their characteristics and environment are well described (e.g., Stevens 2005). Some aspects of stratocumulus are less well understood, such as the impacts of aerosol and mesoscale organization (e.g., Stevens and Feingold 2009). We aim to evaluate whether CAM4 and CAM5 are able to meet conceptual expectations of stratocumulus properties. To do so, we integrate the models in a forecast mode, as described next. Then we provide an overview of the models and our strategy to focus on only points that represent stratocumulus conditions.

a. Cloud-Associated Parameterization Testbed

In the Cloud-Associated Parameterization Testbed (CAPT; aka Transpose Atmospheric Model Intercomparison Project (AMIP)) framework, a climate model is initialized from a realistic atmospheric state, for example, from operational numerical weather prediction analyses, over the global domain, and integrated to produce a forecast. This short-term forecast mode is useful for evaluating parameterized physics (e.g., Phillips et al. 2004; Hannay et al. 2009). Advantages of the forecast approach include 1) avoiding some ambiguities of single-column modeling by retaining interactions between dynamics and physics, 2) being simpler and less computationally expensive to implement than full data assimilation, and 3) allowing direct comparison with observations.

In this study, forecasts are produced for each day of October 2006, with instantaneous output saved every 3 h over the southeast Pacific. This period is chosen for comparison with the Preliminary Variability of the American Monsoon System (VAMOS) Ocean–Cloud–Land–Atmosphere Study (VOCALS) Model Assessment (PreVOCA) Study (Wyant et al. 2010), which included development versions of CAM. The choice of year does not strongly impact conclusions regarding the processes affecting clouds in the region (the example of 2001 is briefly discussed in section 5). The models are initialized with ECMWF analyses of wind \( (u, v) \), surface pressure \( p_{sfc} \), temperature \( T \), and specific humidity \( q \) that are interpolated to the CAM grid. The analyses are combined with the model’s other prognostic variables (e.g., condensate and aerosol amounts or land surface properties) from a previous integration to start a spinup cycle in which the model is integrated forward for 6 h. This spinup cycle allows model variables (e.g., cloud condensate) to adjust to the analysis atmospheric state; an updated analysis state \( (u, v, p_{sfc}, T, q) \) then replaces the model-derived values to start the next 6-h spinup cycle. Successive spinup cycles allow slower parts of the climate system (e.g., the land surface) to adjust to the analysis. For the results presented here the spinup period begins from a climate run forced by prescribed SST a week prior to the forecasts. Because our focus is on the open ocean of the southeast Pacific and SST is specified, a prolonged spinup period is not necessary, though a longer spinup may be required when the land surface is crucial to the forecast evolution (Boyle et al. 2005). Forecasts are 5-day integrations started from the spinup states at 0000 UTC. Previous efforts have concluded that the starting time does not strongly impact the results (Hannay et al. 2009).

An example of the resulting forecasts is shown (Fig. 1), in which the surface pressure at the location of the Woods Hole Oceanographic Institution (WHOI) Improved Meteorological Packages (IMET) buoy (http://uop.whoi.edu/projects/stratus/stratus.html) is shown for each CAM4 forecast. Some forecast skill is suggested by the similarity at overlapped times, though the sensitivity of the solution to changing initial conditions is apparent. These time series also serve as an illustration of the relatively steady conditions in the southeast Pacific during October 2006. The dominant signal apparent in the forecasts is the semidiurnal cycle. There is no indication of spurious noise, and the forecasts appear well initialized. For comparison, the 3-hourly surface pressure from a “climate mode” integration of CAM4 is also included (Fig. 1); the free-running integration shows slightly more synoptic variability than individual forecasts, but also suggests a quiescent environment throughout the month.

Figure 2 compares estimates of the low-cloud fraction and liquid water path (LWP) in the southeast Pacific from satellites and the models. Both models underestimate low-cloud fraction compared to the Multiangle Imaging Spectroradiometer (MISR; e.g., Marchand et al. 2010), in both October 2006 and the long-term average. There is a strong association between cloud fraction and LWP in the models, but this is less apparent in the comparison of cloud fraction from MISR and LWP from the Moderate Resolution Imaging Spectrometer (MODIS; e.g., Pincus et al. 2012). We note that
these comparisons should be considered qualitatively; more careful comparisons can be made with the use of satellite emulation software (see e.g., Kay et al. 2012). Averaging the second day of the October 2006 forecasts shows both models produce spatial distributions of cloud that are similar to the long-term model climatologies. Such similarity is evidence that long-term model errors are connected to the fast processes represented by the parameterized physics.

b. CAM4

Version 4 of CAM, described by Neale et al. (2010a), is similar to version 3 (Collins et al. 2004). There are primarily three differences between the versions. First, the default dynamical core has been changed from the Eulerian spectral transform core to the finite-volume core. The vertical grid used by the parameterized physics is unchanged, however, and the change of dynamical core seems to be unimportant for the issues considered here when equivalent resolutions are applied. We use the 1.9° latitude × 2.5° longitude horizontal grid with 26 vertical levels. Second, the deep convection parameterization has been modified in two ways: CAM4 uses a dilute parcel method (Neale et al. 2008) and includes convective momentum transport (Richter and Rasch 2008). Third is the inclusion of an ad hoc reduction of low-cloud fraction in dry conditions (called “freeze-dry”), which primarily occurs in polar regions (Vavrus and Waliser 2008).

Neither the deep convection scheme nor the freeze-dry cloud reduction play a role in subtropical stratocumulus, but several aspects of the remaining parameterizations are relevant for the present discussion. The boundary layer scheme is a nonlocal K-profile scheme described by Holtslag and Boville (1993). This scheme is conceptually similar to local K-profile schemes, but is reformulated to include transport of heat, moisture, and scalars from nonlocal dry convection. It neither includes a nonlocal term for momentum, nor a representation of turbulence generated by cloud-top radiative cooling, which is a primary energy source for stratocumulus-topped boundary layers. Effects of condensation are also excluded from the scheme, making it effectively a dry PBL parameterization. The shallow convection in CAM4 is nominally handled by the adjustment scheme of Hack (1994), which works on triplets of model levels and introduces large sensitivity to vertical resolution in CAM3 and CAM4, as demonstrated by Williamson (2012). This scheme also comes into play in stratocumulus, as discussed below and by Hannay et al. (2009). The cloud liquid (and ice) water is predicted in CAM4, but cloud fraction is diagnosed; inconsistencies between the predicted condensate and diagnosed fraction can
produce “empty clouds” with large fraction and little water. The cloud fraction is diagnosed primarily through a function of relative humidity, but also through shallow and deep convection, an empirical relationship between stratus fraction and lower-tropospheric stability, and the aforementioned freeze-dry reduction of low cloud. Most phase changes of water are controlled by the stratiform cloud physics described by Rasch and Kristjánsson (1998) and Zhang et al. (2003), which represent numerous macrophysical and microphysical cloud processes.

The formulation of CAM4 makes it difficult for stratocumulus to be realistically represented, as described below in detail. Indeed, these difficulties are among the motivations for changes between CAM4 and CAM5, but understanding the representation of stratocumulus in CAM4 is necessary because of its widespread use, both as an atmospheric general circulation model and also as a component in coupled climate models. This includes configurations of the Community Earth System Model (CESM) that are included in model comparison projects such as CMIP5. Versions of CAM3 and CAM4 are also the basis of the atmospheric components of other coupled modeling frameworks, such as the Beijing Climate Center model (Wu et al. 2010) and the Norwegian Earth System Model (NorESM1; e.g., Zhang et al. 2012), so results from analysis of CAM4 can be extended directly to other models.

c. CAM5

Version 5 of CAM, described by Neale et al. (2010b), shares the finite-volume dynamical core and horizontal resolution of CAM4. The vertical grid is altered: CAM5 has 30 levels rather than CAM4’s 26. The additional levels are in the lower troposphere and almost double the resolution below 700 hPa. These levels improve the performance of the new boundary layer and shallow convection parameterizations in CAM5. A 30-level version of CAM4 is not supported because of biases that arise from the shallow convection formulation with increased vertical resolution in the boundary layer (Williamson...
The CAM5 physics parameterizations are almost entirely different from CAM4. While the deep convection scheme remains the same as for CAM4, the shallow convection and PBL schemes have been replaced with those of Bretherton and Park (2009) and Park and Bretherton (2009). In CAM5 the turbulence kinetic energy is diagnosed by the PBL scheme, which uses it to determine turbulent diffusivities. Entrainment rates are represented explicitly, and shallow convection and PBL turbulence are linked through a cloud-base mass flux. The bulk microphysics of CAM4 has been replaced with a two-moment scheme (Morrison and Gettelman 2008), and updated cloud macrophysics—controlling conversions between condensate and water vapor at the grid scale—improves consistency between cloud water and fraction (S. Park et al. 2012, personal communication). Radiative transfer is also different between the models, but the differences between the parameterizations [Community Atmosphere Model Radiative Transfer (CAMRT) and the Rapid Radiative Transfer Model for GCMs (RRTMG)] have a relatively small impact on tropical boundary layer clouds. Interactive aerosol is introduced in CAM5, with dust and sea salt surface emission predicted and other emission rates prescribed; we touch on the potential role of aerosol later. The aerosol distribution is spun up in the same way as the land model. These major changes to the parameterized physics are discussed in more detail by Neale et al. (2010b).

d. Sampling stratocumulus

The structure and character of clouds in the southeast Pacific varies from thin stratus to broken cumulus, and cloud fraction typically decreases with distance from the coast (e.g., Bretherton et al. 2010). This inhomogeneity necessitates a sampling strategy to avoid conflating these different cloud types and possibly mixing different types of errors, which could change the interpretation. It has been typical to define a geographical region to represent the stratocumulus deck (e.g., Klein and Hartmann 1993), but this method is inadequate for process-level studies because of the variation in cloud and boundary layer structure. Some studies of the southeast Pacific focus on a small geographic area and comparison with observations [especially at the buoy at 20°S, 275°E (e.g., Hannay et al. 2009)]. Others have used the transect along 20°S to show gradients in cloud structure (Wyant et al. 2010; Bretherton et al. 2010).

To understand the processes at work in the CAM4 and CAM5 forecasts, we seek a method that differentiates cloud types in the forecasts while maximizing the retained data for robust statistics. A potential complication is that we are interested in the temporal evolution of the forecasts, so we want to preserve forecasts as time series. Our approach is to classify each 5-day forecast at each grid point in the domain, and sample based on that classification. Figure 3 shows the vertical structure of gridbox mean liquid water constructed in bins of lower-tropospheric stability (LTS = \( \theta_{700} - \theta_{sl} \)), using a 40° × 40° domain covering the southeast Pacific (0°–40°S, 250°–290°E). The LTS value used is the 5-day average for each forecast at each grid point for the models, and for comparison 3-day averages covering October 2006 from

**Fig. 3.** Average liquid water in bins of 5-day mean LTS for the (top) CAM4 and (middle) CAM5 forecasts and (bottom) ERA-Interim. Bins run from 12 to 30 K by 0.5 K. Markers and text at the top show the data distribution by percentile; labels on the horizontal axis show corresponding values of LTS. The vertical axes show the model levels and their nominal pressure value (and ERA-Interim standard pressure levels).
the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim). The figure suggests that mean LTS distinguishes cloud types in this region (cf. Medeiros and Stevens 2011); in both models, liquid water is found at higher levels with decreasing LTS, suggesting a weaker inversion and deeper clouds in less stable conditions. The ERA-Interim sample is qualitatively similar, though the models are biased toward less stable conditions compared to ERA-Interim; the models show larger values of liquid water amount, but note that the liquid water path is similar between CAM4 and ERA-Interim.

To focus on stratocumulus clouds, composite forecasts are constructed by averaging the 90th–95th percentiles in each model’s mean LTS distribution (labeled in Fig. 3). As such, the composites represent conditional averages over space and time. Although the 90th and 95th percentile values differ between the models, the sample size (6% of data) is the same. Inspecting the location and frequency of this sample (Fig. 4) shows similar patterns in the models, and is consistent with ERA-Interim and expectations of the stratocumulus area (Zuidema et al. 2009); the WHOI buoy location, marked in Fig. 4, is also well sampled by this strategy. Using the 95th–99th percentiles (not shown) highlights a smaller area, which is roughly outlined in the figure by the LTS isolines ≈24 K for CAM4 and ≈22 K for CAM5. The reason for using the larger area is to avoid, as much as possible, contamination of the sample by near-coastal points that are strongly influenced by continental processes. The practical impact of this choice is minimal for our analysis.

3. Southeast Pacific stratocumulus in CAM4

Examining the CAM4 forecasts shows the development and maintenance of stratocumulus in the southeast Pacific. The large-scale circulation evolves slowly away from the realistic initial condition, and the circulation over the southeast Pacific is generally steady and comparable to the analysis. Thus, forecast errors are dominated by the parameterized physics. Figure 5 shows the average thermodynamic structure composited from the 90th–95th percentiles of mean LTS, which we loosely define as the stratocumulus deck. Each profile shows the average over a forecast day (ending on the indicated day), so each curve represents a month-long average profile. The evolution of the profiles from day to day expresses the model adjusting away from the initial conditions. During the forecast, the PBL shallows and moistens, and is shallower and less well mixed than in situ observations (Bigorre et al. 2007; dashed profiles in Fig. 5). The liquid water vertical structure evolves dramatically as cloud base descends over 2–4 days. Spatially, the model forms an extensive cloud deck (e.g., Fig. 2) that
slightly expands during the forecast. The temperature and humidity structures also evolve with forecast time, slowly warming and moistening the lowest model levels. The CAM4 results are similar to forecasts and climate biases in CAM3 and a preliminary version of CAM5 (Hannay et al. 2009).

Terms of the surface energy budget along with cloud and precipitation are shown in Fig. 6. Dashed horizontal lines show mean values obtained during the October 2006 maintenance cruise to the WHOI buoy (precipitation statistics printed). Figure 6 suggests a stratocumulus region with extensive low-level, mostly nonprecipitating clouds; the surface budget shows strong latent heat flux and downward longwave radiation. A pronounced diurnal cycle also appears, with maximum LWP near dawn and minimum in the afternoon.

The time series of Fig. 6 appear to evolve through the forecast time, but much of this evolution derives from the fairly large variance associated with the changing weather conditions (even within the 90th–95th percentile of LTS) and the changing locations of the sample. This variance is shown in the figure by vertical bars that denote plus/minus one standard deviation of the 3-hourly snapshots that make up the average each forecast time. The variance in the ship-based observations can also be large, as shown by the large standard deviation of precipitation. The ship-based observations can also differ substantially from other observational estimates, for example, LWP and precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM) are also shown in Fig. 6. The TRMM values are discussed in more detail in section 4, but we note here the average precipitation is 0.125 mm day\(^{-1}\), which is more in line with the CAM4 value than the 2006 cruise average. The average LWP during the cruise (107 g m\(^{-2}\)) is also large compared to regional averages for the month from both TRMM (77 g m\(^{-2}\)) and MODIS (Fig. 2; 82 g m\(^{-2}\)), while the ship-based cloud cover (70%) is somewhat less than the MISR low-cloud fraction for the month (83%). It is useful to bear in mind the spread of observational estimates as well as the variance of the sampled model data.

Even with the large variance in many of the model fields, there is a distinct and robust evolution of the cloud fraction and liquid water in the CAM4 forecasts. This evolution is seen in the vertical structure of the clouds, shown by the composite forecast in Fig. 7. A layer of liquid condensate forms during the night, usually centered on the third model level (\(\approx 929 \text{ hPa}\)). Cloud top remains at the interface between the third and fourth (\(\approx 867 \text{ hPa}\)) levels. Both cloud fraction and liquid water amount decrease during the daytime (sunlit hours shown by gray bars at top of the figure). The cloud fraction (contour lines in Fig. 7) suggests a higher cloud top; this illustrates the inconsistency mentioned earlier between the model’s diagnostic cloud fraction parameterization and the prognostic liquid water content. Cloud base is near the second model level (\(\approx 970 \text{ hPa}\)) during the first hours of the forecasts; this value is lower than observations would suggest, but is not surprising given the coarse vertical resolution of CAM4. Cloud-base descends over the course of the first few days, and by about day 3 the cloud base has reached the lowest model level. This descent occurs for most forecasts, though the timing of the descent and the correspondence between cloud fraction and liquid condensate varies among forecasts. The mean behavior describes the stratocumulus deck abutting the sea surface and extending to \(\approx 830 \text{ hPa}\) (the interface between levels), as has been shown in the model climatology (Hannay et al. 2009; Medeiros and Stevens 2011).
To better understand the adjustment from the initial state and the establishment and maintenance of the stratocumulus, Fig. 8 shows the composite forecast of the cloud liquid water budget terms, expressed as

\[ \frac{\partial q}{\partial t} = \mathbf{U} \cdot \nabla q + T + C_T + C_D + E + P + S. \]  

(1)

Terms on the right-hand side represent the tendencies from advection \( \mathbf{U} \cdot \nabla q \), PBL turbulence \( T \), vertical transport by convection \( C_T \), convective detrainment \( C_D \), large-scale cloud physics (evaporation/condensation) \( E \), precipitation \( P \), and sedimentation of cloud droplets \( S \). Advection of cloud liquid is a small term, acting as a sink of liquid water from the cloud layer as the large-scale flow transports cloud water downstream toward the tropics; the magnitude is approximately proportional to the liquid water content, and it is excluded from Fig. 8, leaving six tendencies that are distributed in an attempt to group sinks of cloud water from the cloud layer (top panel) and sources of cloud water to the cloud layer (bottom panel). The left side of Eq. (1) is the total tendency, which is relatively small (comparable to the first contour of the individual terms) and is shown by color shading in the figure.

As in the previous figures, the diurnal cycle of cloud is prominent in Fig. 8. During the nighttime cloud forms, and during the daytime it reduces. The contributing factors to this cycle are shown by the tendencies in contour lines: sources are solid contours and sinks are dashed. Adjustment away from the initial conditions appears in the liquid budget terms just as it does in the composite cloud and liquid water forecasts; this is seen in Fig. 8 as a descent of the primary sources and sinks of cloud water over the first 2 days or so of the forecasts. The adjustment appears generally similar to the later steady state, except that there is relatively strong conversion to precipitation in the cloud layer (red contours, lower panel) contributing to the afternoon cloud dissipation the first 2 days.

Even CAM4's relatively simple parameterizations show the complexity of representing boundary layer clouds. The cloud deck forms through large-scale condensation during the nighttime growth of the cloud layer, complemented by detrainment of liquid water by shallow convection. Deep convection is rarely active in the stratocumulus, unlike the idealized experiment of Zhang and Bretherton (2008). Detrainment from shallow convection becomes the largest source of liquid water to the cloud layer around midday, and remains the primary source of liquid throughout the afternoon. In the afternoon, however, large-scale evaporation within the cloud layer drives the total tendency to be negative, and the cloud layer partially dissipates, as was seen in Fig. 7. Partly offsetting the condensation and detrainment sources are cloud layer sinks of liquid water by turbulent mixing (i.e., vertical diffusion), convective transport, and droplet sedimentation. In the first 2 days, these sinks are collocated at the heart of the cloud layer, but in the last 2 days sedimentation occurs in the lower half while mixing removes liquid from the upper half of the cloud layer.

At the lowest levels, the processes that remove liquid from the cloud layer become sources of liquid. The turbulent sink within the cloud layer mixes down liquid water and becomes a large source of water for the lowest levels; condensation processes are not included in the turbulent vertical diffusion, so this source is purely transport. Shallow convection often acts in concert with the turbulent mixing, transporting liquid water downward.
from the cloud layer and into the lowest levels. Sedimentation delivers liquid from the cloud layer to the lower layers as well. These low-level sources are mostly compensated by large-scale evaporation, but, as illustrated by Fig. 7, the evaporation is unable to eliminate all the liquid water, and cloud base is maintained basically in the lowest model level. Condensation in the lowest model levels only occurs during nighttime after the PBL has become very shallow. This low cloud base contrasts with the clear subcloud layer that is observed in the atmosphere below subtropical stratocumulus decks.

Figure 8 shows little activity above the fourth model level (~867 hPa) because there is little condensate above the cloud layer. The mean subsidence brings warm, dry air to these levels, keeping the relative humidity low (Fig. 5). In the latter half of the forecasts, daytime convection impinges into this dry region, and detrained liquid water is quickly evaporated.

Even though the large-scale circulation remains fairly realistic, the forecasts show the cloud structure tending toward the preferred model state with a PBL that is too shallow. Nevertheless, there are some realistic aspects of southeast Pacific stratocumulus in CAM4. The cloud fraction and cloud liquid maximize during nighttime and show a thinner, drier cloud layer in late afternoon, which is consistent with the observed diurnal behavior (see also Brunke et al. 2010). The terms of the surface energy budget are not out of line with observed values, and there is little precipitation from stratocumulus. The processes maintaining the stratocumulus and the diurnal variation are liquid water formation by large-scale condensation during the night, supplemented and then surpassed during the daytime by detrainment from shallow convection, which is overwhelmed in the afternoon by large-scale evaporation. The deviation from theory and observations seems to arise from the turbulence being driven only from surface fluxes, rather than by cloud-top radiative cooling; without this additional energy source, the PBL becomes too shallow and the clouds too low (see also Barrett et al. 2009).

4. Southeast Pacific stratocumulus in CAM5

The CAM5 forecasts share a number of features with those of CAM4, including the relatively steady circulation over the forecast periods (as in Fig. 6 for CAM4) and a strong diurnal cycle. The details of the lower troposphere, however, differ in several aspects important for the stratocumulus. One of these is that the CAM5 is slightly less stable in the stratocumulus sample, so the values of mean LTS that are composited here are about 1 K lower in the CAM5 forecasts than CAM4 (discussed in section 2d). Based on a number of alternate sampling strategies and the agreement in location between the
samples (Fig. 4), this mean LTS discrepancy does not appear to cause other differences between the models. To begin to see these differences, we compare the composite stratocumulus profiles from CAM5 (Fig. 9) with those discussed earlier from CAM4 (Fig. 5). The thermodynamic structure in CAM5 shows a deeper and more well-mixed PBL, and the deeper PBL helps mitigate the moist bias relative to the ship-based observations (though a small bias remains). The PBL slightly deepens during the CAM5 forecasts, differing from the collapse seen in previous model versions (e.g., Hannay et al. 2009; Wyant et al. 2010) and in CAM4 (Fig. 5). Consequently, the inversion layer is better captured by CAM5. The difference in the cloud structure is striking: CAM5 maintains a clear subcloud layer and a cloud layer from about 930 to about 860 hPa with little overlying cloud, consistent with observations of stratocumulus (e.g., Bretherton et al. 2010). The maximum cloud water is around 0.06 g kg$^{-1}$, suggesting an in-cloud value of about 0.15 g kg$^{-1}$ (because the cloud fraction is about 40% in that layer; see Fig. 10). Observations suggest much larger in-cloud values, sometimes >0.5 g kg$^{-1}$ in stratocumulus (Wood and Field 2000); this shows that despite the improved geometry of the CAM5 cloud structure, there remain significant challenges in successfully representing boundary layer clouds. By contrast, the inconsistency between CAM4’s cloud fraction and liquid condensate leads to instantaneous in-cloud liquid water content that is often much larger than can be supported by observations.

Figure 10 demonstrates some other differences in the CAM5 forecasts compared to CAM4 (Fig. 6). The surface energy budget differs, with CAM5 having larger latent heat flux and smaller net longwave flux at the surface than CAM4. Compared to the ship-based observations, this suggests that CAM5 improves the longwave flux, but might be somewhat worse in latent heat flux. The CAM5 latent heat flux is larger than that for CAM4 because the boundary layer is deeper and drier in CAM5; the near-surface relative humidity differs by about 5%, increasing evaporation from the surface. Both models have a moist bias compared to the observations, but CAM5 overestimates the latent heat flux. Examination of the contributions to the latent heat flux $LHF = L_v \rho |\mathbf{U}| C_E (q_0 - q_s)$, where the right side is the product of the latent heat of vaporization $L_v$, air density $\rho$, wind speed $|\mathbf{U}|$, exchange coefficient $C_E$, and the difference of the near-surface specific humidity $q_0$ and the saturation specific humidity at the surface $q_s$ suggests that there is a difference in the exchange coefficients of the CAM formulation and that of the observations [which use the Coupled Ocean–Atmosphere Response Experiment (COARE) algorithm; Fairall et al. (2003)]. The difference between the models in the net longwave flux at the surface is primarily due to the difference in the predawn minimum because CAM4 has a small diurnal cycle compared to CAM5. Because the surface temperature is similar between the stratocumulus samples in the models, the difference must be associated with downwelling longwave radiation. About 10 W m$^{-2}$ of difference is in the clear-sky portion of the radiation, which is likely an expression of the slightly larger column-integrated water vapor in the CAM5 forecasts. The difference in downwelling longwave radiation is largest when cloud fraction maximizes, but the difference in maximum cloud fraction between the models is small. Therefore, the remaining difference in net longwave radiation is associated with
differing cloud radiative properties, probably tied to the microphysics formulations and including aerosol effects in CAM5. The contribution to these differences by the different radiative transfer models—as opposed to differences in the composition of the atmosphere—is unclear.

Figures 6 and 10 also show differences in LWP, low-cloud fraction, and precipitation. While CAM4 has averages of 60 g m\(^{-2}\), 72%, and 0.16 mm day\(^{-1}\), CAM5 has smaller averages of 48 g m\(^{-2}\), 63%, and 0.12 mm day\(^{-1}\). The diurnal variation also differs: CAM4 has peak amplitude that is 46% of the mean LWP and only 3% of the mean low-cloud fraction, but CAM5 has diurnal amplitudes of 57% of the mean LWP and 20% of its mean low-cloud fraction. The daily variation in precipitation differs mostly in the origin of the precipitation, with CAM4 raining more and mostly from stratiform processes, while CAM5’s rain is dominated by shallow convective precipitation. The ship-based observations used for Figs. 6 and 10 do not adequately sample the diurnal cycle, so only the mean values are plotted (horizontal, dashed lines), and these values can differ markedly from other observational estimates as previously mentioned. To examine the diurnal cycle, we have included the composite diurnal cycle from TRMM retrievals for LWP and precipitation covering October 2006 in the region (10\(^\circ\)–30\(^\circ\)S, 270\(^\circ\)–290\(^\circ\)E). The approach is similar to that of Wood et al. (2002), though we construct the diurnal cycle by averaging observations for each hour and low-pass filtering to retain the diurnal and semidiurnal harmonics of the composite series. The mean LWP is 77 g m\(^{-2}\) and the mean precipitation is 0.13 mm day\(^{-1}\), and the normalized peak amplitude of LWP is 44% of the mean value. The mean LWP agrees well with Wood et al. (2002; 74 g m\(^{-2}\)), but the diurnal variation is much larger in the October 2006 data than the longer record of Wood et al. (2002; they report around 30%), and the phase is earlier (with a peak of around 0300 compared with about 0600 LT). The smaller sample size of the October 2006 data probably explains most of the discrepancy, though some of the differences could be real. Based on this comparison, and keeping in mind the mean values from MODIS and the ship-based observations, it appears that both models exhibit a low bias in mean LWP, which is partly related to the overestimate of diurnal variation (especially for CAM5). Wood et al. (2002) also report that the normalized amplitude of the diurnal cycle of low-cloud fraction is about half of that for LWP. This suggests CAM4 substantially underestimates cloud variation and CAM5 probably overestimates the daily variability.

The smaller cloud fraction and LWP in the CAM5 forecasts compared to CAM4 and observations are also
apparent in the spatial distribution (e.g., Fig. 2) and the vertical structure of the liquid water and cloud fraction (Fig. 11). In comparison to CAM4 (Fig. 7), the cloud layer is centered higher, cloud base is more clearly defined, cloud top shows more variation diurnally, and the cloud fraction and liquid water show much better correspondence with each other. The daytime breakup of the cloud deck is more pronounced, and (after day 1) the maximum cloud top reaches to nearly 850 hPa, coincident with the maximum LWP around dawn, followed by cloud thinning during the day, with minimum cloud cover in the afternoon. Observations support some daytime cloud thinning (e.g., Wood et al. 2002), but less than CAM5 produces. The diurnal variation of cloud fraction in CAM5 with minimum cloud cover in the afternoon is suggestive of the subcloud and cloud layers becoming decoupled during the daytime, and the afternoon structure becoming more like trade wind cumulus than homogeneous stratocumulus. The highest cloud tops in the CAM5 forecasts occur in the early morning, however, not during the afternoon when shallow convection becomes the primary driver of cloud formation. Daytime PBL decoupling is commonly observed in the southeast Pacific stratocumulus (cf. Jones et al. 2011), though the near disappearance of cloud appears exaggerated in CAM5.

Figure 12 shows the most important terms of the CAM5 version of Eq. (1). Because of differences in the parameterizations, the definition of the terms are slightly different for CAM5: sedimentation of cloud droplets is incorporated into the microphysics term (top panel, blue contours), and grid-scale condensation and evaporation are contained by a revised macrophysics package (bottom panel, black contours). In general, cloud microphysics control conversions between cloud droplets and precipitation while cloud macrophysics control the grid-scale conversion between water vapor and cloud condensate. As in CAM4, the largest balance is between turbulent mixing (vertical diffusion) and large-scale evaporation/condensation (i.e., macrophysics). Microphysical processes are an important sink of cloud water from the cloud layer; sedimentation of cloud droplets is typically the largest component, followed by accretion and autoconversion. Mixing by convection plays a smaller role. Detrainment from shallow convection is a source of moisture to the upper half of the cloud layer and levels above the average cloud top in the daytime. As the detrained liquid above cloud-top evaporates, levels above the stratocumulus are moistened, which can help maintain the cloud deck in the afternoon (by increasing the moisture content of entrained air). Below cloud base, the only substantial sink of liquid is through evaporation, which maximizes during the day. Thus, the CAM5 stratocumulus appears to undergo a diurnal cycle in which the nighttime sees an increasing cloud fraction mostly by condensation, followed by decreasing cloud fraction during the daytime as the PBL becomes decoupled, shallow convective detrainment supplying most water to the cloud layer in the afternoon, and transitioning back to
a well-mixed stratocumulus layer at nighttime as cloud-top radiative cooling once again dominates the turbulent mixing.

It is useful to note that the turbulent transport of cloud water from the cloud layer to the subcloud layer is a consequence of the model formulation. The moist turbulence (i.e., PBL) parameterization vertically transports each water constituent individually (i.e., $q$, $q_v$, and $q_i$) based on the calculated eddy diffusivity and the vertical gradient of the transported quantity. This means these quantities are turbulently transported like conservative tracers, which explains the vertical diffusion pattern in Fig. 12. This approach is consistent with other transport terms that treat the prognostic condensate like conserved quantities. The cloud macrophysics of CAM5 has been revised from CAM4 to be consistent with moisture transport [see S. Park et al. (2012, personal communication), for a detailed account of the revised macrophysics of CAM5]. The model’s parameterizations are time split, so each parameterization acts on the most recent modeled atmospheric state to produce a new, updated state. That updated state is passed into the next parameterization. This artificial separation of processes within the model (e.g., turbulent transport happens separately from condensation–evaporation), combined with the long model time step (1800 s) and the associated time truncation errors, means interstitial tendencies may not be analogous to observations. One example is the turbulent transport of liquid water all the way to the lowest model level, which is unrealistic. The model physics as a whole, however, conserves water and is internally consistent enough to produce a realistic atmospheric state at the end of each time step.

5. Sensitivity experiments and discussion

Short-term forecasts provide perspective on the southeast Pacific stratocumulus deck in CAM4 and CAM5 before long-term climate biases can form. While the large-scale circulation remains realistic throughout the forecasts, the fast processes associated with the boundary layer and clouds adjust toward a model-preferred state that is well correlated with the October climatology of both models. These fast processes slowly alter the thermodynamic state toward the model climatology as well, though the temperature and humidity, as examples, do not reach their climatological values within the 5-day forecast period. The models have been developed to capture aspects of the observed climate, yet the discrepancy in cloud structure shows that such agreement does not guarantee realistic regional features or physical phenomena. This section explores the causes of the low cloud base in CAM4 and the daytime cloud dissipation in CAM5, both of which could negatively impact climate simulations and projections. We test whether these aspects of the forecasts can be changed by choices in the parameterized physics, or whether the model formulation favors these characteristics.

Figures 5 and 7 show the rapid descent of cloud base in CAM4 over the course of the forecasts. Because the cloud fraction and condensation both depend on relative humidity, one hypothesis for this descent is that the analysis thermodynamic structure provides a relative humidity profile that when input to the parameterized physics leads to an elevated cloud layer (as in Fig. 7), but the layer descends as the model’s PBL shallows and higher levels dry. We explore this hypothesis by changing the parameter in CAM4 that determines the relative humidity below which liquid water is evaporated in the lower troposphere. During the evaluation of the model physics, if predicted condensate is nonzero and the relative humidity is below this threshold, then the evaporation
rate is set to remove the condensate until none remains or the saturation specific humidity is reached, whichever comes first. The default relative humidity threshold is 91%, which is not sustained in the daily averages of Fig. 5; Fig. 13 shows results with the default value along with 80%, 85%, and 95%. We might have expected the elevated cloud layer to persist longer in the experiments with the lower threshold because of the relaxed restriction on liquid water. The experiments with the lower threshold, however, experience a similar PBL collapse and cloud-base descent as the default value (or the increased value), though the collapse is only hinted at in the model’s diagnostic PBL depth and lifting condensation level (LCL; derived from the near-surface temperature and humidity) in the figure because of the coarse vertical resolution of CAM4. The reduced threshold increases cloud cover, LWP, and nighttime precipitation, and strengthens the shortwave cloud forcing. Permitting more water to condense strengthens the static stability by enhancing condensation warming in the cloud layer and evaporative cooling at lower levels (not shown). Increasing the threshold value to 95% decreases LWP and cloud fraction, but does not strongly affect PBL depth, LCL, or precipitation. These results suggest that the shallow PBL and low cloud base are intrinsic in the CAM4 formulation, implying that improving lower-tropospheric structure requires different boundary layer and cloud physics.

A number of studies have linked a PBL collapse such as that found in CAM4 to mechanisms for the transition from well-mixed stratocumulus to cumulus. Like the collapse in CAM4, these mechanisms often include stratifying effects of condensation and evaporation (e.g., Paluch and Lenschow 1991; Ackerman et al. 1993; Stevens et al. 1998). In CAM4, however, the PBL structure and cloud properties seem to be weakly coupled, probably because cloud processes are not directly connected with the structure of PBL turbulence.

The thinning and drying of the cloud layer during the daytime in CAM5 suggest the PBL and cloud layer frequently become decoupled. Decoupling refers to situations in which the turbulent mixing occurs in two separate layers, the cloud layer and subcloud layer, separated by a thin layer that is weakly stable (Nicholls 1984). In this configuration, the surface source of water to the cloud layer is removed, and the cloud layer dissipates as dry air is entrained and cloud water is evaporated. Shallow convection can connect the layers, as in the case of cumulus rising into stratocumulus, and in such cases multiple cloud-base levels can be observed (e.g., Miller et al. 1998). Figure 13 (solid, dark blue curves) hints at daytime decoupling as the PBL top lowers in the daytime, approaching the surface LCL and cloud base. Figure 14 also corroborates this interpretation, showing the diurnal cycle of production of turbulence.
kinetic energy by buoyancy [essentially the quantity $g\theta_0^{-1}w'\theta_v'$, where $g$ is gravitational acceleration, $\theta_0$ is a reference temperature, and $w'\theta_v'$ is the vertical flux of virtual potential temperature (e.g., Moeng and Sullivan 1994)] averaged over the last 3 days of the CAM5 forecasts. The figure shows the close association of buoyancy production of turbulence kinetic energy and clouds, including during the afternoon cloud thinning when the PBL top is close to the LCL (shown as dashed and dotted lines) in a layer of minimal buoyancy production. This layer is reminiscent of the transition layer separating the subcloud layer from decoupled stratocumulus [as discussed by Miller et al. (1998), and others]. During the nighttime, the PBL depth is higher, the LCL is slightly lower, and clouds are thicker and more extensive. This diurnal cycle is consistent with observations of the diurnal cycle of stratocumulus, but the breakup in cloud cover is suggestive of cumulus below stratocumulus or even trade wind cumulus layers.

To test whether the cloud breakup is due to the implementation of the Park and Bretherton (2009) shallow convection parameterization, we have repeated the CAM5 forecasts with a decreased efficiency for penetrative entrainment. This efficiency, like the relative humidity threshold in CAM4, has been used to adjust the global climate during CAM5 development. Decreasing this parameter reduces the downward mixing of warm, dry, free-tropospheric air by shallow convection.

As a result of reducing the penetrative entrainment efficiency (from 10 to 5 to 2.5), the average low-cloud fraction and LWP increase (Fig. 13, light blue curves), the nighttime PBL deepens and cloud base rises, and the shortwave cloud forcing strengthens. With less vigorous mixing, the amplitude of diurnal variation increases in several quantities (e.g., LWP). There is also some indication of a change in the phase of diurnal variation, especially in low-cloud fraction, which appears to maximize slightly later in the morning. Small changes in the diurnal behavior could have a strong impact on the long-term average cloud forcing, and there are signs of this in Fig. 13. Reducing the entrainment by shallow convection does not prevent the daytime thinning of the cloud layer, but may slow the cloud dissipation by increasing the nighttime liquid water content in the cloud layer. These results suggest that the decoupling of the cloud and subcloud layers is responsible for the cloud dissipation.

As another test of the hypothesis that decoupling is at the root of the daytime cloud thinning in CAM5, additional forecasts were made for the 2001 East Pacific Investigation of Climate Processes in the Coupled Ocean–Atmosphere System (EPIC2001) period (as in Hannay et al. 2009). That period was characterized by a deep, well-mixed PBL, a strong diurnal cycle, and little cumulus convection (Bretherton et al. 2004). Applying the same analysis as presented above to the EPIC2001 forecasts, similar conclusions are reached. The EPIC2001 forecasts have a cooler PBL than those of 2006, and have a larger cloud fraction at all times of day. Unlike the forecasts in Hannay et al. (2009), the CAM5 PBL does not collapse, but deepens during the forecasts (as in Fig. 9). The diurnal cycle is large, and there is a substantial cloud reduction during the day as in the 2006 forecasts. Comparing the PreVOCA (2006) and EPIC2001 cases shows that CAM5 frequently produces a decoupled PBL structure regardless of cloud cover, but also that the nighttime cloud cover and the magnitude of the daytime cloud dissipation may be linked to low-level temperature.

Experiments with reduced entrainment efficiency have larger cloud fraction and deeper PBL during nighttime, but the daytime cloud reduction is similar to the original CAM5 forecasts. The forecasts of the EPIC 2001 period have larger cloud fractions through the day, but the low-cloud fraction still reduces substantially
6. Summary and conclusions

Forecasts of the southeast Pacific in October 2006 have guided us toward conclusions about the parameterized physics in two versions of CAM. The short forecasts allow the dynamics to be similar to the observed atmosphere, while the fast parameterized processes drive the simulation away from the realistic state. Both model versions produce a stratocumulus deck given the realistic large-scale conditions, but biases reminiscent of their climate biases emerge. In particular, CAM4 develops an extensive cloud deck with cloud base and PBL top lower than observations show, and CAM5 produces less extensive stratocumulus but more realistic cloud layer geometry in a deeper and more well-mixed PBL than CAM4. Both models suffer from a moist bias in the PBL, diurnal variation of LWP that is too large, and average LWP that is biased low.

The cloud liquid water budget illustrates the processes controlling the models' stratocumulus. CAM4 produces condensate by relative humidity–controlled condensation and by detrainment of liquid from shallow cumulus convection. The low cloud base is established by downward mixing liquid water by PBL turbulence and shallow convection; condensation only occurs at the lowest model levels during nighttime after the PBL collapses. Condensation warming in the cloud layer and evaporative cooling below stratify the lower troposphere, inhibit turbulent mixing, and hasten the PBL collapse. The lack of cloud–radiation–turbulence interactions in CAM4 are likely the ultimate cause of the PBL collapse and low cloud base because the model cannot maintain the well-mixed PBL characteristic of subtropical stratocumulus.

Similar to CAM4, the CAM5 forecasts show the cloud water maintained by large-scale condensation and shallow convection detrainment while turbulent mixing and microphysical processes remove water from the cloud layer. A clear subcloud layer is maintained as liquid water mixed downward is evaporated, but the PBL remains well mixed because cloud-top cooling provides a source of turbulence kinetic energy. During daytime, shortwave absorption in the cloud layer offsets the cloud-top cooling, allowing the cloud and subcloud layers to decouple and the cloud layer begins to dissipate. The magnitude of this dissipation is larger than expected compared to observations of cloud cover and LWP. The daily breakup of the stratocumulus deck could play a role in long-term biases in the subtropical stratocumulus regions in CAM5 because exaggerating the breakup reduces shortwave cloud forcing and potentially accelerates the stratocumulus-to-cumulus transition. Forecasts of October 2001 show a less frequently decoupled PBL and larger cloud fraction, but confirm that decoupled layers are associated with cloud dissipation. These results show the connection between the PBL turbulence and cloud structure, and highlight the importance of the diurnal cycle of tropical clouds in climate simulations.

Experiments that adjust constants in the parameterizations show that some characteristics of the stratocumulus region are easily altered. Allowing condensate to exist at lower relative humidity in CAM4 can increase LWP and cloud fraction and enhance shortwave cloud forcing. These changes have little impact on the vertical structure of the PBL, however. This insensitivity to cloud changes, along with inconsistencies between predicted condensate and diagnosed cloud fraction, raises concerns about the ability of CAM4 to simulate the tropical cloud response to a changing climate. In CAM5, reducing the efficiency of penetrative entrainment by shallow convection produces increased LWP and daytime cloud fraction, but the CAM5 PBL still decouples during the daytime and the diurnal cycle of cloud fraction remains very strong. These experiments show that both model formulation and implementation are relevant for the identified errors in stratocumulus distribution and structure. We suspect that the CAM4 stratocumulus is limited mainly by formulation, though, because of the insensitivity of PBL structure to parameter changes. There is some indication of an improved diurnal cycle in the CAM5 experiments, suggesting that further experimentation...
might lead to improved stratocumulus in climate simulations. The comparison between the 2001 and 2006 forecasts, however, might imply more frequent decoupling in warmer conditions and the potential for positive cloud feedbacks in climate simulations.

The CAM5 represents a substantial improvement in the physical representation of subtropical stratocumulus over CAM4. The possible deficiencies of stratocumulus in CAM5, that is, the breakup of the cloud layer, should be further assessed with detailed observations and additional sensitivity experiments. One attractive avenue is to focus on the VOCALS Regional Experiment (VOCALS-Rex) period (Bretherton et al. 2010) and compare with detailed observations of the PBL structure; preliminary analysis of forecasts for that period shows similar characteristics as those presented here. We have not addressed the role of aerosol in the PBL cloud structure, but it could be substantial and comparison with observations may lead to insight about cloud–aerosol interaction. The southeast Pacific stratocumulus deck is also subject to regionally specific features, such as the daily “upsidence wave” propagating away from the continent (Garreaud and Muñoz 2004). This wave has been identified in CAM (Hannay et al. 2009), but we have not addressed it here. The role of regional features should be further considered, and the relative susceptibility of subtropical stratocumulus decks to perturbations ascertained.

Acknowledgments. We are thankful to ECMWF for providing the analysis data. Additional ERA-Interim data were obtained through the ECMWF Data Server (http://data-portal.ecmwf.int/). Monthly data from MODIS and MISR were obtained electronically through the Cloud Feedback Model Intercomparison Program website, and cloud observations for model evaluation are at http://climserv.ipsl.polytechnique.fr/cfmip-obs/. The TRMM microwave imager (TMI) data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science MEaSUREs DISCOVER Project. Data are available at http://www.remss.com. Radiosondes and cruise data were obtained electronically from the NOAA Earth Science website (http://www.esrl.noaa.gov/psd/psd3/synthesis/). We also thank Sungsu Park for helpful discussion of the CAM parameterizations. This work was supported by the Office of Science (BER), U.S. Department of Energy, Cooperative Agreement DE-FC02-97ER62402.

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