A comparison of forecast errors in CAM2 and CAM3 at the ARM Southern Great Plains Site

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ABSTRACT

We compare short forecast errors and the balance of terms in the moisture and temperature prediction equations which lead to those errors for the Community Atmosphere Model versions 2 and 3 (CAM2 and CAM3). The comparisons are made at the ARM Southern Great Plains site for the April 1997 and June/July 1997 Intensive Observing Periods. The goal is to provide insight into parameterization errors in the CAM which ultimately should lead to model improvements. The atmospheric initial conditions are obtained from ERA40 reanalyses. The land initial conditions are spun up to be consistent with those analyses. We identify the differences between the model formulations that are responsible for the major differences in the forecast errors and/or parameterization behaviors. We perform a sequence of experiments, accumulating the changes from CAM3 back toward CAM2, to demonstrate the effect of the differences in formulations.

In June/July 1997 the CAM3 temperature and moisture forecast errors were larger than those of CAM2. The terms identified as being responsible for the differences were 1) the convective time scale assumed for the Zhang-McFarlane deep convection, 2) the energy associated with the conversion between water and ice of the rain associated with the Zhang-McFarlane convection parameterization, and 3) the dependence of the rainfall evaporation on cloud fraction. The latter two were not included in CAM2. In April 1997 the CAM2 and CAM3 temperature and moisture errors are very similar, but different tendencies arising from modifications to one parameterization component were compensated by responding changes in another component. CAM3 includes detrainment of water by the Hack shallow

convection to the prognostic cloud water scheme that was not included in CAM2. This gives a different total parameterization tendency that is balanced by a difference in the advective tendency to yield the same total moisture tendency. The time scale assumed for the Hack shallow convection was halved in CAM3. Thus the convection is relatively weaker in CAM2 but this was compensated by the prognostic cloud water parameterization tendency to give very similar total parameterization tendency. CAM3 also had a variety of changes to the cloud fraction parameterization. These affect the radiative heating which in turn modifies the stability of the atmospheric column and affects the convection. But again, the changes in convection tendency are balanced by changes in the prognostic cloud water parameterization tendency, yielding a similar total parameterization tendency.

1. Introduction

The Community Atmosphere Model version 3 (CAM3), developed in a collaboration between members of the National Center for Atmospheric Research and the scientific research community, was recently released for unrestricted use by the general community. The CAM3 is the atmospheric component of the new version of the Community Climate System Model (CCSM3) which is intended for coupled ocean-atmosphere-sea-ice applications, including climate change studies such as those carried out for the IPCC. The CCSM3 is documented in Collins et al. (2006a) and in a series of papers in a special issue of the Journal of Climate (2006, Vol. 19, 2121-2632).

The CAM3 can also be run in a stand-alone mode with specified Sea Surface Temperatures (SST) and sea-ice extent while coupled with the Community Land Model (CLM) (Bonan et al. 2002a; Oleson et al. 2004). A complete technical description of CAM3 is provided by Collins et al. (2004). It is closely related to its predecessor CAM2 (Collins et al. 2003, Kiehl and Gent 2004) with a few of its component parameterizations essentially unchanged. Nevertheless, extensive modifications have been introduced into the cloud and precipitation processes to remove inconsistencies in the treatment of clouds that were present in CAM2, to ameliorate biases in the climate simulated by CAM2, and to provide new mechanisms for the interactions between cloud properties and other components of the model (Boville et al. 2006).

Compared to CAM2 the prognostic cloud water scheme of Rasch and Kristjansson (1998) was updated by Zhang et al. (2003). CAM3 has separate prognostic equations for liquid and ice condensate, includes detrainment, sedimentation, and resolved scale advection of cloud condensate, and treats frozen and liquid precipitation separately. Snowfall is computed explicitly in CAM3 and the latent heat of fusion is included for all freezing and melting processes which eliminates an energy inconsistency that was present in the CAM2 formulation.

Both deep and shallow convection parameterizations can detrain cloud condensate directly into stratiform clouds. CAM2 included detrainment of condensate, but it was used only to moisten the large scale environment. The convective parameterizations themselves were not modified to include latent heat of fusion. Instead a separate step follows each scheme in which the condensate is partitioned into ice and liquid. Evaporation is included for sedimenting cloud particles and for all parameterized sources of precipitation at a rate determined from Sundqvist (1988). CAM3 also has modifications to the diagnostic cloud fraction formulation which will be detailed later.

Radiative processes in the CAM3 have also been updated. The radiation code includes a generalized treatment of cloud geometrical overlap. In addition, CAM3 includes the radiative effects of an aerosol climatology in the calculation of shortwave fluxes and heating rates. The CAM2 used globally uniform sulfate aerosol distribution. These and additional changes are described in Collins et al. (2006b).

Many of the formulation changes summarized above were introduced to eliminate significant biases in CAM2 which limited its utility for several applications. For example the tropical tropopause was too cold in CAM2 by around 3 K. This resulted in an unrealistic drying of the stratosphere (Boville et al. 2006). As part of the development and evaluation of CAM3, adjustable coefficients in the parameterization of clouds and precipitation were also modified. Such changes are desirable in order to produce similar and realistic cloud radiative forcing characteristics when the model is applied at different resolutions. Hack et al. (2006b) provide an excellent overview of the need to "tune" adjustable parameters in response to changes in large scale fields which accompany resolution changes.

As alluded to above, the CAM3 was developed by comparing its simulated climate to similar statistics obtained from atmospheric observations and analyses, with the goal of matching the atmospheric statistics as closely as possible. In fact CAM3, although not perfect, provides a better match than CAM2 did, indicating that the design criteria were largely satisfied. Collins et al. (2006a) cite improvements in the boreal winter land-surface temperatures, surface insolation, and clear-sky surface radiation in polar regions. Collins et al. (2006b) demonstrate that CAM3 has more realistic tropical tropopause temperatures and spatial structure of tropical precipitation. They also show that the radiative effects of tropical clouds improved correlations of shortwave and longwave cloud forcing. They attribute these improvements to the introduction of convective cloud cover, the addition of sedimentation and advection of cloud condensate and the export of liquid water produced by the shallow convection scheme to the parameterizations of cloud condensate. Boville et al. (2006) document the improvements in the tropical tropopause temperature and relate them to specific changes in the clouds and precipitation parameterizations. Hack et al. (2006a) present aspects of the global hydrological cycle and Rasch et al. (2006) discuss the tropical transient aspect of the hydrological cycle. Hurrell et al. (2006) describe the dynamical simulation of the CAM3. All these papers and others in the special issue (Journal of Climate, 2006, Vol. 19, 2121-2632) indicate that the simulated climate of CAM3 is an improvement over that produced by its predecessor CAM2. While all these papers concentrate on improvements to the simulated climate they also list important remaining biases which reduce the fidelity of CAM3 simulations.

2. CAM3 versus CAM2

As indicated above, CAM3 does a credible job of simulating current climate; however, for it to be most useful it must do so by correctly simulating the processes that create that climate. Evaluation of those processes when the model is in its climate equilibrium may be misleading because a process might be responding to or creating compensating errors. In addition evaluation of the modeled processes is difficult and perhaps not possible on a global scale. However, with colleagues at PCMDI we have developed an approach to examine the processes in climate models by following the lead of NWP model development; that is to examine the climate model applied to weather forecasts. The goal is not to produce the best possible forecast, but rather to compare model parameterized variables such as clouds and radiation and parameterized tendencies to detailed estimates from field campaigns such as provided by the DOE Atmospheric Radiation Measurement (ARM) program. Such comparisons can only be made in limited regions and for limited periods, but they do shed light on how the models are working there. The parameterizations are examined when they are based on the observed atmospheric state rather than a model simulated state. Our general approach, which has been named the CCPP-ARM Parameterization Testbed (CAPT) is described in Phillips et al. (2004). We emphasize that our goal is to gain insight into model parameterization errors, which we hope will lead to suggestions for model improvements. Boyle at al. (2005) and Williamson et al. (2005) apply the approach to CAM2 for a few periods and locations.

Here we compare forecasts made by CAM3 to matching ones made by CAM2 at the ARM Southern Great Plains (SGP) site for the April 1997 and June/July 1997 Intensive Observing Periods (IOP). Both versions were run at T42 spectral truncation with 26 vertical levels. We do not catalog the details of all the differences between CAM2 and CAM3. Similarly we do not identify the effect of all those differences between CAM2 and CAM3 on the errors in the modeled processes or in the balances between processes. Rather we identify the primary differences between the model formulations that are responsible for the major differences in the forecast errors and/or parameterization behavior. As will be seen these involve the changes in the values of some parameters, changes in the details of some parameterizations, and the inclusion of additional processes in CAM3.

Williamson et al. (2005) showed that for these periods and locations the primary

CAM2 forecast errors form rapidly within 24 hours. We have found that the errors in CAM3 are similar to those in CAM2 and form equally rapidly. Therefore we consider the temperature and specific humidity errors of 24 hour forecasts and the terms in the temperature and moisture prediction equations averaged over the first 24 hours of the forecasts. In addition, to reduce the noise we consider composite forecast errors rather than the errors of individual forecasts. The composites are chosen over forecasts with common errors and behavior as in Williamson et al. (2005). The rationale given there for CAM2 applies equally to the CAM3 forecasts.

The specific humidity and thermodynamic prognostic equations can be written

$$\frac{\partial q}{\partial t} = -\mathbf{V} \cdot \nabla q - \dot{\sigma}\frac{\partial q}{\partial \sigma} + S \tag{1}$$

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \kappa T\frac{\omega}{p} + Q \tag{2}$$

where the moisture source term S and heating term Q represent the sub-grid scale parameterizations. The first two terms on the right-hand-sides of (1) and (2) are the *horizontal* and *vertical advection*. We also consider the sum of these two – referred to as the *total advection*. We refer to the term $\kappa T\omega/p$ in (2) as the *energy conversion term* since the momentum equation includes a corresponding term and the global integrals of the two sum to zero in the total energy equation.

For the purposes of identification in the following analysis of differences we define here the terms we will use to characterize the various processes examined. In general, we separate the parameterizations, S and Q, into three primary components referred to as the *moist processes parameterization*, the *planetary boundary layer* (PBL) parameterization, and *radiation*. The last has no direct effect on S. The PBL parameterization includes the surface fluxes which are distributed in the vertical by the PBL parameterization (Holtslag and Boville, 1993). The moist processes include the Zhang and McFarlane (1995) deep convection parameterization, the Hack (1994) shallow convection parameterization, and a prognostic cloud water parameterization (Rasch and Kristjansson, 1998). These three can be thought of as creating condensate or rain water from water vapor. We refer to these as the *primary parameterization schemes* included in the moist processes, but each has complementary processes associated with it which act on the condensate produced by of that primary parameterization. These processes include the evaporation of falling rain water created by the prognostic cloud water, by the Zhang-McFarlane deep convection parameterization, and by the Hack shallow parameterization. We refer to these as *rainfall evaporation*. In CAM2 there is no rainfall evaporation associated with the Hack shallow parameterization. CAM2 includes a term associated with the Zhang-McFarlane deep convection parameterization that evaporates a fraction of the detrained water back into the environment. We refer to this as *environmental detrainment*. This term is not included in CAM3. Additional processes included in CAM3 which are not included in CAM2 are the *partitioning of condensate* into liquid and ice, the *freezing* of rain water to snow or ice and the inverse *melting* of snow or ice back to rain water. These are associated with each of the three primary parameterizations of the moist processes and all follow the formulation of Rasch and Kristjansson (1998). As mentioned earlier, this aspect of snow formation provides an energy consistency in CAM3 that was lacking in CAM2.

We use the same atmosphere and land initial conditions for CAM3 as were used for

CAM2 in Boyle at al. (2005) and Williamson et al. (2005) with minor modifications required by differences in the models. These will be described shortly. The initial atmospheric conditions for the earlier CAM2 forecasts were obtained by mapping high resolution ECMWF reanalyses (ERA40, Simmons and Gibson, 2000) to the coarse resolution CAM grid in a way that is consistent with the low resolution topography, and leads to smooth, balanced forecasts. We followed the interpolation method used in the IFS system jointly developed by the ECMWF and Meteo-France (White, 2001). In the CAM2 study we also created initial conditions from the NCEP-DOE reanalyses (R2, Kanamitsu et al. 2002). The general characteristics of the forecast errors from the two sets of initial conditions were the same, although the magnitudes of the errors differed somewhat. By comparison with the independent ARM data at the SGP site, we concluded that the ERA40 initial conditions provided a better indication of the CAM error even though in June/July 1997 the model error was actually larger with the ERA40 initial conditions than with the R2 (Williamson et al. 2005). The R2 initial conditions contained less moisture than in reality (as determined from the ARM observations), and this lower moisture amount was more consistent with the CAM2 natural errors, leading to a smaller but less representative error in the forecasts. Therefore, here we consider only forecasts from ERA40.

The land initial conditions for the CLM2 which was coupled to CAM2 were obtained by a spin-up procedure in which the CLM2 responds to and interacts with the CAM2 while the CAM2 is forced with the ERA40 analyses to evolve like the observed atmosphere. This is described in more detail in Phillips et al. (2004) and in Boyle et al. (2005). Some indication of the quality of the land initial conditions is provided in Boyle et al. (2005)

and Williamson et al. (2005) where it is argued that any deficiencies in the land initial conditions are not responsible for the primary errors seen in those papers in the atmospheric forecasts. The CLM2 was based on a grid box containing multiple plant function types, each with its own soil column. The CLM3 includes the effects of competition for water among plant function types by having a single soil column shared by all the plant function types within a grid box (Bonan et al. 2002a; Oleson et al. 2004). For the CLM3/CAM3 forecasts considered in the following we set the initial soil column in each grid box to match the initial CLM2 column of the dominant plant function type. We also carried out forecasts using the average of the CLM2 soil columns in each grid box weighted by plant type fraction, and using the original CAM2 initial data with CLM3 set in non-compete mode with multiple soil columns in the grid box. The differences between the CAM3 forecasts were minimal.

The prognostic parameterized variables, i.e. those variables which carry information from one time step to the next, were initialized in the spin-up procedure used for the land. The only modification to the CAM2 variables needed for CAM3 was to partition the total condensate into liquid and ice forms. The algorithm included in the CAM2 prognostic cloud water scheme (Rasch and Kristjansson, 1998) was used.

We emphasize that we consider only two specific seasons (April 1997 and June/July 1997) at a single grid column, namely the ARM SGP site. However, the April case does appear to be representative of other years (Boyle et al. 2005), and the June/July errors might be relevant to the model behavior in other moist regions such as the tropical western Pacific (Williamson et al. 2005). The analysis presented here is not necessarily representative of the model's behavior everywhere. Nevertheless, they do however shed some light on the workings of some of the parameterizations.

We calculate the model errors by comparing with the ARM IOP data sets that were developed for forcing and diagnosing single column and cloud resolving models. These have been processed with the constrained variational analysis method of Zhang and Lin (1997) and Zhang et al. (2001). These data include the variables needed to drive single column models and additional fields such as estimates of the sub-grid scale forcing equivalent to what would be calculated by a model parameterization suite. These are obtained as a residual of the total tendency minus the advective or dynamical terms.

To demonstrate the changes in model formulation that we have identified as responsible for the major differences between the CAM2 and CAM3 forecast errors we start with the CAM3 formulation and modify selected aspects to match those of CAM2. We perform a sequence of experiments, accumulating the changes from CAM3 back toward CAM2. Each set of forecasts in the sequence will be referred to as an "experiment".

3. June/July 1997 IOP Forecasts

Williamson et al. (2005) showed that the dominant errors in CAM2 in June/July at the SGP site were persistent, occurring in every forecast. Therefore we average over all forecasts for this period as was done in the analysis of Williamson et al. (2005). Fig. 1a and b show the vertical profiles of the mean forecast temperature and specific humidity errors at day 1 for CAM3 (solid line) and CAM2 (short dashed line) at the ARM SGP site. The CAM2 values replicate the corresponding DAY 1 curves in Fig. 1 of Williamson et al. (2005). The long dashed line is from an additional experiment which will be discussed shortly. The CAM3 errors are larger than the CAM2 errors at this location and season. Corresponding profiles of June/July simulation climatological errors at this grid point are shown in Fig. 1c and d for CAM3 and CAM2. The larger CAM3 upper tropospheric forecast temperature error is reflected in the CAM3 climatological error also being larger than that of CAM2. CAM2 has a larger lower tropospheric climatological temperature error because the land model develops a warm, dry bias (Bonan et al. 2002b) in the summer. This error develops in the climate simulation on a longer time scale than the short forecasts considered here. The CAM3 climatological moisture bias is also larger than that of CAM2 except near the surface where the CAM2 land dry bias affects the atmospheric climatology. Again the land climatological bias sets up over a longer period than the few day forecasts considered here. The CAM forecast biases do appear to be relevant to the climatological biases.

Williamson et al. (2005) show that the moist processes are driving most of the temperature error in the CAM2 forecasts at this season, and within that set of processes, the Zhang-McFarlane deep convection parameterization is dominant, the others being relatively inactive. Of course, as pointed out there, the formulation of the parameterization might not be in error. It might be responding to errors in other processes. Nevertheless, it is a good starting point to attempt to understand the sources of the errors, or differences in the errors that are indicated here. Two parameters in the Zhang-McFarlane deep convection parameterization that differ between CAM2 and CAM3 are the time scale for convection (2 hours in CAM2, 1 hour in CAM3), and a coefficient controlling the autoconversion of cloud water to precipitation as it is lifted (2×10^{-3} in CAM2, 3×10^{-3} in CAM3.)

The increase in the autoconversion coefficient in CAM3 results in more rain water being produced which becomes available for evaporation as it falls through lower layers. The time scale difference makes the convection more active in CAM3. The errors from a set of forecasts from CAM3 with these two parameters set back to their CAM2 values are also plotted in Fig. 1a and b as the long dashed line. We label this EXPJ1. The temperature error from this experiment falls half way between CAM3 and CAM2 values except around 700mb where the error is less than that of CAM2. The moisture error is two-thirds of the way from CAM3 to CAM2, with no particularly noticeable feature at 700mb. A separate set of forecasts changing only the convective time scale from the CAM3 to the CAM2 value (not shown) shows that the changes from CAM3 to EXPJ1 seen in Fig. 1a and b are primarily due to the convective time scale change and not to the change in autoconversion coefficient.

Fig. 2a and b show the 24-hour averaged total temperature and moisture tendencies along with their two components, the dynamics or advection tendencies and the parameterization tendencies, for the CAM3, CAM2 and EXPJ1. The dynamics cools more in CAM3 than CAM2 throughout the column (Fig. 2a). Presumably the dynamics are responding to the differences caused by the parameterizations during the first day since the dynamical approximations are identical in CAM2 and CAM3, and the initial data and surface boundary data are nearly the same. In fact examination of 3-hour averages shows that the dynamics and moisture advections in CAM3 match those of CAM2 during the part of the day when the convection is inactive (6-15 hours). The differences in temperature and moisture created by the parameterizations during the first 6 hours are not large to affect the dynamics and advection from 6-15 hours. The dynamics and advection differences then grow from 15-24 hours when the convection is active. The convection gives a different heating rate which in turn drives a different vertical motion. The differences in the dynamics are in fact in the vertical advection and energy conversion term. The horizontal advection matches in the CAM2 and CAM3 forecasts. This was further verified by examining sets of forecasts initialized at 06Z and at 12Z. The dynamics and moisture advection match in the two sets of forecasts before the convection is activated. The dynamical tendency in EXPJ1 with the convective time scale and autoconversion coefficient set to CAM2 values is closer to that of CAM2 (Fig. 2a), consistent with the state being closer to that of CAM2. However the parameterized heating and moistening still differ between EXPJ1 and CAM2. Williamson et al. (2005) compared the CAM2 parameterized moistening to that from the ARM variational data set. This showed significant errors in CAM2 which are exacerbated in CAM3. Fig. 2c indicates that the difference is primarily caused by the moist processes, with a very small contribution from the radiation.

Fig. 3a shows the temperature tendency for the three primary parameterization schemes comprising the moist processes which create condensate. Fig. 3b, c, and d show the additional processes associated with each of the primary schemes. Fig. 3a represents the conversion of vapor to liquid condensate in the case of the prognostic cloud water scheme and to rain or detrained water for the Zhang-McFarlane deep and Hack shallow convection parameterizations. The Zhang-McFarlane deep convection is the dominant component and EXPJ1 is close but not identical to CAM2. Fig. 3b shows the rainfall evaporation associated with the three parameterizations for the three experiments. This term includes the evaporation of cloud water sedimentation in the prognostic cloud water scheme; however that component is negligible in these experiments. CAM2 did not include rainfall evaporation with the Hack shallow scheme, but that term is also essentially zero in CAM3 and EXPJ1 and is not responsible for the differences. The rainfall evaporation is relatively small for the prognostic cloud water scheme. The rainfall evaporation associated with the Zhang-McFarlane deep convection dominates the three and for it, EXPJ1 is closer to CAM3. Fig. 3c shows heating due to the freezing of rain water to ice or snow associated with each scheme. This is essentially the ice/liquid repartitioning for the prognostic cloud water scheme with a similar repartitioning applied to the rain water produced by the two convection schemes. In the prognostic cloud water scheme this term includes additional freezing of cloud water but this aspect is negligible here. Fig. 3d shows the cooling due to the melting of snow for each scheme. These last two processes involving liquid/ice conversions were not included in CAM2 for any of the primary parameterizations. Fig. 3c and d show that these conversion terms are small for the Hack shallow and prognostic cloud water parameterizations and that the conversions associated with the Zhang-McFarlane deep convection scheme dominate. The tendencies of EXPJ1 remain close to those of CAM3 as opposed to zero in CAM2 indicating that these processes are likely to be responsible for some of the differences between CAM3 and CAM2.

Therefore we carried out a series of forecasts based on EXPJ1 with the conversion between water and ice associated with the convection parameterizations eliminated. We refer to this experiment as EXPJ2. Results are shown in Fig. 4. Comparison of EXPJ2 in Fig. 4a with EXPJ1 in Fig. 1a shows that the temperature differences with CAM2 have been reduced in EXPJ2, especially in the upper troposphere. The moisture differences have been only slightly reduced in EXPJ2 in the lower troposphere (Fig. 4b versus Fig. 1b). Note that the phase conversion does not directly affect the atmospheric water vapor specific humidity. It only directly affects the temperature, and ice and liquid water components. The kink between 600mb and 700mb in the temperature error in CAM3 (Fig. 4a) is eliminated in EXPJ2. It was caused by the melting of falling snow which led to localized cooling there (Fig. 3d). The difference in heating from the Zhang-McFarlane deep convection scheme (Fig. 4c) between CAM2 and EXPJ2 is rather small. The difference in temperature error however is not negligible. Between 900mb and 200mb the difference in temperature between EXPJ2 and CAM2 (Fig. 4a) is nearly constant. Similarly the water vapor also shows a nearly constant difference from 900mb to 500mb (Fig. 4b), and that difference mimics the rainfall evaporation difference in temperature associated with the Zhang-McFarlane deep convection parameterization (Fig. 4d). Note that the corresponding water vapor tendencies from rainfall evaporation (not shown) are just the negative of the temperature tendencies scaled by the latent heat of vaporisation. Thus one suspects there is a remaining difference in the rainfall evaporation formulation between EXPJ2 and CAM2. That is in fact the case. A multiplicative term $(1 - C_f)$ was included in CAM3 in the rainfall evaporation equation, where C_f is the cloud fraction.

Fig. 5 shows the result of a series of forecasts with the parameterizations as in EXPJ2 and the cloud fraction term eliminated from the convective rainfall evaporation equation (EXPJ3). Now the q error in EXPJ3 is very close to that of CAM2 (Fig. 5b) and the evaporation term itself is also very close to that of CAM2 (Fig. 5d). The temperature tendency from conversion of vapor to liquid in the Zhang-McFarlane deep convection scheme matches CAM2 well with slight differences around 500mb (Fig. 5c). The temperature error itself shows differences with CAM2 of 0.5K above 500mb (Fig. 5a).

At this point we have identified the primary changes that were responsible for the differences between CAM3 and CAM2 in June/July 1997 at the SGP site. They are all associated with the Zhang-McFarlane deep convection. Small differences do however remain. In particular note that the prognostic cloud water tendency in EXPJ3 remains different from CAM2 (yellow lines, Fig. 5c). There are also differences in other terms. Fig. 6a shows the tendencies for the total moist processes, PBL, and radiation parameterizations for CAM3, CAM2, and EXPJ3. The total moist processes for EXPJ3 are significantly closer to CAM2 over much of the troposphere than the Zhang-McFarlane deep convection parameterization alone is (Fig. 5c) indicating some compensation from other moist processes such as prognostic cloud water also seen in Fig. 5c. The radiation heating in EXPJ3 is actually farther from CAM2 than it is from CAM3. The individual components shown in Fig. 6b indicate that most of the radiation difference is in the longwave component, probably related to differences in the parameterized clouds. Changes in the cloud fraction parameterization will be considered in the next section. It appears we have hit the point of diminishing returns in chasing down the sources of the remaining differences. Therefore we do not pursue the effect of changes in other components of CAM for this period as the remaining differences are rather small. Many of the differences between CAM2 and CAM3 are rather subtle and their effects on the climate are interactive. In the prognostic water parameterization the differences include methods of solution of an ordinary differential equation associated with the microphysics. In one version an Euler Forward or Backward scheme is used depending on the relative size of the source term, in the other the Euler Backward is always used. There are also differences in the handling of cloud water change when the cloud volume changes. We consider some of the prognostic cloud water differences in the next section for a situation where it and the Hack shallow convection parameterization are dominant and the Zhang-McFarlane deep convection is inactive.

4. April 1997 IOP Forecasts

We now consider forecasts initialized in April 1997. Williamson et al. (2005) showed that unlike the summer case, in April the CAM2 captures the episodic nature of the precipitation observed in ARM very well. The terms in the moisture and temperature prediction equations are very different on rain and no rain days. Therefore, for the April forecasts we consider composites of days with significant precipitation. The compositing is done here exactly as it was done in Williamson et al. (2005). We do not compare the composite forecast temperature and moisture errors with the model simulated climate error as we did in July since the composite represents only a small sample of states comprising the climate.

Fig. 7a shows the vertical profiles of the 0-24 hour average total moisture tendency along with its two components, advection and parameterization for CAM3 (solid line) and CAM2 (short dashed line). The long dashed line shows the ARM estimates from the variational analysis. The total tendency is very similar in CAM2 and CAM3, but both are different from ARM as discussed in Williamson et al. (2005) for CAM2. The CAM2 and CAM3 specific humidity errors at day 1 (not shown, but which, with units g/kg, are simply the difference between a CAM curve and the ARM curve in Fig. 7a) increases with increasing pressure to around 1 g/kg at 850 mb, then jumps to around 3 g/kg approaching the surface. The CAM2 and CAM3 temperature tendencies (not shown) are also very similar to each other, yielding similar temperature errors at day 1. These errors are small from the tropopause down to 300mb, then range around 1K from 300mb to 659mb and increase to 4K at 750mb and below. The error can be seen for CAM2 in Fig. 5 of Williamson et al. (2005). Although the temperature and moisture errors in CAM2 and CAM3 are very similar, we will see in the following that there are compensating responses in the dynamics and parameterizations to changes in the parameterizations that create those same total errors in the two models. Thus as components of the parameterization suite are changed from CAM3 back to CAM2, other components respond to compensate and lead to a rather invariant total tendency.

Fig. 7a shows that the two components of the total tendency, advection (ADV) and parameterizations (PAR) are very similar in CAM2 and CAM3 except at a single grid level (675mb) where a compensating decrease occurs in both components in CAM3 compared to CAM2, taking each further from the ARM estimates. Since the advection approximations are identical in CAM2 and CAM3, and since the initial conditions are also the same in the two experiments, the advection difference is probably a reflection of different heating rates produced by the different parameterizations in the two models as was argued in the July case above. Above 900mb the parameterizations in CAM2 are dominated by the moist processes (Williamson et al. 2005). As might be expected, this is also the case in CAM3.

Fig. 7b shows the total moist process tendency and the tendencies of the three primary parameterizations for CAM3 and CAM2. The tendencies from the associated rainfall evaporations (and environmental detrainment associated with the Zhang-McFarlane deep convection scheme in CAM2) contribute little to the total moist process tendencies at this column and therefore are not included in the figure (see Fig. 6d of Williamson et al. (2005) for CAM2 curves.) The Hack shallow convection (green curves) generally has stronger drying in CAM3 than in CAM2, while the prognostic cloud parameterization (yellow curves) shows less drying in CAM3 than in CAM2, turning to moistening at the 675mb grid level in CAM3. The differences in the tendencies of the two components compensate in most of the troposphere except at the two grid levels above 700mb where the prognostic cloud water parameterization is moistening the atmosphere in CAM3. Since the prognostic cloud water scheme is a vapor source there in CAM3 and not in CAM2, some other process in CAM3 is probably providing liquid water to the prognostic cloud water scheme which is then available for evaporation. We seek to identify such a source by examining the components of the cloud liquid as opposed to the vapor budget of Fig. 7a and b.

Fig. 7c. shows the dominant cloud liquid water budget terms for the CAM3 forecasts. Only the total liquid water tendency (labeled D(H2O)/DT) and the most significant terms which make up the total are included. These are the formation of liquid condensate from vapor by the prognostic cloud water scheme (Q→H2O), the conversion of liquid condensate to rain (H2O→PRECIP), the conversion of liquid condensate to ice (H2O→ICE), and the convective detrainment of water (DETRAIN). The formation of liquid condensate from vapor by the prognostic cloud water scheme (Q→H2O) is the mirror image of the vapor tendency from the prognostic cloud water scheme (yellow line, Fig. 7b) except in the upper troposphere where conversion to ice also comes into play. The convective detrainment of water to the cloud water scheme (green line, Fig. 7c) is a large source of liquid water above 700mb in CAM3. CAM2 included detrainment of water from the Zhang-McFarlane deep convection scheme but not from the Hack shallow scheme. CAM3 also includes it from the Hack shallow scheme. Since the Zhang-McFarlane tendency is not significant in these forecasts, the Hack shallow scheme must be responsible for the observed detrainment in CAM3. Therefore we performed a series of forecasts with CAM3 but eliminating the convective detrainment of water from the Hack shallow convective parameterization (EXPA1).

Fig. 7d. shows the cloud water budget terms from EXPA1 which is based on CAM3 but has the Hack shallow convective detrainment of water eliminated to match CAM2. By design the convective detrainment (DETRAIN) in this case is close to zero (possibly not identically zero since the Zhang-McFarlane deep convection parameterization might still detrain). Without that liquid source in the cloud water balance, the formation of liquid condensate from vapor by the prognostic cloud water scheme ($Q \rightarrow H2O$) is now positive everywhere indicating that there is no vapor source from evaporating liquid condensate in the prognostic cloud water scheme in EXPA1. This is verified in Fig. 8a which shows the vapor budget tendency terms for EXPA1 along with repeating those of CAM2 and CAM3. The prognostic cloud parameterization tendency (yellow line) is negative everywhere above the first model level. In fact both the Hack shallow convection and the prognostic cloud water tendencies in EXPA1 are very similar to those of CAM2. The total moist parameterization tendencies for CAM2 and EXPA1 are also very similar as shown in Fig. 8b.

Although with this one change the total moist process and the primary parameterization tendencies now match CAM2 closely, there may be other significant changes from CAM2 to CAM3. We are aware of another that we would expect to have a significant effect on the model behavior given the results in the June/July case discussed earlier, namely a decrease in the adjustment time scale of the Hack shallow convection from 60 minutes to 30 minutes. A similar change in the Zhang-McFarlane deep convection parameterization led to an increase of the convection tendency in the June/July forecasts and we might expect a similar behavior with the Hack shallow convection here, i.e. CAM3 convection would be stronger than that of CAM2 from that difference alone. That is in fact the case as seen in Fig. 8c which shows the terms from an experiment based on EXP1 but with the time scale of the Hack shallow convection parameterization increased from 30 minutes to 60 minutes to match CAM2. The experiment is labeled EXPA2. The increased time scale results in a decrease in the Hack shallow convective tendency so that it is now smaller than that of CAM2, which in turn was smaller than CAM3. This difference between EXPA1 and EXPA2 in the Hack shallow convection parameterization tendency is balanced by an opposing difference in the prognostic cloud water tendency which now has greater drying than that of CAM2. Although the Hack shallow and prognostic cloud water tendencies each differ between EXPA2 and CAM2 (Fig. 8c), the total moist parameterization tendency (MOIST) agrees rather well between EXPA2 and CAM2 (Fig. 8d) as it also does in the previous experiment (EXPA1, Fig. 8b). Once again we see that a change made to one component leads to a compensating response in another which yields a very similar net drying.

Although the total moist tendencies of EXPA2 and CAM2 agree well, Fig. 8c shows that the individual components do not. The remaining changes from CAM2 to CAM3 can be divided into two packets, one comprised of changes to the prognostic cloud water scheme and the other of changes in the cloud fraction scheme. Converting the prognostic cloud water packet to match CAM2 has little effect on the simulation with a plot of the moist parameterization components (not shown) looking very much like Fig. 8c. On the other hand, adding the cloud fraction packet to the previous experiment EXPA2, which we label EXPA3, produces a simulation in which the moist parameterization component tendencies look like those of CAM2 (Fig. 9a) as does the total moist parameterization tendency itself (Fig. 9b).

The packet of changes to the cloud fraction scheme includes the following: the minimum relative humidity for low stable clouds was changed from 85% in CAM2 to 90% in CAM3 while that for high stable clouds was changed from 90% in CAM2 to 80% in CAM3. The low cloud value is effective below 750 mb and the high cloud above 750 mb. CAM2 convective cloud fraction depends on the detrainment rate from deep convection, while that of CAM3 depends on the convective mass flux. Finally in CAM2 the total cloud fraction is the maximum of the stable and convective cloud fractions (maximum overlap), while in CAM3 the total cloud is the sum of the stable and convective cloud fractions.

In EXPA3 without the CAM3 cloud fraction modifications the mid-level cloud fraction in particular, is seen to be less than that of CAM3 (Fig. 9d) while with them (EXPA2) the fraction is closer to that of CAM3 (Fig. 9c). In fact a design goal of CAM3 was to increase the mid-level clouds over those of CAM2. The decreased mid-level clouds in EXPA3 (relative to CAM3 and EXPA2) results in increased longwave cooling below 600mb extending down to 850mb (not shown.) The shortwave radiation heating is affected less by these clouds so the net radiation has increased cooling in EXPA3 relative to CAM3 and EXPA2 from 600mb to 800mb. That destabilizes the atmosphere leading to stronger convection in EXPA3 which then matches CAM2 in drying.

EXPA3 is very close to CAM2 in the total moist parameterization heating (Fig. 9b), in the moist parameterization components (Fig. 9a), and in the cloud fraction (Fig. 9d). Small subtle differences do remain but we do not try to identify their causes. Our goal was to determine which model formulation changes had the largest effects. It was not to identify all the model changes which lead to small and subtle interactions between processes. Therefore we stop the exercise here.

5. Conclusions

The studies described in the introduction have shown that the simulated climate of CAM3 matches similar statistics obtained from atmospheric observations and analyses better than the simulated climate of its predecessor CAM2 does. As such, CAM3 represents a significant improvement over CAM2. The comparison of CAM3 with CAM2 in this paper attempts to examine the modeled processes that create the climates of the models by examining the models applied to weather forecasts. We compare the model forecast evolution to estimates of that evolution at the ARM SGP site for several IOPs. For such comparisons we are limited to specific locations and periods. With these limited locations and periods we can only sample a small set of the phenomena that make up the global climate of the model. We compute the model errors by comparing with the ARM constrained variational analysis (Zhang and Lin 1997; Zhang et al. 2001) that was developed to drive and analyze single column models.

We isolated the primary model changes from CAM2 to CAM3 which affect the simulated forecast processes and errors. There are significant differences in the errors in forecasts made with CAM3 and CAM2 at the ARM SGP site in June/July 1997. In April 1997 the temperature and moisture forecast errors are quite similar, but the individual components that combine to yield the total error can be quite different in compensating ways. We performed a series of experiments to establish which changes in the model formulation were responsible for the major changes in the errors and balances. Many smaller, more subtle changes were not pursued. We did not attempt to isolate all terms which led to small changes as the nonlinear interactions ultimately make it very difficult to isolate the smallest effects.

In June/July 1997 the CAM3 temperature and moisture forecast errors were in fact larger than those of CAM2 at this SGP site. We concentrated on the temperature balance terms as they include terms from the phase change between liquid water and ice that have no direct effect on the water vapor itself. The terms identified as being responsible for the differences were 1) the convective time scale assumed for the Zhang-McFarlane deep convection which was halved in CAM3, 2) the energy associated with the conversion between water and ice of the Zhang-McFarlane rain which was not included in CAM2, and 3) the dependence of the rainfall evaporation on cloud fraction which was also not included in CAM2.

In April 1997 the CAM3 and CAM2 forecast temperature and moisture forecast errors were very similar, yet when certain parameterization components were modified, other components reacted in a compensating way. We examined the water vapor balance terms in detail. The detrainment of water by the Hack shallow convection to the prognostic cloud water scheme that was included in the CAM3 led to a different total parameterization tendency from that of CAM2, but this difference was balanced by a compensating change in the advective tendency to yield the same total moisture tendency. The convective time scale assumed for the Hack shallow convection was halved in CAM3. Thus the convection tendency was weaker in CAM2 but compensated by the prognostic cloud water parameterization tendency which responded to give very similar total parameterization tendencies. CAM3 also had a variety of changes to the cloud fraction parameterization. These affect the radiative heating which in turn modifies the stability of the atmospheric column and affects the convection. But again, the resulting difference in convection tendency that arises from the different stability were balanced by responses in the prognostic cloud water parameterization tendency, yielding a similar total parameterization tendency.

Except for the detrainment of water by the Hack shallow convection the modifications to the parameterizations from CAM2 to CAM3 studied here in the April case all led to compensating changes between the tendencies from the Hack shallow convection parameterization and the prognostic cloud water parameterization. In other words several different parameter settings lead to same net tendency, but distributed differently among potentially competing processes. This indicates the need for more observations to establish which setting is correct., i.e. to tie down parameters in each component. Of course we cannot observe individual processes as formulated in the model, but other variables such as clouds might help. Or perhaps the parameterizations should not be considered as individual processes but unified in some manner that is still cost effective to solve. These are all examples of the delicate balance that determines the model climate and indicate why it is important for each process to be modeled correctly if the model is to be applied to climate change studies.

Although the analysis presented here was performed after the fact in the model development process, it illustrates that this type of analysis would have been useful during the development phase. Based on the findings here different decisions might have been made in the development cycle. Clearly, however, basing development decisions solely on the two periods studied here at a single model column would be dangerous. A large number of cases covering all phenomena being simulated by a climate model is needed. Then the trade offs required in specifying the details of any model can be considered more logically and systematically.

We did not pick the ARM SGP site to deliberately uncover deficiencies in CAM3. It was a site of opportunity where detailed observations are available for periods which have been examined extensively in the past. We also note that perhaps the model climate errors in this region received less attention during development as they were less serious than those that were concentrated on and at least decreased if not eliminated.

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FIGURE LEGENDS

Fig. 1. Mean day 1 forecast temperature (a) and specific humidity (b) errors for CAM3 (solid), EXPJ1 (long dash), and CAM2 (short dash) for the June/July 1997 IOP. Mean CAM3 and CAM2 climate temperature (c) and specific humidity (d) errors for June/July. All at the ARM SGP site.

Fig. 2. Mean forecast 0-24 hour average of terms in the temperature and specific humidity prediction equation for the June/July 1997 IOP for CAM3 (solid), EXPJ1 (long dash) and CAM2 (short dash): (a) total (TOT), dynamics (DYN) and parameterization (PAR) temperature tendencies, (b) total (TOT), advection (ADV) and parameterization (PAR) specific humidity tendencies, (c) moist process (MOIST), radiation (RAD) and PBL parameterization (PBL) temperature tendencies.

Fig. 3. Mean forecast 0-24 hour average temperature tendencies for CAM3 (solid), EXPJ1 (long dash), and CAM2 (short dash) for the June/July 1997 IOP: (a) formation of condensate, (b) rainfall evaporation, (c) freezing of rain water, and (d) melting of snow, each associated with Zhang-McFarlane deep convection (ZHANG), Hack shallow convection (HACK), and prognostic cloud parameterization (CLOUD).

Fig. 4. Mean day 1 forecast temperature (a) and specific humidity (b) errors for CAM3 (solid), EXPJ2 (long dash), and CAM2 (short dash) for the June/July 1997 IOP. Mean forecast 0-24 hour average temperature tendencies from (c) formation of condensate and (d) rainfall evaporation associated with Zhang-McFarlane deep convection (ZHANG), Hack shallow convection (HACK), and prognostic cloud parameterization (CLOUD).

Fig. 5. Mean day 1 forecast temperature (a) and specific humidity (b) errors for CAM3 (solid), EXPJ3 (long dash), and CAM2 (short dash) for the June/July 1997 IOP. Mean forecast 0-24 hour average temperature tendencies from (c) formation of condensate and (d) rainfall evaporation associated with Zhang-McFarlane deep convection (ZHANG), Hack shallow convection (HACK), and prognostic cloud parameterization (CLOUD).

Fig. 6. Mean forecast 0-24 hour average temperature tendencies for CAM3 (solid), EXPJ3 (long dash), and CAM2 (short dash) for the June/July 1997 IOP: (a) moist process (MOIST), PBL parameterization (PBL) and total radiation (RAD), and (b) total (RAD), shortwave (SW), and longwave (LW) radiation.

Fig. 7. Mean forecast 0-24 hour average of terms in the specific humidity prediction equation for the April IOP for CAM3 (solid), ARM (long dash) and CAM2 (short dash): (a) total (TOT), advection (ADV) and parameterization (PAR), (b) moist process (MOIST), Zhang-McFarlane deep convection (ZHANG), Hack shallow convection (HACK), and prognostic cloud parameterization (CLOUD). Mean forecast 0-24 hour average of terms in the liquid water prediction equation: total liquid water tendency (D(H2O)/DT), formation of liquid condensate from vapor by the prognostic cloud water scheme (Q→H2O), conversion of liquid condensate to rain (H2O→PRECIP), conversion of liquid condensate to ice (H2O→ICE), and convective detrainment (DETRAIN) for (c) CAM3, and (d) EXPA1.

Fig. 8. Mean forecast 0-24 hour average Zhang-McFarlane deep convection (ZHANG), Hack shallow convection (HACK) and prognostic cloud parameterization (CLOUD) specific humidity tendencies for (a) CAM3 (solid), EXPA1 (long dash) and CAM2 (short dash), (c) CAM3 (solid), EXPA2 (long dash) and CAM2 (short dash). Mean forecast 0-24 hour average moist process (MOIST) tendencies for (b) CAM3 (solid), EXPA1 (long dash) and CAM2 (short dash), (d) CAM3 (solid), EXPA2 (long dash) and CAM2 (short dash).

Fig. 9. (a) Mean forecast 0-24 hour average Zhang-McFarlane deep convection (ZHANG), Hack shallow convection (HACK) and prognostic cloud parameterization (CLOUD) specific humidity tendencies and (b) moist process (MOIST) tendencies for CAM3 (solid), EXPA3 (long dash) and CAM2 (short dash). Mean forecast 0-24 hour average cloud fraction for (c) CAM3 (solid), EXPA2 (long dash) and CAM2 (short dash) and (d) CAM3 (solid), EXPA3 (long dash) and CAM2 (short dash).

Table 1. Sequential series of experiments for June/July 1997
with accumulated changes from CAM3 back to CAM2

EXPJ1	CAM3 with Zhang convective time scale and autoconversion coefficient set to CAM2 values
EXPJ2	EXPJ1 with conversion between water and ice associated with convective parameterization eliminated
EXPJ3	EXPJ2 with $(1 - C_f)$ term eliminated from rainfall evaporation

Table 2. Sequential series of experiments for April 1997
with accumulated changes from CAM3 back to CAM2

EXPA1	CAM3 without convective detrainment of liquid water associated with the Hack parameterization
EXPA2	EXPA1 with Hack convective time scale set to CAM2 values
EXPA3	EXPA2 with cloud fraction scheme converted to CAM2 scheme