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Energy considerations in the Community Atmosphere Model (CAM)

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Abstract. An error in the energy formulation in the Community Atmosphere Model (CAM) is identified and corrected. Ten-year AMIP simulations are compared using the correct and incorrect energy formulations. Statistics of selected primary variables all indicate physically insignificant differences between the simulations, comparable to differences with simulations initialized with rounding sized perturbations. The two simulations are so similar mainly because of an inconsistency in the application of the incorrect energy formulation in the original CAM. CAM used the erroneous energy form to determine the states passed between the parameterizations, but used a form related to the correct formulation for the state passed from the parameterizations to the dynamical core. If the incorrect form is also used to determine the state passed to the dynamical core the simulations are significantly different. In addition, CAM uses the incorrect form for the global energy fixer, but that seems to be less important. The difference of the magnitude of the fixers using the correct and incorrect energy definitions is very small.

1. Introduction

Atmospheric models represent highly complex, nonlinear processes which continually interact with each other in space and time. Some components such as the atmospheric flow are of relatively large scale and can be approximated with a variety of numerical methods common in computational fluid dynamics. Other components, such as precipitation processes, occur on small scales, often finer than the scales used to represent the fluid flow, and require other approaches to approximate them.

Because of this difference in scales, atmospheric models are conceptually divided into two primary components commonly referred to as the dynamical core and the parameterization suite. The dynamical core approximates the resolved fluid (air) flow of the three-dimensional atmosphere. The discrete representation of the dynamical core generally defines the grid points and/or grid cells underlying the approximations. In order for the model to be computationally tractable the areas associated with those points and cells are generally larger than the scale of the physical processes important for climate. Therefore those processes must be parameterized in the model. The parameterization suite attempts to approximate this subgrid-scale forcing in terms of grid-scale properties from the dynamical core, hence the term parameterization.

The parameterization component itself consists of many interrelated and interacting complex nonlinear processes and is thus further divided into sub-components in order to make the collection practical to solve, hence the reference to a suite of processes. The processes considered individually typically include deep convection, shallow convection, surface exchange, planetary boundary layer turbulent mixing, longwave and shortwave radiation, cloud formation and evolution. Since the processes are subgrid-scale and depend on the grid box averages, the approximations for each process are formulated for a single horizontal grid box, independent of its neighbors. However, the approximations generally involve the vertical column of grid boxes through the depth of the atmosphere. Each column is solved independently of its neighboring columns.

Beginning with the first version of the Community Atmosphere Model, labeled CAM2, the individual components in the parameterization suite in the CAM series have calculated and applied the tendencies in a time-split manner [*Collins et al.*, 2003]. In that splitting, each parameterization component updates the state; the ensuing parameterization component starts from the state updated by the preceding component, and in turn updates the state further. CAM has several dynamical cores available that combine differently with the parameterization suite. The finite volume dynamical core, considered here, is coupled to the parameterization suite in a time-split manner, and receives as input the updated state resulting from the last component of the parameterization suite. By contrast, the spectral transform Eulerian and semi-Lagrangian cores are coupled to the parameterization suite in a process-split manner in which both components start from the same state. The result of the parameterization suite is applied as a forcing in the dynamical core. The terminology used to designate different splitting methods is not universal, see *Williamson* [2002] for more complete descriptions of such terminology used in association with CAM. In this paper, we limit our discussion to the time-split form of the finite volume dynamical core.

The conservation of total energy (including internal, kinetic, and potential energy) is a property of the continuous atmospheric equations and should also be a property of the discrete, time-split numerical approximations. Energy conservation could be easily achieved if total energy were made a prognostic variable and prognosed with conservative numerical schemes. However, that does not guarantee an accurate solution and total energy is not a prognostic variable in almost all atmospheric model formulations. Nevertheless, energy must be conserved to a minimal level in atmospheric models when they are coupled to ocean, sea-ice and land models intended for long climate simulations. *Boville* [2000] originally suggested the atmospheric component should conserve energy to at least 0.1 W m^{-2} to avoid spurious long-term trends in the coupled system. However, for centuries-long climate projections it is probably safer to conserve to 0.01 W m^{-2}. Such conservation can be obtained with the application of an energy fixer as discussed below.

In the parameterization suite each process is formulated and solved individually. Thus, each processe should conserve energy individually in the sense that the energy change by the process equals the net source/sink calculated by that process. When the dynamical core is time-split from the parameterization suite the core provides an approximate solution to the source-free continuous fluid equations. In energy terms, the processes in the dynamical core include transport of energy and conversion of potential to kinetic energy, under conservation of the global integral of total energy. In addition, kinetic energy dissipation either from viscous processes represented explicitly as a term in the momentum equations, or implicitly as a property of the numerical approximations, should conserve energy by contributing heat to the fluid. A heating associated with explicit viscous terms can often be derived and included in the approximations as is done in the CAM spectral transform dynamical core [*Collins et al.*, 2004; *Neale et al.*, 2010a, b] and the spectral element dynamical core [*Taylor*, 2011; *Neale et al.*, 2010b]. However, such heating might not truly represent the physics of the frictional energy transformation. Viscous terms introduced as horizontal diffusion could be treated as a separate parameterization. However they are generally considered as part of the dynamical core, in part because they involve horizontal neighbors and are often implemented for pragmatic reasons to control numerical noise, and in part because the numerical approximations may generate additional damping as a numerical artifact [*Jablonowski and Williamson*, 2011]. Such implicit damping is difficult to determine locally but the global average value can be obtained as a residual. In such cases a global energy fixer can be applied. For example the semi-Lagrangian dynamical core version of CAM3 uses a form described in *Williamson et al.* [2009] and *Jablonowski and Williamson* [2011] while the finite volume dynamical core in CAM uses a different form discussed in *Neale et al.* [2010a, b]. These fixers add a uniform increment to the temperature field to compensate for the global average energy lost by the dynamical core that time-step. While this ensures a global energy balance, any impact of the conservation error would be in the spatial distribution which cannot be determined.

In the time-split approach, the subgrid-scale parameterizations need to calculate changes in the energy associated with sources and sinks. Since the parameterizations are formulated for a grid column, the integral of the energy in the column at the end of the process should equal the integral at the beginning of the process plus the net source given by the fluxes through the column. *Boville and Bretherton* [2003] derive the form of energy to be conserved within the parameterization suite and present a method to update the atmospheric state so that their energy is conserved at all stages within the parameterization suite. Their form of energy is also used in CAM for the global energy fixer associated with the finite volume dynamical core. Unfortunately, the energy they derive is not the appropriate form for the system of equations used in CAM. In the following we summarize their development, explain why their form is inappropriate, describe the necessary corrections to the model formulation, and discuss the impacts on the model simulations.

2. Energy Equations

Boville and Bretherton [2003] derive a total energy equation in the height coordinate system with the goal of constructing energy conservative parameterizations in CAM. That equation, their Eqn. (9), slightly simplified here with regard to the notation for the fluxes, takes the form

$$\frac{d}{dt}\left(K + c_p T + \Phi\right) = \frac{1}{\rho}\frac{\partial p}{\partial t} + F_{net} \tag{1}$$

where $K \equiv \mathbf{v}\cdot\mathbf{v}/2$, $\mathbf{v}$ is the vector velocity, T is temperature, ρ is density, p is pressure, t is time and c_p is specific heat capacity of dry air at constant pressure. The term F_{net} here includes the last two terms in Boville and Bretherton Eqn. (9). The geopotential, Φ, is related to the temperature by the hydrostatic equation. The net fluxes calculated by the parameterizations, i.e. the heating and momentum forcing, are denoted F_{net}. Here we follow *Boville and Bretherton* [2003] and do not include the energy associated with water in its various forms which could be included in the conservation equation, so F_{net} also includes heating/cooling associated with the phase changes of water. Water is assumed to be conserved by the numerical approximations. In CAM, the individual parameterizations do not change pressure, and do not include dynamical processes such as resolved advection since those are handled by the time-split dynamical core. Thus for application to the parameterizations in a column *Boville and Bretherton* [2003] simplified

Eqn. (1) to

$$\frac{\partial}{\partial t}\left(K + c_p T + \Phi\right) = F_{net} \tag{2}$$

The implementation of Eqn. (2) in CAM adopted a simple forward differencing which for temperature updated by the ith parameterization component in the time-split sequence can be written

$$c_p T^i + \Phi\left(T^i\right) = c_p T^{i-1} + \Phi\left(T^{i-1}\right) + \Delta t F(T)^i_{net} \tag{3}$$

where T^{i-1} is the state from the previous component, $F(T)^i_{net}$ is the thermal energy tendency from the ith component and T^i is the updated state. Since $\Phi(T)$ depends on T, the combination $[c_p T^i + \Phi(T^i)]$ can be inverted to obtain T^i. *Boville and Bretherton* [2003] describe how this is done in CAM. Similar update equations are applied in CAM for momentum and thus the kinetic energy component. These terms are treated correctly in *Boville and Bretherton* [2003] and thus we do not include them here. Only the thermodynamic component needs correction. Eqns. (1) and (2) were derived for the z vertical coordinate but applied to CAM which is based on transformed pressure vertical coordinates. Those equations do not apply in that system. We derive the corresponding form for the hybrid-pressure vertical coordinate of CAM shortly.

CAM also incorrectly implemented a global energy fixer based on the energy defined in Eqn. (2). The fixer conserves the vertical and global integral of that form since the dynamical core calculates energy exchanges along with transport which are not necessarily local. As is the case in CAM, dynamical core numerical approximations are often derived to conserve the average of the conversion of potential energy to kinetic energy. In such models the global energy fixer is intended to compensate for energy loss from inherent numerical dissipation, and non-conservation due to time truncation errors. It may also include other non-conservative numerical processes such as vertical remapping or possibly errors in the parameterizations.

We now summarize the global energy integrals appropriate for conservation by the dynamical core in CAM and then derive the local form appropriate for the parameterization updates following the approach of *Boville and Bretherton* [2003]. *Laprise and Girard* [1990], following *Kasahara* [1974], derive the appropriate equations in the hydrostatic transformed pressure coordinates:

$$\frac{\partial}{\partial t}\int_A \left[\int_{\eta_{top}}^{\eta_s} \left(K + c_p T\right)\frac{\partial p}{\partial \eta} d\eta + p_s \Phi_s\right] dA = \int_A \int_{\eta_{top}}^{\eta_s} F_{net}\frac{\partial p}{\partial \eta} d\eta \, dA \tag{4}$$

An equivalent form is

$$\frac{\partial}{\partial t}\int_A \left[\int_{\eta_{top}}^{\eta_s} \left(K + c_v T + \Phi\right)\frac{\partial p}{\partial \eta} d\eta + p_{top} \Phi_{top}\right] dA = \int_A \int_{\eta_{top}}^{\eta_s} F_{net}\frac{\partial p}{\partial \eta} d\eta \, dA \tag{5}$$

with c_v denoting the specific heat at constant volume [*Neale et al.*, 2010b, Section 3.2.2]. The transform pressure vertical coordinate is denoted by η, subscripts s and top denote the bottom (surface) and top of the model, respectively, and the integral dA denotes the global horizontal integral. It is immediately apparent that the energy form in Eqn. (2) is inconsistent with either form appropriate for the dynamics, Eqn. (4) or Eqn. (5). The dynamics equation involving c_p, Eqn. (4), does not include Φ in the vertical integral and the equation which includes Φ in the vertical integral, Eqn. (5), has c_v instead of c_p.

When the dynamical core is time-split from the parameterization components as with the finite volume core there is no net forcing and the right-hand side Eqn. (4) or (5) should be zero in CAM. As explained in *Boville and Bretherton* [2003], generally, if the model includes an explicit horizontal momentum diffusion to stabilize the numerical approximations or to shape the tail of the energy spectrum, a compensating heating can be added to give zero net forcing. However, if the numerics contain inherent damping, or if other diffusion terms are added to the dynamics, a global "energy fixer" is generally added to yield energy conservation since the associated local damping is difficult or impossible to determine and compensate [*Jablonowski and Williamson*, 2011]. CAM-FV has inherent numerical damping and thus applies a global energy fixer to obtain conservation [*Neale et al.*, 2010b]. However, rather than being based on Eqn. (4) or Eqn. (5) that fixer is based on the global integral of the form of energy in Eqn. (2). The assumptions that went into Eqn. (2) are clearly inappropriate for the dynamical core. We do not know why this energy was chosen, unless it was thought to be more consistent with the parameterizations, or perhaps a stable climate with a small global average net energy flux could not be obtained from the parameterizations in a long simulation when the dynamical core and parameterizations conserved different energies.

We now derive the local energy equation for the hydrostatic transformed pressure coordinates of CAM following the approach of *Boville and Bretherton* [2003]. Starting with the thermodynamic equation in transformed pressure coordinates, *Laprise and Girard* [1990] Eqn. (2.2), adding $d\Phi/dt$ to both sides and substituting the hydrostatic equation gives

$$\frac{d}{dt}\left(c_pT+\Phi\right)=\frac{\partial\Phi}{\partial t}+\frac{RT}{p}\frac{\partial p}{\partial t}+c_pQ+\mathbf{v}\cdot\nabla\Phi+\frac{RT}{p}\mathbf{v}\cdot\nabla p \qquad (6)$$

where R is the gas constant for moist air and Q is the parameterized sub-grid scale heating. Starting with the momentum equation in transformed pressure coordinates, *Laprise and Girard* [1990], Eqn. (2.1), and taking the dot product with $\mathbf{v}$ gives, after some manipulation,

$$\frac{d}{dt}(K) = -\mathbf{v} \cdot \nabla\Phi - \mathbf{v} \cdot (RT\nabla \ln p) + \mathbf{v} \cdot \mathbf{F} \tag{7}$$

where **F** is the parameterized momentum forcing. Adding Eqn. (6) and Eqn. (7) gives

$$\frac{d}{dt}(K + c_pT + \Phi) = \frac{\partial \Phi}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial t} + F_{net} \tag{8}$$

which has an additional term compared to the *Boville and Bretherton* [2003] form, Eqn. (1). For the CAM parameterizations, where pressure is not changed and dynamics is absent, Eqn. (8) simplifies to

$$\frac{\partial}{\partial t}(K + c_pT) = F_{net} \tag{9}$$

Eqn. (9) is completely consistent with Eqn. (4). The parameterizations can be updated by

$$c_pT^i = c_pT^{i-1} + \Delta t F(T)^i_{net} \tag{10}$$

rather than Eqn. (3) and the dynamical core global energy fixer can be based on Eqn. (4) with complete consistency.

We note that with the application of time-splitting each parameterization that changes water vapor should change the pressure because pressure in CAM is defined to be moist. However, the individual parameterizations in CAM do not change the pressure. Instead, after the entire parameterization suite is completed, the pressure is corrected in each layer to account for the net water vapor change which preserves the dry mass of the atmosphere. At the same time, constituent specific ratios are modified to conserve constituent masses. The moisture-related change in pressure also has energy implications associated with energy of the non-vapor water components. *Boville and Bretherton* [2003] (end of Section 3) state that a form conserving the energy transferred to and from the non-vapor components was being tested but apparently it was not successful and was not adopted in the model. This moisture effect energy conservation discrepancy, about 0.3 W m^{-2} global-annual average sink in CAM, was folded into the global energy fixer associated with the dynamical core. We do not discuss this further here, but work to rectify this issue is underway.

3. Simulations

We have implemented the correct energy in the parameterization updates and in the global energy fixer associated with the finite volume dynamical core in CAM5.2 and carried out a 1 degree AMIP type simulation starting from 1 January 1979. CAM5.2 is the atmospheric component of CESM1.1 (see http://www.cesm.ucar.edu/models/cesm1.1/cam.) In all simulations presented here all free parameters are set to the standard CAM5.2 values. We present 10-year annual averages of a few variables from the simulation averaged for 1980 to 1989. These are compared to a matching control simulation with the standard 1 degree CAM5.2. In the following these simulations are labeled CORRECT and CAM, respectively. These and other experiments are summarized in Table 1. The distinction between the two columns giving T passed to the parameterizations and T passed to the dynamical core will become clear after Eqn. (11) is introduced. The code flow for the simulations is also summarized in Fig. 1.

Table 2 compares ten-year annual average, global averages of a few primary variables that are routinely examined when tuning the model. These are a subset of the many considered during model development. The averages from the two simulations (columns one and three) are remarkably close. In fact one might think these are just from two different realizations of the same model rather than from two different models.

To address this possibility we ran a simulation with the corrected model starting with a perturbed initial condition - a rounding sized random increment was added to the temperature in the initial file. The second column of Table 2 labeled CORRECT/PERT gives the global averages for this simulation. The differences between CORRECT and CAM are of similar magnitude to the differences between the runs with different initial conditions. None are physically significant.

Figure 2 (top) shows the ten-year annual average, zonal average temperature difference between the simulations with the correct energy formulation (CORRECT) and with CAM. These differences are also remarkably small, being less than 0.25K over most of the domain. The maximum difference is just over 0.5K in the southern lower polar stratosphere. The middle panel shows the difference between the two simulations with the correct energy formulation (CORRECT and CORRECT/PERT). Recall the only difference is the initial condition. The differences are comparable in magnitude to those in the top panel but the structures are slightly different. Table 3 shows the RMS differences of ten-year annual averages of selected horizontal fields. The left column contains CORRECT minus CAM. The middle contains CORRECT minus CORRECT/PERT. As with the other measures the RMS differences between the two different models are very small and comparable to the differences from the perturbation simulation.

One might wonder why the differences associated with the different energy definitions are so small. CAM uses Eqn. (3) to update the temperature after each parameterization and passes that temperature to the next parameterization, while CORRECT uses

Eqn. (10). However, after the last parameterization in CAM the final temperature from Eqn. (3) is not passed to the dynamical core. Instead, unexpectedly, a final temperature is passed that is calculated from the sequence of fluxes $F(T)^i_{net}$ determined by the parameterizations.

$$T^I = T^0 + \frac{1}{c_p} \sum_{i=1}^{I} \Delta t F(T)^i_{net} \tag{11}$$

At first glance this looks consistent with updating the temperature using the correct energy Eqn. (10). However the temperature T^{i-1} which was input to the parameterization to calculate $F(T)^i_{net}$ comes from Eqn. (3) rather than from Eqn. (10) and the two input temperatures are only the same for the first parameterization called in the suite. *Boville and Bretherton* [2003] do describe this calculation of the final temperature in the top left column of page 3884 stating that this leads "to a small energy imbalance" that "will be addressed in a future model revision." We have calculated the time average, global average of this energy imbalance in CAM5.2 (i.e in terms of the *Boville and Bretherton* [2003] energy) to be effectively a source of 0.9 W m^{-2}, which is absorbed into the global average energy fixer applied after the dynamics. We do not know why this choice was made in CAM. In fact a code comment refers to it as a "kludge". We queried C. Bretherton and he replied that turbulent dissipation heating due to momentum diffusion was his main contribution to the paper and he was not sure why Boville ultimately introduced that kludge (personal communication, 2013). At the end of this section we will show the effect of passing T from Eqn. (3) instead of from Eqn. (11) to the dynamical core.

It is also not clear why using the temperature from Eqn. (3) in the parameterizations in CAM instead of that from Eqn. (10) as in the corrected model seems to have such a small effect on the heating rates calculated by the parameterizations. Both CAM and

CORRECT essentially use Eqn. (11) to obtain the temperature passed to the dynamical core, the only difference being the sequence of temperatures passed between the parameterizations and thus defining the input values to the parameterizations. We might expect more of an accumulated effect in fluxes calculated by the parameterizations themselves, but this appears not to be the case. It is possible that there is a compensation between the different processes, in which a change in heating by one process is offset by an opposite change in a following process, especially with the time-split formulation. This does not appear to be the situation here. We have examined the differences between the two experiments in the heating from individual processes. There is only a small compensation between the shallow convection and the macrophysics. The difference in the total heating does seem to be an accumulation over the processes with little compensation.

Another difference between the two models is the energy definitions used in the global average energy fixers. It is possible that this difference offsets differences in the parameterized fluxes. To examine this possibility we did an additional simulation modifying CAM to pass T from Eqn. (10), i.e. the correct formulation, to the parameterizations rather than T from Eqn. (3), the incorrect formulation, but continuing to use the incorrect energy formulation for the global energy fixer. This simulation is labeled CAM/PARAMS CORRECT. The resulting ten-year annual averages are shown in Fig. 2 and the Tables. Table 2 presents the global averages from this simulation in the last column. They are very close to the other simulations. However, the net energy fluxes are closer to the two simulations with the correct energy formulation than to CAM, presumably reflecting the different states passed to the parameterizations. This implies that the energy formulation used for the global energy fixer has less effect. In fact, the difference between the fixers from the cases CORRECT and CAM is very small, the 10-year average difference being 1.52×10^{-5} K/day compared to 4.30×10^{-3} K/day and 4.32×10^{-3} K/day for the values themselves for CORRECT and CAM simulations, respectively. The right column of Table 3 shows the RMS differences of CAM/PARAMS CORRECT with CAM. The differences are similar to the others in the table, perhaps slightly larger for a few variables but not physically significant. Figure 2 bottom shows the zonal average temperature difference between CAM/PARAMS CORRECT and CAM. The structure of the difference resembles that of the difference between CORRECT and CAM, but the amplitude is slightly larger. This also implies that the structure of the difference is likely due to the different fields passed between the parameterizations and thus the heating passed to the dynamics, rather than to the energy formulation applied in the global fixer. However the differences are still quite small, comparable to the differences from the perturbation run.

In a single time step, after each parameterization the difference in T from Eqn. (3) (used by CAM) and from Eqn. (11) (but accumulated only through the previous parameterizations and calculated as a diagnostic) is rather small. The top panel of Fig. 3 shows the ten-year annual average zonal-mean of the difference of temperature after the last parameterization of the suite, calculated according to Eqns. (3) and (11) from the standard CAM simulation which used Eqn. (3) for the parameterization updates but passed the value from Eqn. (11) to the dynamical core. The largest average differences are 0.01K. The difference in fluxes calculated by the parameterizations are probably also relatively small. However we are not able to determine that without a major change to the model to allow a second, diagnostic calculation of each parameterization based on the other temperature. Apparently however, the difference in fluxes has little effect on the simulation as indicated by CAM/PARAMS CORRECT in the Tables and Figures. On the other hand, if the temperature from Eqn. (3) is passed to the dynamical core, i.e. if CAM had used the incorrect energy formulation consistently, the effect on the simulations becomes significant. This is seen in the global averages in Table 2 and in the bottom panel of Fig. 3 which shows the difference of a simulation with the standard CAM5.2 minus a simulation with CAM5.2 where the updates that use Eqn. (3) are not replaced by the kludge at the end of the parameterization suite. This latter simulation is labeled INCORRECT. Note the contour interval in Fig. 3 is 10 times larger than in Fig. 2 and that the ordinate is logarithmic rather than linear since the largest differences are at and above the tropopause where they reach maxima of about 10K near the poles. Typical errors in the tropics and in the mid-latitudes are of the order of 1-2K. The meridional dependence of the climate's sensitivity to the parameterization updates is consistent with a stronger cancellation between diabatic and dynamic heating tendencies characteristic of the tropics. The total diabatic heating rates for example show systematic differences of 10% between the simulations in the annual means. Seasonal means show larger differences still. Also noteworthy are systematic regional differences in the net total heat flux at the surface, which have implications for coupled simulations with an interactive ocean component and lead to systematically different simulated SST patterns. Nevertheless, given the difference in vertical structures arising from the different temperature calculations shown in the top panel of Fig. 3 and in Fig. 1 of *Boville and Bretherton* [2003] we might have expected larger differences in the tropics. However those differences interact with the dynamics to create the different climates.

The time-split structure and energy conservation issues of CAM5.2 discussed above are not restricted to the finite volume dynamical core. The spectral element core shares the same structure. Since the correct energy formulation was proposed for inclusion in CAM5.4, as part of the development evaluation it was further tested in standalone simulations with both the finite volume and spectral element dynamical cores in CAM5.3. Such standalone simulations were carried out for most of the candidate changes. These simulations are documented at www.cesm.ucar.edu/working_groups/Atmosphere/development/cam6/cam5.4/. Atmospheric Model Working Group (AMWG) standard diagnostics comparing the simulations from CAM5.3 modified to use the correct energy with ones from standard CAM5.3, which continued to use the incorrect energy formulations of CAM5.2, are reachable from that site under categories C8 and C8b for the finite volume and spectral element cores, respectively. Although the standard contour intervals used there are not as discriminating as used in this paper, there is no indication that the conclusions drawn here with the finite volume core are invalid for the spectral element core. On that web site, the differences introduced by the energy definition changes can also be compared with differences introduced by other changes proposed during the CAM5.4 development.

4. Summary

An error in the energy formula used in CAM is identified. The error has percolated through all versions of CAM up to and including CAM5.2. The incorrect form of energy was derived and used to conserve energy when updating the time-split components within the parameterization suite. It was originally derived for non-hydrostatic and hydrostatic height coordinates but applied to hydrostatic hybrid pressure coordinates. We derive the correct form of energy for application to the parameterization suite for the hydrostatic hybrid pressure system. The incorrect form was also used in the global energy fixer applied with the finite volume dynamical core, but not in the fixer applied to the other dynamical cores available in CAM.

We implemented the correct energy in the parameterizations and in the global energy fixer and carried out a long simulation. We present 10-year annual averages of AMIP simulations from the corrected model and from the original model. We present a few global averages which indicate insignificant changes in cloud radiative properties, in the net energy fluxes at the top and bottom of the atmosphere and in the precipitation and precipitable water. The changes are comparable to natural variability determined by a second simulation with the correct energy formulation but starting from a different initial condition. The zonal average temperature differences are also insignificant, as are RMS differences for selected horizontal fields. The primary reason the differences are not significant is that the incorrect energy was not used consistently in the original CAM. It was used for the global energy fixer and to determine the state passed between parameterizations. However, the final temperature from the parameterization suite that was passed to the dynamical core was calculated from the parameterized fluxes applied in a manner consistent with the correct energy. On the other hand, when the incorrect energy is used consistently, i.e. when the state passed to the dynamical core from the parameterized fluxes is determined using the incorrect energy, the simulation is affected significantly. In this case all aspects of the model are based on the incorrect energy. The major differences are around and above the tropopause. Application of the incorrect energy for the global energy fixer has an insignificant effect. The difference between the fixers using the different energy definitions was 0.05% of the fixers themselves. The results here are based on AMIP simulations with specified sea-surface temperatures. There might be small, local systematic differences in surface fluxes that affect coupled simulations. However, in developing CAM5.4 any such effect on coupled runs has been small compared to changes in the parameterizations.

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Table 1. Simulation summary with equations used by different components

LABEL	DESCRIPTION	T passed to params[a]	T passed to dynam[b]	Energy Fixer[c]
CORRECT	CAM5.2 with correct energy	Correct (10)	Correct (10)	Correct (4)
CAM	CAM5.2 CONTROL simulation	Incorrect (3)	Correct (11)	Incorrect (2)
CORRECT/ PERT	initial perturbation added to CORRECT	Correct (10)	Correct (10)	Correct (4)
CAM/PARAMS CORRECT	CAM5.2 modified to pass correct energy to parameterization	Correct (10)	Correct (11)[d]	Incorrect (2)
INCORRECT	CAM5.2 modified to pass incorrect but consistent energy to dynamics	Incorrect (3)	Incorrect (3)	Incorrect (2)

[a] Equation for T passed to the next parameterization.

[b] Equation for T passed to the dynamical core.

[c] Equation for energy used in global energy fixer with dynamical core.

[d] When Eqn. (10) is used for T passed to the parameterizations, Eqn. (11) is equivalent to Eqn. (10) for T passed to dynamical core.

Table 2. Ten-year annual average, global averages

VARIABLE	CORRECT	CORRECT/ PERT	CAM	CAM/PARAMS CORRECT	INCORRECT
Net energy flux ($W\ m^{-2}$)[a]					
Top of model	0.485	0.479	0.558	0.485	3.866
Surface	0.477	0.480	0.542	0.458	3.833
Cloud fraction (%)					
High	37.590	37.541	37.545	37.623	40.562
Low	41.936	41.984	41.894	41.982	42.322
Middle	25.700	25.673	25.713	25.671	25.679
Total	63.144	63.173	63.109	63.196	65.348
Cloud forcing ($W\ m^{-2}$)					
Longwave	22.395	22.393	22.447	22.425	25.017
Shortwave	−48.677	−48.665	−48.677	−48.720	−49.548
Precipitation (mm day^{-1})	3.029	3.028	3.029	3.027	2.921
Precipitable water (mm)	25.125	25.097	25.124	25.125	25.003

[a] Positive downward.

Table 3. RMS differences of ten-year annual averages

VARIABLE	CORRECT versus CAM	CORRECT versus CORRECT/ PERT	CAM/PARAMS CORRECT versus CAM
Surface Pressure (mb)	0.42	0.43	0.48
200 mb Temperature (K)	0.17	0.17	0.21
850 mb Temperature (K)	0.18	0.18	0.18
200 mb zonal wind (m s^{-1})	0.65	0.69	0.83
500 mb Geopotential height (m)	0.05	0.05	0.06
Precipitation (mm day^{-1})	0.19	0.02	0.19
Precipitable water (mm)	0.29	0.29	0.30
Longwave cloud forcing (W m^{-2})	0.96	0.99	0.94
Shortwave cloud forcing (W m^{-2})	1.65	1.64	1.68

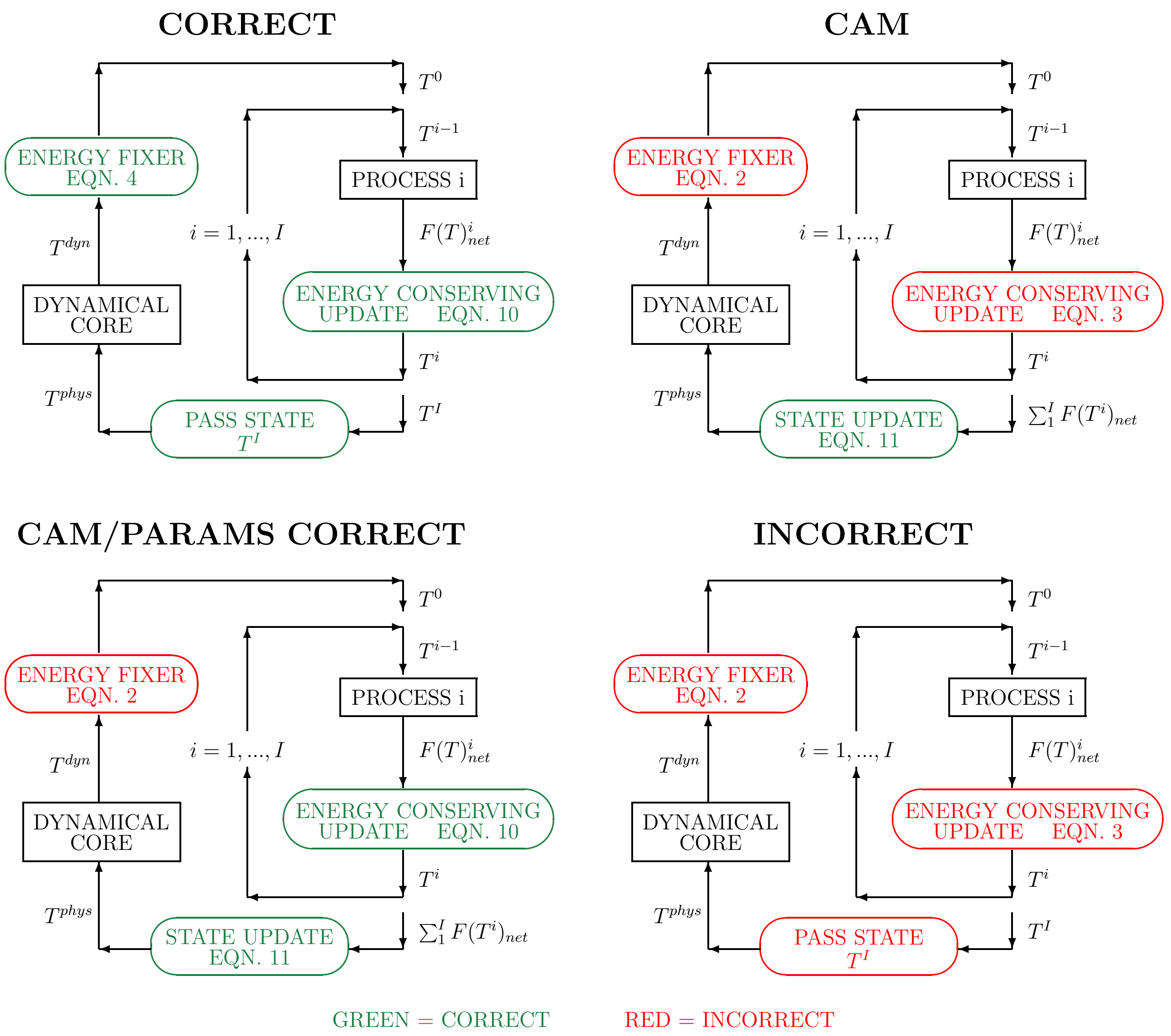

Figure 1. Schematic code flow diagrams illustrating the processes discussed in this paper for the cases listed in Table 1. Green denotes correct energy used, red denotes incorrect used.

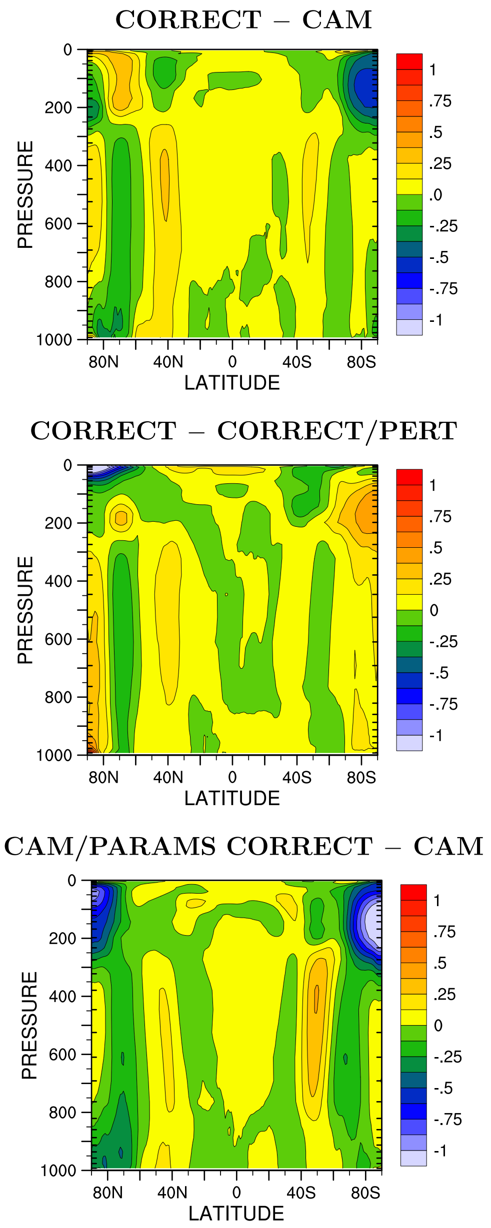

Figure 2. Ten-year annual average, zonal average temperature differences. Top: simulation with correct energy formulation minus simulation with standard CAM5.2. Middle: simulation with correct energy formulation minus simulation with initial perturbation added to same model. Bottom: simulation with CAM/PARAMS CORRECT, which passes T from Eqn. (10) between parameterizations, minus simulation with CAM5.2, which passes T from Eqn. (3) between parameterizations. Contour interval: 0.125 K.

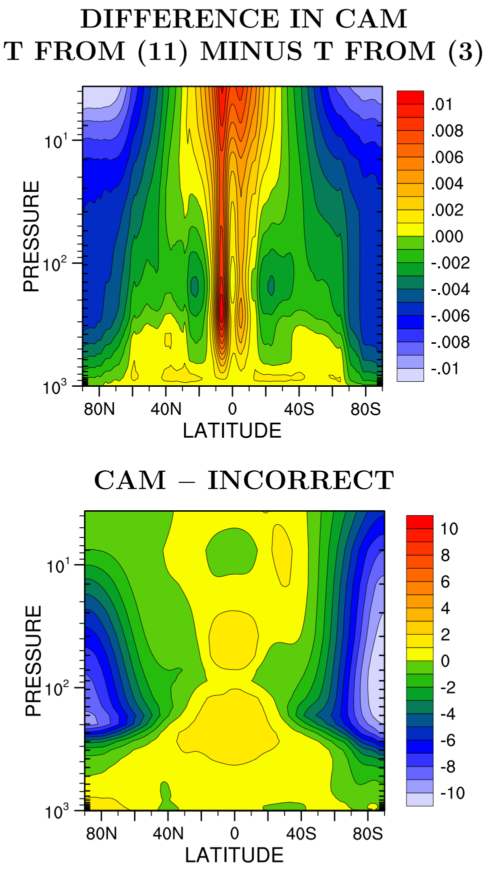

Figure 3. Top: Difference in temperature at the end of the parameterization suite obtained from Eqn. (11) minus that obtained from Eqn. (3) in a single simulation with CAM5.2 which uses the values from Eqn. (3) in the parameterizations. Values from Eqn. (11) were passed to the dynamical core. Contour interval: 0.001K. Bottom: Difference of temperatures in two simulations passing different temperatures from parameterization to dynamical core: CAM which passes T from Eqn. (11) minus INCORRECT which passes T from Eqn. (3). Contour interval: 1 K.