CCM notes and tuning

Phil Rasch pjr@ucar.edu
Bill Collins?
Jim Hack?
any others?

National Center for Atmospheric Research
P.O. Box 3000-80307
Boulder CO 80307

August 7, 2000

Contents

1 Introduction:

This document contains notes relevant to tuning, testing and extending the so-called “baseline” model prototype for CCM4 (currently version number ccm3.x.y). The prototype is to form the base upon which a matrix of simulations are to be made and evaluated. Here is the matrix definition as of 15 April 2000.

Dynamics	variation on Zhang/McFarlane Hack	Relaxed Arakawa Shubert	Prognosed Arakawa Shubert	other?
Eul/SLT	x	x	x	x
SLT	x	x	x	x
Lin Rood	x	x	x	x
SEAM?	x	x	x	x

The baseline model is a descendent of the standard CCM3 that has been modified in the following ways:

- Extensive modifications to improve portability, improve the coupling implementation between component models, and allow better multitasking on a broad variety of computing platforms.
- Extensive modifications to the long and shortwave radiation codes (Collins 2000, in preparation) to improve upon the the CCM3 random overlap assumption by a more careful cloud overlap treatment. This is necessary for: 1) a better physical representation of clouds; 2) to allow a much higher vertical resolution without the extremely high cloud cover generated with a random overlap assumption.
- The addition of the prognostic cloud water parameterization documented in [Rasch and Kristjánsson(1998)].
- A change in the number of vertical levels from 18 in the standard CCM to 30 in the prototype.
- Addition hooks appearing as "stubs" (which are calls to dummy subroutines) to facilitate running climate change calculations that include an interactive sulfur cycle [Barth et al.(2000), Rasch et al.(2000), Kiehl et al.(2000)].

While the model is in a good top of atmosphere balance, and hence can be run for meaningful multi-year, or coupled runs, it has not been carefully re-tuned to maximize the quality of the simulation at this time. The simulation is currently somewhat degraded compared to the standard CCM simulations described in the special issue of *J. of Climate* ([Randall(1998)]), or the paper describing the *prognostic cloud water* simulations ([Rasch and Kristjánsson(1998)]). [**A web page is under development to document the climate of the model. The procedure to access that web page will be indicated here when it is available.**] We believe the degradation can be entirely attributed to the increased vertical resolution of the prototype, which exacerbates biases already present in the 18 layer version. We believe it is important to include the higher vertical resolution because the lower resolution is marginal for many boundary layer processes. We expect that changes to the boundary layer and convective parameterizations will improved the quality of future simulations.

The next two sections outline

- How a new convection scheme can be coupled into the CCM. See also CCM users guide for generic advice on modifying the CCM.
- Some ways to tune the model

2 Advice on coupling new convection schemes into the model

Typically, a parameterization is invoked in two stages: 1) an initialization subroutine which sets up constants in common blocks or modules is called prior to beginning the time loop, and 2) blocks of columns are processed within the time loop. Historically the block of columns would reside along a line of constant latitude, but this is changing with new stratagems for parallel processing.

The initialization scheme is typically called in subroutine `inti`.

The convection scheme itself is called in subroutine `tphysbc`.

Inside `tphysbc` we typically proceed by sequentially invoking the following physics parameterizations

- dry adiabatic scheme (subroutine `dadadj`)
- deep convection scheme to update the temperature (heat) and water vapor fields (currently the Zhang/McFarlane scheme `conv_ccm`).
- convective transport of other constituents (not water vapor or heat — subroutine `convtran`)
- shallow convection scheme (currently the Hack scheme `cmfmca`)
- cloud fraction parameterization (subroutine `cldfrc`)
- cloud water parameterization (subroutine `pcond`)
- backup stratiform condensation scheme (subroutine `cond`)
- radiation (subroutine `radctl`)
- setup surface transfer of fields

In addition to changing the temperature and water vapor fields, the convection scheme needs to interact with the other parameterizations in the following ways:

- Convection should provide a mechanism for transporting other trace constituents. Currently the model also convectively transports cloud water. Other species are not required for the evaluation of the quality of the simulation, but will be required before the formulation can be accepted as an official part of the CCM. Please talk to Phil Rasch when you are ready to deal with this issue, as the interaction between convection and scavenging of soluble species is very complex. *For a first test you can comment out the calls to convtran.*
- The model currently assumes that the fraction of the gridbox occupied by cirrus anvils is proportional to the rate (units of 1/s) at which convection from updrafts detrain into the environment above 500 hPa. The variable returned to `tphysbc`by the current convection scheme `conv_ccm` is called `du2`, which is in turn used by `cldfrc`. Cloud cover is not strongly dependent upon this calculation, because the current convection scheme usually saturates a volume where detrainment occurs, so that a cloud is also generated through the relative humidity criterion. If your parameterization does not supply water vapor so vigorously to the upper troposphere, this cirrus anvil parameterization may be important to you. If you don't think it is important then `du2` may be left set to zero.
- Subroutine `pcond` allows the possibility that convection will detrain cloud condensate from the updrafts into both the environment and directly into the non-convective clouds (anvils and decaying cloud elements). A fraction of the detrained condensate is assumed to evaporate immediately into the environment. The balance of condensate is fed immediately into the cloud water variable. The variable representing the detrainment of cloud water from updrafts is called `dlf`. If you decide to allow this option you must put a line that looks like

  ```
  #define PCWDETRAIN
  ```

  into the file called `params.h` and fill `dlf` with appropriate values (units of kg/kg/s). PCWDETRAIN is not defined in the 30 level version of the CCM because it allows a massive detrainment of cloud water at about 800 mb at 30S in the western pacific, and western atlantic. The standard Zhang/McFarlane scheme in CCM3 prevented this by forcing all detrained cloud water to be converted immediately to rain, and fall out of the column as precipitation when the relative humidity exceeded 80% (following [Tiedtke(1989)]). With the 18 level version of CCM including cloud water I was able to relax this constraint. With the 30 level model I was not able to, and so reverted to the original `conv_ccm` behavior.

2.1 Conservation issues

It is important that all parameterization satisfy column conservation constraints. These are:

- The water vapor removed from the column, must appear as either: 1) detraining cloud water (`dlf`); or 2) precipitation at the surface (`precc`). That is,

  $$\int_0^{P_s} (q_{new} - q_{old}) dp/g = (precc + \int_0^{P_s} (dlf) dp/g) \Delta t$$

  where q_{new} is the water vapor mixing ratio after the convective parameterizations, and q_{old} is the mixing ratio before convection.

- The water vapor converted to condensate must release the appropriate amount of latent heat which appears as a temperature change. The convection should conserve a thermodynamic invariant (like moist static energy) within a column.

- Any other trace species transported by the convection scheme should conserve mass.

There are currently very small conservation errors in the prototype model. These are caused by:

- Extremely rare corrections to negative mixing ratios generated by the convection and vertical diffusion parameterizations. Error messages are issued by subroutines when these corrections take place.

- ignoring the latent heat of fusion in the conversion of water vapor to condensate or phase change of condensate at temperatures below freezing.

These conservation errors result in small imbalances ($<< 1$ W/m^2) in the CCM. We note that there are also small inconsistencies present in conservation that are associated with the use of a *moist mixing ratio*, and *moist surface pressure* in the model. In principle, as any process removes water vapor from a cell, the surface pressure (P_S), and the mass of air (dp) should change in a grid volume. This ought to also imply a change to any mass specific quantity affected by the parameterization. These changes are ignored in CCM parameterizations from one process to the next. We typically insist that processes conserve assuming a fixed mass of air (and hence a fixed surface pressure) within a parameterization.

3 Advice on retuning the model

3.1 Knobs that can be tuned to adjust TOA radiative energy balance.

Whenever you change the model simulation in any important way, the model energy balance will change. Presumably, the changes you make will improve the simulation in some way. After you perturb the model it is important to retune the model energy balance so that the simulation conserves energy (e.g. Energy in = Energy out in the longterm average). Here are some parameters that can be adjusted to restore energy balance.

- **Cloud Fraction:** The cloud fraction in the model may be adjusted in subroutine `cldfrc`. There are a number of relevant parameters one can adjust to improve the TOA balance (see section 4.a.1 of the CCM document for a discussion of how the parameters enter in the model).
  - The **relative humidity threshold** `rhminl` controls the point at which low clouds (pressure greater than 750 hPa) begin to form. By increasing this threshold you decrease cloud fraction, and thus primarily the brightness of the planet.
  - The **recipricol of the Brunt-Vaisala frequency parameter** `rbvflim` modulates the relative humidity threshold for high clouds (see equation 4.a.8 of the CCM model description, where `rbvflim` appears as the constant 3.5 x 10^{-4}). The assumption is that unstable volumes have more inhomogeniety so clouds are more prevelant in unstable situations than in stable situations at a given relative humidity. By changing this parameter you influence the relative humidity threshold for high clouds. The high cloud amount strongly influences the outgoing longwave radiation and associated longwave cloud forcing. The current model is very moist in the upper tropical troposphere. This means that the model has a very high cloud fraction in the upper tropical troposphere. In stable situations, high clouds do not form until a cell is nearly saturated.
  - The parameter controlling the **shutdown of clouds under subsidence** conditions(ω_c, see equation 4.a.4 of [Kiehl et al.(1996)]) can be varied to differentially modulate low cloud amount between equatorial and extra-tropical low clouds. If you set the parameter to zero you allow no clouds in subsiding air. Setting the value higher allows some clouds to form in subsidence. This parameter tends to modulate low clouds quite strongly in the midlatitudes.
  - **differential threshold at which clouds form over land vs ocean**. [Kiehl et al.(1996)] made the relative humidity threshold for low clouds above ice free land masses different from that over ocean surfaces, arguing that clouds ought to form more easily when more particles are available as CCN. This phenomena is actually more easily represented by a dependency in the cloud microphysics, but the parameterization was developed prior to the prognostic cloud parameterization. In principle one could remove this dependence — but there is at least one other reason clouds might form more easily over land masses. This is the existence of subgridscale orographic features that introduce subgridscale variability in vertical velocity, and relative humidity. One could imagine therefore that clouds still form more easily where these inhomogenieties exist ([?]. Therefore I have modified the parameterization to remove the dependence on snow cover, but still allow the earlier onset of clouds over land masses (we could put something in to make it resolution dependent, but I haven't done it.
- The optical properties of clouds depend strongly on the **Effective radius of the cloud droplets and ice crystals**. These parameters are defined in subroutine `cldefr`. There are two parameters, `rei`, and `rel` that control the ice crystal and liquid water drop effective radius, and thus influence the cloud optical depth (see eqns 4.b.3-6 of CCM3 documentation). The ice cloud optical depth is strongly influenced by changing `rei`. A decrease in the effective radius will increase the optical depth, and thus make the ice clouds more important optically. The parameterization for ice radius is also temperature/pressure dependent. Small particles are assumed at low altitudes, to allow the parameterization to agree qualitatively with the small particles seen near the surface in polar regions. larger ice particles are assumed at higher altitudes characteristic of mid-latitude and tropical ice clouds. The warm cloud effective radius is controlled by changing `rel`. Thus, changing `rei` affects longwave cloud forcing most

strongly, with a secondary influence on the brightness of polar clouds (controlled by changing the vertical distribution assumed for the ice clouds). Low cloud brightness is most strongly controlled by changing `rel`, with a secondary weak influence on tropical and midlatitude OLR.

- **Cloud water mass**, is determined in subroutine `pcond` (file cldwat.F). Condensate mass also affects the cloud optical depth (again, see section 4.b of the CCM model description). Increasing the mass of condensate will increase the cloud optical thickness in both the longwave (tending to warm the atmosphere), and the shortwave (tending to cool the atmosphere). The microphysical processes that control the cloud water amount are defined in [Rasch and Kristjánsson(1998)]. There are currently 5 processes that effect the condensate distribution. These are:

  - Autoconversion of liquid condensate to precipitation (PWAUT).
  - Autoconversion of ice condensate to precipitation (PSAUT).
  - Accretion of liquid water by rain (PRACW).
  - Accretion of liquid water by snow (PSACW).
  - Accretion of ice water by snow (PSACI).

  Figure 1 of [Rasch and Kristjánsson(1998)] shows the relative importance of each of these terms in controlling removing condensate as a function of latitude and height. The fractional contribution of each of these terms is written to the history files so you can examine their role by plotting these fields. By increasing or decreasing the importance of each term you will effect the mass of condensate preferentially in some region and season. Of course, due to the crudity of the approximations in the representation of each process, some freedom is available for adjusting parameters within the parameterization. Here are some comments about the role of each process, and how to adjust that process:

  - We note that the radiation and microphysics actually work with the *in-cloud* condensate amount. Subroutine `pcond` returns the *grid-box averaged* cloud water amount to the rest of the model. The relationship between the two is

    $$q_c = q_c^{gb}/f$$

    where q_c is the in-cloud condensate amount, q_c^{gb} is the grid-box averaged amount, and f is the cloud fraction. The condensate amount is further partitioned into a liquid and ice fraction by a temperature dependent weighting function.
  - The autoconversion of ice (PSAUT) controls the background value of ice mass. The process is adjusted most naturally by changing the threshold `icrit` for the onset of precipitation, although you can also change the conversion rate, if necessary. This process is most important in controlling ice mass in the upper troposphere and polar regions.
  - Ice condensate at all levels where precipitation occurs can be reduced below the PSAUT equilibrium value (where the condensate production balances removal by PSAUT) by changing the ice accretion process (PSACI). One easy way that I have used in the past to reduce the importance of PSACI is by decreasing the collection efficiency of snow accreting ice (`esw`) from the standard value of 1.0 to some smaller number, which will increase the ice mass (primarily in the 400-700 hPa) levels, where there is significant frozen precipitation)..

  - The autoconversion of liquid (PWAUT) controls the background value of liquid mass, and is most important in regulating the condesate amount of warm, non-precipitating, or drizzling clouds. Autoconversion begins when the diagnosed radius of a cloud drop exceeds a critical radius $r_{\ell,c}$ (variable `rcrit`, assumed to be 5 μm currently) . The radius r of the cloud drop is diagnosed by assuming

    $$r = [Cq_\ell/N]^{1/3}.$$

    where C is a constant, q_ℓ is the *in-cloud* liquid water mixing ratio, and N is the number density of the cloud drops (assumed to vary with altitude, and over land and water). Changing the prescription of N changes the diagnosed r, and thus the onset of precipitation. N varies between limits defined by `capnw` for land points (currently assumed to be 400 cm^{-3}) and `capcw` (assumed to be 150 cm^{-3}) over ocean. Increasing these limits will decrease the diagnosed radius so the onset of precipitation takes place at higher cloud water amounts. The rate that condensate converts to precipitation also goes as $N^{-1/3}$ (see equation (21) of Rasch and Williamson), so increasing N will lead to a decrease in the rate of conversion. Increasing the threshold `rcrit` will increase condensate amounts over both land and ocean.
  - I have not yet needed to adjust the PSACW or PRACW microphysical processes to tune the model. These processes currently play a less important role in the determination of condensate amount. Please contact PJR to ask questions or advide me on the adjustment of these processes.

- **Background Aerosol formulation** When the CCM is not run with the sulfur cycle, a uniform background boundary layer aerosol optical depth is included in the CCM. The aerosol is assumed to be well mixed below 900 hPa. There is some freedom in how the the assumed background optical depth is set:
  - The CCM3 formulation assumes that the visible optical depth `tauvis`= 0.14 for the atmosphere only version, and some other number (?) when coupled to the CSM. This value can be changed in the model namelist, and used for modest adjustments to the global TOA balance that do not require any discriminaton based on time or season.
  - A different formulation was employed for the aerosol optical depth in the sulfate aerosol study of [Kiehl et al.(2000), Boville et al.(2000)]. The new formulation assumes different optical properties for the aerosol, and a hygroscopic growth of the aerosol as a function of relative humidity. JET: HOW DO WE TURN THIS PARAMETERIZATION ON? Turning on the new formulation brightens the planet by 2 W/m^2 compared to old formulation.

  The brightness of the planet can be influenced by changes to `tauvis` in either of these formulations.

3.2 Strategies for retuning the model for TOA balance.

Here are few hints meant as a strategy for tuning the model. The suggested strategies are by no means sufficient for a quality CCM simulation. They merely identify some necessary but not sufficient conditions for a reasonable simulation.

- run the model for a few time steps, then extend for a few days until you think the scheme and model is behaving reasonably. When you think it makes physical sense *check conservation constraints* (section2.1).

- run for 6 months starting with the September initial conditions. Ignore the first 3 months, and compare the simulation to the control (*JET_bill30e* mentioned above). Look at the results for the winter season DJF: if they make physical sense look at the global budgets at the top of atmosphere and the surface. Make sure you are comfortable with the differences. You can use the global numbers to tell you something about what is going to happen in the annual average. For example, if the globally averaged TOA outgoing longwave radiation is changed by 2 W/m^2 during DJF, it is quite likely that the Annual average will change by a similar amount (e.g. 2 W/m2).
- when you are ready, continue the run out through the first year. Look at the runs for all seasons. Look at the TOA global budgets. You should be making sure the TOA (incoming - outgoing energy) balances to a few W/m2 at a minimum. By the time you have finished tuning we suggest the balance be good to 1 W/m2. Make sure the surface energy budget also makes sense, e.g., ...

References

[Barth et al.(2000)] Barth, M., P. J. Rasch, J. T. Kiehl, C. M. Benkovitz and S. E. Schwartz, 2000: Sulfur chemistry in the National Center for Atmospheric Reseach Community Climate Model: Description, evaluation, features and sensitivity to aqueous chemistry. *J. Geophys. Res.*, pp. 1387—1415.

[Boville et al.(2000)] Boville, B. A., J. T. Kiehl, P. J. Rasch and F. O. Bryan, 2000: Improvements to the NCAR CSM-1 for transient climate simulations. *J. Clim.*, in press.

[Kiehl et al.(1996)] Kiehl, J. T., J. Hack, G. B. Bonan, B. A. Boville, B. P. Briegleb, D. L. Williamson and P. J. Rasch, 1996: *Description of the NCAR Community Climate Model (CCM3).* NCAR Tech. Note, NCAR/TN–420+STR. Nat. Cent. for Atmos. Res., Boulder, Colo., U.S.A.

[Kiehl et al.(2000)] Kiehl, J. T., T. L. Schneider, P. J. Rasch, M. Barth and J. Wong, 2000: Radiative forcing due to sulfate aerosols from simulations with the National Center for Atmospheric Research Community Climate Model, Version 3. *J. Geophys. Res.*, pp. 1441—1457.

[Randall(1998)] Randall, D. A., Ed., 383 pp, 1998: Special issue devoted to the Climate Systems Model. *J. Clim., 11.*

[Rasch et al.(2000)] Rasch, P. J., M. Barth and J. T. Kiehl, 2000: A description of the global sulfur cycle and its controlling processes in the NCAR CCM3. *J. Geophys. Res.*, pp. 1367—1385.

[Rasch and Kristjánsson(1998)] Rasch, P. J. and J. E. Kristjánsson, 1998: A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. *J. Clim.*, **11**, 1587—1614.

[Tiedtke(1989)] Tiedtke, M. A., 1989: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Weather Rev.*, **117**, 1779—1800.