CAM prognostic condensate and precipitation parameterization

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April, 28, 2008
Controlling equations

- Water vapor mixing ratio
  \[ \frac{\partial q}{\partial t} = A_q - Q + E_r \]

- Temperature
  \[ \frac{\partial T}{\partial t} = A_T + \frac{L}{c_p} (Q - E_r) \]

- Total cloud condensate (water)
  \[ \frac{\partial l}{\partial t} = A_l + Q - R_l \]
Controlling Equations

- $A_q$, $A_T$, $A_l$
  tendencies other than large-scale cond/evap of cloud and rain. Advective, expansive, radiative, turbulent, and convective tendencies.
- $Q$
  net stratiform condensation of cloud meteors (cond-evap)
- $E_r$
  evaporative rate of rain and snow
- $R_l$
  Conversion rate of cloud water to rain and snow
The system

\[ \frac{\partial q}{\partial t} = A_q - Q + E_r \]

\[ \frac{\partial T}{\partial t} = A_T + \frac{L}{c_p} (Q - E_r) \]

\[ \frac{\partial l}{\partial t} = A_l + Q - R_l \]

\[ \frac{\partial U}{\partial t} = \alpha \frac{\partial q}{\partial t} - \beta \frac{\partial T}{\partial t} \]

\[ = \alpha A_q - \beta A_T - \gamma (Q - E_r) \]

Empirical(1)
Two component

- Macroscale
  exchange of water substance between condensate and the vapor pressure.
  \( Q \)

- Microphysical
  the conversion from condensate to precipitation.
  \( E_r \) and \( R_l \)
Macroscale

- $E_r = 0$ and $U = 1$

\[ \frac{\partial U}{\partial t} = \alpha \hat{A}_q - \beta \hat{A}_T - \gamma \hat{Q} = 0. \]

\[ \hat{Q} = \frac{\alpha \hat{A}_q - \beta \hat{A}_T}{\gamma} \]

$\Rightarrow$ \[ \frac{\partial l}{\partial t} = A_l + Q - R_l \]

- In cloud condensate equation

\[ \frac{\partial l}{\partial t} = \hat{A}_l + \frac{\alpha \hat{A}_q - \beta \hat{A}_T}{\gamma} - \hat{R}_l. \]
Grid Cell

The total cloud condensate

\[ l = C \hat{l} \]

\[ \frac{\partial l}{\partial t} = C \frac{\partial \hat{l}}{\partial t} + \hat{l}^* \frac{\partial C}{\partial t} \]

\[ C = \text{cloud fraction} \]

existing clouds

Newly formed/dissipated clouds

Theoretically, this part of cloud should have zero cloud water content. Because of the finite time step, this part is nonzero.

\[ \hat{l}^* = \hat{l} \]

[Rasch and Kristjansson, 1998]
Link Q and \( \frac{\partial C}{\partial t} \)

- Insert \( \frac{\partial l}{\partial t} = A_l + Q - R_l \) and \( \hat{\frac{\partial l}{\partial t}} = \hat{A}_l + \frac{\alpha \hat{A}_q - \beta \hat{A}_T}{\hat{\gamma}} - \hat{R}_l \).

- Insert into \( \frac{\partial l}{\partial t} = c \frac{\partial \hat{l}}{\partial t} + \hat{l}^* \frac{\partial C}{\partial t} \) with \( R_l = c \hat{R}_l \hat{A}_T = \hat{A}_T, \) \( A_q = \hat{A}_q, \) and \( A_l = \hat{A}_l \).

- \( \hat{l}^* \frac{\partial C}{\partial t} = (1 - c) A_l + Q - C \left( \frac{\alpha A_q - \beta A_T}{\hat{\gamma}} \right) \)

- Q is linked with C as required by the total water budget.
Link C and $U$

- $C$ is related to relative humidity $U$

\[ C = C(U, b) \]

$B$ denotes a generic variable for vertical stability, local $R_i$ #, cumulus mass flux, etc

\[
\frac{\partial C}{\partial t} = \frac{\partial C}{\partial U} \frac{\partial U}{\partial t} + \frac{\partial C}{\partial b} \frac{\partial b}{\partial t} \]
\[
F_a = \frac{\partial C}{\partial U} \quad F_b = \left[\frac{\partial C}{\partial b}\right]/\left[\frac{\partial C}{\partial U}\right] \frac{\partial b}{\partial t} \]
\[
F_a^{-1} \frac{\partial C}{\partial t} = \frac{\partial U}{\partial t} + F_b \]
\[
\frac{\partial U}{\partial t} = \alpha A_q - \beta A_T - \gamma (Q - E_r) \]
\[
F_a^{-1} \frac{\partial C}{\partial t} = \alpha A_q - \beta A_T - \gamma (Q - E_r) + F_b \]

Empirical(2)
The budget of condensation

\[ Q = c_q A_q - c_T A_T - c_l A_l + c_r E_r + \sigma \hat{l}^* F_b \]

- Moist advection
- Cold advection
- Evaporation of rain/snow water
- Import of cloud water

Non-water source, require condensation

\[
\begin{align*}
c_q &= \frac{\alpha}{\hat{\gamma}} C + \left(1 - \frac{\gamma}{\hat{\gamma}} C\right) \sigma \hat{l}^* \\
c_T &= \frac{\beta}{\hat{\gamma}} C + \left(1 - \frac{\gamma \beta}{\hat{\gamma} \beta} C\right) \sigma \hat{l}^* \\
c_l &= (1 - C) \sigma F^{-1}_a \\
c_r &= \sigma \gamma \hat{l}^* \\
\sigma &= \frac{1}{F^{-1}_a + \gamma \hat{l}^*}
\end{align*}
\]
Four cases for obtaining $Q$

- If $U = 1$, \[ \hat{Q} = \frac{\alpha \hat{A}_q - \beta \hat{A}_T}{\hat{\gamma}} \]

- If $1 > U \geq U_{00}$
  \[ Q = c_q A_q - c_T A_T - c_l A_l + c_r E_r + \sigma \hat{l}^* F_b \]

- If $U < U_{00}$ but $l > 0$, $Q = -l$

- If $U < U_{00}$ and $l = 0$, $Q = 0$
Microscale

- Bulk microphysics: formation and dissipation of precipitation $E_r$ and $R_l$
- Four types of condensate in mixing ratio
  - Liquid and ice phase for suspended condensate $q_l$ and $q_i$
  - Liquid and ice phase for falling condensate (precipitation) $q_r$ and $q_s$
- Currently, only $q_l$ and $q_i$ integrated in time; $q_r$ and $q_s$ are diagnosed.
Partitioning of liquid and ice

\[ f_i = \frac{T - T_{\text{max}}}{T_{\text{min}} - T_{\text{max}}}, \quad T_{\text{min}} \leq T \leq T_{\text{max}} \]

\[ T_{\text{max}} = -10^\circ \text{C} \quad T_{\text{min}} = -40^\circ \text{C} \]

- Liquid and ice mass mixing ratio \((l \text{ and } q)\) are *independently* advected, diffused, and transported by convection.

- Recalculated from total cloud condensate

\[ l_{n'} = (\ell_n + I_n)(1 - f_i) \]

\[ I_{n'} = (\ell_n + I_n)f_i \]

Empirical(3), adjustable(2)
Evaporation of precipitation $E_r$

- At level $k$, rain + snow

$$E^k = k_e (1 - c^k) \left(1 - \min(1, \frac{q^k}{q_e})\right) (F^{k-})^{1/2}$$

$k_e$ is an adjustable constant. For stratiform precipitation $k_e = 1 \times 10^{-5}$. For convective precipitation, resolution and dy-core dependent.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FV</th>
<th>T85</th>
<th>T42</th>
<th>T31</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{e,\text{conv}}$</td>
<td>1.0E-6</td>
<td>1.0E-6</td>
<td>3.0E-6</td>
<td>3.0E-6</td>
</tr>
</tbody>
</table>

$(1-C^k)$: random overlap assumption (precip. Falling into the existing cloud in a layer does not evaporate).

$F^{k-}$ the mass flux at upper interface

$$F^{k+} = F^{k-} + \frac{\delta^k P (P^k - E^k)}{g}$$

Empirical(4), adjustable(3)
Evaporation and melting of snow

- **Evaporation,** $E_s$
  Proportion to the fraction of snow in the precipitation flux on the upper interface

  \[
  E_s^k = E^k F_{s^-}^k / F_{s^-}^k
  \]

  \[
  F_{s^+}^k = F_{s^-}^k + \frac{\delta^k p}{g} (P_s^k - E_s^k - M^k)
  \]

  \[\text{production} \quad \text{Melting} \quad \text{evaporation}\]

- **Melting,** $M$

  \[
  T^k > 0\ C, \quad M^k = F_{s^-}^k \frac{g}{\delta^k p}
  \]

Empirical(4), adjustable(3)
Production of precipitation, $P$

- $P = \text{PW Aut}$, conversion of liquid water to rain
- + $\text{PRACW}$, collection of cloud water by rain
- + $\text{PS Aut}$, auto-conversion of ice to snow
- + $\text{PSACI}$, collection of ice by snow
- + $\text{PSACW}$, collection of liquid by snow
Production of precipitation, $P$

\[ PW \ AUT = C_{l,aut} q_i^2 \rho_a / \rho_w (q_i \rho_a / \rho_w N)^{1/3} H(r_{3l} - r_{3lc}) \]

\[ C_{l,aut} = 0.55 \pi^{1/3} k (3/4)^{4/3} (1.1)^4 \quad k = 1.18 \times 10^6 \text{ cm}^{-1} \]

$N$ is 400/cm$^3$ over land near the surface, 150/cm$^3$ over ocean, and 75/cm$^3$ over sea ice.

$H(x) = (0, 1)$ for $x(\leq, \geq)0$.  $R_{3lc}$ is 15 um

\[ PRACW = C_{racw} \hat{q}_l q_r \]

\[ C_{racw} = 0.884 (g/ (\rho_w 2.7 \times 10^{-4}))^{1/2} \text{ s}^{-1} \]

Empirical(7), adjustable(8)
Production of precipitation, $P$

\[ PSAUT = C_{i,aut} H(\hat{q}_i - q_{ic}) \]

$C_{i,aut}$ is set to $10^{-3} \text{s}^{-1}$

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</thead>
<tbody>
<tr>
<td>$q_{ic,\text{warm}}$</td>
<td>8.e-4</td>
<td>4.e-4</td>
<td>4.e-4</td>
<td>4.e-4</td>
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<tr>
<td>$q_{ic,\text{cold}}$</td>
<td>11.e-6</td>
<td>16.e-6</td>
<td>5.e-6</td>
<td>3.e-6</td>
</tr>
</tbody>
</table>

$T = 0^\circ C$

$T = -20^\circ C$

\[ PSACI = C_{sac} e_i \hat{q}_i \]

$C_{sac} = c_7 \rho_a c_8 \bar{P}^{c_9}$

$c_1 = \pi N_s c \Gamma(3 + d)/4$

$c_2 = 6(\pi \rho_s N_s)^{d+4}/[c \Gamma(4 + d) \rho_0^{0.5}]$

$c_3 = (3 + d)/(4 + d)$

$c_4 = (3 + d)/4$

$c_7 = c_1 \rho_0^{0.5} c_2 \rho_s^{c_9} [\rho_s N_s]^{c_6}$

$c_8 = -0.5/(4 + d)$

$c_5 = 152.93$

$d = 0.25$

$N_s = 3 \times 10^{-2}$

Empirical(9), adjustable(13)
Production of precipitation, $P$

- $PSACW = C_{sae} e_w \hat{q}_l$
- $e_w = 0.1$

- Snow production, $P_s$

- $P_s^k = f_s P^k$
- $f_s = \frac{T - T_{s,\text{max}}}{T_{s,\text{min}} - T_{s,\text{max}}}$, $T_{\text{min}} \leq T \leq T_{\text{max}}$

Adjustable constants
- $T_{\text{min}} = -5^\circ \text{C}$
- $T_{\text{max}} = 0^\circ \text{C}$

Empirical(11), adjustable(16)
Sedimentation of liquid and ice

- Fluxes are computed at interfaces, using fall velocities and concentration at midpoints.
- Particles only evaporate if the cloud fraction is larger in the layer above.

\[ f_o = \min \left( \frac{f_c^k}{f_c^{k-1}}, 1 \right) \]

- Sedimenting particles evaporate if they fall into the cloud free portion of a layer. If supersaturated, the evaporated portion will be accounted for the subsequent cloud condensate tendency calculation.

Empirical(11), adjustable(16)
Fall velocity

- Ice particles
  - Effective radius: $R_e < 40 \times 10^{-6}$ m
    
    Stokes formula
    
    $v_i = \frac{2 \rho wgR_e^2}{9 \eta}$
    
    $\eta = 1.7 \times 10^{-5}$ kg m/s is the viscosity of air

- $R_e > 40 \times 10^{-6}$ m
  
  Linear dependence on
  
  $r = 10^{-6} \times R_e$
  
  $v_i(r) = v_i(40) + (r - 40) \frac{v_{400} - v_i(40)}{400 - 40}$

Empirical(13), adjustable(18)
Fall velocity

- Liquid particles

\[ v_i = v_{i, \text{land}} f_{\text{land}} + v_{i, \text{ocean}} f_{\text{ocean}} \]

- \( f_{\text{land}} \) and \( f_{\text{ocean}} \) are the land and ocean fractional areas of the cell
- \( v_{i, \text{land}} = 1.5 \) and \( v_{i, \text{ocean}} = 2.8 \text{ cm/s} \)

Empirical(13), adjustable(20)
Conclusion

- The non-convective cloud scheme is set up by solving a set of conservation equations for water vapor, temperature, and cloud condensate.
- Macroscale: The condensation rate $Q$, is obtained by connecting with the cloud fraction as required by total water budget.
- Microscale: use a bulk microphysical scheme to obtain the conversion from condensate to precipitation ($E_r$ and $R_l$).
- The parameterization are engineering code based on physics. There are 13 explicit empirical relations and 20 adjustable constants.
- Can be replaced be a LUT.
Reference:

- Collins et al, 2004. CAM3.0 scientific description, Chapter 3. NCAR.