Linear response functions of two convective parameterization schemes*

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Abstract

Two 1D atmospheric column models containing convective parameterization schemes are compared to a 3D cloud system resolving model (CSRM) using a recent technique that admits study of responses of convection to small temperature and moisture anomalies. There exist notable differences between the responses of the column models and those of the CSRM. While the CSRM exhibits responses throughout the depth of the modeled troposphere, responses in both column models are predominantly local and ignore certain aspects of the PBL response. Sign errors as well as a conspicuously lack of moisture advection are evident in certain column model responses. Such differences have implications for the simulation of large-scale convective phenomena. The technique employed herein can be used as a basis for tuning and modifying convective parameterization schemes.
Motivation

Noting the importance of parameterized convection in theoretical research and weather/climate simulation, we pose the following question:

How well do convective parameterization schemes simulate the responses of the real atmosphere to temperature and moisture anomalies?

This question is very difficult to answer! Though, we may begin by asking a more tractable one:

How well do convective parameterization schemes simulate the responses of a cloud system resolving model (CSRM) to temperature and moisture anomalies?

Seeking a robust comparison, we apply the linear response function analysis of Kuang (2010) to three different atmospheric models.
The Models

The CSRM used is the **System for Atmospheric Modeling (SAM)** \(^1\), version 6.8.2, an implementation of the anelastic approximation of the equations of motion. We use 28 vertical levels extending to 32 km with 2 km horizontal resolution on a square 128 km domain. The vertical grid spacing is \(\sim 100 \text{ m} \) near the surface and coarsens to \(\sim 1 \text{ km} \) in the mid troposphere. A bulk formula is used for surface sensible and latent heat fluxes and a simple Smagorinsky-type closure is used for the effect of subgrid scale turbulence.

The **CONVECT** \(^2\) parameterization embedded within the MIT Single Column Model \(^3\) (MSCM), and **Diabat3** \(^4\) (D3), a toy cumulus parameterization embedded within a simple single column model, are the convective schemes of study. They are described in some detail, below.

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\(^1\) Khairoutdinov and Randall, 2003.  
\(^2\) Emanuel 1991.  
\(^3\) Emanuel and Živković, 1999.  
\(^4\) Raymond, 1994; Raymond, 2007.
The CONVECT subroutine takes as input columns of absolute temperature, specific humidity, momentum, and pressure. In turn, CONVECT predicts tendency columns of temperature, moisture and momentum. In the simplified form used in this paper, the MIT Single Column Model plus CONVECT is essentially a convective parameterization, though it also calculates turbulent fluxes at the surface and radiative cooling aloft. The convection scheme represents shallow and deep convecting, precipitating cumuli and contains a dry adiabatic adjustment. Sea surface temperature and surface winds are held constant.

Although MSCM incorporates convective downdraft feedback and Reynolds-type correction terms in the aerodynamic flux formulae, we disable these to match the other models in the study. Interactive radiation is also shut off, which disables the interactive cloud scheme. This column model as well as Diabat3, described below, employs constant vertical resolution of $\Delta z = 250$ m and columns of 80 grid cells giving domain heights of 20 km.
Diabat3

The Diabat3 (D3) toy cumulus scheme predicts convective tendencies for equivalent potential temperature, total cloud water mixing ratio and momentum based on input columns of potential temperature, total cloud water mixing ratio and momentum. These tendencies are determined as the weighted sum of sources due to shallow and deep convective modes. The weighting factor for deep convection is determined by the amount of convective inhibition (CIN) above the sub-cloud layer.

The sources returned by the scheme are calculated via a conservative adjustment toward a mass-weighted average within the convective layer, combined with a distribution of surface fluxes throughout the depth of the convective column according to a rate constant. Deep convective tendencies are furthermore a strong function of the saturation fraction. In addition to the above effects, the moisture source is modified by convective and stratiform precipitation and evaporation, each of which occurs at a unique, prescribed constant rate.
Identical Forcing

In order to minimize model differences, we have simplified radiative and surface flux processes in all models:

**Constant radiative cooling**

**Simplified bulk surface fluxes**

- $FT_{surf} \propto C_D U_0 (SST - T_0)$
- $Fq_{surf} \propto C_D U_0 (q_s0 - q_0)$
- $U_0 = \sqrt{V_0^2 + W_{Ref}^2}$
- $C_D = 1 \times 10^{-3}$
- $V_0 = 5 \text{ m s}^{-1}$
- $SST = 28 \degree \text{C}$
- $W_{Ref} = 3 \text{ m s}^{-1}$
In addition, $T$ and $q$ near the tropopause are relaxed to temporal mean values over $\sim 1/2$ day to compensate for the lack of significant convective adjustment occurring in the stratosphere.
Procedure I

We assume the convective response in each model can be approximated by a linear transformation matrix $M$ acting upon an anomalous state vector $x$:

$$\dot{x}_{\text{conv}} = Mx, \quad x = (T', q').$$

We construct this matrix for each model by applying a complete set of perturbation tendencies to the radiative-convective equilibrium (RCE) state that each model attains under the above simplified forcing. A new equilibrium state is attained under this extra forcing for all $n$ tendencies:

$$dT'/dt_n, dq'/dt_n \rightarrow T_n, q_n.$$

The difference in equilibria gives a corresponding anomalous state:

$$T_n' = T_n - T_{RCE},$$

$$q_n' = q_n - q_{RCE}.$$

*(Kuang, 2010)*
The set of applied tendencies and resulting anomalous states become the columns of

\[
\dot{X} = \begin{bmatrix}
\dot{T}_{0,0} & \ldots & \dot{T}_{0,n} \\
\vdots & \ddots & \vdots \\
\dot{T}_{m,0} & \ldots & \dot{T}_{m,n} \\
\dot{q}_{0,0} & \ldots & \dot{q}_{0,n} \\
\vdots & \ddots & \vdots \\
\dot{q}_{m,0} & \ldots & \dot{q}_{m,n}
\end{bmatrix}
\]

and

\[
X = \begin{bmatrix}
T'_{0,0} & \ldots & T'_{0,n} \\
\vdots & \ddots & \vdots \\
T'_{m,0} & \ldots & T'_{m,n} \\
q'_{0,0} & \ldots & q'_{n,0} \\
\vdots & \ddots & \vdots \\
q'_{m,0} & \ldots & q'_{m,n}
\end{bmatrix},
\]

respectively, which combine to form

\[
M = \dot{X}X^{-1}.
\]

We then predict convective responses in each model by applying various temperature and moisture anomalies to \(M\). To avoid the fastest decaying eigenmodes of \(M\), which have a negligible effect on the resulting state, we examine the average response over a two hour period:

\[
\bar{\dot{x}} = M \bar{x}.
\]
RCE columns

Radiative-convective equilibrium profiles of temperature and relative humidity for SAM, D3 and MSCM. Dots along the right sides of the temperature plots show the vertical resolution of each model.
\( \bar{x} \) for \( T' \) near 800 hPa

- **SAM**: cooling at anomaly and aloft; moistening below
- **D3**: some drying aloft
- **MSCM**: no cooling aloft; negligible moistening below
\(\bar{x}\) for \(T'\) near 650 hPa

- **SAM:** cooling at anomaly and aloft; moistening below and in PBL
- **D3:** highly localized cooling and moistening; little change in PBL
- **MSCM:** heating inflection point; (see D3 response)
$\bar{x}$ for $q'$ near 800 hPa

- **SAM**: strong localized drying; warming at, above anomaly
- **D3**: some cooling and moistening aloft; $|\Delta q| : |\Delta T| \approx 2 : 5$
- **MSCM**: negligible warming at and above anomaly
$\bar{x}$ for $q'$ near 650 hPa

- **SAM**: strong localized drying; warming at, above anomaly
- **D3**: some cooling aloft, below anomaly; $|\Delta q| : |\Delta T| \approx 2 : 5$
- **MSCM**: no warming at anomaly or aloft
2:5 ratio

\[ MSE = c_p T + gz + L_v q \]

If a pseudoadiabatic process (rain) occurs at some level...

\[ \Delta MSE \big|_{z=z_0} = c_p \Delta T + L_v \Delta q = 0 \]

\[ \Delta q / \Delta T = -c_p / L_v \approx -2/5 \]
Conclusions

- The linear transformation matrix $\mathbf{M}$ is a useful medium for comparison.
- The three models arrive at significantly different relative humidity profiles under the same, simple forcing scheme.
- D3 and MSCM manifest highly localized convective responses.
- D3 and MSCM have different PBL responses than those of the CSRM.
- D3 expresses phase changes where advection may be more important (2:5 ratio). This may be a parameter tuning issue, i.e., the ratio of time constants directing convective mixing and phase changes of water could be modified.
- D3 shows slight sign errors in $\dot{T}$ and $\dot{q}$, which may disrupt/prevent certain dynamic phenomena (e.g. convectively-coupled waves). These may be due to the conservative relaxation used to effect convective mixing in the model.
- Both D3 and MSCM are based on boundary layer quasi-equilibrium. Shared contrasts among the column models with SAM may result from the degree to which these models adhere to this theory.
References


Emanuel, K. A., 2002: Description of subroutine Convect. unpublished manuscript.


