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Toward stochastic deep convective parameterization in general circulation models

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[1] For the first time, a stochastic deep convective parameterization to represent variability arising from small-scale processes that are unresolved by traditional deterministic moist convective parameterizations is tested in a general circulation model. Two physical pathways of representing small-scale variability as a stochastic process are explored. First, the relationship between cloud-base mass flux M_b and large-scale convective available potential energy (CAPE) is posited to have a stochastic component (the CAPE-M_b scheme). Second, the vertical structure of heating is modified by a simple random process about the structure given by the traditional convective scheme (the VSH scheme). The CAPE-M_b scheme increases the overall variance of precipitation toward observations with a realistic spatial pattern. The VSH scheme has smaller impacts on precipitation variance but yields preferential enhancement at large spatial scales and low frequencies. *INDEX TERMS:* 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Lin, J. W.-B., and J. D. Neelin, Toward stochastic deep convective parameterization in general circulation models, *Geophys. Res. Lett.*, *30*(4), 1162, doi:10.1029/2002GL016203, 2003.

1. Introduction

[2] Parameterizations of moist convection in general circulation models (GCMs) are generally deterministic functions of the large-scale variables, implicitly representing only the ensemble mean or Reynolds average of the sub-grid scale convective elements. However, results from a variety of model studies [*Salby and Garcia*, 1987; *Xu et al.*, 1992; *Yu and Neelin*, 1994; *Buizza et al.*, 1999; *Ricciardulli and Garcia*, 2000] suggest it may be important to represent higher-order moments associated with convection (e.g. variance). *Yano et al.* [2001] suggests tropical convective variability from 1–30 days can be considered $1/f$ noise. One way of representing these higher-order moments is through a stochastic parameterization for convection. *Lin and Neelin* [2000] (hereafter LN00) and *Lin and Neelin* [2002] (hereafter LN02) use such an approach in an intermediate-complexity model of the tropical atmosphere and find that the stochastic parameterization noticeably affects intraseasonal variability.

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[3] How a stochastic convective parameterization is implemented affects the response: in LN00, the stochastic component is implemented within the existing *Betts and Miller* [1986]-type convective scheme while in LN02, the stochastic parameterization attempts to directly control the statistics of convection based upon an empirically based probability distribution predetermined prior to model integration.

[4] In the present study, we test two different mechanisms by which a stochastic deep convective parameterization could affect atmospheric variability using the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3, v3.6.6; *Kiehl et al.*, 1998; see electronic supplement[1] for details). In the first (the CAPE-M_b scheme), we posit that the stochastic process acts upon cloud-base mass flux M_b (which is a function of CAPE in the CCM3) in the model's convective parameterization, representing small-scale convective and mesoscale variability in the grid cell. This pathway is similar to the method used in LN00 and has considerable appeal on physical grounds. In the second test (the VSH scheme), we examine simple stochastic perturbations to the vertical structure of heating in the deep convective scheme to provide a first analysis of the importance and type of impact these may have in stochastic convective parameterization.

2. Stochastic Convective Parameterizations

[5] Deep convection in CCM3 is described by the Zhang-McFarlane scheme (*Zhang and McFarlane* [1995], hereafter ZM) which represents sub-grid convection by an ensemble of quasi-steady updrafts and downdrafts (modified from *Arakawa and Schubert* [1974]'s scheme). Mid-level and shallow convection are parameterized by the Hack scheme [*Hack*, 1994].

2.1. CAPE-M_b Scheme

[6] An essential postulate of the closure in ZM is that convection tends to remove positive CAPE at a rate proportional to the CAPE so, if acting alone, convection would cause CAPE to decay exponentially on a timescale τ_c. In our stochastic closure, we posit that the convective tendency of CAPE $(\partial_t A)_c$ is modified by a stochastic process, ξ:

$$(\partial_t A)_c = -\tau_c^{-1}(A + \xi), \tag{1}$$

for $(A + \xi) \geq 0$, so random variations occur about the ZM exponential decay tendency. The convective CAPE tendency is also obtained from the updraft/downdraft model, which

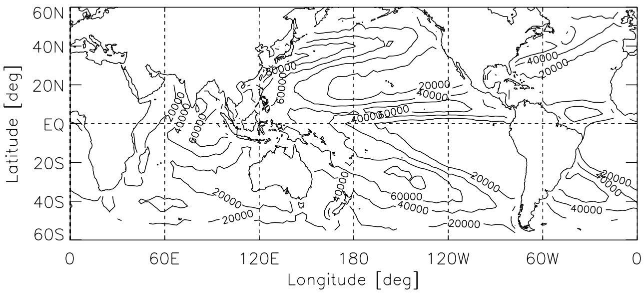

Figure 1. Variance of MSU daily precipitation. Units $(\mathrm{W\ m^{-2}})^2$. Contour interval is 20,000.

can be expressed as $-M_bF$ where M_b is the updraft cloud-base mass flux and F is the CAPE tendency per unit M_b. Equating this tendency to that due to the closure (1) yields

$$M_b = \frac{A + \xi}{\tau_c F}, \tag{2}$$

with the additional condition $M_b \geq 0$.

[7] The conventional ZM case is simply $\xi = 0$. The introduction of a stochastic element in the CAPE decay closure implies that the cloud base mass flux has random variations. Physically, this has the appeal of being consistent with a small ensemble of convective elements responding to small-scale dynamical factors in addition to the large-scale CAPE. The timescales of such processes are represented by including a temporal autocorrelation in ξ. The closure is mathematically equivalent to introducing a stochastic perturbation to CAPE within the computation of convective heating. Such a stochastic scheme is the "CAPE scheme" closure postulated based on very simple arguments in LN00. We regard the derivation here as more fundamental and it is serendipitous that it provides justification for the LN00 closure. The present scheme is referred to as the "CAPE-M_b scheme" due to the importance of the relation to M_b.

[8] The noise value ξ_t at a given timestep is also added to CAPE in a condition that tests whether CAPE is greater than a threshold value (C_{lim} = 70 J kg^{-1}) required for convection to be possible. In the numerical implementation, there are caps placed on large values of M_b for numerical stability reasons and these significantly reduce the variance of M_b that can be achieved.

[9] In both the CAPE-M_b and VSH schemes, the noise added at time t (ξ_t) has the form of a first-order Markov process

$$\xi_t = \epsilon_\xi \xi_{t-1} + z_t \tag{3}$$

where z_t is white noise with zero mean and standard deviation σ_z, and ϵ_ξ is an autoregressive coefficient that yields an autocorrelation time τ_ξ for the process. Because the sub-grid convective variability that the stochastic parameterization aims to represent can have timescales ranging from hours (cloud scale) to days (mesoscale), it is not obvious what the value of τ_ξ should be. In LN00 and LN02, values of 20 min to 1 day were tested, with the greatest impacts at intraseasonal timescales occurring for the latter. Thus τ_ξ = 1 day is used in the explorations here. In the CAPE-M_b scheme runs presented here σ_z = 1000 J kg^{-1}, though due to the numerical caps on M_b considerably smaller values of σ_z could be used to yield similar variance of M_b.

2.2. VSH Scheme

[10] Unlike the intermediate-level model used in LN00 and LN02, we can test vertical structure dependence in a GCM. The CAPE-M_b scheme uses the vertical structure obtained from the conventional ZM scheme, but there is potentially also variability in the vertical structure that should be represented stochastically. Physically, this dependence might correspond, for instance, to differing levels of detrainment for individual convective elements or to differences in squall line organization due to vertical shear. To test the impacts of random variations in the vertical structure of the heating on large-scale dynamics, we use a scheme justified by its simplicity rather than by detailed convective physics. At each timestep, noise is added directly to the adjustment of temperature at each level by the convective scheme at locations where ZM deep convection occurs. To satisfy energy conservation, since no perturbation is applied to the convective moisture sink, the mass weighted vertical mean of the noise $\langle \xi_t \rangle$ is removed from the heating. Thus, for each level k at each timestep t:

$$T = \tilde{T}_t + \xi_t - \frac{\Delta p_k}{\Delta p_{\mathrm{tot}}} \langle \xi_t \rangle, \tag{4}$$

where $\tilde{T}$ is the value of grid-scale temperature after applying deep convective heating from the deterministic ZM scheme

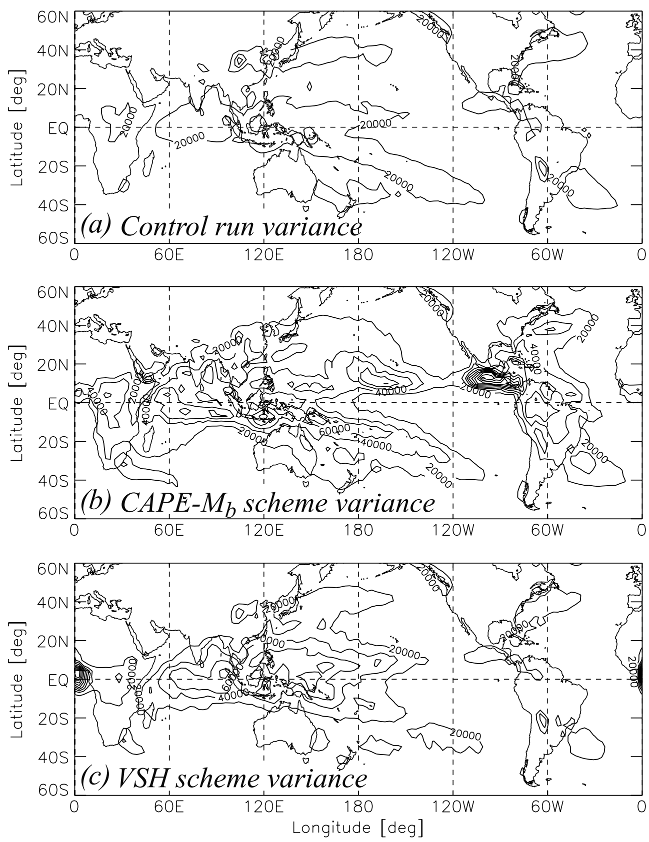

Figure 2. Variance of daily precipitation for (a) control run, (b) CAPE-M_b scheme, and (c) VSH scheme. Units $(\mathrm{W\ m^{-2}})^2$. Contour interval is 20,000.

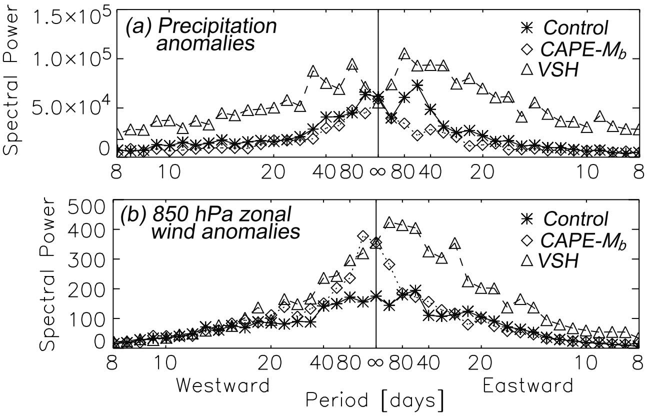

Figure 3. Wavenumber one spectral power of equatorial region (a) precipitation anomalies and (b) 850 hPa zonal wind anomalies for control run (asterisk), CAPE-M_b scheme (diamond), and VSH scheme (triangle). Units (a) $(W\ m^{-2})^2$ and (b) $(m\ s^{-1})^2$.

and $\Delta p_k/\Delta p_{tot}$ is the layer k fraction of column air mass. The magnitude of the white noise forcing in ξ_t is set by σ_z = 0.3 K in (3), with the caveat that this is an overestimate for testing purposes on the order of maximum heating rates during convective events.

[11] This scheme does not affect precipitation (or vertical mean heating) as calculated by the ZM scheme at any given time step. Thus in principle, any effects of the noise on the precipitation must go through the large-scale dynamics and physics of the rest of the model before they feed back on precipitation. Some variation from this may occur for mid-level and shallow convection since the Hack scheme [*Hack*, 1994] is called subsequent to the ZM scheme.

3. Analysis Methods and Results

[12] See electronic supplement[1].

3.1. CAPE-M_b Scheme

[13] Microwave sounding unit (MSU; *Spencer*, 1993) observed daily precipitation variance (Figure 1) is concentrated in areas of high climatological precipitation such as the intertropical convergence zone (ITCZ) and the Southern Pacific convergence zone (SPCZ). The CCM3 control run (Figure 2a) severely underestimates the variance magnitude throughout the tropical domain. The approximate shape of the SPCZ variance maximum is captured but not that of the eastern Pacific ITCZ. The CAPE-M_b scheme (Figure 2b) brings the daily variance much closer to observed and improves the placement of the SPCZ and ITCZ variance, broadening the longitudinal extent of both.

[14] Figure 4 shows OLR spectral power compared to the model background following the method of *Wheeler and Kiladis* [1999] (hereafter WK). Both the control run (Figure 4a) and the CAPE-M_b run (Figure 4b) show eastward propagating disturbances consistent with moist Kelvin waves. The signature in the 10–20 m s^{-1} phase speed band is significantly stronger in the CAPE-M_b run, especially for periods of 5–30 days. However, the CAPE-M_b scheme does little to improve the model's representation of tropical variability at frequencies lower than 30 days,

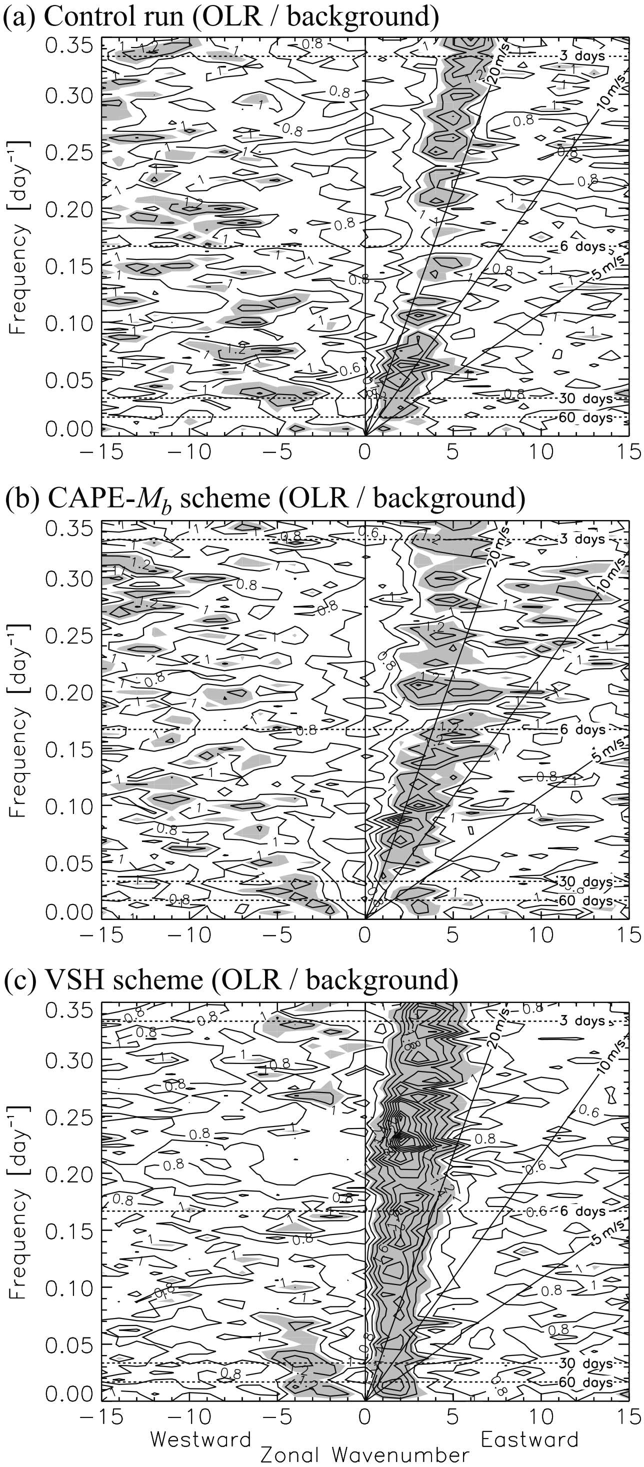

Figure 4. Equatorial region OLR spectral power normalized by estimate of OLR background spectral power for (a) control run, (b) CAPE-M_b scheme, and (c) VSH scheme. Values higher than 1.1 are shaded and are taken as significant at the 95% level. Phase speed lines for 5, 10, and 20 m s^{-1} are shown. Contour interval is 0.2.

[1]Supporting material is available via Web browser or via anonymous FTP from ftp://ftp.agu.org, directory "append" (Username = "anonymous", Password = "guest"); subdirectories in the FTP site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

especially at the lowest wavenumber, relative to the control in both precipitation (Figure 3a) and 850 hPa zonal wind (Figure 3b).

3.2. VSH Scheme

[15] While the VSH scheme enhances precipitation variance magnitude to values comparable to those observed in certain regions, it does little to improve the placement of the variance maxima from the control run (Figure 2c). The VSH scheme, however, preferentially enhances variability at large spatial scales and intraseasonal timescales (Figures 3a and 3b). In the WK plots (Figure 4c), an enhancement in OLR similar to a Kelvin wave signature occurs at phase speeds roughly in the 20–60 m s^{-1} range, suggestive of waves dominated by dry dynamics.

[16] We thus hypothesize that the dominant pathway for VSH impacts is: heating variations excite waves with a spectrum of vertical structures; the fast phase speeds of dry waves acts as a dynamical filter that tends to select large spatial structures in the wind and temperature fields; these then impact the precipitation and OLR. The selective enhancement of low-wavenumber OLR variability under VSH is thus largely via dry dynamics. The CAPE-M_b scheme impacts precipitation directly with a signature that is initially spatially white and dynamical feedbacks occur subsequent to this.

4. Discussion

[17] The CAPE-M_b scheme has an appealing match with the physical machinery of the existing ZM convective scheme and can be interpreted in terms of a random distribution of cloud-base mass flux, M_b, whose mean tends to increase with CAPE. This scheme impacts simulated large-scale variability, including some variance identified as moist Kelvin waves. It succeeds in raising tropical daily precipitation variance toward observed. This suggests that a substantial part of the observed daily variability arises from small scale processes. The pairing of a closely related stochastic and conventional scheme, as in the ZM and CAPE-M_b scheme, provides a useful tool for evaluating the importance of this. The general similarity of mean climate in the model runs with and without this variability may be taken as a partial justification of conventional convective schemes for some purposes.

[18] The CAPE-M_b scheme has little impact on power at low-wavenumbers and low-frequencies. This aspect differs from findings in LN00 and may depend on interaction with low frequency variability that exists in the control.

[19] Another pathway by which variations arising from the small scales may act is via the vertical structure of the convective heating. The VSH scheme separates this impact from that of M_b for evaluation. The VSH scheme gives selective enhancement of the low-wavenumber and low-frequency power, apparently through dynamical filtering of the response prior to the interaction with cloud-base mass flux and precipitation. This spectral signature may help identify phenomena for which vertical structure effects are important in stochastic parameterizations.

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