Explicitly Stochastic Parameterization of Nonorographic Gravity Wave Drag

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ABSTRACT

A straightforward methodology is presented for converting the deterministic multiwave parameterizations of nonorographic gravity wave drag, currently used in general circulation models (GCMs), to stochastic analogs that use fewer waves (in the example herein, a single wave) within each grid box. Deterministic discretizations of source-level momentum flux spectra using a fixed spectrum of many waves with predefined phase speeds are replaced by sampling these source spectra stochastically using waves with randomly assigned phase speeds. Using simple conversion formulas, it is shown that time-mean wave-induced drag, diffusion, and heating-rate profiles identical to those from the deterministic scheme are produced by the stochastic analog. Furthermore, in these examples the need for bulk intermittency factors of small value is largely obviated through the explicit incorporation of stochastic intermittency into the scheme. When implemented in a GCM, the single-wave stochastic analog of an existing deterministic scheme reproduces almost identical time-mean middle-atmosphere climate and drag as its deterministic antecedent but with an order of magnitude reduction in computational expense. The stochastically parameterized drag is also accompanied by inherent variability about the time-mean profile that forces the smallest space–time scales of the GCM. Studies of mean GCM kinetic energy spectra show that this additional stochastic forcing does not lead to excessive increases in dynamical variability at these smallest GCM scales. The results show that the expensive deterministic schemes currently used in GCMs are easily modified and replaced by cheap stochastic analogs without any obvious deleterious impacts on GCM climate or variability, while offering potential advantages of computational savings, reduction of systematic climate biases, and greater and more realistic ensemble spread.

1. Introduction

Finite computational resources force global weather and climate prediction models to run at spatial resolutions that do not resolve the full spectrum of gravity waves that can exist in the atmosphere. Since the dissipation of gravity wave momentum and energy induce significant body forces, heating, and constituent mixing at synoptic scales, general circulation models (GCMs) must parameterize these missing gravity wave–induced effects on the resolved flow (Kim et al. 2003). Parameterizations of drag due to unresolved orographic gravity waves were first implemented in weather and climate models over two decades ago, where they had immediate positive influences in the winter extratropical troposphere and stratosphere (Palmer et al. 1986; McFarlane 1987). They are now essential components of any credible global weather or climate prediction system.

Parameterizations of gravity waves from nonorographic sources were longer in coming, despite emerging understanding of their primary role in controlling the large-scale circulation of the middle atmosphere, particularly in the tropics and summer extratropics (Lindzen and Holton 1968; Dunkerton 1982b; Holton 1983; Garcia and Solomon 1985). Development was stymied at first by insufficient observational and theoretical knowledge of relevant nonorographic wave sources. High-resolution observations of gravity wave–induced velocity and temperature perturbations later revealed a broad spectrum of waves throughout the troposphere and middle atmosphere with surprisingly reproducible spectral shapes (Smith et al. 1987), which motivated an initial generation of nonorographic gravity wave drag parameterizations based on a quasi-invariant global background spectrum of many waves from indistinct tropospheric sources (e.g., Fritts and VanZandt 1993; Warner and McIntyre 1996). A variety of these spectral nonorographic gravity wave drag schemes now exist (e.g., Kiehl et al. 1996; Alexander

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and Dunkerton 1999; Medvedev and Klaassen 2000; Scinocca 2003; Garcia et al. 2007) and they constitute the standard means of parameterizing nonorographic gravity wave drag in global models at present (see, e.g., Table 1 of Eyring et al. 2006). A next generation of schemes is slowly emerging, based on physical models of gravity wave generation from specific nonorographic sources such as deep convection and frontogenesis: they too launch a broad spectrum of gravity waves (e.g., Charron and Manzini 2002; Song and Chun 2005) and can thus often be implemented by simply replacing the uniform source-level momentum flux function of a preexisting spectral nonorographic scheme (e.g., Beres et al. 2005; Richter et al. 2010).

These parameterizations of nonorographic gravity wave drag typically specify source-level wave momentum flux as a function of ground-based horizontal phase speed c, denoted $\boldsymbol{\tau}_{\mathrm{src}}(c)$, which is then discretized among n_{gw} individual gravity waves of phase speed c_j and momentum flux $\boldsymbol{\tau}_j$, where $j = 1, \ldots n_{\mathrm{gw}}$. After assigning the remaining parameters of each tagged wave j (e.g., horizontal wavenumber vectors $\mathbf{K}_j$), the propagation and dissipation modules then determine how each wave's momentum flux is deposited into higher model levels. The resulting tendencies due to all the waves are summed and then applied to modify model winds and temperatures.

These $\boldsymbol{\tau}_{\mathrm{src}}(c)$ functions are typically broad, so that a large n_{gw} is often required for a sufficiently accurate discretization. Thus, unlike orographic gravity wave parameterizations that typically launch only one or two waves in each model grid box (Scinocca and McFarlane 2000; Webster et al. 2003), nonorographic schemes can launch anywhere from $n_{\mathrm{gw}} \sim 10$ to 1000 parameterized waves (Alexander and Dunkerton 1999; Scinocca 2003; Garcia et al. 2007; Zhu et al. 2010; Orr et al. 2010). Consequently, nonorographic gravity wave drag parameterizations can be computationally expensive, which has spurred recent efforts to speed up specific schemes to make practical their integration into GCMs used for production runs (e.g., Warner and McIntyre 2001; Scinocca 2003). This generally involves a set of simplifications or optimizations specific to that particular parameterization that do not change the underlying algorithm or output in any major way.

Here we investigate a different approach to this issue that is potentially applicable to any existing multiwave parameterization of nonorographic gravity wave drag. The central idea is to replace the deterministic discretizations of $\boldsymbol{\tau}_{\mathrm{src}}(c)$ into n_{gw} individual waves with a stochastic discretization that can involve just a single parameterized wave in each model grid box. The approach is developed mathematically in application to a specific multiwave parameterization of nonorographic gravity wave drag described in section 2. The stochastic analog is described in section 3 and compared to its deterministic parent in single-column tests in section 4. The two are implemented in a GCM in section 5 and the GCM climate and variability that result from each in long-term integrations are compared and contrasted. The results are discussed in section 6 and the major findings and implications summarized in section 7.

2. Deterministic parameterization

While the ideas to follow are general, we illustrate and implement them here for one specific scheme: the multiwave parameterization of nonorographic gravity wave drag implemented in version 3.0 of the Whole Atmosphere Community Climate Model (WACCM), as summarized in appendix A of Garcia et al. (2007). Full details of the scheme's formulation and numerics are provided by Kiehl et al. (1996), Collins et al. (2004), and Garcia et al. (2007), while our appendix outlines the recent generalization of this parameterization code into a ''team scheme'' for use in GCMs at various U.S. institutions. Here we discuss only those aspects of the scheme salient to the present work.

The scheme's prescribed source-level momentum flux function takes the Gaussian form

$$\boldsymbol{\tau}_{\mathrm{src}}(c) = \tau_b \exp\left[\frac{-(c - c_{\mathrm{off}})^2}{c_w^2}\right], \tag{1}$$

$$\boldsymbol{\tau}_b = \boldsymbol{\tau}_b^* F(\phi, t), \tag{2}$$

with a phase-speed width $c_w = 30$ m s^{-1}. Here, $\boldsymbol{\tau}_b$ is the ''background'' momentum flux and is scaled from the constant baseline value $\boldsymbol{\tau}_b^*$ by a factor $F(\phi, t)$, which varies with latitude ϕ and time (season) t, as given by (A24)–(A26) of Garcia et al. (2007) and plotted in Fig. 1a. The Gaussian form (1) is a practical choice that simplifies fitting of $\boldsymbol{\tau}_{\mathrm{src}}(c)$ to observed climatological distributions of gravity wave phase speeds and momentum fluxes in the troposphere (see, e.g., Alexander and Vincent 2000; Gong et al. 2008).

This source flux is discretized at the launch pressure level $p_{\mathrm{src}} = 500$ hPa by assigning an equispaced distribution of ground-based horizontal phase speeds

$$\begin{aligned} &c_j = c_{\mathrm{off}} + j_* \Delta c, \\ &j_* = -n_c, -n_c + 1, \ldots + n_c - 1, +n_c = j - n_c + 1, \\ &\qquad (j_* \in \mathbf{Z}, n_c \in \mathbf{N}), \end{aligned} \tag{3}$$

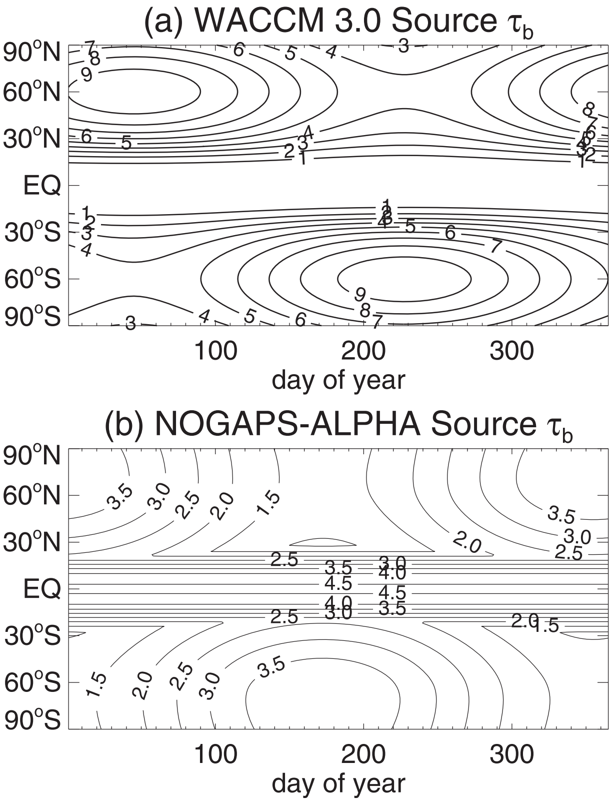

FIG. 1. Background momentum flux (mPa) based on two different functions $F(\phi, t)$ in (2) used by (a) WACCM 3.0 ($\boldsymbol{\tau}_b^* = 7$ mPa) and (b) NOGAPS-ALPHA ($\boldsymbol{\tau}_b^* = 10$ mPa).

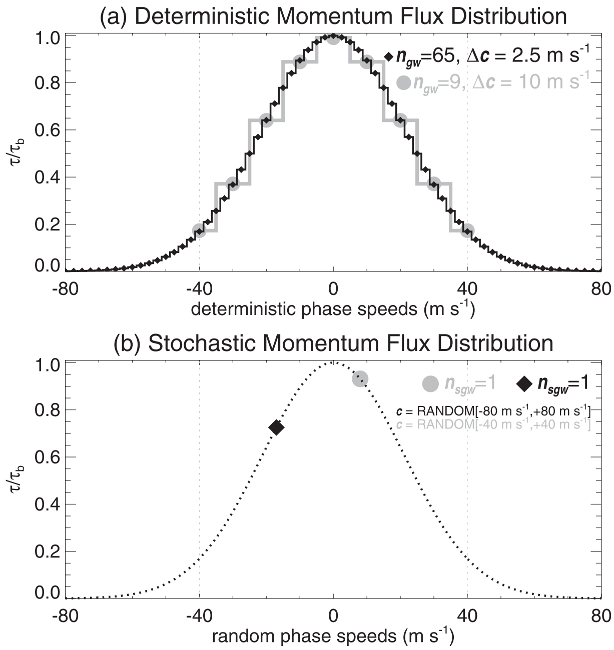

FIG. 2. Values of $\boldsymbol{\tau}_{\rm src}(c_j)/\boldsymbol{\tau}_b$ for (a) the deterministic $n_{\rm gw} = 65$ (black) and $n_{\rm gw} = 9$ (gray) discretizations of Garcia et al. (2007) and Kiehl et al. (1996), respectively, and (b) their corresponding stochastic analogs using $n_{\rm sgw} = 1$.

where Δc is the phase-speed resolution, yielding a total of $n_{\rm gw} = 2n_c + 1$ individual gravity waves of momentum flux $\boldsymbol{\tau}_{\rm src}(c_j)$. This phase speed distribution is symmetric about $c_{\rm off}$ and thus samples (1) symmetrically about its peak.

In the Garcia et al. (2007) formulation, $c_{\rm off} = U_{\rm src} = |\mathbf{U}_{\rm src}|$, where $\mathbf{U}_{\rm src}$ is the horizontal velocity vector at $p_{\rm src}$. Horizontal wavenumber vectors $\mathbf{K}_j$ align parallel to $\mathbf{U}_{\rm src}$, yielding a symmetric distribution of intrinsic horizontal phase speeds with flux peaking near zero intrinsic phase speed. Garcia et al. (2007) assign $n_{\rm gw} = 65$ waves with $\Delta c = 2.5$ m s^{-1}, which yields intrinsic phase speeds spanning the range ± 80 m s^{-1}. The resulting discretized sampling of the normalized flux function $\boldsymbol{\tau}_{\rm src}(c)/\boldsymbol{\tau}_b$ is plotted in black in Fig. 2a. For comparison, the $n_{\rm gw} = 9$, $\Delta c = 10$ m s^{-1} discretization used by Kiehl et al. (1996) is shown in gray, which, since they set $c_{\rm off} = 0$, spans a ± 40 m s^{-1} range of ground-based phase speeds.

The subsequent deposition of wave momentum flux at higher altitudes is parameterized for each wave using a Lindzen (1981) parameterization of hydrostatic irrotational vertical propagation subject to critical-level removal and linear saturation thresholds (for details, see Kiehl et al. 1996; Garcia et al. 2007). The ensuing mean-flow acceleration $a_{j,k}$ (or gravity wave drag per unit mass) at model layer k due to wave j of c_j is

$$a_{j,k} = g\epsilon \frac{\partial \boldsymbol{\tau}_{j,k}}{\partial p}, \tag{4}$$

where g is gravitational acceleration, p is pressure, and ϵ is a constant in the range $0 < \epsilon \le 1$ that represents the "intermittency" or "efficiency" of wave breaking. Intermittency factors appear in many multiwave nonorographic gravity wave drag schemes but their implementation and effects can vary from scheme to scheme. The implementation here follows that in Alexander and Dunkerton (1999), and so, as in their scheme, if we retain the same ± 80 m s^{-1} range of phase speeds, then ϵ scales linearly with changes in Δc and inversely with the corresponding changes in $n_{\rm gw}$ to retain the same total mean-flow acceleration.

That total mean-flow acceleration

$$a_k^{\rm tot} = \sum_{j=1}^{n_{\rm gw}} a_{j,k}, \tag{5}$$

directed parallel to $\mathbf{U}_{\rm src}$, is projected into zonal and meridional components that are applied as tendencies to the model's horizontal velocity field $\mathbf{U}_k$. The WACCM 3.0

scheme implements as options a number of additional limits on single-wave and total tendencies. These limits are applied in such a way that flux is redistributed rather than removed or added, so as to conserve column-integrated momentum. The version used here deposits all remaining wave flux in the top two model layers to ensure robust circulation and climate responses (Shaw et al. 2009).

With accelerations specified, other quantities follow based on the Lindzen (1981) saturation model. The effective vertical diffusion coefficient due to the turbulence generated by wave breaking is

$$(D_{\text{gwd}})_k = \sum_{j=1}^{n_{\text{gw}}} \left[\left(\frac{\text{Pr}^{-1}|c_j - U_k^{\text{proj}}|}{2N_k^2} \right) a_{j,k} \right], \tag{6}$$

where U_k^{proj} is the component of the wind vector $\mathbf{U}_k$ projected along $\mathbf{K}_j$, N_k is the buoyancy frequency in layer k, and Pr is the effective Prandtl number, here set equal to 4 following Garcia et al. (2007).

The wave-induced heating rate employed here is

$$\frac{\partial T_k}{\partial t} = \sum_{j=1}^{n_{\text{gw}}} \left\{ \frac{1}{C_p}(c_j - U_k^{\text{proj}}) a_{j,k} - \frac{T_k}{(1+\text{Pr})} \frac{\partial}{\partial p} [\rho_k (c_j - U_k^{\text{proj}}) a_{j,k}] \right\} \tag{7}$$

and is based on the work of Medvedev and Klaassen (2003), where T_k and ρ_k are temperature and density, respectively, in layer k, and C_p is mass specific heat at constant pressure. The first term is a uniformly positive irreversible heating term due to deposition of total wave energy, both the frictional dissipation of wave kinetic energy and the thermal dissipation of wave potential energy. The second is a differential heating/cooling term associated with vertical variations in the wave's vertical heat flux, which Akmaev (2007) shows can only result from thermal dissipation of wave potential energy, leading to the $1/(1 + \text{Pr})$ factor in (7). This heating rate expression is the only part of the parameterization used here that differs substantially from that described by Garcia et al. (2007).

3. Stochastic analog

To motivate what follows, deeper physical interpretations of $\boldsymbol{\tau}_{\text{src}}(c)$ and ϵ are useful here. We can view the background source-level momentum-flux spectrum $\boldsymbol{\tau}_{\text{src}}(c)$ as the state that emerges over time as sporadically generated waves from various nonorographic sources attain some form of statistical mechanical equilibrium (an analogy pursued explicitly in some spectral gravity wave models; e.g., Allen and Joseph 1989; Souprayen et al. 2001). Since wave sources are not always present, ϵ quantifies their time-mean geophysical intermittency of occurrence (Alexander and Dunkerton 1999; Hertzog et al. 2008).

Given the above, the equilibrium spectrum $\boldsymbol{\tau}_{\text{src}}(c)$ and source intermittency ϵ should emerge only over a volume and time both large and long enough, respectively, for the full ensemble of sources and waves to form and equilibrate. The deterministic parameterization in section 2 assumes that this equilibrium state exists within each GCM grid box. Yet, given gravity wave horizontal wavelengths of up to 1000 km and periods and group-propagation times of up to a day, typical GCM gridbox dimensions of 10–1000 km and time steps of 1–60 min would not appear to be either large or long enough, respectively, for this wave ensemble to emerge. Rather, equilibrium states would only appear when averaged over wider horizontal areas encompassing many GCM grid boxes, and when averaged over a number of GCM time steps. At any given GCM time step, subgrid-scale wave fluxes would vary as individual grid boxes contained either different subsets of sporadic sources and wave field members of the broader wave ensemble, or no source and hence no wave activity.

Since individual nonorographic sources are not specified in these background spectral parameterizations, here we investigate whether this kind of explicit variability can be built into the parameterization by stochastically sampling a wave spectrum governed in the long-term mean by $\boldsymbol{\tau}_{\text{src}}(c)$ and ϵ. Potential positive GCM impacts of such an approach have been reviewed by Palmer et al. (2005) and Wilks (2008).

A very simple approach to parameterizing such states is depicted in Fig. 2b. Instead of discretizing (1) deterministically with n_{gw} equispaced wave phase speeds (Fig. 2a), we now sample it randomly by choosing n_{sgw} "stochastic" waves with phase speeds

$$c_j = c_{\text{off}} + c_R(2R_j - 1), \tag{8}$$

where $j = 1 \ldots n_{\text{sgw}}$, $c_R = 80 \text{ m s}^{-1}$ is the phase speed range, and R_j is the output from a random number generator with a uniform mean distribution, such that $0 \le R_j \le 1$. In this implementation, the random R_j values are repopulated at every grid point and at every model time step so that there are no spatiotemporal correlations in wave properties between adjacent grid boxes or model time steps, in contrast to the original deterministic scheme in which waves at adjacent grid boxes and times are highly correlated.

For a given bulk intermittency ϵ used in the original deterministic scheme, the same time-mean momentum fluxes and total accelerations are attained in the stochastic analog by using a scaled intermittency in (4) of

$$\epsilon_s = \epsilon\left(\frac{n_{\mathrm{gw}}}{n_{\mathrm{sgw}}}\right). \tag{9}$$

If ϵ parameterizes the bulk effects of intermittency in the deterministic scheme, one could argue that such factors should be removed entirely from the stochastic analog in which the intermittency is now explicit. Doing so is straightforward by adding a second uniformly distributed random variable S_j $(0 \leq S_j \leq 1)$ and choosing a limit $\hat{S}$, such that if $S_j \leq \hat{S}$ the stochastic acceleration a_k^{tot} is applied in the model, but if $S_j > \hat{S}$ we set $a_k^{\mathrm{tot}} = 0$. Setting

$$\hat{S} = \epsilon\left(\frac{n_{\mathrm{gw}}}{n_{\mathrm{sgw}}}\right), \tag{10}$$

analogously to (9), then allows ϵ to be removed entirely from (4), with one caveat. Equations (9) and (10) can yield values in excess of unity. While $\epsilon_s > 1$ is technically unphysical, the stochastic parameterization algorithm still works using such ϵ_s settings. By contrast, $\hat{S} > 1$ cannot be accommodated, and so n_{sgw} needs to be increased until $\hat{S} < 1$ is achieved.

One can view (10) as a generalization of the stochastic scheme to a noninteger mean number of waves per grid box:

$$\hat{n}_{\mathrm{sgw}} = n_{\mathrm{sgw}}\hat{S}. \tag{11}$$

This permits, for example, implementations with less than one stochastic wave per grid box on average $(0 < \hat{n}_{\mathrm{sgw}} < 1)$, by choosing $n_{\mathrm{sgw}} = 1$ and nonvanishing $\hat{S} < 1$.

For simplicity, in this paper we only show results using the ϵ_s formulation, given the more straightforward connection to its deterministic antecedent.

4. Offline single-column tests

A convenient feature of the stochastic implementation in section 3 is the close connection that is maintained to the original deterministic scheme. The latter has been carefully refined and tuned for use in global models over many years. The simple relations in section 3 allow the core physics and tuned parameter settings of the deterministic scheme to translate to the stochastic analog, which should in turn yield the same mean drag profiles. We demonstrate this here using offline single-column tests.

Figures 3a and 3b show vertical profiles of instantaneous zonal and meridional winds at a grid point near the Alps after +12 h of a T79L68 global model forecast initialized at 0000 UTC 1 June 2007. The model in question is the Advanced-Level Physics High-Altitude prototype of the Navy Operational Global Atmospheric Prediction System (NOGAPS-ALPHA), and the fields are part of the high-altitude forecast assimilation runs described by Eckermann et al. (2009).

The forecast model in those runs used the deterministic WACCM 3.0 scheme to parameterize nonorographic gravity wave drag. Thus, at this time and location the model passed these exact wind (and other meteorological) profiles to that parameterization, which in turn returned zonal and meridional mean-flow accelerations, vertical diffusivities, and dynamical heating rates shown with thick solid gray curves in Figs. 3c–f. Here we have used the same tuned parameter settings as in Eckermann et al. (2009), specifically $n_{\mathrm{gw}} = 65$, $\Delta c = 2.5$ m s^{-1}, $p_{\mathrm{src}} = 500$ hPa, $\tau_b^* = 1.75$ mPa, and $\epsilon = 0.0175$.

Other curves in these lower four panels show results from our stochastic analog of this scheme that uses only a single wave ($n_{\mathrm{sgw}} = 1$). Here output from the stochastic parameterization was averaged over a number of separate calls ranging from 1 to 10 000, using the same input wind profiles in every case, but with R_j from (8) independently reinitialized during each call. The mean accelerations, diffusivities, and heating rates after 1–10 calls in Figs. 3c–f are substantially different from the deterministic reference (gray curve) because of the random nature of the wave field. However, after 100 calls the mean profiles are quite similar to the reference curve, and after 1000–10 000 calls the mean profiles overlay the deterministic reference curves. However, as shown in Fig. 4, while the long-term means are the same, the stochastic version produces large standard deviations about that mean, whereas for the same input meteorological profiles the original deterministic scheme has zero standard deviation.

Since $n_{\mathrm{sgw}} = 1$ and $n_{\mathrm{gw}} = 65$, from (9) we used a modified stochastic intermittency $\epsilon_s = 65\epsilon \sim 1.138$. Thus, by incorporating intermittency into the parameterization explicitly (Fig. 4), the need for a parameterized bulk intermittency factor of small value is now largely obviated. Of course the $\epsilon_s \sim 1$ result is specific to the tuned settings for this particular model configuration and thus probably fortuitous, with tuned values for other models likely leading to $\epsilon_s \neq 1$. Nonetheless, the trend away from very small ϵ values, implying highly intermittent or inefficient wave breaking, to values nearer unity through an explicit stochastic representation of intermittency in the parameterization, is clearly both a robust and physically self-consistent result.

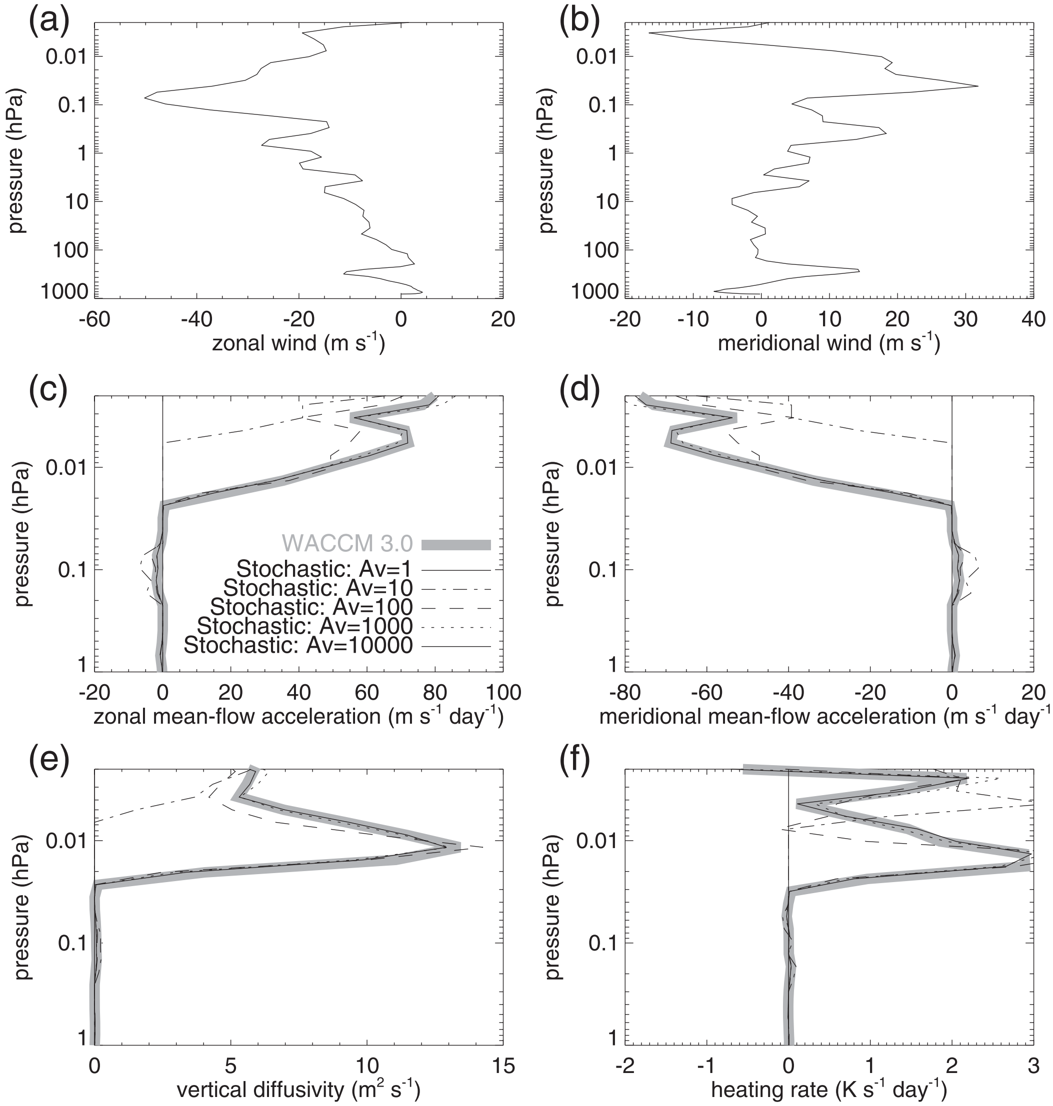

FIG. 3. Vertical profiles of (a) zonal and (b) meridional winds input to the nonorographic gravity wave drag parameterization, which returns (c) zonal and (d) meridional mean-flow accelerations, (e) vertical diffusion coefficients, and (f) wave-induced heating rates. As labeled in (c), the gray curves show results from the WACCM 3.0 scheme, while the black curves show output from the stochastic analog averaged over 1, 10, 100, 1000, and 10 000 separate calls.

One can reduce the large standard deviations in Fig. 4 by increasing n_{sgw}. Figure 5 shows the corresponding mean zonal accelerations and standard deviations as n_{sgw} is progressively increased, with ϵ_s rescaled in each case as in (9). As n_{sgw} increases, the standard deviation reduces toward the vanishing deterministic limit. Thus $n_{sgw} > 1$ yields hybrid states that are a blend of the stochastic ($n_{sgw} = 1$) and deterministic ($n_{sgw} \rightarrow \infty$) limits.

5. Global model tests

Next we compare how the equivalent stochastic and deterministic versions of this nonorographic gravity wave drag parameterization perform in a GCM. We use the forecast model component of NOGAPS-ALPHA with the same T79L68 formulation and physics settings described by Eckermann et al. (2009), except that here we

1) use a Webster et al. (2003) parameterization of orographic gravity wave and flow-blocking drag instead of the Palmer et al. (1986) scheme, and
2) apply the nonorographic gravity wave-induced heating rate (7) to GCM temperature fields using Pr = 4.

The GCM is initialized on 1 June 2007 using the NOGAPS-ALPHA analysis fields described by Eckermann et al. (2009) and then is integrated forward in time without

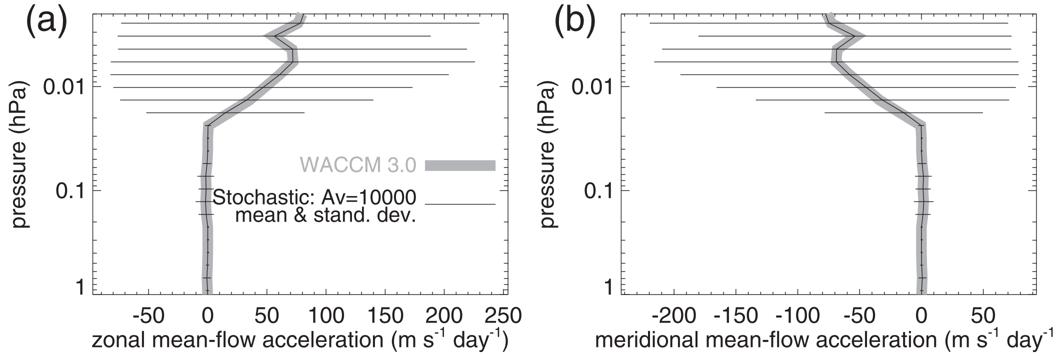

FIG. 4. (a) Zonal and (b) meridional mean-flow accelerations from the (deterministic) WACCM 3.0 gravity wave drag parameterization (gray curve) and the 10 000-point mean from the stochastic analog (black curve) with corresponding standard deviations shown as error bars (the deterministic WACCM 3.0 profile has zero associated standard deviation).

data assimilation update cycles to 1 January 2010. This ''nature run'' is constrained by 12-hourly analyzed sea and land surface temperatures, snow depths, and ice concentrations at the lower boundary.

A series of these nature runs was performed initially to tune the nonorographic gravity wave drag parameterization to yield a realistic zonal-mean middle-atmosphere climate, which led to several changes from the default WACCM 3.0 settings described in earlier sections. First, $\boldsymbol{\tau}_b$ from (2) was modified, as shown in Fig. 1b, to center flux peaks closer to the solstices and to increase wave momentum fluxes at the equator. Second, we chose to launch nonorographic waves zonally rather than along the source-level wind direction. Third, we reduced the

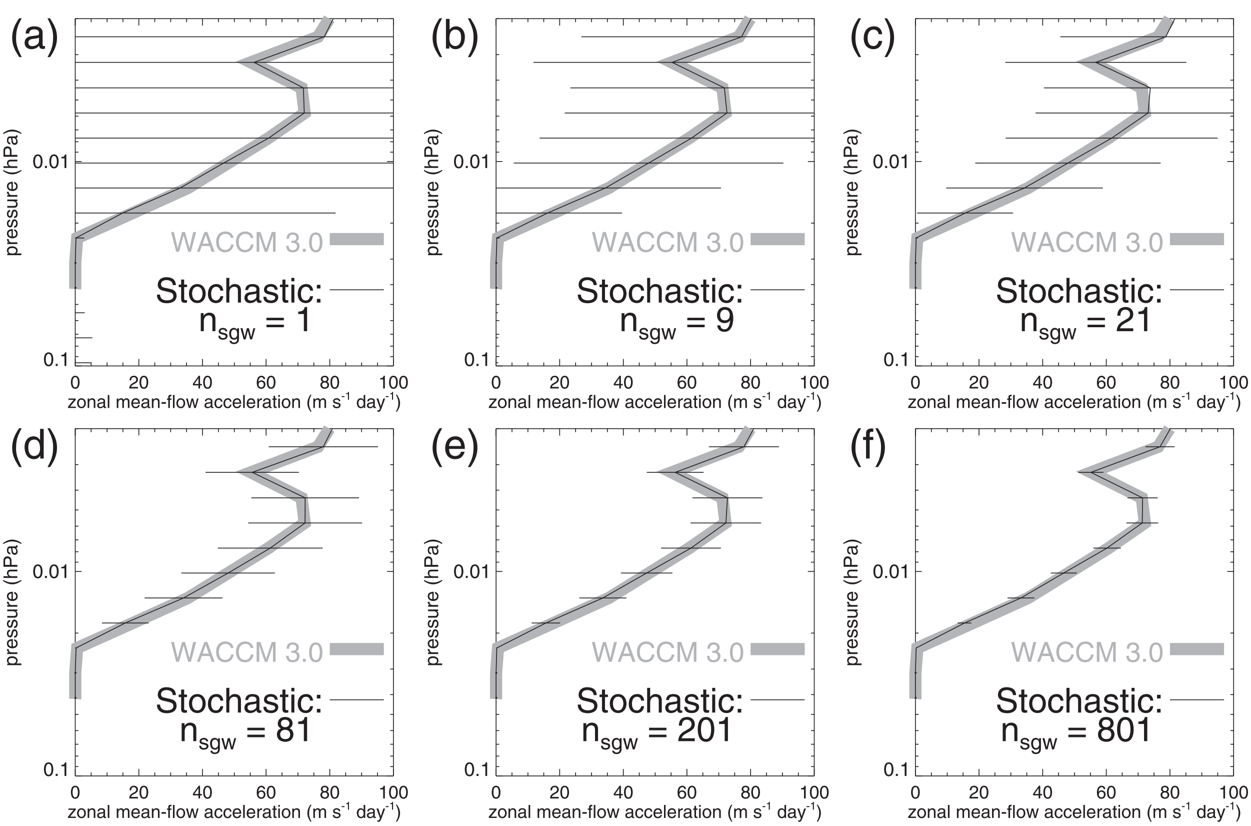

FIG. 5. As in Fig. 4a, but now showing means and standard deviations from the stochastic analog for n_{sgw} values of (a) 1 (as in Fig. 4a), (b) 9, (c) 21, (d) 81, (e) 201, and (f) 801. In each case the number of calls was adjusted to yield a total of 10 000 waves.

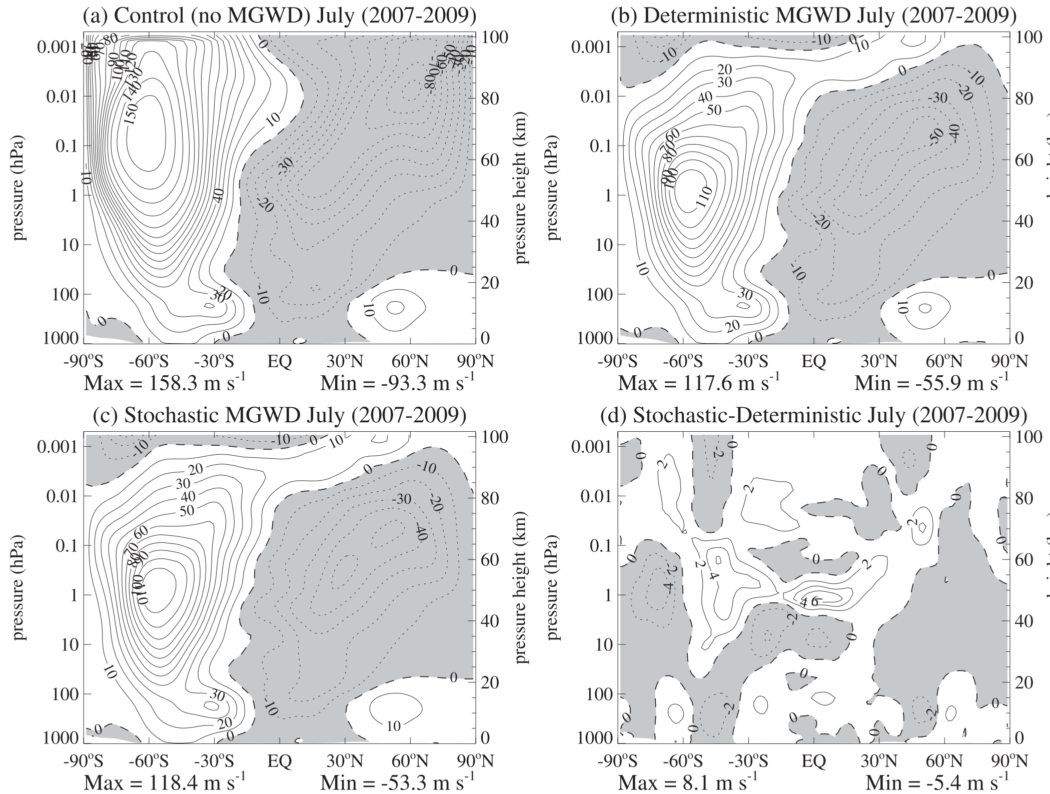

FIG. 6. Zonal-mean zonal winds (m s^{-1}) for July 2007–09 from NOGAPS-ALPHA nature runs: (a) control run without parameterized nonorographic gravity wave drag, and runs using the (b) deterministic and (c) stochastic parameterizations of nonorographic gravity wave drag with equivalent settings to produce the same time-mean drag. (d) Differences in the zonal-mean zonal winds between the stochastic and deterministic simulations.

critical inverse Froude number for nonorographic gravity wave breaking Fr_c^{-1} from 1 to 0.1, to force parameterized waves to break at lower altitudes, an approach often used to tune both orographic and nonorographic gravity wave drag in GCMs (e.g., Norton and Thuburn 1999; Webster et al. 2003; Scinocca et al. 2008) and recently defended on theoretical grounds by Scinocca and Sutherland (2010).

Figure 6a shows 3-yr average zonal-mean zonal winds for July from a control run without parameterized nonorographic gravity wave drag, revealing unrealistically strong stratospheric jets that extend through the mesosphere. Figure 6b shows corresponding mean winds from the nature run in which the deterministic nonorographic gravity wave drag was activated using the tuned settings noted above, with $\boldsymbol{\tau}_b^* = 10$ mPa, $\epsilon = 0.0375$, and $n_{\mathrm{gw}} = 65$. These simulations with tuned nonorographic gravity wave drag show more realistic stratospheric jets in both hemispheres, including better tilting of the winter (southern) jet and realistic reversal of the summer (northern) jet in the upper mesosphere.

Figure 6c shows results from the nature run using the stochastic analog of the tuned deterministic nonorographic gravity wave drag, using $n_{\mathrm{sgw}} = 1$ and thus $\epsilon_s = 2.275$ according to (9). Visual comparison of Figs. 6b and 6c reveals almost identical zonal wind structure, despite the imposition of explicitly stochastic, highly intermittent, and ''noisy'' gravity wave drag and heating rates in the latter GCM simulation. To verify this visual impression, Fig. 6d plots the mean zonal wind difference fields between the stochastic and deterministic nature runs. Differences everywhere are small, particularly in the summer hemisphere.

Figure 7 plots the 3-yr zonal-mean zonal mean-flow accelerations (top) and heating rates (bottom) for July due to parameterized nonorographic gravity wave drag from the deterministic and stochastic nature runs. The time-mean accelerations and heating rates in the GCM again look largely identical. Small values of the difference fields, plotted on the right of Fig. 7, again confirm that impression.

Since our offline single column simulations demonstrated that the stochastic approach gave identical time-mean accelerations and heating rates to its deterministic antecedent, these GCM results might not seem all that surprising. However, in a fully interactive nonlinear GCM, it is not a given that highly intermittent stochastic drag

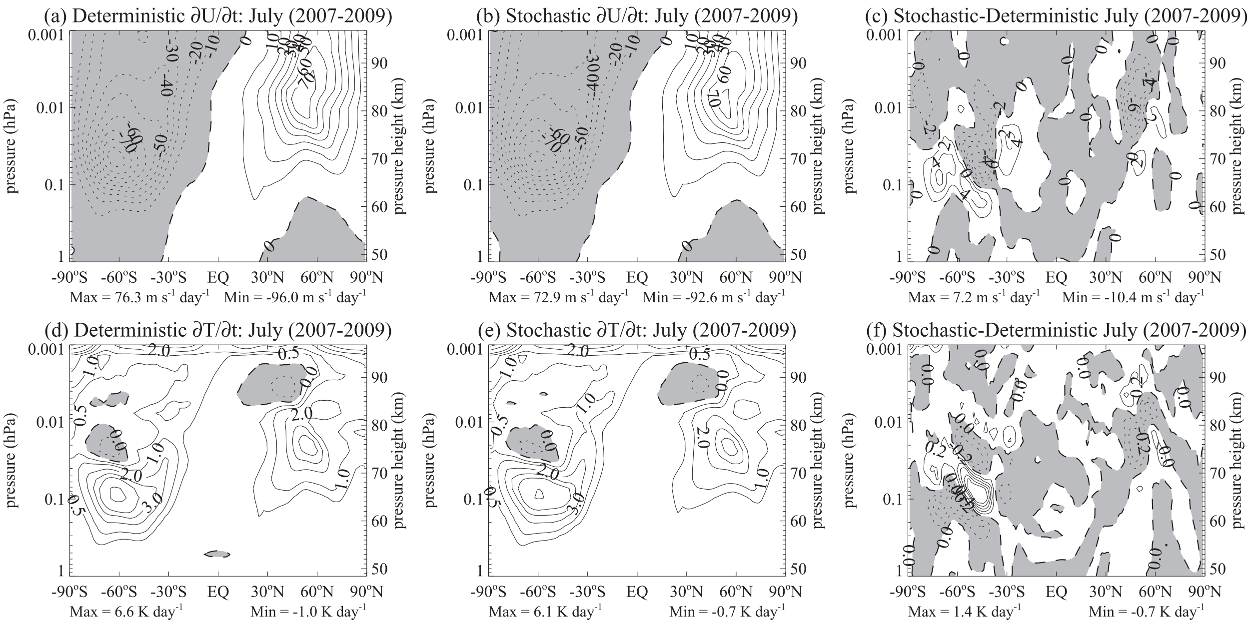

FIG. 7. (a)–(c) Zonal-mean zonal mean-flow accelerations (m s^{-1} day^{-1}) and (d)–(f) zonal-mean heating rates (K day^{-1}) due to parameterized nonorographic gravity wave drag averaged for July 2007–09 from NOGAPS-ALPHA nature runs that used (left) the deterministic parameterization and (middle) its stochastic analog. (right) Differences in these means between the stochastic and deterministic experiments.

will produce the same long-term GCM climate as its smooth deterministic progenitor. Indeed, the corresponding 2-yr zonal-mean zonal winds in January, plotted in Fig. 8, show that the winter (northern) stratospheric zonal winds in this case are very different between the stochastic and deterministic nature runs. These differences arose due to spontaneous stratospheric warmings in both Januaries of the stochastic run that did not occur in the deterministic simulation: the latter generated a warming only in December 2007, which did not occur in the stochastic run. Of course, stratospheric warmings in northern winter are a well-known source of natural interannual variability in GCMs, and nature runs extending for 25–50 yr or more would be needed to deduce any real systematic differences in zonal-mean northern winter stratospheric climate or stratospheric warming frequency due to use of stochastic or deterministic nonorographic gravity wave drag (Charlton et al. 2007). Nonetheless, Fig. 8 highlights the potential for the stochastic scheme to generate different GCM behavior than the deterministic version by more random forcing that can seed large irreversible changes via nonlinear interactions and feedbacks. The differences in the summer hemisphere in Fig. 8b, which are also larger than those in the summer hemisphere in Fig. 6d, are probably due to interhemispheric coupling through a modified mesospheric pole-to-pole residual circulation caused by modified gravity wave driving in northern winter due to the differently disturbed winter stratospheres in each simulation (Becker and Fritts 2006).

Variability in the deterministic scheme's drag comes solely from variability in resolved GCM winds and temperatures, which in turn peaks at planetary wavenumbers. Thus, the deterministically parameterized nonorographic gravity wave drag forces variability most strongly at the gravest GCM wavenumbers. By contrast, the stochastic scheme's drag also varies significantly and randomly from point to point in both space and time (Fig. 4), and thus could force significant variability at the smallest space–time scales of the GCM. Since these smallest GCM scales can be unreliable and can alias to larger scales (Lander and Hoskins 1997), such small-scale forcing might have undesirable side effects on the GCM simulations.

To investigate this, in each nature run the GCM's instantaneous global spectral fields were saved at 0000 UTC on every model day. Figure 9a plots mean total kinetic energy spectra at 0.055 hPa for June (2007–09) for the stochastic and deterministic runs, along with the vortical and divergent contributions, as computed directly from these daily spherical harmonic spectral coefficients of GCM vorticity and divergence (e.g., Koshyk et al. 1999). In computing these long-term means, we also computed standard deviations at each total wavenumber, which are plotted in Fig. 9b. In the bottom row, we plot the ratio of these spectral distributions between the GCM fields using stochastic and deterministic drag, for both

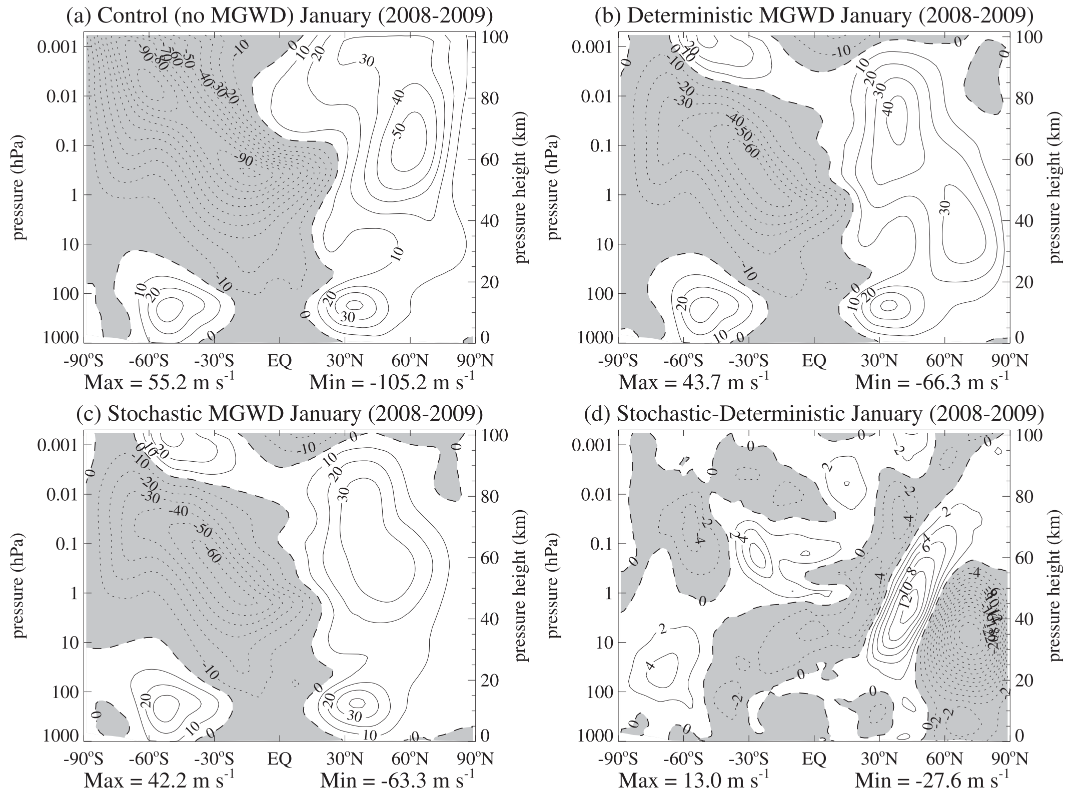

FIG. 8. Zonal-mean zonal winds (m s^{-1}) for January 2008–09 from NOGAPS-ALPHA nature runs: (a) control run without parameterized nonorographic gravity wave drag, and runs using the (b) deterministic and (c) stochastic parameterizations of nonorographic gravity wave drag with equivalent settings to produce the same time-mean drag. (d) Differences in the zonal-mean zonal winds between the stochastic and deterministic simulations.

the mean spectra (Fig. 9c) and their standard deviations (Fig. 9d). Overall, we do not see any noticeable change in the shape, intensity, or standard deviation of the GCM kinetic energy spectra, although the ratios in the bottom panels do reveal small increases at the largest total wavenumbers.

To study these high-wavenumber enhancements as a function of altitude, we averaged the spectral means and standard deviations at each height over the band of total wavenumbers 70–78 (shaded in Figs. 9c and 9d). Figure 10 plots the height variation of the resulting ratios of the mean spectra and their standard deviations between the stochastic and deterministic nature runs. While moderate increases are evident at most altitudes in the upper stratosphere and mesosphere where the gravity wave drag is strongest, at no altitude are these relative increases especially large. These results indicate that highly stochastic and intermittent parameterizations of gravity wave forcing, in addition to producing reliable GCM climate, do not appear to be accompanied by unrealistic increases in small-scale dynamical variability within the GCM.

6. Discussion

While there have been occasional efforts to parameterize nonorographic gravity wave drag stochastically in GCMs (e.g., Dunkerton 1982a; Piani et al. 2004), the parameterizations currently used in production GCM configurations are exclusively multiwave deterministic formulations. A strong practical motivation for the current stochastic approach to parameterizing nonorographic gravity wave drag is to reduce the computational expense of these multiwave deterministic schemes in GCMs. When the 65-wave WACCM 3.0 scheme of Garcia et al. (2007) was implemented in NOGAPS-ALPHA, for instance, it alone consumed 20%–40% of the forecast model's total run time. The extension of NOGAPS-ALPHA into the middle atmosphere involves additional model layers and physics that are slated for future transition to the operational NOGAPS. As a numerical weather prediction (NWP) prototype, new NOGAPS-ALPHA features compete for scarce computational resources with many other potential upgrades to NOGAPS with potentially greater immediate

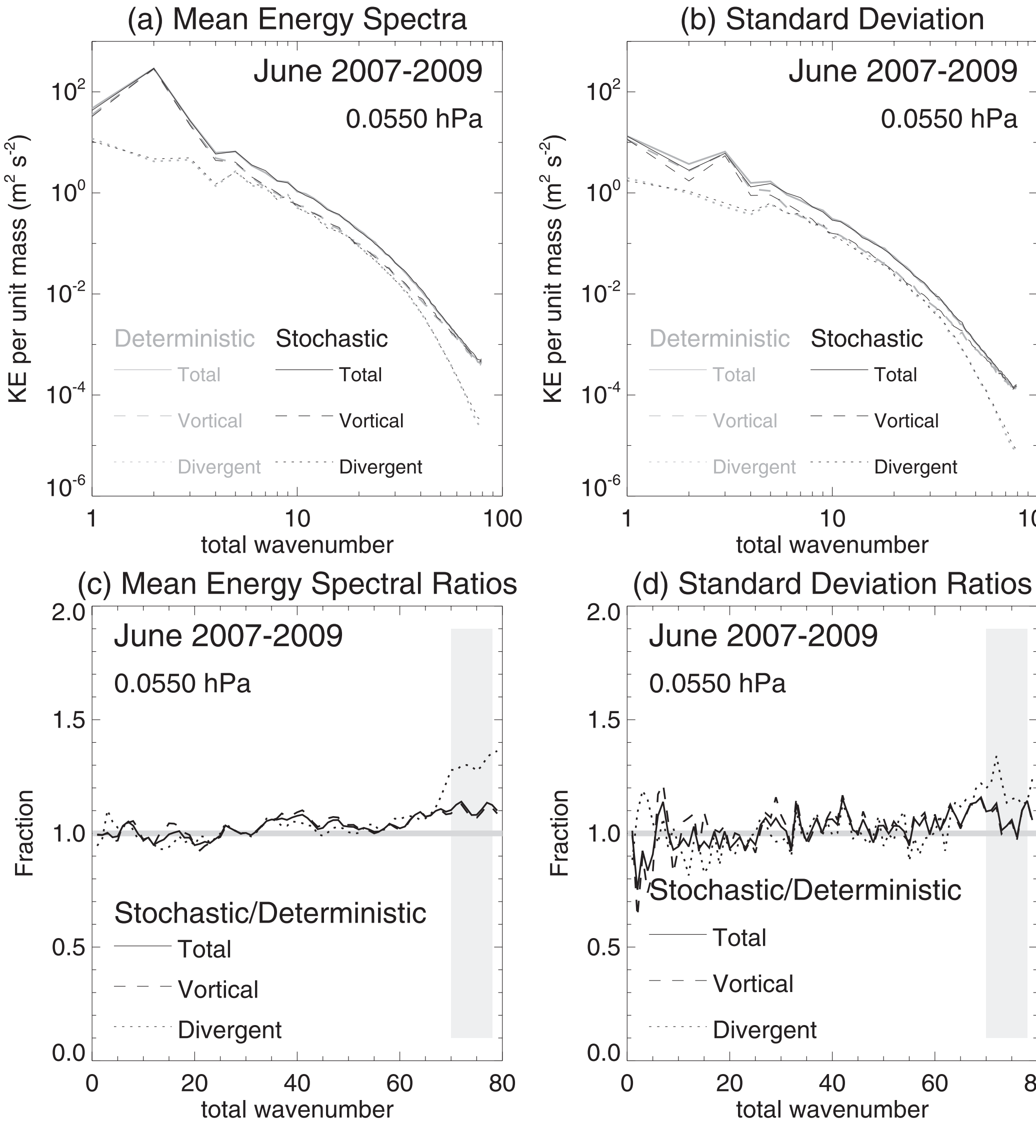

FIG. 9. (a) Mean kinetic energy spectra and (b) their standard deviations, plotted as a function of total wavenumber at 0.055 hPa, as averaged from daily 0000 UTC spectral NOGAPS-ALPHA GCM fields for June 2007–09 for nature runs in which nonorographic gravity wave drag was parameterized deterministically (gray curves) and stochastically (black curves). The vortical (dashed curves) and divergent (dotted curves) contributions to total kinetic energy (solid curves) are also shown. (c),(d) The ratios of the stochastic to the deterministic spectral curves in (a) and (b), respectively; the shaded area in the total wavenumber range 70–78 is used to form profile means in Fig. 10.

impact on NWP (e.g., higher horizontal resolution, more tropospheric observations for assimilation, etc.). Thus, to be a viable candidate for near-term transition to operations, parameterizations of nonorographic gravity wave drag must be both accurate and computationally cheap relative to the total run time of the system.

The single-wave stochastic analog of the 65-wave scheme developed here should ideally yield close to a 65-fold increase in computational speed. As discussed in the appendix, it was implemented here within the existing parameterization code, which contains significant additional overhead associated with internal calculations of different meteorological profiles and time-mean statistics, and thus a 65-fold speed increase cannot be expected. Nonetheless, without any additional effort to optimize this parameterization subroutine, the single-wave stochastic option yields an order of magnitude increase in the speed of this subroutine relative to the deterministic 65-wave version in the NOGAPS-ALPHA nature runs reported here. The single-wave stochastic scheme consumes approximately 2%–5% of the forecast model's total run time and thus becomes a viable transition candidate.

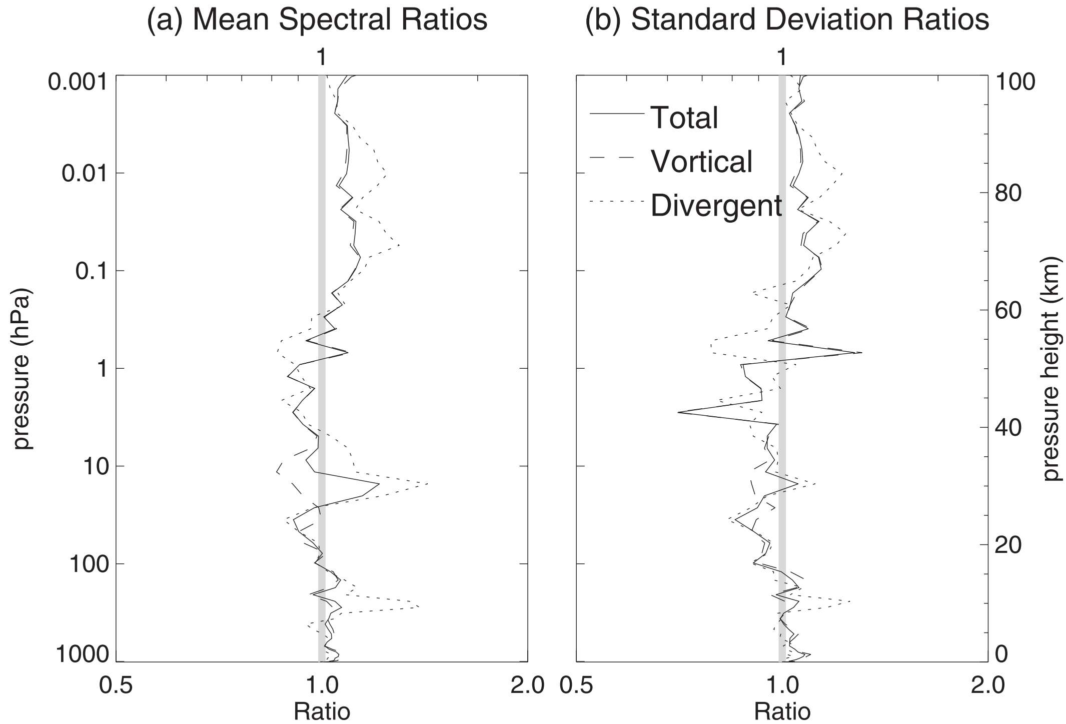

FIG. 10. Total (solid), divergent (dotted), and vortical (dashed) (a) mean spectral kinetic energy and (b) its standard deviation in the NOGAPS-ALPHA spectral GCM fields, plotted as the ratio of two simulations that used stochastic and deterministic parameterizations of nonorographic gravity wave drag, respectively. This ratio was computed at each altitude from mean energy spectra for June 2007 over the total wavenumber range 70–78 (gray bands in Figs. 9c,d). Values greater (less) than unity imply increased (decreased) kinetic energy at wavenumbers 70–78 in the GCM fields generated using the stochastic parameterization, relative to those using the deterministic parameterization.

The computational expense issue is unique neither to this particular parameterization nor to this particular GCM. For example, in their implementation of the deterministic nonorographic gravity wave drag scheme of Scinocca (2003) in the European Centre for Medium-Range Weather Forecasts Integrated Forecast System (ECMWF IFS), Orr et al. (2010) discretized their source momentum-flux spectrum using $n_{\mathrm{gw}} = 80$ individual waves. Because of the resultant computational expense, they found it necessary to update the tendency from this scheme every 2 h only, to reduce the overall computational burden to approximately 3% of the total run time. Our stochastic approach allows us to achieve similar or greater computational savings without resorting to a coarser space–time physics grid in the GCM.

A convenient aspect of the stochastic formulation developed here is the close relationship that is retained to the antecedent deterministic schemes, given that the latter schemes are now common in GCMs and have been exhaustively tuned over many years to yield realistic middle atmosphere climate. Using simple conversion relations, our offline single-column simulations showed that identical time-mean mean-flow accelerations, heating rates, and diffusivities could be generated using a straightforward stochastic analog of a tuned deterministic scheme. More importantly, when implemented within a GCM, nearly indistinguishable zonal-mean drag and zonal-mean climate were produced in July, for example. Such reproducible GCM climate responses were not assured given the potentially large nonlinear feedbacks involved in transitioning from drag that is smooth and deterministic to drag that is noisy and random on small space–time scales. These findings essentially accord with those of McLandress and Scinocca (2005), who found that GCMs were remarkably insensitive to the precise ways in which nonorographic gravity wave momentum fluxes were deposited as a function of height in different deterministic schemes.

The stochastic scheme produces random drag variability at the smallest space–time scales of the GCM that is entirely absent in the deterministic parent scheme. In essence, this variability now makes explicit in the GCM the inherent gravity wave intermittency that is parameterized in the deterministic scheme using ϵ. A body of literature has highlighted potential advantages of an explicit representation of such random intrinsic intermittency in GCM parameterizations (Palmer 2001; Palmer et al. 2005; Wilks 2008), such as more realistic ensemble spread and variability (Buizza et al. 1999, 2005; Teixeira and Reynolds 2008; Reynolds et al. 2008) and mean error reduction via more realistic population of different climate and weather regimes (Molteni and Tibaldi 1990; Jung et al. 2005). Figure 8, for example, showed very different mean winter polar stratospheric winds in January between the stochastic and deterministic nature runs due to stratospheric warmings in the stochastic GCM simulation that did not occur in the deterministic simulation. These 2.5-yr runs are far too short to deduce any systematic differences in stratospheric warming frequency. Nonetheless, these results are at least superficially consistent with simple conceptual models that show how small amounts of random gravity wave forcing can trigger large regime transitions that generate stratospheric warmings that do not occur in a corresponding deterministic model without random gravity wave forcing (Birner and Williams 2008).

Despite intense forcing at the smallest space–time scales of the GCM by the stochastic gravity wave drag scheme, our GCM simulations did not reveal any excessive systematic increases in mean kinetic energy or variability at the smallest spatial GCM scales, relative to the corresponding deterministic simulation. This finding may explain why GCMs that numerically suppress realistic kinetic energy at small space–time scales see greatest improvements not via stochastic parameterization alone, but also by explicitly injecting additional stochastic kinetic energy back into these smallest resolved GCM scales (Jung et al. 2005; Berner et al. 2009; Charron et al. 2010).

Recent work has also found that mesoscale GCM kinetic energy in the mesosphere is intrinsically chaotic and stochastic because of the dominance of divergent gravity wave motions that have fast decorrelation times (Liu et al. 2009; Nezlin et al. 2009). Thus, the random stochastic forcing of the smallest mesospheric space–time scales of a GCM using a stochastic nonorographic gravity wave drag parameterization may in fact mimic the true stochastic nature of these dynamics in the GCM.

7. Conclusions and outlook

We have presented a simple methodology for generating an explicitly stochastic analog of an existing deterministic multiwave parameterization of nonorographic gravity wave drag, the principles of which (if not the precise mathematical details) should be applicable to other GCM parameterizations of gravity wave drag. Our approach maintains a close association to the original deterministic scheme, such that the stochastic version is implemented here as an option and minor modification of the original deterministic parameterization code. Through the use of simple scaling terms, we show how the stochastic analog reproduces identical time-mean drag, diffusion, and heating rates to the deterministic parent scheme, which greatly simplifies replacing the latter with the former in GCMs using the existing tuned parameter settings of the deterministic antecedent.

When implemented in a GCM, our single-wave stochastic analog of the 65-wave WACCM 3.0 nonorographic gravity wave drag scheme produced largely identical zonal-mean climate and very similar spectral energy distributions in long-term nature runs to those from corresponding runs using the original deterministic scheme. In addition to reproducing very similar GCM climate and variability, the stochastic scheme yields the following additional beneficial features:

- an order-of-magnitude reduction in computational expense;
- explicit parameterization of gravity wave intermittency, which largely replaces the tuned bulk intermittency factor ϵ in the deterministic scheme; and
- stochastic GCM variability that can realistically increase ensemble spread and reduce mean climate biases.

Given these benefits along with no apparent disadvantages to date, we are now routinely parameterizing nonorographic gravity wave drag in NOGAPS-ALPHA using the single-wave stochastic parameterization outlined here. Having made this change, new parameterization possibilities now open up. For example, there are emerging observations of gravity wave momentum-flux intermittency (e.g., Hertzog et al. 2008), which could be used to constrain the statistical properties of our stochastically parameterized momentum-flux spectra more realistically (see, e.g., Fig. 5). Similarly, there are other parameters in the scheme besides wave phase speeds that could be converted from deterministic to stochastic variables. Obvious candidates are those that are poorly constrained observationally or theoretically and which are likely to vary quasi-randomly rather than having set values, such as the background momentum flux $\boldsymbol{\tau}_b^*$ and the launch pressure level p_{src}, among others.

A longer-term goal is to transition from the crude background source spectrum used here to more physical parameterizations of gravity wave momentum fluxes from specific subgrid-scale nonorographic sources, such as deep convection and jet instabilities (Charron and Manzini 2002; Beres et al. 2005; Richter et al. 2010). One might assume that physical source models would yield deterministic $\boldsymbol{\tau}_{\mathrm{src}}(c)$ forms with inherent geophysical intermittency ϵ that then obviate any further need for stochastic variables. However, that may not be the case: here, too, stochastic variables could play an important role in capturing realistic inherent variability in the parameterized momentum fluxes of waves from these unresolved sources, particularly within the context of ensemble prediction (Palmer 2001; Palmer et al. 2005).

For example, GCM parameterizations of convection remain challenging, and are themselves moving from deterministic to explicitly stochastic schemes (Plant and Craig 2008; Teixeira and Reynolds 2008). The latter suggests a need for a corresponding stochastic range of variability in parameterized subgrid-scale gravity wave momentum fluxes generated by such stochastically parameterized sources of GCM convection. Similarly, jet instabilities and circulations that generate gravity waves are highly resolution dependent (e.g., Scinocca and Ford 2000; Plougonven and Snyder 2007). When resolved by the GCM, these instabilities likely generate resolved waves that do not need to be parameterized (e.g., O'Sullivan and Dunkerton 1995). For parameterization, subgrid-scale jet instabilities that generate the unresolved waves must be estimated diagnostically from properties of the resolved GCM flow (Charron and Manzini 2002; Richter et al. 2010). The inherent uncertainty in these estimated subgrid-scale jet source terms could again be parameterized explicitly via realistic stochastic spread of the associated source-level gravity wave momentum fluxes. Finally, it should be noted that aspects of orographic gravity wave drag also appear to be inherently stochastic (Doyle and Reynolds 2008; Eckermann et al. 2010), which may motivate explicitly stochastic schemes to replace the deterministic parameterizations of orographic gravity wave and flow-blocking drag that are currently used in GCMs (e.g., Palmer 2001).

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APPENDIX

Nonorographic Gravity Wave Drag Module

In 2006, the National Aeronautic and Space Administration (NASA), the National Center for Atmospheric Research (NCAR), and the Naval Research Laboratory (NRL) began a collaborative project to develop gravity wave–drag parameterization jointly for all three member GCMs: the Goddard Earth Observing System version 5 (GEOS5), WACCM, and NOGAPS-ALPHA, respectively. The scheme described by Kiehl et al. (1996) formed the basis for parameterized nonorographic gravity wave drag initially implemented within both WACCM and GEOS5. That common parameterization subsequently diverged. NCAR, inter alia, added more parameterized waves, used a wider phase-speed distribution, and changed the source-level momentum flux for WACCM (Garcia et al. 2007). NASA adopted different source functions and modified the propagation and dissipation modules for use in GEOS5. The Garcia et al. (2007) formulation in WACCM was later implemented in NOGAPS-ALPHA, where it, too, was modified and tuned for data assimilation applications (see section 3 of Eckermann et al. 2009). At the same time, the version in WACCM underwent further large independent changes (Richter et al. 2010).

It soon proved impossible for each center to continually integrate into its version of the code all the new features emerging at the other two centers, especially as the codes at each center diverged more and more over time. This spurred a programming effort to combine the three different versions of the code at each center into a single common parameterization that all institutions could then implement in their GCMs and develop jointly from a common code and repository.

This so-called team scheme was carefully coded from scratch to adhere rigidly to the 11 ''plug compatibility'' rules proposed by Kalnay et al. (1989) to facilitate easier exchange of parameterizations among modeling centers. The biggest change relative to the antecedent codes was the creation of separate setup and running subroutines (rule 2), the former entirely new. This new setup subroutine is called just once at the start of a GCM run. Through two simple input labels—a ''model'' and an ''experiment'' identifier—a series of specific statements and parameter settings are activated that define subsequent behavior of the gravity wave–drag subroutine. The model label identifies a particular GCM by activating gravity wave drag options and parameter values used in that GCM and deactivating all other features used in other GCMs. The experiment label activates a secondary series of settings that activate preprogrammed ''tuned'' parameter values for a particular GCM experiment, configuration, or resolution.

Given that the team scheme aims to be a community, multi-institution GCM resource, the new setup subroutine offers many advantages. These include the following:

- Backward compatibility: older code and/or tuned parameter settings can be retained and easily reactivated to rerun historical GCM experiments or configurations.

- Faster transitions: new physics options developed for one center's GCM now become immediately available for other centers to activate and test in their GCM.
- Greater flexibility: all physics options are available and can now be easily mixed and matched, or simply deactivated.
- Separation of ''tuning'' from code development: casual GCM users seeking only to tune the parameterization in a GCM need only to make a few simple edits to the setup subroutine. The core physics subroutines of the parameterization should now never need to be edited by anyone other than parameterization developers.

While this integrated capability comes with an inevitable increase in the overall length and complexity of the code relative to its antecedents, this is more than compensated by these and other advantages.

Offline and online tests of the team scheme have verified exact reproduction of the results of the three antecedent nonorographic gravity wave–drag codes previously run at NCAR, NASA, and NRL, so that each center can now use the team scheme without any change in the tuned gravity wave drag settings that they have always used in their GCM. There is also no significant speed penalty of the new code relative to those antecedent codes in timing tests to date using the NOGAPS-ALPHA GCM.

This team scheme also integrates the different orographic gravity wave drag schemes used at each center, specifically (a) an orographic gravity wave scheme based on McFarlane (1987) used by NCAR and NASA (Kiehl et al. 1996) and (b) a Webster et al. (2003) parameterization of orographic gravity wave and flow-blocking drag used in NOGAPS-ALPHA. In the team scheme, source-level orographic gravity wave fluxes from either scheme are sent to the same common propagation and dissipation modules used in the nonorographic gravity wave calculations.

The stochastic parameterization of nonorographic gravity wave drag outlined in this paper has also been implemented in the team scheme as a new option, and was used to generate all the offline and online (GCM) results presented in this paper.

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