Implementation of a Stochastic Eddy-Diffusivity/Mass-Flux Parameterization into the Navy Global Environmental Model

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ABSTRACT

A unified boundary layer and shallow convection parameterization based on a stochastic eddy-diffusivity/mass-flux (EDMF) approach is implemented and tested in the Navy Global Environmental Model (NAVGEM). The primary goals of this work are to improve the representation of convectively driven boundary layers and the coupling between the boundary layer and cumulus regions. Within the EDMF framework the subgrid vertical fluxes are calculated as a sum of an eddy-diffusivity part, which in the current implementation is based on the approach developed by Louis in the late 1970s, and a stochastic mass-flux parameterization. The mass-flux parameterization is a model for both dry and moist convective thermals. Dry thermals, which represent surface-forced coherent structures in a flow, provide countergradient mixing in the boundary layer and, if conditions permit, are the roots for moist thermals. Moist thermals represent shallow convective clouds. The new parameterization implemented in a single-column model (SCM) version of NAVGEM is shown to be able to realistically simulate a variety of dry and moist convective cases. The NAVGEM SCM results are validated against large-eddy-simulation results. The skill of NAVGEM as a global weather forecasting model is considerably improved with the new EDMF parameterization. The EDMF parameterization became part of the operational NAVGEM in November 2013.

1. Introduction

Spatial and temporal resolutions of state-of-the-art weather prediction models are not fine enough to explicitly resolve turbulent motion. Therefore, the influence of turbulence on the resolved flow has to be parameterized. In most of the models, the turbulence parameterization is split among different computational routines such as the planetary boundary layer and moist (shallow and deep) convection. The parameterizations are derived by simplifying basic conservation laws to agree with a specific conceptual model of turbulence. Often, each of these parameterizations is based on a different conceptual model that is derived from a different archetypal turbulence structure regime. For example, planetary boundary layer parameterizations are most often derived by expansion of higher-order moments (e.g., Mellor and Yamada 1974, 1982) and simplified to an eddy-diffusivity parameterization. Moist convection is usually represented by mass-flux models (e.g., Arakawa and Schubert 1974). The above-described approach simplifies the treatment of turbulence, but the negative consequences are that it becomes unclear how to model interactions of turbulence between different conceptual models and the need for new closure assumptions arises (e.g., cloud-base closures for mass-flux models). It is important to note that these new closures do not describe the realm of physics, but are introduced artificially only as a result of modeling turbulence with different conceptual models.

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One example of such an operational global forecasting model is the Navy Global Environmental Model (NAVGEM). NAVGEM is developed and maintained by the Naval Research Laboratory (NRL) while the operational forecasts are produced by the Fleet Numerical Meteorology and Oceanography Center (FNMOC). NAVGEM became operational in February 2013 (Hogan et al. 2014) and replaced the Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond 1991). As with typical weather prediction models, the turbulence parameterization in NAVGEM is split between the boundary layer, shallow convection, and deep convection. The boundary layer parameterization is modeled with the eddy-diffusivity parameterization from Louis (1979). In the current implementation, this parameterization assumes that the turbulent mixing approaches zero as the wind shear production of turbulence is small. The convection parameterization in NAVGEM is modeled with a simplified Arakawa–Schubert (SAS) mass-flux model (Moorthi et al. 2001) and parameterizes the subgrid vertical fluxes in the moist convection-dominated regions. Buoyancy, but not wind shear, plays a key role in the production of turbulent kinetic energy over large areas of the earth’s boundary layer (primarily in the tropical and subtropical regions). We expect that over these regions the NAVGEM-derived planetary boundary layer turbulent mixing is too weak. The vertical transport of moist static energy by the boundary layer parameterization and its coupling to the moist convection is a key factor that determines how active the parameterized moist convection is.

One way of improving the representation of convective turbulence in NAVGEM is to design a unified boundary layer parameterization, which would relate the boundary layer and moist convection parameterization in a consistent manner. The eddy-diffusivity/mass-flux (EDMF) parameterization originally proposed by Siebesma and Teixeira (2000) and Teixeira and Siebesma (2000) is one such approach. The idea behind EDMF is simple. The subgrid fluxes are parameterized as a sum of eddy-diffusivity and mass-flux contributions throughout the whole atmosphere, so that the same parameterization can be used in the boundary layer and convection-dominated regions. Here, the eddy-diffusivity part of the parameterization represents the small-scale turbulent mixing and the mass flux the surface-forced updrafts. Originally, the EDMF parameterization was used for dry convective boundary layers (Siebesma et al. 2007; Witek et al. 2011a,b), but a number of versions that include nonprecipitating moist convection have been developed (Soares et al. 2004; Neggers et al. 2009; Neggers 2009; Angevine et al. 2010; Suselj et al. 2012, 2013). In these works, the mass flux represents both dry and moist updrafts. Dry updrafts typically provide mixing in the subcloud layer and are also roots for moist updrafts, while moist updrafts represent convective clouds. The appealing advantages of moist EDMF schemes are that (i) a single scheme can be used to simulate the turbulence in the boundary layer and (ii) due to moist convection, a closure for moist convection at cloud base is not needed, while (iii) it is computationally inexpensive and conceptually simple, and (iv) it could also include the parameterization of precipitating and deep convection.

There are a number of alternative approaches based on higher-order closures (e.g., Golaz et al. 2002a,b; Lappen and Randall 2001a–c). Recently, Bogenschutz et al. (2012) implemented a higher-order moment scheme in the Community Atmosphere Model (CAM). Their results are encouraging. They show an improvement of CAM over the operational version when simulating a variety of moist boundary layer cases. One key disadvantage of this approach is its high computational cost and complexity.

In this paper, a simplified version of the Suselj et al. (2013) stochastic unified boundary layer and non-precipitating moist convective EDMF is implemented in NAVGEM (see section 2 and the appendix for details). As the primary aim of the new parameterization is to improve the representation of convection-dominated boundary layers, the skill of the EDMF NAVGEM in simulating representative dry and moist convective cases is explored within the framework of a single-column model (SCM). The simulated cases include dry convection, a quasi-steady-state case of marine boundary layer, and a diurnal cycle of convection over land. These results are compared to large-eddy-simulation (LES) results (section 3a). Finally, the performance of NAVGEM as a global forecasting model is tested by comparing 2 months of global forecasts from two NAVGEM versions: EDMF and Control (NAVGEM without the EDMF parameterization) against analysis (section 3b). The discussion and conclusions are presented in section 4.

2. Model description

The forecast model NAVGEM is the U.S. Navy’s operational global atmospheric model (Hogan et al. 2014). The dynamical core of NAVGEM is a hydrostatic, three-time-level semi-Lagrangian/semi-implicit (SL/SI) algorithm based on the work of Ritchie (1991). Dynamic variables in the SL scheme are horizontal winds, virtual potential temperature, specific humidity, terrain pressure, ozone, cloud liquid, and ice water. The physics includes parameterization of the turbulent eddy
diffusivity \cite{Louis1979}, orographic gravity wave drag \cite{Webster2003}, shallow cumulus \cite{Han2011}, deep convection \cite{Moorhi2001}, cloud water microphysics \cite{Zhao1997}, the Rapid Radiative Transfer Model for general circulation models \cite{Clough2005}, stratiform cloud fraction prediction \cite{Teixeira2002}, a four-layer land–sea ice parameterization \cite{Hogan2007}, and ozone photochemistry \cite{McCormack2006}. For data assimilation, NAVGEM is coupled to the NRL Atmospheric Variational Data Assimilation System—Accelerated Repr er (Rosmond2006) with a variational bias correction approach for satellite radiances.

\subsection{EDMF parameterization}

Within the EDMF framework, the subgrid vertical flux is expressed as a sum of the eddy-diffusivity and the mass-flux components:

\[ \overline{w'q'} = -K_{h,m} \frac{\partial \phi}{\partial z} + \sum_{i=1}^{I} M_{ii} (\phi_{ii} - \phi), \quad \text{where} \quad \phi = (\theta, q_{w}, u, v). \tag{1} \]

The underlying assumption for the above equation is that the horizontal grid area of the atmospheric model can be partitioned into \( I \) updrafts, which are represented by laterally entraining convective (either dry or moist) plumes and the remaining “environment.” Subgrid mixing in the environment is described by the first term, and mixing due to updrafts by the second term on the rhs of Eq. (1). Variable \( K_{h,m} \) represents the eddy-diffusivity coefficient for thermodynamic variables \( K_h \) or wind speed components \( K_m \). The formulation of the eddy-diffusivity parameterization is given in section 2b. Variable \( M_{ii} = a_{ii} w_{ii} \) represents the mass flux of the \( i \)th updraft (which is a product of its horizontal area \( a_{ii} \) and vertical velocity \( w_{ii} \)) and \( \phi_{ii} \) is the value of \( \phi \) in the \( i \)th updraft. Variable \( \phi \) represents potential temperature \( \theta \), water vapor mixing ratio \( q_{w} \), or zonal \( u \) and meridional \( v \) wind speed components. Variable \( z \) is the height. The updraft properties are calculated with the mass-flux model described in section 2c. In this study, ozone, cloud liquid water, and cloud ice water are not included in the mass-flux scheme.

The EDMF parameterization used in this work closely follows the one from Susselj et al. \cite{Susselj2013} with the following key differences. (i) The eddy-diffusivity parameterization is based on Louis \cite{Louis1979} (i.e., it is the same as the boundary layer parameterization in the Control model) instead of a turbulent-kinetic-energy model. (ii) Parameterization of moist thermals at the cloud base is simplified. Below we first give a short overview of the Louis \cite{Louis1979} eddy-diffusivity parameterization, and then we describe the mass-flux parameterization. A numerically stable implementation of the mass-flux parameterization is described in the appendix.

\subsection{Eddy-diffusivity parameterization}

The goal of the eddy-diffusivity parameterization is to provide values for eddy-diffusivity coefficients \( (K_h \text{ and } K_m) \). According to the boundary layer parameterization by Louis \cite{Louis1979}, the eddy-diffusivity coefficients can be written as

\[ K_{m} = l_{m}^{2} \frac{\partial U}{\partial z} f_{m}(Ri_{h}) \quad \text{and} \tag{2} \]

\[ K_{h} = l_{h}^{2} \frac{\partial U}{\partial z} f_{h}(Ri_{h}), \tag{3} \]

where \( Ri_{h} \) represents the bulk Richardson number (e.g., Stull \cite{Stull1988}), which is essentially the ratio of buoyancy production or consumption to the shear production of turbulence; \( f_{m} \) and \( f_{h} \) are prescribed functions of the bulk Richardson number; \( l_{m} \) and \( l_{h} \) are the mixing length scales; and \( |\partial U|/\partial z \) represents the vertical gradient of wind speed.

The mixing length scales \( (l_{m} \text{ and } l_{h}) \) are defined to approach the Prandtl mixing length \( L_{0} \) \cite{Stull1988} close to the surface \((l_{0} \approx kz, \text{ where } k \approx 0.4 \text{ is the von Kármán constant and } z \text{ is the height above the surface})\) and converge to their maximum prescribed values with increasing height. Our experience with the model is that the eddy diffusivity alone provides insufficient mixing, especially for convectively driven boundary layers. One solution is to extend the eddy diffusivity with a \( K \)-profile parameterization (e.g., Troen \& Mahrt \cite{Troen1986}) for dry convective boundary layers. Instead of this, we implement a mass-flux component that in a convectively driven boundary layer provides a mixing term that is not a function of local gradients as is the case with an eddy-diffusivity parameterization.

\subsection{Mass-flux parameterization}

The mass-flux model represents laterally entraining, steady-state plumes and is expressed with a set of ordinary differential equations. In this model, the mass-flux parameterization is active only if the surface buoyancy flux is positive; otherwise, its contribution to the subgrid vertical flux equals zero. The mass-flux parameterization is expressed in terms of moist conserved variables: liquid water potential temperature \( \theta_{l} = \theta - (L_{v}/c_{p})q_{l} \), where \( L_{v} \) is the specific latent heat for water, \( c_{p} \) is the specific heat of air at constant pressure and \( q_{l} \) is the liquid water mixing ratio and total water mixing ratio.
In this version of the model, the difference between moist conserved and dry variables is neglected when estimating the mass-flux component of subgrid vertical fluxes in Eq. (1) (i.e., \( w_\theta/L_{\text{MF}} = w_\theta' \)) and the second terms on the rhs of Eqs. (7) are the roots of the moist updrafts. Dry updrafts provide countergradient subgrid mixing in the dry boundary or subcloud layer and are the roots of the moist updrafts. The vertical velocity and moist conserved variables within the thermal are modeled as in Sūselj et al. (2013):

\[
\frac{1}{2} \frac{\partial w_u^2}{\partial z} = aB_u - (b + ce)w_u^2 \quad \text{and} \quad \frac{\partial \theta_u}{\partial z} = -c(\theta_u - \varphi), \quad \text{where} \quad \varphi = (\theta_L, q_t, u, v); \quad (5)
\]

where \( B_u = g[(\theta_w/\theta_u) - 1] \) represents the buoyancy of the thermal, and where the constants are \( a = \frac{1}{2}, b = 0.002 \text{m}^{-1}, \) and \( c = 1.5 \). The variable \( \epsilon \) represents the lateral entrainment rate (defined below) and is one of the key closures of the parameterization.

Boundary conditions for the updrafts at the surface are defined as follows:

\[
w_u|_{s} = \alpha_w w_\ast, \quad (6)
\]

\[
\theta_L|_{s} = \theta_L + \max \left( \frac{w_\theta'}{w_\ast}, 0 \right), \quad (7)
\]

\[
q_t|_{s} = q_t + \max \left( \frac{w_\theta q_t'}{w_\ast}, 0 \right), \quad (8)
\]

\[
uu|_{s} = u|_{s}, \quad (9)
\]

\[
v_u|_{s} = v|_{s}, \quad \text{and} \quad (10)
\]

\[
a_u|_{s} = 7.5/100, \quad (11)
\]

where \( \alpha_{\theta_L} = \alpha_q = 0.57, \alpha_w = 3.6, w_\ast \) is the Deardorff convective velocity scale (e.g., Stull 1988), and the subscript \( s \) denotes surface values. The updraft velocity at the surface is proportional to the convective velocity scale [Eq. (6)], and the second terms on the rhs of Eqs. (7) and (8) are convective temperature and moisture scales multiplied by constant factors \( (\alpha_{\theta_L} \) and \( \alpha_q, \) respectively). This scaling is similar to the surface Monin–Obukhov scaling for convective boundary layers (e.g., Stull 1988).

The mass-flux parameterization is integrated as follows. If the surface buoyancy flux is positive, a single dry updraft \( (q_{tu} = 0) \), which occupies a small fraction area \( (a_{u}|_{s}) \) and with the properties defined in Eqs. (6)–(11), is initialized at the surface. The equations for the updraft properties [Eqs. (4) and (5)] are integrated vertically as long as the updraft velocity remains positive. This model assumes that the updraft horizontal fraction area does not change with height as long as the vertical velocity remains positive and is zero above that level, or until the condensation in the updraft occurs. During integration of a dry updraft, at each vertical level, the model checks whether condensation within the updraft occurs. Condensation occurs if \( q_{tu} = q_{su}(\theta_{Lu}, p) \) [where \( q_{su}(\theta_{Lu}, p) \) represents the saturated water mixing ratio], and if this is the case, the updraft is split into a predefined number \( N (N = 10) \) of updrafts, each having a horizontal fraction area \( a_{u}|_{s}/N \). Each of the \( N \) updrafts is independently integrated vertically from the condensation level as long as its vertical velocity remains positive. Condensation, if it occurs, is a key source of the updraft buoyancy. The liquid water mixing ratio is calculated simply as \( q_{su} = \max[q_{tu} - q_{su}(\theta_{Lu}, p), 0] \). The key difference among the \( N \) updrafts is their different entrainment rates. In the typical cumulus-dominated layer where the atmosphere is conditionally stable, the updrafts that entrain less reach higher altitudes compared to the updrafts that entrain more. The moist updrafts thus represent the statistical distribution of convective clouds within the model grid box where the convective clouds typically have a well-defined base, but reach different cloud-top heights. As a result, the total updraft horizontal area (the sum of the updraft area of \( N \) updrafts) gradually decreases from the cloud base to the cloud top.

To parameterize the entrainment rate, we follow the approach of Sūselj et al. (2013) and use two different formulations of the entrainment rate. For simplicity, we assume that entrainment in the dry updrafts below the cloud base is a continuous process with a fixed entrainment rate: \( \epsilon = 8.5 \times 10^{-4} \text{m}^{-1} \). Above the condensation level, entrainment is assumed to occur as a discrete event with prescribed probability. When the updraft travels a distance \( dz \), the probability of an entrainment event is assumed to be equal to \( dz/L_0 \), where \( L_0 \) represents the entrainment length. For simplicity, it is assumed that each entrainment event entrains a fixed ratio of updraft mass flux \( \epsilon_d \). Along the finite length \( \Delta z \), the probability of an entrainment event follows a Poisson distribution and the entrainment coefficient can be written as

\[
\epsilon(\Delta z) = \frac{1}{\Delta z} \epsilon_d \mathcal{P}(\Delta z/L_0), \quad (12)
\]

where \( \mathcal{P} \) is a random number drawn from the Poisson distribution and represents the number of entrainment
events that occur when the thermal travels a distance $\Delta z$.

In the current implementation, we choose $\epsilon_0 = 0.2$ and $L_0 = 200$ m. The updrafts have to travel 200 m on average to entrain once and at each entrainment event they entrain 20% of the updraft mass.

3. Results

We first investigate the ability of the EDMF parameterization to realistically simulate representative cases of convective boundary layers and then explore which version of NAVGEM (EDMF or Control) is better as a global prediction model. To do this, we first construct an SCM version with the EDMF parameterization and use it to simulate three types of idealized well-studied convective boundary layers. These cases represent (i) diurnal growth of the dry convective boundary layer as in Witek et al. (2011a), (ii) A quasi-steady-state marine-cumulus-dominated boundary layer based on the Barbados Oceanographic and Meteorological Experiment (BOMEX; Siebesma et al. 2003), and (iii) a diurnal cycle of continental shallow convection derived from Atmospheric Radiation Measurement Program (ARM) observations (Brown et al. 2002). These results are validated against large-eddy simulations (LES) of the same cases. Comparing up to 5 days of global forecasts with analysis over two calendar months assesses the skill of both NAVGEM versions for predicting weather.

a. Single-column model simulations of convective boundary layers

The SCM framework provides useful information about the skill of the boundary layer parameterization, as their effects can be studied separately from the

<table>
<thead>
<tr>
<th>Case name</th>
<th>Surface sensible heat flux (W m$^{-2}$)</th>
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<tbody>
<tr>
<td>A1</td>
<td>30</td>
</tr>
<tr>
<td>A2</td>
<td>60</td>
</tr>
<tr>
<td>A3</td>
<td>90</td>
</tr>
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<td>A4</td>
<td>120</td>
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TABLE 1. List of the dry free convective cases and their corresponding surface sensible heat fluxes.

FIG. 1. Dry free convection. Profiles of (top) liquid water potential temperature and (bottom) total water mixing ratio, averaged between the (left) first and second and (right) fourth and fifth simulation hours. Solid lines indicate the LES results and dashed lines indicate the EDMF simulations (circles denote the vertical levels of the model).
complicated three-dimensional dynamics and other physical processes, and allows for a straightforward comparison to the LES results. In the SCM simulations, height-dependent forcing (such as horizontal advection, radiation, and geostrophic wind speed) and surface turbulent fluxes are prescribed. To prescribe the turbulent fluxes instead of surface temperature, times were adjusted. The forcing in all simulations has been specified in the same manner as in the LES results. In the SCM, 91 hybrid vertical levels were specified with 11 levels in the lower 100 hPa of the atmosphere. The definitions of the levels were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) 91-vertical-level model [for the vertical resolution in the lower troposphere see Teixeira (1999)]. This vertical resolution is somewhat denser than the vertical resolution of global model simulations discussed in section 3b. The performance of the Control NAVGEM for these particular cases is not realistic (not shown).

1) DIURNAL GROWTH OF DRY CONVECTIVE BOUNDARY LAYERS

The ability of EDMF to represent the growth of convective boundary layers is first tested on a family of dry free convective cases. The initial conditions and forcing are taken from Witek et al. (2011a) and compared to their LES results. These cases are relatively simple; there is no phase change of water and therefore no interaction between turbulence and condensation. Initially, the boundary layer is well mixed (vertical gradients of water vapor mixing ratio and potential temperature are zero in the boundary layer), and it extends from the surface to a height of 1350 m where it is capped by a stable free troposphere with a constant lapse rate of potential temperature ($\partial \theta / \partial z = 2 \text{ K km}^{-1}$) and water vapor mixing ratio ($\partial q_v / \partial z = -9.4 \times 10^{-4} \text{ km}^{-1}$). The boundary layer growth is forced by positive surface sensible and latent heat fluxes, which are kept constant throughout the simulation. The four cases differ in the

Fig. 2. Dry free convection. Profiles of subgrid vertical fluxes of (top) liquid water potential temperature and (bottom) total water mixing ratio, averaged between the (left) first and second and (right) fourth and fifth simulation hours after the start of simulation. Solid lines indicate the LES results and dashed lines indicate the EDMF simulations (circles denote the vertical levels of the model).
amount of surface sensible heat flux, while the latent heat flux is the same and around 63 W m$^{-2}$. Table 1 lists the names of the cases and the corresponding sensible heat fluxes.

Figure 1 compares the profiles of thermodynamic variables and Fig. 2 compares the corresponding subgrid vertical fluxes of potential temperature averaged between the first and second and between the fourth and fifth simulation hours from NAVGEM EDMF and LES. The EDMF model seems to represent the growth of the boundary layer well. The EDMF profiles of potential temperature and water vapor agree reasonably well with the LES results. There are however some differences between the LES and EDMF results. Most importantly, the boundary layer in the EDMF model is not as well mixed as the LES results indicate. It is important that the EDMF is able to simulate the negative subgrid vertical fluxes of potential temperature at the top of the boundary layer. A reasonable representation of the subgrid fluxes at the top of the boundary layer is key for the successful simulation of entrainment of the free tropospheric air into the boundary layer and consequently the growth of the boundary layer. Further analysis (not shown) indicates that the mass-flux term represents the majority of the subgrid vertical flux throughout the whole boundary layer. The eddy-diffusivity part contributes less than 10% of the total flux at all levels, except at the surface where the prescribed surface flux is by design of the EDMF scheme attributed to the eddy-diffusivity part of the turbulence parameterization. This choice seems to result in a slight kink of the near-surface values of the thermodynamic variables.

To investigate the skill of the EDMF model in representing the growth of the boundary layer, it is useful to scale the problem and write it in terms of non-dimensional variables. According to Batchvarova and Gryning (1991), a surface-forced dry boundary layer is expected to grow exponentially, governed by

$$h(t) = h(t_0) \exp \left( \frac{w' \theta' \Delta t}{\gamma} \right),$$

where $\gamma$ is the lapse rate above the boundary layer and $\Delta t = t - t_0$. More recent work by Teixeira and Cheinet (2004) suggests a different functional relationship.
between the growth of the boundary layer and the product of the terms in the exponent on the right-hand side of Eq. (13). For the analysis presented here, the exact functional relationship is not essential. Figure 3 compares the growth of the boundary layer height from the LES and EDMF, as scaled by Eq. (13). One advantage of this scaling is that the growth of the boundary layer, as simulated by all four LES cases, can be described by a single function. The key result here is that the boundary layer from the EDMF model grows reasonably well compared to the LES for all cases taking into account the vertical resolution of the SCM.

2) BOMEX CASE

The BOMEX case (Siebesma et al. 2003) is a well-studied case representing shallow cumulus convection over ocean. Radiation and large-scale forcing are prescribed so that the case is nearly stationary. The well-mixed subcloud layer extends from the surface to around 600 m, and is capped by a shallow cumulus layer that extends up to roughly 2000 m above sea level. The initial conditions and the forcing for the simulation are taken from Siebesma et al. (2003) and compared to the multiensemble LES results from the same work.

Figure 4 compares the moist conserved variables and Fig. 5 compares the subgrid vertical fluxes of moist conserved variables averaged between the second and third simulation hours [(left) liquid water potential temperature and (right) total water mixing ratio]. Black lines represent the mean values from the LES results and gray shading represents the interquartile range from the LES. Brown lines represent the eddy-diffusivity part of the subgrid vertical flux from SCM, blue lines represent the mass-flux part from the SCM, and red lines represent the total mass flux (sum of the eddy diffusivity and mass flux).

LES results in the cumulus-dominated layer (from around 600 to 2000 m). Compared to the LES, the lower part of the cloud layer is slightly drier and the upper part is slightly moister. This is a consequence of a simulated peak of the subgrid vertical fluxes of the total water mixing ratio in the lower part of the cloud layer in the SCM. The reason that EDMF represents the profiles of moist conserved variables well is its realistic representation of subgrid vertical fluxes. In the EDMF model, the subgrid vertical fluxes are dominated by the mass-flux part of the parameterization. In the parameterization described in our previous work (Sušelj et al. 2013), the subgrid fluxes in the subcloud layer are dominated by the eddy-diffusivity part of the parameterization. The reason for this difference is that in the NAVGEM EDMF the eddy-diffusivity mixing in the subcloud layer is weaker compared to the model from our previous work. The weaker eddy-diffusivity mixing is compensated with a stronger mass-flux mixing, which indicates the robustness of the EDMF method in representing subgrid fluxes.

To further understand how well the parameterization in the EDMF scheme represents the updraft properties from the LES, we compare the horizontal mean of moist updraft variables from the SCM with the mean “cloud” and “cloud core” sampled fields from the LES. The horizontal mean of moist updraft variables from the SCM is calculated as the mean of the variable over all moist updrafts within a simulation hour, but calculated independently for each vertical level of the SCM. Mean cloud fields from the LES represent the slab-mean values of LES grid points that contain liquid water and cloud-core fields represent the mean slab values of fields.
containing liquid water that are positively buoyant with respect to the slab mean (Siebesma et al. 2003). The values of the mean updraft properties from the SCM are expected to be between the cloud and cloud-core values from the LES (e.g., Couvreux et al. 2010; Sušelj et al. 2013). Figure 6 shows this comparison. In the SCM, the cloud fraction peaks at the cloud base (around 500 m above the ground) and decreases toward the cloud top, as expected from the LES results. The decrease in the cloud fraction with height in the SCM is essentially the result of the stochastic entrainment rate and is a key component for the proper representation of convective boundary layers (Sušelj et al. 2013). The liquid water mixing ratio, vertical velocity, and excesses of moist conserved variables from the SCM are reasonably close to the cloud and cloud-core sampled values from the LES. This comparison shows that all components of the updrafts, which represent shallow cumulus, are well

**Fig. 6.** BOMEX case. Mean moist updraft variables from the SCM (red lines; circles indicate model levels) and the cloud-core (green line) and cloud (black line) sampling from the LES. All data are averaged between the second and third simulation hours.
simulated by the EDMF scheme. The fact that the subgrid vertical fluxes in the SCM are well represented is no coincidence but the consequence of a physically sound representation of all the updraft properties.

3) ARM CASE

The ARM case (Brown et al. 2002) represents a diurnal cycle of convection over land primarily forced by time-varying surface latent and sensible heat fluxes. This case is based on observations over the Southern Great Plains. The simulation is initialized at 1130 UTC (0530 local time) with a shallow boundary layer and negative surface sensible heat fluxes, which increase during the morning and early hours and peak at 1800 UTC. The forcings in the SCM are the same as specified in Brown et al. (2002) and the results of the SCM are compared with the LES results also used in Sušelj et al. (2012). All times noted here are hours after the start of simulation (i.e., after 1130 UTC). Figure 7 compares the time evolution of the cloud base and cloud top from the LES and SCM. The cloud base and cloud top in the SCM were defined as the lower and upper model levels where the horizontal area of moist mass flux is greater than zero within each half an hour. The onset of the moist convection in the SCM starts around 3.5 h after the start of the simulation, which is around 0.5 h earlier than in
the LES results. Lifting of the cloud base in the SCM through the afternoon represents the LES results reasonably well. The moist updrafts from the SCM in the early afternoon seem to be too active compared to the LES results and reach too high. However, after the fifth simulation hour the top of the cloud layer from the SCM slightly decreases and later in the afternoon agrees well with the LES results.

Figure 8 shows hourly averaged vertical profiles of the moist conserved variables and the corresponding subgrid vertical fluxes every 2 h through the simulation time. The shallow boundary layer deepens over the course of the day and is well mixed and topped by a shallow cumulus layer after the fifth simulation hour. The SCM represents the deepening of the boundary layer well. The profiles of liquid water potential temperature agree well with the LES results. In the SCM, the well-mixed boundary layer is more moist than in the LES results and consequently the cumulus-dominated cloud layer is drier compared to the LES results. The subgrid vertical fluxes of moist conserved variables are reasonably well represented. In the first simulation hours the subgrid fluxes tend to reach zero values at higher altitudes, which is in agreement with the higher cloud top.

b. Global weather prediction simulations

A most important test for the addition of the EDMF to the operational NAVGEM is its skill in predicting the global atmospheric conditions. To investigate which NAVGEM version (Control or EDMF)\(^1\) improves the forecast skill and reduces forecast errors, full data assimilation/forecast tests were performed on both versions for two Northern Hemispheric winter (January and February 2013) and summer (August and

\(^1\) The Control and the EDMF versions are identical, except that the EDMF version includes the mass-flux part of the parameterization as in the SCM cases.
September 2013) months. Here, we show the results for January and August only, as the results for February and September are practically the same as in January and August, respectively. The data assimilation cycle is every 6 h, but only the 0000 and 1200 UTC forecasts were carried out to 120 h and shown in this work. For this study NAVGEM was run at a horizontal spectral resolution of T425, equivalent to about 31-km horizontal grid spacing, with 60 vertical levels, which is written as T425L60. The model top is at 0.04 hPa (71 km).

The forecast skill is characterized in terms of anomaly correlations (ACs) and mean biases as a function of forecast time (up to 120 h). Figure 9 shows the 500-hPa geopotential height ACs from both versions of NAVGEM for the winter and summer months. The skill of the EDMF version is considerably better than the Control for both hemispheres in their corresponding winters. For both hemispheres in their corresponding summers, the skill of the Control and the EDMF versions is essentially the same. Similar results hold for the 1000-hPa geopotential height AC (not shown). Figure 10 shows the 120-h monthly mean height errors for the two NAVGEM versions. Except at the poles, the EDMF version considerably reduces the mean height errors in the troposphere. The reason for the EDMF version being more successful in simulating geopotential height is its better representation of the thermal structure of the troposphere compared to the Control version. Figures 11 and 12 show the 120-h monthly mean temperature bias and moisture content bias, respectively. In the Control version the tropospheric temperatures throughout most of the tropics, subtropics, and mid-latitudes are consistently colder compared to the analysis. This negative bias in the subtropics and midlatitudes is likely due to the interaction between the surface and troposphere being too weak as a result of subgrid mixing by the boundary layer parameterization being too weak. In the tropics the negative bias is probably the consequence of convective activity that is too weak, likely the result of insufficient transport of moisture from the surface. This is also supported by the moisture content being too low throughout most of the subtropical and tropical troposphere (Fig. 12). These negative temperature biases are to a large degree improved by the EDMF as the vertical mixing is increased. The EDMF
version also greatly improves the moisture budget as increased moisture is being moved in the troposphere. This is also evident in the fact that the EDMF scheme has a 10% increase in total precipitation compared to the Control version (not shown).

4. Discussion and conclusions

A new unified boundary layer and shallow convection parameterization based on the EDMF approach was implemented in NAVGEM. The EDMF parameterization was constructed with the goal of improving the representation of convective boundary layers and cumulus. The main idea behind the EDMF framework is to optimally combine the eddy-diffusivity and mass-flux parameterizations to represent subgrid vertical fluxes. The EDMF parameterization is used to represent boundary layer turbulence and moist convection subgrid vertical fluxes, with no artificial discontinuities between them and no need for closure assumptions relating the turbulence in these two regions. The eddy-diffusivity part of the parameterization represents local, small-scale mixing and the mass-flux part represents the surface-forced dry thermals, which, if conditions allow, become saturated and condense and thus represent cumulus clouds. The current scheme does not allow for precipitation within the moist thermals or transition to deep convection.

The EDMF scheme implemented in NAVGEM is similar to the one from Suselj et al. (2013), but with a couple of differences that are discussed below. The eddy-diffusivity scheme in Suselj et al. (2013) is based on the turbulent-kinetic-energy parameterization. In this work we used the Louis (1979) eddy-diffusivity parameterization, which is the boundary layer parameterization in the Control simulation. The mass-flux parameterization has been somewhat simplified compared to the parameterization in Suselj et al. (2013). One simplification is that the properties of the N moist updrafts at the cloud base are the same. In Suselj et al. (2013), the cloud-base properties were sampled from a probability density function. This simplification does not have a considerable influence on the results of the simulation. The length scale $L_0$, which defines the length over which, on average, updrafts entrain once, has been set to a constant value. In Suselj et al. (2013), this length scale was proportional to the depth of the expected cloud layer and was diagnosed...
from the thermal structure of the boundary layer. We found that by using a constant $L_0$, the simulation results agree well with the LES results, and that the diagnosed value of $L_0$ is sensitive to the vertical resolution of the model. A couple of parameters in the EDMF scheme were changed: the surface updraft fraction is larger, the constants defining the updrafts’ initial conditions in Eqs. (6)–(8) were adjusted, and the entrainment in the dry updraft has been changed. These changes have been made primarily to increase the mixing by the mass-flux part of the parameterization in order to compensate for the weaker mixing by eddy diffusivity in the well-mixed dry boundary layer and in the subcloud layer. For completeness, the mass-flux parameterization for horizontal momentum is included. In the current mass-flux scheme, the horizontal momentum is treated as a conserved variable and it is only transported by the updrafts, while its source terms have been neglected. The possibility of parameterization of momentum sources such as in Gregory et al. (1997) will be considered in the future. The numerical discretization of the mass-flux equation is different from the approach used by Suselj et al. (2013). This has been done to assure the numerical stability of the parameterization in a model with a coarser vertical resolution.

The performance of NAVGEM EDMF was assessed first by simulating well-studied cases of dry, moist marine and continental convection within the framework of an SCM. The model represents all types of convective cases reasonably well. One notable difference between the results from this model simulation and those from our previous work (Suselj et al. 2013) is the partitioning of the fluxes between eddy-diffusivity and mass-flux components. For the convective cases studied here, the eddy-diffusivity part of the parameterization provides weaker mixing in the boundary layer than did our previous model. The small mixing by eddy diffusivity is compensated by larger mixing due to the mass-flux part of the parameterization. This also indicates the robustness of the EDMF approach: if one part of the parameterization provides smaller mixing, this can be compensated by the other part of the scheme. Both EDMF and Control NAVGEM are used as forecasting models and their results were compared against analyses. The EDMF version of the model simulates the thermal structure of the atmosphere considerably

![FIG. 12. Zonal-mean bias of NAVGEM total water mixing ratio with respect to the analysis for the 120th simulation hour. Results are shown for the (top) Control and (bottom) EDMF during (left) January and (right) August 2013.](image-url)
better, which results in a higher level of skill. Based on these and other results, the EDMF parameterization became part of the operational NAVGEM on 6 November 2013.

Implementing EDMF in NAVGEM is a first step toward unifying all convective parameterizations in NAVGEM. In the future, we plan to implement a simple microphysical scheme within the convective updrafts. That parameterization (in addition to dry and shallow convection) will also be able to simulate deep convection.

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APPENDIX

Numerical Discretization of the Mass-Flux Model

The NAVGEM time solver integrates the EDMF equations in a semi-implicit manner. The eddy-diffusivity part of the integration is solved semi-implicitly and the mass flux with an explicit scheme. This is done differently than originally done by Teixeira and Siebesma (2000), who solved the mass flux with a semi-implicit scheme. In our implementation, we experienced numerical instabilities when integrating the updraft equations [Eqs. (4) and (5)]. To understand the source of this numerical instability, we first investigated the numerical approximation of Eq. (5), discretized by a typical upwind differencing scheme (e.g., Pielke 2002), which is the same as in our previous work (Sušelj et al. 2013):

\[ \phi^{k+1}_u = \phi^k_u (1 - \epsilon^k \Delta z) + \epsilon^k \Delta z \phi^k. \]  

(A1)

In Eq. (A1), the superscript denotes the vertical level of the model (counting from the surface upward) and \( \Delta z = z^{k+1} - z^k \). Equation (5) is in essence a relaxation equation of \( \phi_n \) toward \( \phi \). Therefore, the discretized solution \( \phi^{k+1}_u \) must be bound by the values of \( \phi^k_u \) and \( \phi^k \). Clearly, to satisfy this, \( \epsilon^k \Delta z \leq 1 \) [see Eq. (A1)]. In the current EDMF model, \( \epsilon^k \Delta z = \epsilon_d P(\Delta z/L_0) \). If, for example, the vertical resolution of the model is 400 m (representative of atmospheric models at heights of a few thousand meters above the ground) and \( \epsilon_d = 0.2 \) and \( L_0 = 200 \text{ m} \), the criterion that \( \epsilon^k \Delta z \leq 1 \) is violated around 20% of the time. To derive a numerically stable discretized version, Eq. (5) is first integrated from \( z^k \) to \( z^{k+1} \):

\[ \int_{z^k}^{z^{k+1}} \frac{\partial \phi^k_u}{\partial \phi} \Delta \phi = - \int_{z^k}^{z^{k+1}} \epsilon \Delta z. \]  

(A2)

When integration in Eq. (A2) is performed, \( \epsilon \) and \( \phi \) are taken to be constant between vertical levels \( z^k \) and \( z^{k+1} \). Consistent with an upward differencing approximation the values of \( \phi \) and \( \epsilon \) are taken at level \( k \) to get a solution:

\[ \phi^{k+1}_u = \phi^k u (1 - e^{-\epsilon^k \Delta z}) + \phi^k e^{-\epsilon^k \Delta z}. \]  

(A3)

The solution of Eq. (A3) satisfies the conditions discussed above; namely, it stays within values of \( \phi^k_u \) and \( \phi^k \), even if \( \epsilon^k \Delta z \leq \infty \). In essence, the difference between the approximations in Eqs. (A1) and (A3) is that in the former we linearized the term \( \epsilon (\phi_n - \phi) \) and in the latter only the entrainment rate \( \epsilon \) was linearized. A similar approach is used for deriving a discretized version of the updraft vertical velocity equation [Eq. (4)]. The solution is

\[ (w^{k+1}_u)^2 = (\alpha w^k_u)^2 + (1 - \alpha^2) \frac{ab^k u}{b + c\epsilon^k}, \]  

(A4)

where

\[ \alpha = e^{-(b + c\epsilon^k) \Delta z}. \]  

(A5)

Updraft equations are integrated only as long as the values of Eq. (A4) are real numbers. The complex solution indicates that the vertical velocity of the updraft is assumed to terminate and the updraft has detrain.


