Simplified High Order Closure in FV3 GFS

Alexei Belochitski[1,2], Steven Krueger[3], Shrinivas Moorthi[2], Peter Bogenschutz[4], Anning Cheng[1,2]

[1]IMSG, [2]NOAA/NWS/NCEP/EMC, [3]U. of Utah, [4]DOE/LLNL

email: **alexei.a.belochitski@noaa.gov**

1 Introduction

One approach to high order turbulence closure is to assume a functional form of the subgrid probability density distribution of relevant model variables, determine parameters of this distribution using its lower order moments that the model explicitly prognoses and/or diagnoses, and then use the distribution to infer the unknown higher order moments necessary to close the model. Ideally, the PDF should be flexible enough to account for all the regimes of subgrid scale (SGS) moist turbulence in the atmosphere as well as transitions from one regime to another, yet sufficiently simple so the model only needs to predict a computationally feasible number of moments. A joint PDF, $P(w,\theta_l,q_t)$, trivariate in subgrid vertical velocity, w, liquid water potential temperature, θ_l, and total specific cloud condensate content, q_t, based on a double Gaussian function in each variable was demonstrated to be a good fit for the data observed by aircraft and simulated by LES with a 100 m horizontal resolution for stratocumulus, as well as in trade wind and continental cumulus cases by Larson et al. (2002). This analysis was extended with similar results for CRM data with horizontal resolutions up to 25 km for a clear convective boundary layer, non-precipitating and precipitating marine and continental shallow cumulus, marine stratocumulus, and transition from stratocumulus to cumulus by Bogenschutz et al. (2010).

The trivariate double Gaussian PDF has 19 parameters. However, the complete set of 19 first, second, and third order moments does not uniquely determine parameters of this PDF. If some parameters of the PDF are expressed in terms of others, then the number of independent parameters can be reduced and the functional form of the PDF effectively modified to potentially be uniquely realizable in terms of its moments. One such simplification, the Analytic Double Gaussian 1 (ADG1), has 13 parameters that are uniquely determined by the following 10 moments: $\overline{w}$, $\overline{\theta_l}$, $\overline{q_t}$, $\overline{w'^2}$, $\overline{\theta_l'^2}$, $\overline{q_t'^2}$, $\overline{w'\theta_l'}$, $\overline{w'q_t'}$, $\overline{\theta_l'q_t'}$, $\overline{w'^3}$. Note that only one third order moment, $\overline{w'^3}$, is needed to recover the PDF.

An additional advantage of using a PDF in the form of $P(w,\theta_l,q_t)$ is that it can be integrated over the saturated part of the $\theta_l - q_t$ plane to obtain the cloud fraction and amount of total condensate. Moreover, SGS buoyancy flux can be computed from the same PDF. Overall, the PDF provides a self-consistent way of deriving the higher order moments of SGS turbulence along with properties of SGS cloudiness.

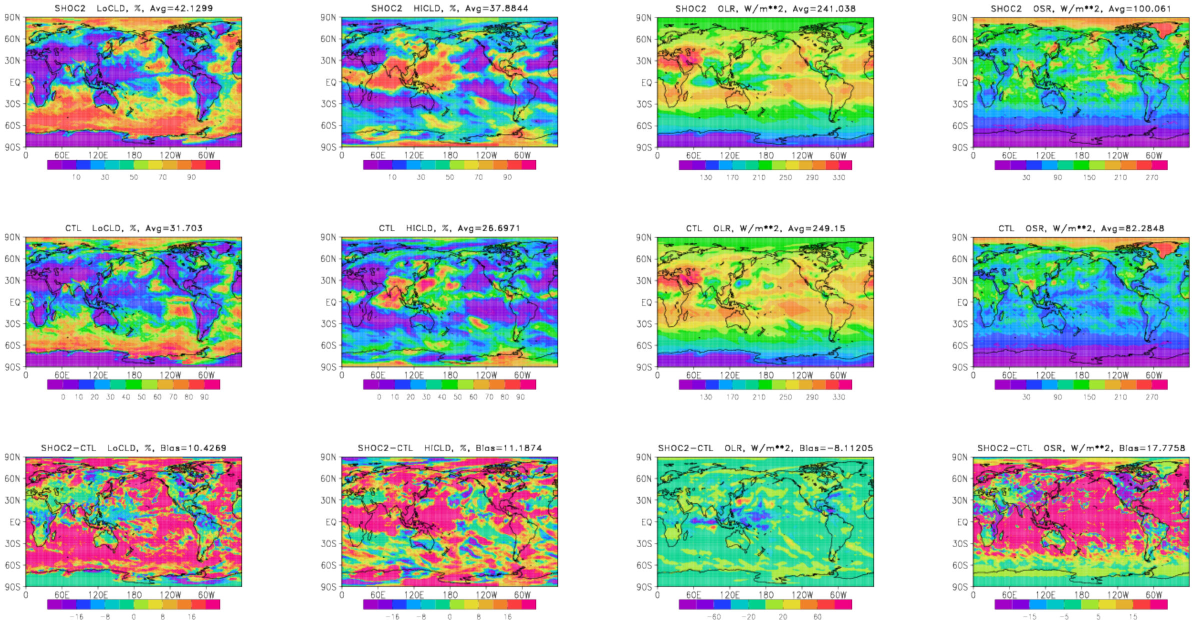
2 Simplified High Order Closure

Cheng et al. (2010) used a CRM with a $1\frac{1}{2}$-order TKE-based closure that calculated turbulent diffusion coefficients from SGS TKE following the Smagorinsky-Lilly approach, and diagnosed the SGS fluxes $\overline{w'\theta_l'}$ and $\overline{w'q_t'}$ using a simple downgradient diffusion method. They found that both the TKE and diagnosed SGS fluxes were too weak compared to a corresponding LES simulation. However, when they replaced the TKE calculation in the CRM with TKE computed in the corresponding LES run, they found that the diagnosed SGS fluxes along with resolved circulation were drastically improved.

Bogenschutz and Krueger (2013) conjectured that as long as the right amount of TKE is predicted, then *all* second order moments, $\overline{\theta_l'^2}, \overline{q_t'^2}, \overline{w'\theta_l'}, \overline{w'q_t'}, \overline{\theta_l'q_t'}$, can be predicted correctly using the downgradient diffusion method ($\overline{w'^2}$ can be inferred from TKE). They used a diagnostic expression for $\overline{w'^3}$ from Canuto et al. (2001) that is dependent on the values of lower order moments, and coupled a prognostic TKE equation in another $1\frac{1}{2}$-order closure CRM to ADG1, calculating SGS PDF's parameters using the diagnostic approach outlined above. The SGS PDF was used to calculate a SGS buoyancy flux term for the TKE equation and as a condensation/cloud fraction scheme for the CRM. They called this approach Simplified High Order Closure (SHOC).

The prognostic TKE equation is the "backbone" of SHOC, as the success or failure of the scheme hinges on an accurate calculation of SGS TKE. CRMs dissipate TKE too efficiently due to the under-prediction of turbulence length scale, which enters the denominator of the TKE dissipation term. Bogenschutz and Krueger (2013) proposed a novel length scale formulation where sub-cloud and cloud layers are treated separately. Individual treatment of the cloud layer addresses address the issue of the commonly small in-cloud length scale values predicted by other schemes. Separate formulations can be interpreted as a reflection of the fact that sub-cloud and in-cloud circulations can become decoupled. Both formulations are non-local, allowing the capture of the sizes of the largest eddies in a given column, and both are weighted by SGS TKE strength, reflecting the fact that with grid size increase (decrease) SGS TKE on average becomes larger (smaller), accompanied by the corresponding increase (decrease) of the turbulence length scale. The new formulation was validated against high resolution LES data up-scaled to a CRM resolution, and in CRM runs with up to 25 km horizontal resolution for a variety of cloud regimes. Prognosed SGS TKE values are used to diagnose turbulent diffusion coefficients that are supplied to the host model's diffusion equation solver, and are utilized in the calculation of higher order moments of SGS PDF by the downgradient diffusion method.

SHOC is a scale-aware parameterization by virtue of the fact that with increasing resolution prognosed SGS TKE values decrease along with the magnitudes of diagnosed diffusion coefficients, leading to a decrease in the values of diagnosed higher order moments (e.g., variances) of the SGS PDF, until at the limit of infinitesimal grid size the SGS PDF collapses into a delta function in each variable with amplitude determined by the variable's grid mean value. SHOC replaces the boundary layer,



(a) Low cloud fraction, % (b) High cloud fraction, % (c) OLR, W/m^2 (d) OSR, W/m^2

Figure 1: SHOC vs control, Zhao-Carr MP, averaged over days 3-10 of a C96 forecast initialized on 8/1/17.

shallow convection, and cloud macrophysics parameterizations in a host model in a unified and self-consistent manner. As a result, the host model's cloud microphysics scheme is applied to both stratiform and shallow convective clouds, as opposed to stratiform clouds only, further unifying the representation of cloud processes.

3 SHOC Implementation in FV3 GFS

To introduce a tighter coupling between the parameterization of deep convection and the SGS cloud scheme, we replaced the diagnostic treatment of $\overline{\theta_l'^2}$, $\overline{q_t'^2}$ with prognostic equations for both moments with added source terms for the variances from deep convective detrainment following Klein et al. (2005), leading to an improvement in the simulation of upper tropospheric tropical cloudiness. Currently, only the Chikira-Sugiyama deep convection parameterization with Arakawa-Wu extension is coupled to SHOC in this manner.

A number of assumptions originally imposed on the analytical form of ADG1 were substantially relaxed, and additional damping was introduced in grid boxes with excessive diagnosed skewness of w, resulting in a better representation of stratocumulus.

The cloud macrophysics scheme was re-formulated following Firl (2013).

Fluxes $\overline{w'\theta_l'}$ and $\overline{w'q_t'}$ are now computed from the tendencies of temperature and total cloud condesate due to diffusion calculated in the diffusion subroutine by the tridiagonal matrix solver, improving the coupling to surface processes.

To account for grid variability in the vertical, interpolation from the layer centers to layer interfaces in SHOC now uses a monotone piecewise cubic Hermite interpolant. There were a number of other improvements and bug fixes.

Figure 1 shows the averages over days 3-10 of 10-day forecasts initialized on 08/01/17 at C96L64 resolution (~ 100 *km* horizontal grid size) produced by the current pre-operational FV3 GFS (control) and the same model using SHOC with the modifications listed above. Both runs use Zhao-Carr microphysics.

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