Final Report: A generalized parameterization for clouds and turbulence in WRF

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1 Background on this DTC project

There is a need to improve the parameterization of turbulence and clouds in WRF. A report from the WRF Research Applications Board (http://www.wrf-model.org/development/wrab/docs/RAB-plan-final.pdf) states: "The requirements for substantially improved parameterized physics, particularly for high-resolution applications, is emphasized in all of the major model application areas. Improved parameterization techniques are most critical for the PBL and surface layer, cloud microphysics, and radiation."

Partly in response to this need, a project was undertaken with the Developmental Testbed Center (DTC) in order to test a new parameterization of clouds and turbulence in WRF. The results of this project are described in this report. The main scientific content of this report was originally published in the conference paper of Larson et al. (2012a) and is re-iterated here.

2 Introduction

Microphysical process, such as drizzle formation, depend sensitively on small-scale variability in cloud fields (Pincus and Klein 2000; Larson et al. 2001). To cite a simple example, rain formation occurs within cloudy regions but not within subsaturated regions. When the cloud variability occurs on smaller scales than the size of a model's grid box, then microphysical parameterizations may benefit from incorporating information on subgrid-scale cloud variability, such as cloud fraction. (The Weather Research and Forecasting (WRF) model does contain a method to diagnose cloud fraction that is used in radiative transfer calculations. However, it may be beneficial to compute cloud fraction and other subgrid-scale information in the planetary boundary layer and/or cumulus parameterizations and pass it to the microphysics schemes.)

The problem of parameterizing subgrid variability is difficult for several reasons, three of which are listed here. First, numerical weather prediction (NWP) models often contain multiple parameterizations, e.g. for the planetary boundary layer and deep convection, that must work well together. Second, the grid spacing for many NWP forecasts lies within the "grey-zone" or "terra incognita" in which clouds and turbulent eddies are partly but not fully resolved (Wyngaard 2004). Such grid spacings may pose difficulties for, e.g., those mass-flux schemes that assume that cloudy updrafts occupy only a small fraction of a grid column. Third, parameterizing subgrid variability is also difficult in part because many physical processes have "memory." For example, deep convection may evolve from and depend on prior shallow convection (Grabowski et al. 2006; Mapes and Neale 2011). Such time evolution may be difficult to simulate with parameterizations that are diagnostic.

To compute subgrid variability in WRF, we have implemented in WRF a parameterization called "Cloud Layers Unified By Binormals" (CLUBB). CLUBB predicts the probability density function (PDF) of subgrid variability in temperature, moisture, and vertical velocity. From the subgrid PDF, subgrid cloud fraction is diagnosed and can be fed into a microphysics scheme. CLUBB is a unified parameterization in the sense that it predicts subgrid variability from shallow cumulus, deep cumulus, and stratiform clouds using a single equation set (Golaz et al. 2002; Larson and Golaz 2005; Larson et al. 2012b). CLUBB makes no assumption about the fraction of a grid box that is occupied by updrafts, and most of CLUBB's equations are prognostic.

The combined model, WRF-CLUBB, is used for this DTC project to simulate clouds observed during the VAMOS Ocean-Cloud-Atmosphere-Land Study – Regional Experiment (VOCALS-REx) (Wood et al. 2011). VOCALS focused on marine stratocumulus (Sc) clouds off the coast of Chile in the Southeast Pacific. However, the domain of our simulation includes both marine Sc over the ocean and deep convective clouds over South America. In addition, the oceanic boundary layer clouds include pockets of open cells, which are organized structures of drizzling cumulus clouds. The wide variety of clouds in the VOCALS observations provides a challenging test of WRF-CLUBB. Although our DTC project had originally intended to perform a series of verification simulations over the contiguous United States, simulating the VOCALS case is less computationally expensive.

In this report, we first present an overview of CLUBB's formulation (Section 3). Then we discuss WRF-CLUBB's simulation of VOCALS observations (Section 4). Finally, we summarize the findings in Section 5 and list major project outcomes in Section 6.

3 Formulation of our PDF parameterization, CLUBB

In essence, the parameterization problem consists of estimating the subgrid turbulent vertical fluxes of heat, moisture, and momentum, and additionally estimating subgrid cloud fields such as cloud fraction. The subgrid fluxes are needed to calculate the corresponding resolved (mean) fields, and the subgrid cloud fields are helpful for calculating radiative transfer, microphysics, and atmospheric chemistry. In WRF, CLUBB serves as a unified parameterization for both the planetary boundary layer (PBL) and deep convection.

To estimate the needed subgrid fluxes and cloud fields, CLUBB follows the following three-step procedure for each time step:

1. *Prognose subgrid moments.* The host model, i.e. WRF, prognoses grid-box averages of momentum, temperature, and moisture. CLUBB extends WRF's equation set by prognosing various subgrid moments of the vertical velocity w, horizontal velocity components u and v, liquid water potential temperature θ_l, and total water (vapor + liquid) mixing ratio r_t. In particular, CLUBB prognoses relevant covariances (e.g. fluxes) ($\langle w'\theta_l'\rangle$, $\langle w'r_t'\rangle$, and $\langle r_t'\theta_l'\rangle$), variances ($\langle w'^2\rangle$, $\langle u'^2\rangle$, $\langle v'^2\rangle$, $\langle \theta_l'^2\rangle$, $\langle r_t'^2\rangle$), and one third-order moment ($\langle w'^3\rangle$). (Here $\langle\rangle$ denotes a spatial grid-box average.) The mathematical framework for the higher-order moments can be derived from governing equations, but many terms within those equations are unclosed and must be parameterized.

2. *Specify the PDF for each grid box and time step.* Based on the prognosed moments, CLUBB specifies the subgrid PDF for a given grid box

and timestep. The functional form of the PDF is assumed *a priori* to be the sum of two Gaussians, i.e. a double Gaussian or binormal. However, the centering of the PDF is determined by the grid-box averages, the width by the variances, and the skewness by $\langle w'^3 \rangle$ and $\langle w'^2 \rangle$. The PDF is multi-variate, and the covariances influence the correlations between variates.

3. *Diagnose needed quantities for closure and other physical parameterizations.* Once the PDF is known, then CLUBB diagnoses various terms that are required to close the prognosed higher-order moment equations. Such terms include, for example, the buoyant generation of turbulence kinetic energy. In addition, CLUBB outputs other useful quantities, such as subgrid cloud fraction, which depends on variability within a grid box. Additional terms, for processes involving pressure and turbulent dissipation, must be closed separately from the PDF.

At this point, all closure information is available, and CLUBB advances another time step. CLUBB allows the PDF to vary from one grid box to another and to evolve from time step to time step. CLUBB's prognostic moment equations are derived from the governing equations of fluid flow, albeit with many parameterized terms.

4 Model Results

4.1 Cloud case that we simulate: VOCA

As a test case, we simulate the VOCA model intercomparison case led by M. Wyant. VOCA is a follow up to the PreVOCA intercomparison (Wyant et al. 2010). VOCA is a regional simulation of the VOCALS observations of marine Sc off the coast of Chile. This marine Sc deck is vast, and it is important because it reflects shortwave radiation and hence cools the climate. VOCA also serves as a difficult test of numerical models because it contains several cloud types, including decoupled stratocumulus and deep cumulus clouds over the Amazon.

VOCA simulates the full observational period from 15 Oct 2008 to 15 Nov 2008. The case specification is described at
http://www.atmos.washington.edu/~mwyant/vocals /model/VOCA_Model_Spec.htm.

4.2 Model configuration

The WRF-CLUBB simulations reported here are based upon version 3.1.1 of the Advanced Research WRF model.

The vertical grid uses 45 levels, with refined grid spacing in the boundary layer. The horizontal grid spacing is 50 km. The timestep is 60 s for both WRF and CLUBB.

To represent microphysics, we use the Morrison double-moment scheme (Morrison et al. 2009). Our simulation contains no aerosol-cloud interactions or chemistry computations. We impose a constant cloud droplet number concentration of 150 cm^{-3}. To represent radiative transfer, we use the RRTM longwave (Mlawer et al. 1997) and the Dudhia shortwave (Dudhia 1989) parameterizations.

The initial and lateral boundary conditions are derived from the Global Forecast System (GFS). The model domain spans approximately -45 S to 5 N and from -115 W to -60 W. The grid projection is Mercator.

4.3 Planform of cloud cover

Figure 1 displays cloud cover. The observations show overcast clouds near the coast at 20 S and another maximum of cloud fraction near 40 S. The simulated cloud field exhibits a similar pattern with two maxima, but the northern maximum is displaced too far to the north.

4.4 Vertical cross sections of cloud cover and water vapor

The VOCALS field experiment devoted special attention to the east-west transect at 20 S (e.g. Bretherton et al. 2010). Moving west from the coast along this transect, the observed cloudy boundary layer starts shallow and overcast, and gradually deepens and becomes more decoupled to the west.

Figure 2 shows a cross-section along 20 S of observed and simulated cloud fraction. The observations and simulations both show that the cloud layer is thicker, less overcast, and higher toward the west. As compared to the observations, however, the simulations exhibit lower cloud fraction and a more elevated cloud top toward the west, and a shallower cloud top toward the east.

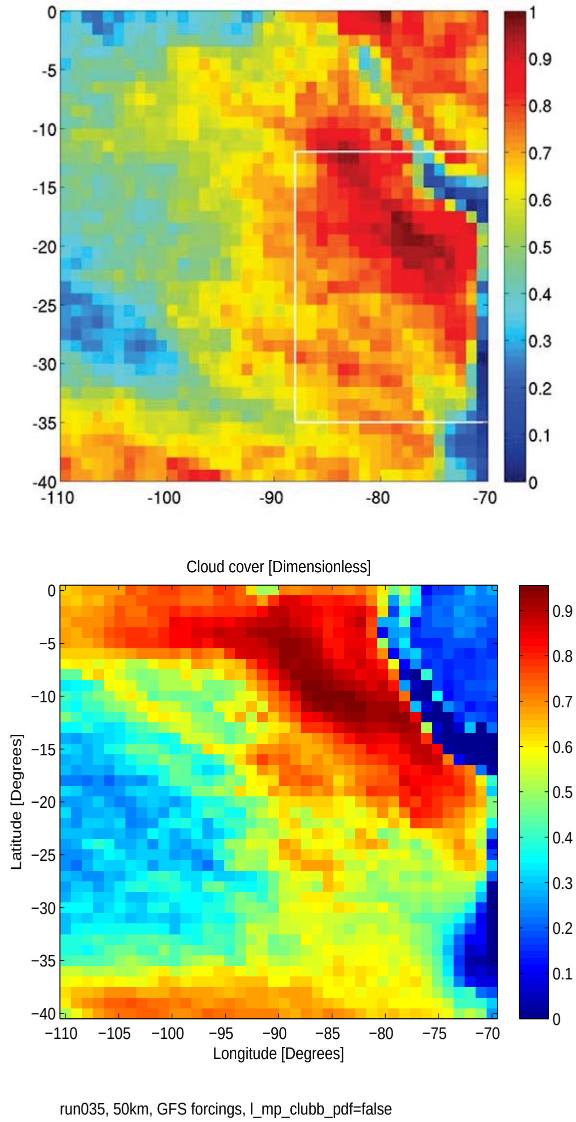

Figure 1: *Upper panel:* Observed cloud cover over the VOCALS region as retrieved by MODIS (courtesy R. Wood and M. Wyant). Data are the mean (10:30am local time) total cloud cover from MODIS on the NASA Terra Satellite Oct 15-Nov 15th 2008. *Lower panel:* Simulated cloud cover as predicted by WRF-CLUBB. The agreement between WRF-CLUBB and MODIS is satisfactory except north of 10 S.

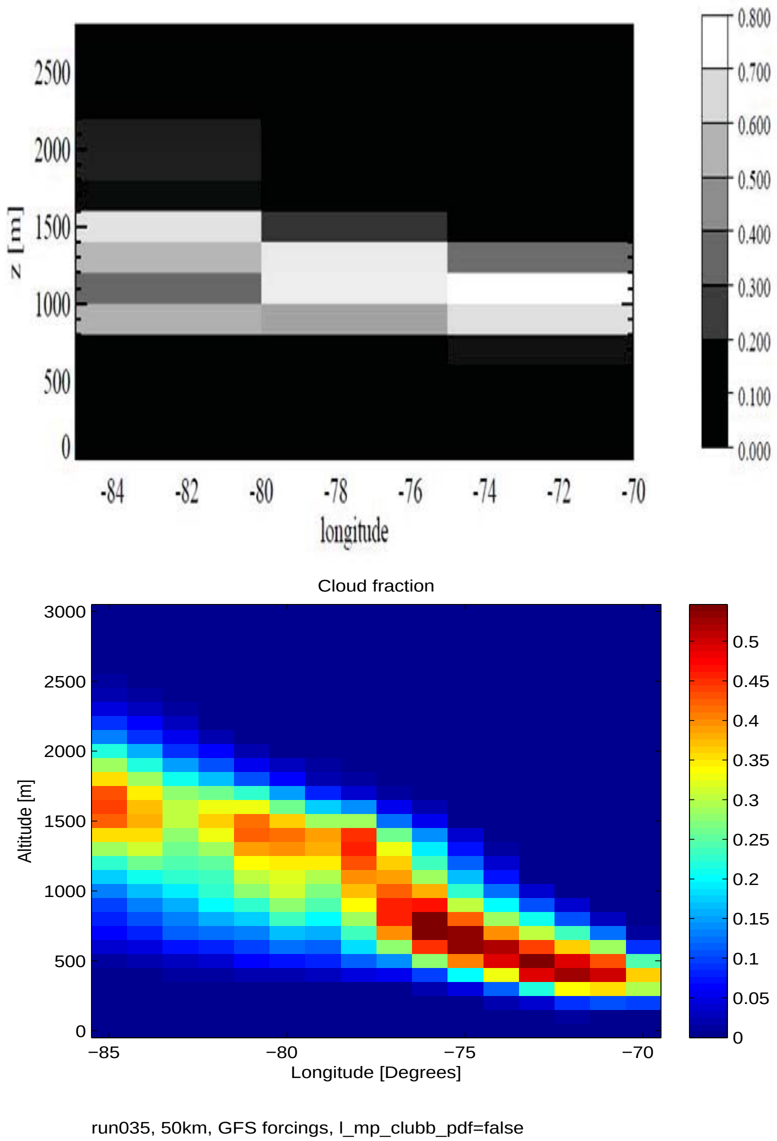

Figure 2: *Upper panel:* Observed vertical cross-section of cloud fraction along 20 S (courtesy R. Wood). Data are gridded campaign means from all the C-130 flights (18-22 deg S latitude) during VOCALS-REx (Wood et al. 2011). *Lower panel:* Simulated vertical cross-section of cloud fraction along 20 S as predicted by WRF-CLUBB. Both the observations and WRF-CLUBB show increasing cloud top height and decreasing cloud cover toward the west (i.e. away from the coast).

Figure 3 shows a cross-section along 20 S of water vapor mixing ratio. The observations are compiled from a variety of data sources, including radiosondes and aircraft observations (Bretherton et al. 2010). Although the cloud layer is decoupled and partly cloudy to the west, the decrease in moisture near cloud top is relatively sharp. In contrast, the simulations show a more gradual vertical decrease in moisture across the inversion. Both observations and simulations show increased moisture nearer the coast.

5 Scientific Conclusions

CLUBB is a unified parameterization that can represent shallow cumulus, stratiform, and deep convective clouds with the same equation set. This unified approach obviates the difficult problem of interfacing different cloud schemes. CLUBB has been implemented in WRF and used to simulate the VOCA case off the coast of Chile.

In our simulation of the VOCA case, CLUBB is able to parameterize both shallow maritime clouds and deep convective clouds over South America. WRF-CLUBB overpredicts marine cloud cover near the equator, but produces acceptably accurate regional variations of clouds over the ocean south of 10 S. WRF-CLUBB simulates the observed increase in cloud top height as one moves away from the coast, but WRF-CLUBB exaggerates the increase. WRF-CLUBB simulates a qualitatively reasonable vertical distribution of water vapor, but does not produce a sufficiently well-mixed profile of water vapor within and below stratocumulus clouds. Nevertheless, these early results are encouraging.

Future plans include performing simulations at higher horizontal resolution and interfacing parameterized subgrid variability more closely with the microphysics. Feeding information about subgrid variability into the microphysics scheme in WRF could significantly improve simulations, particularly at coarse resolutions (e.g. 50 km).

6 Beneficial outcomes of the project

The visit to DTC benefitted me in several ways, and the research performed may have benefits for DTC and the larger WRF community.

1. Before accepting the DTC fellowship, most of my prior experience was

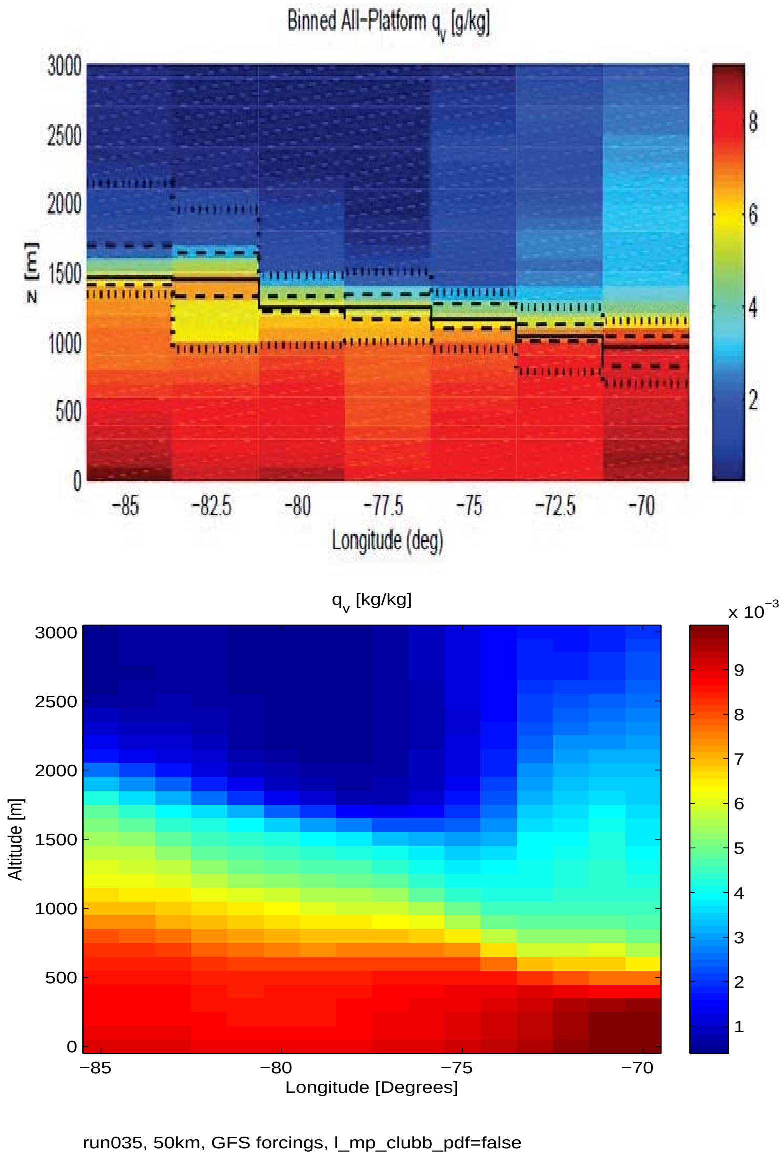

Figure 3: *Upper panel:* Observed vertical cross-section of water vapor mixing ratio along 20 S (Fig. 5 of Bretherton et al. 2010). *Lower panel:* Simulated vertical cross-section of water vapor mixing ratio along 20 S as predicted by WRF-CLUBB. WRF-CLUBB's decrease of water vapor at the inversion is not as sharp as the observed decrease.

in theory or single-column modeling. The DTC fellowship was one of my first experiences with running non-idealized 3D simulations and with using a supercomputer. I acquired useful knowledge.

2. In the course of the fellowship, a PDF parameterization was tested for the first time in WRF. The PDF approach is a newer parameterization methodology that we believe ought to be explored further for forecasting applications.

3. In the course of the research, we noticed an omission in the WRF framework, namely the inability to feed cloud fraction and other subgrid variability predicted by boundary layer or deep convective parameterizations to other physical parameterizations, such as radiation or microphysics. This omission is not present in climate models. Noting this omission may stimulate future development in WRF, by us or others.

   Feeding the cloud fraction into the microphysical calculation may have benefits. In WRF, microphysics schemes take grid box averages as inputs. For instance, the microphysics scheme may perform a saturation adjustment based on grid box mean liquid and vapor in order to update the liquid water content. A grid box containing subgrid cumulus clouds surrounded by dry clear areas may be subsaturated on average. In such a grid box, the microphysics' saturation adjustment will spuriously eliminate the cloud water.

4. Our initial tests of WRF-CLUBB have paved the way for possible future implementation of CLUBB in the public version of WRF. We encountered and overcame several unforeseen obstacles that are not discussed here, but significant work remains. The chief remaining obstacle is that WRF, unlike climate models, does not provide software infrastructure to feed subgrid information computed by a boundary-layer parameterization into the microphysics or radiation parameterizations. The lack of such infrastructure vitiates a chief advantage of CLUBB. We have implemented prototype code for the infrastructure in our copy of WRF-CLUBB, but it needs to be generalized and approved before it can be incorporated into the public version of WRF.

7 Acknowledgments

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