

# Evaluation of the WRF PBL Parameterizations for Marine Boundary Layer Clouds: Cumulus and Stratocumulus

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## ABSTRACT

The performance of five boundary layer parameterizations in the Weather Research and Forecasting Model is examined for marine boundary layer cloud regions running in single-column mode. Most parameterizations show a poor agreement of the vertical boundary layer structure when compared with large-eddy simulation models. These comparisons against large-eddy simulation show that a parameterization based on the eddy-diffusivity/mass-flux approach provides a better performance. The results also illustrate the key role of boundary layer parameterizations in model performance.

## 1. Introduction

Stratocumulus and shallow cumulus clouds in subtropical oceanic regions cover thousands of square kilometers and play a key role in regulating global climate (e.g., Tiedtke et al. 1988; Klein and Hartmann 1993). Stratocumulus cools the climate by strongly reflecting incoming shortwave radiation, playing an important role in ocean–atmosphere interaction (e.g., Teixeira et al. 2008), while cumulus clouds play a key role in regulating the planet’s evaporation and moisture transport to the deep tropics. Numerical modeling is an essential tool to study these clouds in regional and global systems, but the current generation of climate and weather models has difficulties in representing them in a realistic way. Stratocumulus boundary layers in models are often unrealistically shallow and have too little cloud (e.g., Duynkerke and Teixeira 2001; Zhang et al. 2005; Stevens et al. 2007). Additionally, current models have

difficulties in simulating the critical transition from stratocumulus to shallow cumulus clouds (Siebesma et al. 2004; Teixeira et al. 2011).

While numerical models resolve the large-scale flow, subgrid-scale parameterizations are needed to estimate small-scale properties (e.g., boundary layer turbulence and convection, clouds, radiation), which have significant influence on the resolved scale due to the complex nonlinear nature of the atmosphere. For the cloudy planetary boundary layer (PBL), it is fundamental to parameterize vertical turbulent fluxes and subgrid-scale condensation in a realistic manner. The Weather Research and Forecasting (WRF) Model version 3.1 provides multiple parameterization choices, which include nine PBL schemes, 12 microphysics, and 6 moist convection parameterizations (Skamarock et al. 2008). In addition to a typical model structural drawback—an artificial separation between turbulence and convection parameterizations—this long menu suffers from a variety of issues including an uncertainty regarding the optimal combinations to select.

In this study, we aim to investigate the performance of the various WRF PBL schemes in cloud simulations of both marine stratocumulus and shallow cumulus.

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Meanwhile, we also evaluate the ability of a new scheme [total-energy–mass-flux (TEMF), which is described below] based on the eddy-diffusivity–mass-flux (EDMF) concepts. We design a set of several WRF single-column model (SCM) simulations for three well-known large-eddy simulation (LES) case studies based on field campaigns. Including the TEMF scheme, five PBL parameterizations are examined against LES. Resolving the large eddies that are responsible for the transport of mass, momentum, and energy in the PBL, the LES result has been used to serve as a proxy of reality to guide the development of PBL parameterization. Section 2 briefly introduces the EDMF and TEMF schemes. Section 3 describes the experimental design. Section 4 presents the simulation results followed by a discussion in section 5.

## 2. EDMF and TEMF parameterizations

The EDMF parameterization was first introduced by Siebesma and Teixeira (2000) and subsequently tested and implemented in the European Centre for Medium-Range Weather Forecasts (ECMWF) model (e.g., Teixeira and Siebesma 2000; Koehler 2005). Recent studies have shown its potential to represent the shallow and dry convective PBL (Soares et al. 2004; Siebesma et al. 2007; Neggers 2009; Witek et al. 2011; Suselj et al. 2012). Later, using total turbulent energy to calculate eddy-diffusivity (Mauritsen et al. 2007), Angevine et al. (2010) modified the EDMF parameterization to what is referred to as the TEMF parameterization. The TEMF scheme implemented in WRF version 3.1 is evaluated in this study.

Rather than a specific parameterization, EDMF is an approach based on an optimal combination of the eddy-diffusivity (ED) parameterization, used to simulate turbulence within the PBL, and the mass-flux (MF) parameterization, used for moist convection. Though differences in the details are present in different EDMF implementations on weather or climate models, the fundamental idea is the same: local mixing is parameterized by the ED term, while the nonlocal transport due to convective thermals is represented by the MF term. The governing equation for the vertical fluxes in EDMF is

$$\overline{w'\psi'} = -K \frac{\partial \psi}{\partial z} + M(\psi_{\text{up}} - \psi), \quad (1)$$

where  $\psi$  can be any scalar quantity, such as liquid water potential temperature ( $\theta_l$ ), total water specific humidity ( $q_t$ ), or total energy ( $E$ ). Here  $K$  and  $M$  are the ED and MF terms, respectively; the subscript up in  $\psi_{\text{up}}$  indicates the value of  $\psi$  in the updraft. The temporal evolution of

the mean variable  $\psi$  is then given as the vertical gradient of the flux:  $\partial \psi / \partial t = -\partial(\overline{w'\psi'}) / \partial z$ .

The main difference between TEMF and EDMF is in the calculation of the ED coefficient: EDMF often uses turbulent kinetic energy (TKE) while TEMF uses total turbulent energy (TTE), a combination of TKE and turbulent potential energy. Better handling of stably stratified conditions is the main reason for using TTE rather than TKE (Mauritsen et al. 2007). For a full description of TEMF, the reader is referred to Angevine (2005), Mauritsen et al. (2007), Siebesma et al. (2007), and Angevine et al. (2010).

## 3. Experimental design

### a. Study sites

We perform a suite of simulations using the SCM version of WRF for three case studies associated with field experiments, which are chosen because they have been intensively studied using LES models. The three field campaigns are the following: 1) the Second Dynamics and Chemistry of the Marine Stratocumulus field study (DYCOMS-II), 2) the Barbados Oceanographic and Meteorological Experiment (BOMEX), and 3) the Rain in Cumulus over Ocean (RICO) experiment (Fig. 1). DYCOMS-II took place in the subtropical Pacific, while BOMEX and RICO were in the tropical Atlantic. The marine clouds in BOMEX and RICO are classified as shallow cumulus while the DYCOMS-II case is classified as stratocumulus. DYCOMS-II was conducted in the center of the northeast Pacific stratocumulus deck, about 500 km west-southwest of San Diego, California, during July 2001 (Stevens et al. 2003, 2005). The first research flight mission of DYCOMS-II is selected for this study because it provides many appropriate atmospheric conditions for the LES experiment, such as a relatively homogeneous atmospheric environment and a uniform cloud distribution. BOMEX (phase III) took place during June 1969 over a 500 km<sup>2</sup> region near Barbados. The aim was to investigate the large-scale heat and moisture budgets using radiosondes (Delnore 1972; Holland and Rasmusson 1973). In this study, the SCM setup and initialization for BOMEX use the same settings as previous LES studies (e.g., Siebesma and Cuijpers 1995; Siebesma et al. 2003). RICO was carried out near the Caribbean islands during a two-month period between November 2004 and January 2005 (Caesar 2005; Rauber et al. 2007). Here the SCM initialization for RICO follows the designs of an LES intercomparison study presented in the Ninth GCSS Boundary Layer Cloud Workshop (<http://www.knmi.nl/samenw/rico/index.html>).

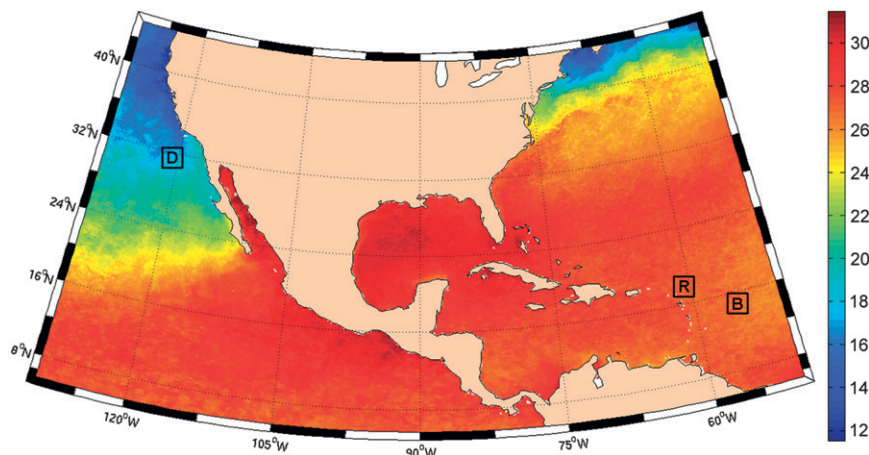


FIG. 1. Locations of the selected experiments in this study: the DYCOMS-II (D), the BOMEX (B), and the RICO (R). The color map represents the averaged sea surface temperature ( $^{\circ}\text{C}$ ) of remotely sensed data collected by the Advanced Very High Resolution Radiometer (AVHRR) during July 2001.

All LES ensemble results (for three study sites) shown in the following analyses are taken from these intercomparison studies.

*b. Single-column model setup*

This study uses WRF version 3.1 for all SCM experiments. In addition to TEMF, four other PBL schemes are used: the Yonsei University (YSU) scheme (Hong et al. 2006), the Mellor–Yamada–Janjic (MYJ) scheme (Mellor and Yamada 1982; Janjic 2002), the Mellor–Yamada–Nakanishi–Niino (MYNN) scheme (Nakanishi and Niino 2004, 2006), and the Medium-Range Forecast (MRF) scheme (Hong and Pan 1996). Note that YSU

and MRF are classified as first-order schemes while the others are TKE closure schemes, where a prognostic TKE equation is used to determine the eddy diffusivity. All PBL schemes used in this study are listed in Table 1. In addition, a moist convection parameterization, the Kain–Fritsch scheme (Kain and Fritsch 1993; Kain 2004), is selected for the non-TEMF SCM simulations of the BOMEX and RICO cases. This allows us to compare the results using the existing WRF PBL schemes with TEMF for shallow cumulus cases. The TEMF code used in WRF version 3.1 was a prereleased version, TEMF was not released until version 3.3. However, the two versions are similar.

TABLE 1. List of boundary layer parameterizations and microphysics schemes used for the single-column model experiments in this study.

Boundary layer parameterization		
Name of parameterization	Nomenclature	Selected reference
Yonsei University	YSU	Hong et al. (2006)
Mellor–Yamada–Janjic	MYJ	Mellor and Yamada (1982); Janjic (2002)
Mellor–Yamada–Nakanishi–Niino	MYNN	Nakanishi and Niino (2004, 2006)
Medium-Range Forecast	MRF	Hong and Pan (1996)
Total-energy/mass-flux	TEMF	Siebesma et al. (2007); Angevine et al. (2010)
Microphysics scheme		
Name of scheme	Nomenclature	Selected reference
Kessler	Kessler	Kessler (1969)
Purdue Lin	Lin	Lin et al. (1983)
WRF single-moment 3-class	WSM-3	Hong et al. (2004)
WRF single-moment 5-class	WSM-5	Hong et al. (2004)
Eta	Eta	Zhao and Carr (1997)
WRF single-moment 6-class	WSM-6	Hong and Lim (2006)
Goddard	Goddard	Tao and Simpson (1993)
WRF double-moment 5-class	WDM-5	Morrison et al. (2009)
WRF double-moment 6-class	WDM-6	Morrison et al. (2009)

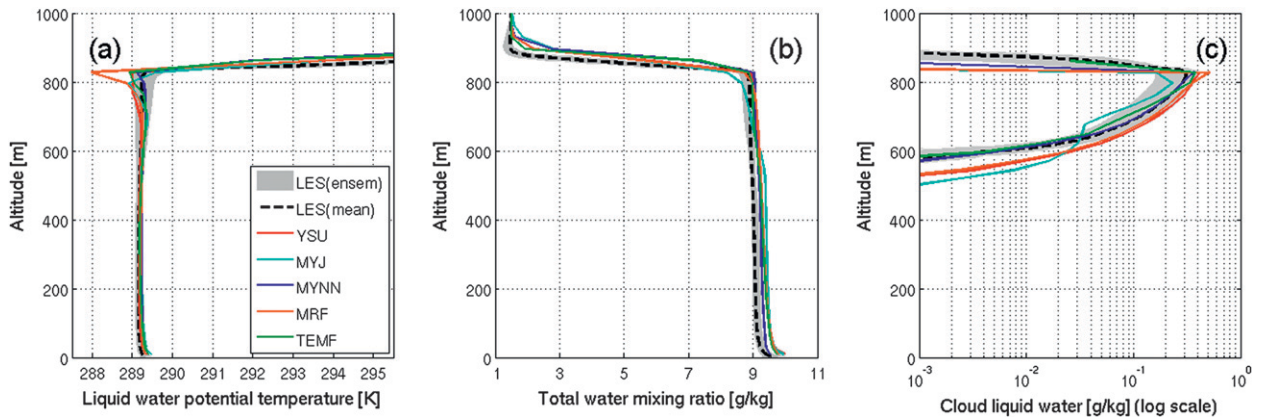


FIG. 2. Vertical profile of (a) liquid water potential temperature, (b) total water vapor mixing ratio, and (c) cloud liquid water (on log scale) for the DYCOMS-II experiments. See text for more details.

In WRF, the cloud microphysics component estimates the amount of various types of condensed water (i.e., cloud, rain, and ice). Thus, for a given WRF PBL scheme, the estimated cloud liquid water can vary with the choice of microphysics scheme. For each PBL scheme used in this study, we perform nine simulations with each of the nine available microphysics schemes, also listed in Table 1. However, because of the qualitative similarity of the vertical profile shapes across microphysics schemes, the average over the ensembles of simulations using the various microphysics schemes is presented. The vertical domain of the SCM experiments includes 116 levels up to an altitude of 12 000 m and the simulation time step is 30 s. Other model setups are consistent with previous LES intercomparison studies.

#### 4. Results

Vertical profiles of the temperature and water content variables are illustrated in the following figures to

compare temporally averaged SCM estimates and the LES results for the DYCOMS-II (Fig. 2), BOMEX (Fig. 3), and RICO (Fig. 4) cases. In each subplot, shaded areas and black dashed lines represent the range of output of the LES ensembles and the ensemble mean value, respectively. The LES ensembles are the results selected from previous LES intercomparison studies, where 6, 12, and 14 different LES models were used for the DYCOMS-II, BOMEX, and RICO experiments, respectively. Note that to show a more clear comparison, we plot the cloud liquid water  $q_c$  profiles in logarithm scale (Figs. 2c, 3c, and 4c). Quantitative statistics are listed in Table 2. High correlation coefficients for temperature and humidity profiles between SCM and LES are expected, so we only show the root-mean-square error (RMSE) for these two terms. On the other hand, because we focus on the vertical structure of cloud, instead of liquid water amount, we calculate the correlation coefficient ( $\rho$ ) between SCM and LES for the liquid water term.

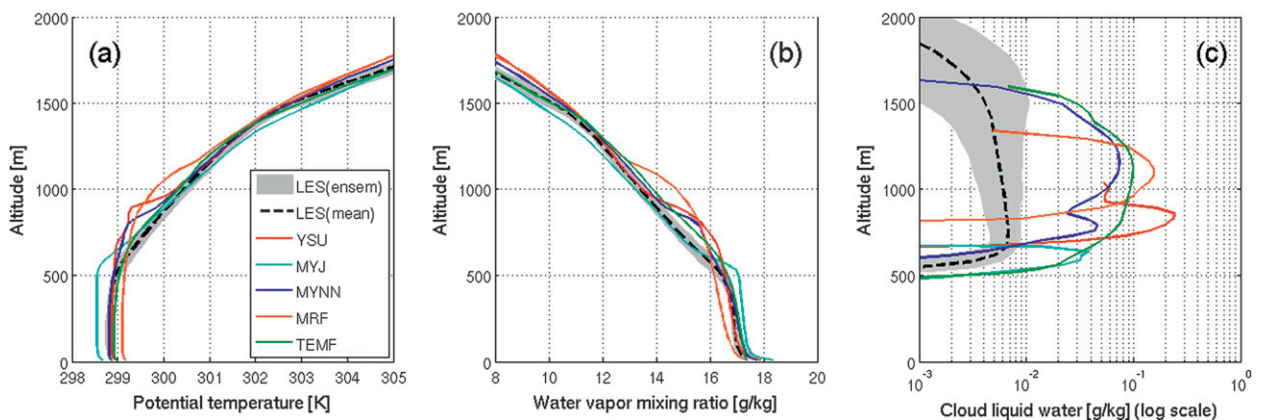


FIG. 3. Vertical profile of (a) potential temperature, (b) water vapor mixing ratio, and (c) cloud liquid water (on log scale) for the BOMEX experiments.

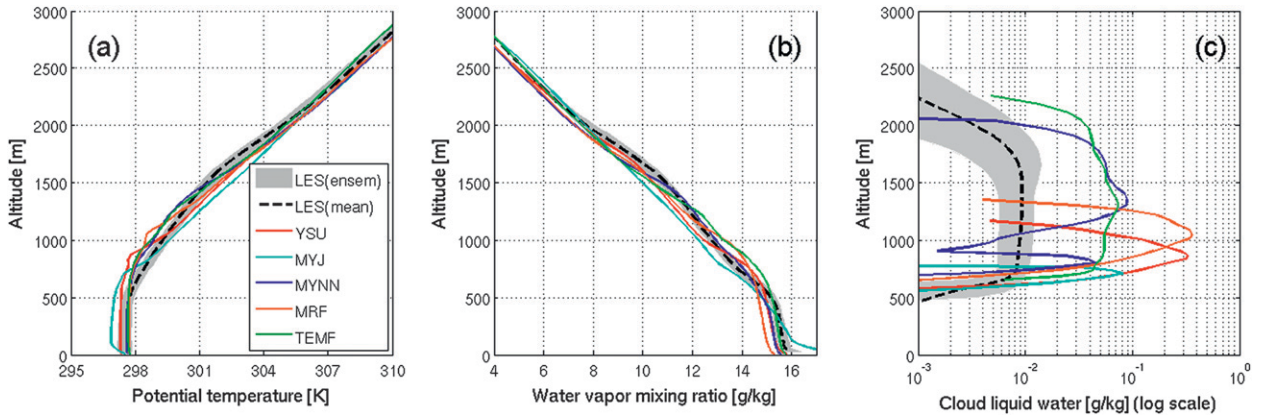


FIG. 4. As in Fig. 3, but for the RICO experiments.

a. Stratocumulus case (DYCOMS-II)

While all liquid water potential temperature  $\theta_l$  profiles are within the range of the LES ensemble, there are slight differences in the inversion of the PBL (Fig. 2a). In particular, near the entrainment zone the MRF parameterization creates a small temperature inversion that could be an issue due to numerical instability. All SCM experiments simulate comparable profiles of total water mixing ratio  $q_t$ , but a small overestimate within the PBL is seen (Fig. 2b). No significant difference is seen in  $q_c$  across PBL schemes (Fig. 2c) mostly because this plot uses a log scale and the cloud cover in this stratocumulus case is close to 1. Estimates of  $q_c$  in the MYNN and TEMF experiments are quite close to LES, while larger values are simulated by YSU and MRF and a smaller value is performed by MYJ. The peak  $q_c$  estimates vary from  $0.23 \text{ g kg}^{-1}$  in MYJ to  $0.52 \text{ g kg}^{-1}$  using MRF, while the LES ensemble mean is  $0.31 \text{ g kg}^{-1}$ .

b. Shallow cumulus case I: BOMEX

Figure 3 shows the vertical profiles from the BOMEX case. For potential temperature  $\theta$ , TEMF and MYNN provide the most realistic profiles, while MYJ is too cold and shallow, and YSU leads to subcloud layers that are too deep (Fig. 3a). For water vapor mixing ratio  $q_v$  (Fig. 3a), the parameterizations show similar biases. The significant differences between the parameterizations are clear for cloud liquid water. The  $q_c$  profiles from all PBL parameterizations are significantly larger than LES (Fig. 3c). Essentially, this shows the dangers of the unphysical coupling between boundary layer, convection, and cloud microphysics parameterizations in the WRF Model. In addition, the SCM liquid water vertical structures shown in Fig. 3c are profoundly different from one another. The liquid water profiles that better resemble the LES results are seen in TEMF (and to

a certain extent MYNN) with realistic cloud-base and cloud-top heights. YSU and MRF produce clouds that are too shallow (500 m deep instead of over 1 km) with very large peak values, while MYJ produces a very shallow cloud. This figure shows that TEMF (and to a certain extent MYNN) produces the more realistic vertical structures for this case and quantitative statistics (e.g.,  $\rho$ ) listed in Table 2 also confirm this result.

c. Shallow cumulus case II: RICO

Profiles for RICO are plotted in Fig. 4. The results overall are similar to BOMEX, which shows the robustness (or lack of it) of the various schemes. The TEMF (and to a certain extent MYNN) parameterization is again superior to the others, producing profiles of potential temperature (Fig. 4a) and water vapor (Fig. 4b) that are relatively close to the LES ensembles. The liquid water figure (Fig. 4c) shows again how poor the

TABLE 2. Statistical comparison of temperature and water content variables between SCM results and LES ensemble mean. RMSE and  $\rho$  indicate the root-mean-square error and correlation coefficient, respectively.

Boundary layer scheme		YSU	MYJ	MYNN	MRF	TEMF
DYCOMS-II						
$\theta_l$	RMSE (K)	0.95	0.89	0.61	0.92	0.71
$q_t$	RMSE ( $\text{g kg}^{-1}$ )	0.65	0.67	0.40	0.66	0.48
$q_c$	$\rho$	0.81	0.78	0.83	0.83	0.85
BOMEX						
$\theta_v$	RMSE (K)	0.24	0.48	0.20	0.26	0.35
$q_v$	RMSE ( $\text{g kg}^{-1}$ )	0.40	0.61	0.24	0.52	0.34
$q_c$	$\rho$	0.51	0.01	0.82	0.54	0.82
RICO						
$\theta_v$	RMSE (K)	0.73	0.92	0.65	0.69	0.55
$q_v$	RMSE ( $\text{g kg}^{-1}$ )	0.55	0.66	0.62	0.67	0.53
$q_c$	$\rho$	0.39	0.17	0.77	0.50	0.85

WRF SCM simulations for shallow convection situations are with SCM versions overestimating liquid water by about one order of magnitude. TEMF shows a vertical structure of liquid water that although overestimating the overall values (as for all other parameterizations) produces realistic cloud-base and cloud-top heights. Again YSU and MRF produce clouds that are quite shallow (around 500 m deep vs 2 km for the LES) and MYJ produces even shallower (and lower) clouds. Table 2 also illustrates that the vertical cloud structures from the MYNN and TEMF experiments are the ones most close to LES.

## 5. Conclusions and discussion

An intercomparison of five PBL parameterizations in the WRF Model for marine cloudy boundary layers is presented in this study. Four existing WRF PBL schemes and the recently developed TEMF scheme (based on the EDMF approach) are evaluated for their performance against LES results in terms of the vertical profiles of meteorological states for one stratocumulus case and two shallow cumulus cases.

For the stratocumulus case there are some differences in the upper region of the PBL with some parameterizations producing an artificial and noisy vertical structure in potential temperature. In liquid water, all models produce a similar structure but with some differences in terms of absolute values. For both shallow cumulus cases, the results are fairly similar with TEMF, and to a certain extent MYNN, producing superior depictions of the thermodynamic vertical structure. All SCMs clearly overestimate the values of liquid water when compared to the LES results, mostly because of the unphysical coupling between boundary layer and cloud microphysics parameterizations in WRF. In spite of this large positive bias, the TEMF version produces realistic cloud base and cloud heights for both BOMEX and RICO. Other parameterizations produce cloud structures that are too shallow not resembling shallow cumulus boundary layers at all in this context.

In spite of its simplicity, this study leads to some key general conclusions:

- 1) A parameterization based on the EDMF approach (i.e., TEMF) that unifies different components (turbulence and moist convection) produces a better result when compared with LES, with realistic vertical structures for stratocumulus and cumulus regimes.
- 2) Existing PBL parameterizations in WRF are not able to produce fully realistic results when simulating stratocumulus and shallow cumulus regimes.
- 3) The often artificial modularity of parameterizations as they are implemented in WRF produces unreliable

results that are virtually impossible to interpret because of the plethora of available parameterizations and their coupling.

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