Stable and transitional (and cloudy) boundary layers in WRF

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Abstract

Comparisons of results from WRF with the new Total Energy – Mass Flux (TEMF) boundary layer scheme and with an established scheme (MYJ) are shown, with emphasis on the behavior of the schemes for stable, transitional, and cloudy conditions. TEMF displays more "ideal" behavior in stable conditions, and allows for weak intermittent turbulence at night. In the Southern California bight, where stratocumulus clouds were sampled, TEMF allows the correct boundary layer depth to be simulated. Top entrainment in TEMF conforms to expectations. Other differences are minor in the cases examined.

1. Introduction

The Weather Research and Forecast modeling system (WRF) is widely used for research and operations. As a community resource, and unlike most other models, WRF has many options, including two distinct dynamical cores and a variety of advection schemes. Among other physics options, ten planetary boundary layer (PBL) schemes are available in WRF version 3.3. Given the obvious impossibility of testing all possible combinations, most researchers focus on a few choices. In this study, I look at how WRF behaves in stable, transitional, and cloudy boundary layers with two PBL schemes, the new Total Energy – Mass Flux (TEMF) formulation, and the well-established Mellor-Yamada-Janjic (MYJ) scheme. The Advanced Research WRF (ARW) dynamical core is used, and the tests are all on WRF version 3.3. Other physics and dynamics options are shown in table 1.

Process	CalNex	BLLAST
Grid (horizontal (km), levels)	36/12/4, 60	9/3, 50
Initial and boundary conditions	ERA-Interim, Navy GODAE HRSST	ECMWF analysis
Microphysics	Eta	WSM3 (simple ice)
Radiation (LW, SW)	RTTM-G	RRTM-G
Cumulus	Grell-Devenyi (36 km only)	Kain-Fritsch
PBL	MYJ or TEMF	MYJ or TEMF
Land surface	5-layer thermal diffusion (slab)	5-layer (slab) or Noah

Table 1: WRF configurations for the cases shown.

TEMF is a member of the family of Eddy Diffusivity – Mass Flux (EDMF) schemes (Siebesma et al. 2007). Such schemes use both traditional eddy diffusion ("K-theory") and mass flux components (carried by one or more updrafts) to carry out vertical mixing. It should be noted that in WRF, as in many models, the PBL scheme is responsible for vertical mixing/diffusion at all levels, not only within the PBL itself. TEMF is described by Angevine et al. (2010) and references therein. While the basic concept of all EDMF schemes is the same, many details can differ. Perhaps the most important difference is whether the eddy diffusivity is formulated from a defined profile (first-order) or from a prognostic energy variable (1.5-order). TEMF is unique in using total turbulent energy (TE) rather than turbulent kinetic energy (TKE) as the energy variable. Other differences between TEMF and other EDMF schemes are in the lateral entrainment and detrainment rates of the updraft (a very sensitive aspect); the length scale; the closure of updraft mass flux at cloud base; the initialization of updraft properties at the lowest level and the location of that level; the surface layer formulation; and which variables are transported by the updraft. TEMF is formulated in moist conserved variables (liquid water potential temperature and total water mixing ratio), the only WRF PBL scheme so designed. It should also be mentioned that TEMF uses a mixed velocity scale, allowing the convective velocity w* to contribute to transport when the friction velocity is small.

Why do we use an energy variable? In the early development of the unstable-only predecessor of TEMF (Angevine 2005), I found the need to justify the amount of eddy diffusivity in the cloud layer. There were no known formulae for this. Using an energy variable (originally TKE) which could be transported by the updraft provided an elegant framework. In the stable boundary layer (and stable layers aloft), the use of total turbulent energy eliminates the implicit critical Richardson number, allowing for the possibility of continued turbulence even under very stable conditions (Mauritsen et al. 2007). There are also some practical advantages of TE over TKE. In the (slightly statically stable) upper part of the convective boundary layer or subcloud layer, TKE can be damped by buoyancy destruction, while TE is not affected. This allows for a reasonable amount of eddy diffusivity in the upper boundary layer and through cloud base without adding extra terms to the formulation. Energy can also be advected, which may be useful in strongly heterogenous situations simulated on fine grids (Angevine et al. 2006). The version of WRF shown here does not advect the energy variable.

The evaluation results shown below are from two sets of simulations. One set is for the CalNex field experiment carried out in California in May and June 2010. The other is for the BLLAST campaign in June and July 2011 in France.

2. CalNex results

For CalNex, WRF was run for two months on a large domain covering all of California. During the study, the model was run in forecast mode with daily initialization from the Global Forecast System (GFS) analysis and forecasts. Subsequently, retrospective runs have been made. Because we found some shortcomings in the GFS analyses, especially too little moisture and excessively shallow boundary layers offshore, we switched to ERA-Interim reanalysis for initial and boundary conditions. Three levels of nested grids were used, at 36, 12, and 4 km horizontal spacing. The retro runs have 60 vertical levels, 18 below 1 km, with the lowest level approximately 15 m above ground level. High-resolution sea surface temperature data were provided by the U.S. Navy GODAE project. Two parallel runs were made, differing only in the PBL scheme, either MYJ (denoted REF for "reference" configuration) or TEMF.

Figure 1 shows the effective bulk transfer coefficient for heat as the relationship between the surface temperature difference and the sensible heat flux divided by the wind speed. The cloud of points are the values at each point of the 4-km grid for two hours, 1200 UTC (4:00 AM local standard time, early morning) and 2100 UTC (1:00 PM LST, midday) on a single day. The extent of the domain and variety of terrain provide a range of stability at each hour. The key point here is that the heat transfer

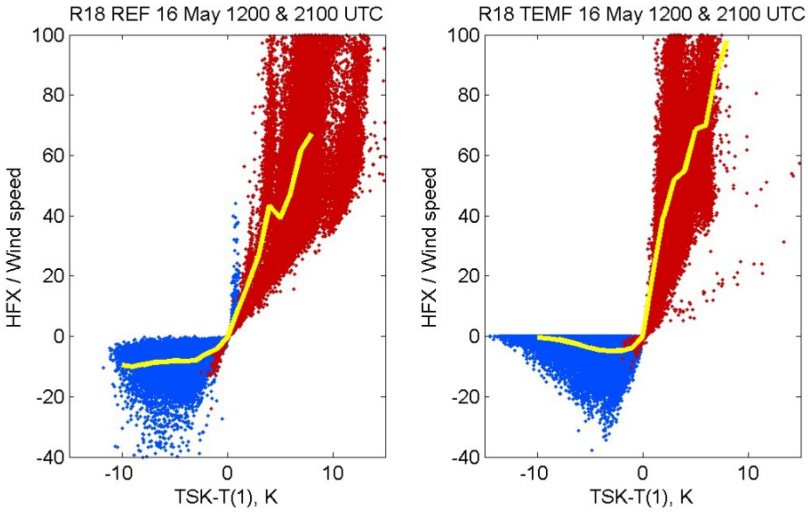

Figure 1: Heat transfer coefficient vs. surface stability for early morning (blue) and midday (red) with MYJ PBL (left) and TEMF (right) on the 4-km CalNex domain.

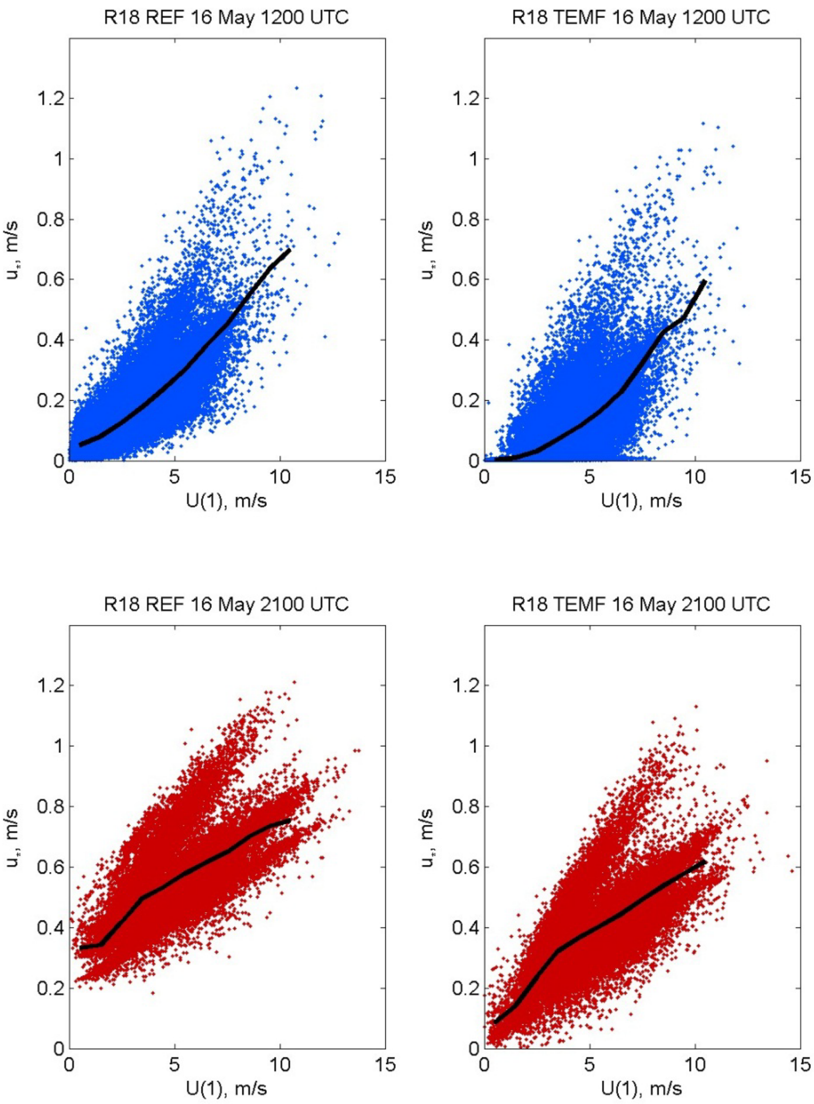

Figure 2: Surface friction velocity vs. first-level wind speed at early morning and midday for two PBL schemes.

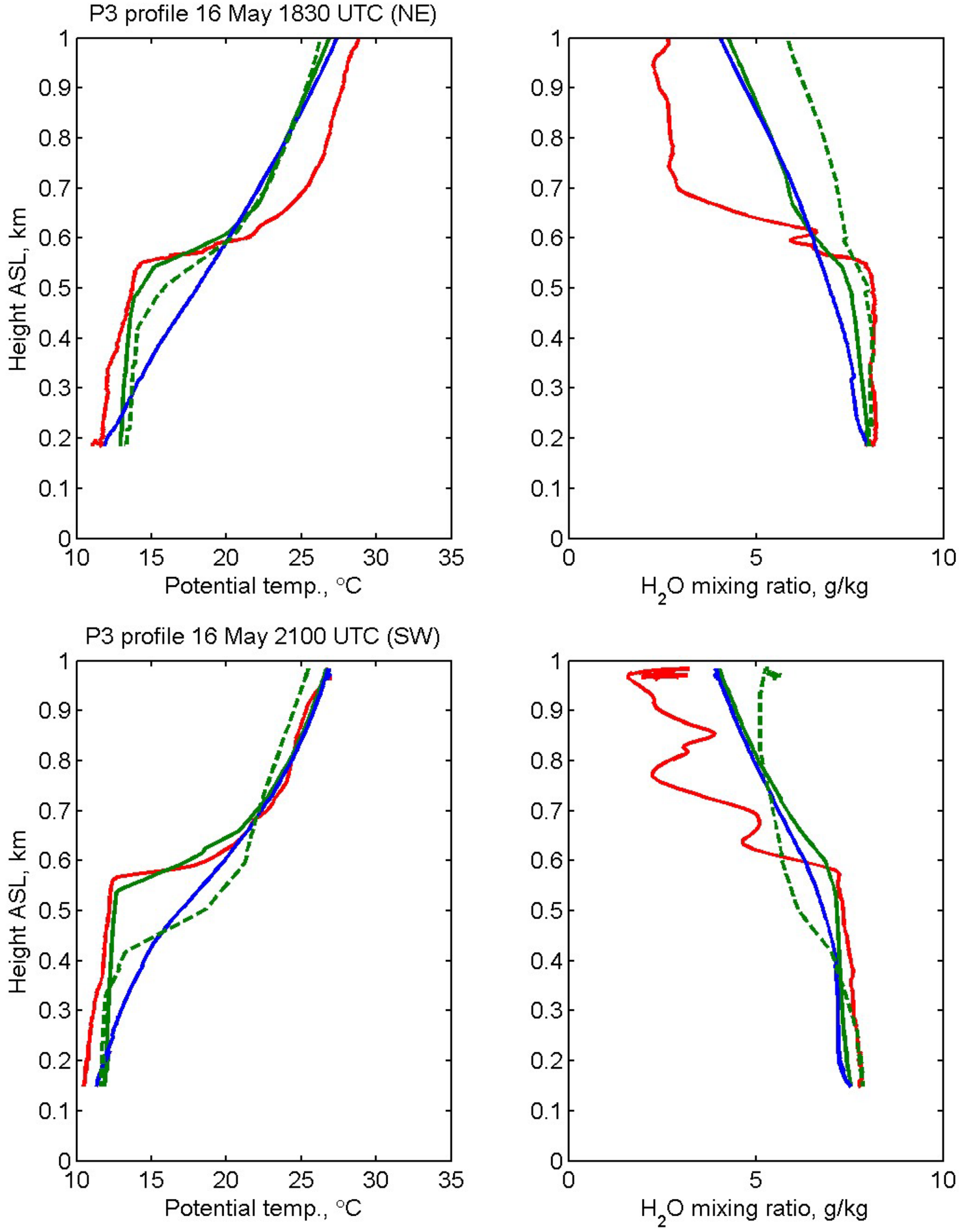

Figure 3: Profiles over the Southern California Bight. Aircraft measurements in red, WRF MYJ blue, WRF TEMF solid green, WRF TEMF with GFS initialization green dashed.

decreases at strong stability in TEMF, as expected from theory and meaurements. The MYJ scheme does not show this behavior. Also note that the heat transfer increases more steeply with increasing surface instability in TEMF, and that TEMF does not allow very strong instability. This is because the mass flux component efficiently transfers heat away from the surface, and because the mixed velocity scale has a contribution from w*.

A relationship for momentum is shown in figure 2. At night, TEMF has less average stress and fewer small wind speeds, and allows near-zero stress in some cases despite larger wind speeds. These are presumably the most stable cases. During the day, the average stress at low winds is less in TEMF than in MYJ, and the stress goes to zero along with the wind. Stress in MYJ remains high even at very low wind speeds.

On 16 May 2010, the NOAA P3 aircraft flew a mission that was partly dedicated to sampling clouds over the Southern California bight. Two profiles are shown in figure 3. The area was partly cloudy. The TEMF run captured the correct boundary layer depth and nearly well-mixed structure, while the boundary layer in the MYJ run was too shallow and stable. It is also interesting to note that an earlier TEMF run with GFS initialization (dashed line) also had a boundary layer that was too shallow.

3. BLLAST results

The Boundary Layer Late Afternoon and Sunset Turbulence study was conducted near Lannemezan, France in June and July 2011. As the name suggests, the study addressed the transition from fully turbulent daytime to stable nocturnal conditions. A mesoscale model intercomparison is planned. The results shown here are a first attempt to simulate a period of BLLAST. I compare model behavior relevant to the transition between configurations using the TEMF and MYJ boundary layer schemes, and two land surface schemes. The GABLS3 study (Bosveld et al., in preparation) showed that the land surface coupling strongly influences transition behavior.

Figure 4 shows the bounday layer height simulated on 30 June. Three of the four configurations produce similar results. The MYJ/slab combination is the outlier, with a much deeper boundary layer and late, abrupt transition. These are three-dimensional simulations, so the flow patterns are different, and the results for a particular column reflect changes not only in that column but elsewhere in the domain. In a nearly one-dimensional situation, I expect the boundary layer height to decrease somewhat in the afternoon before it becomes shallow and stable (Angevine 2008). Another feature to note is that both TEMF runs have relatively deep (~300 m) boundary layers in the early morning hours of the first night, while MYJ/slab has something similar in the evening.

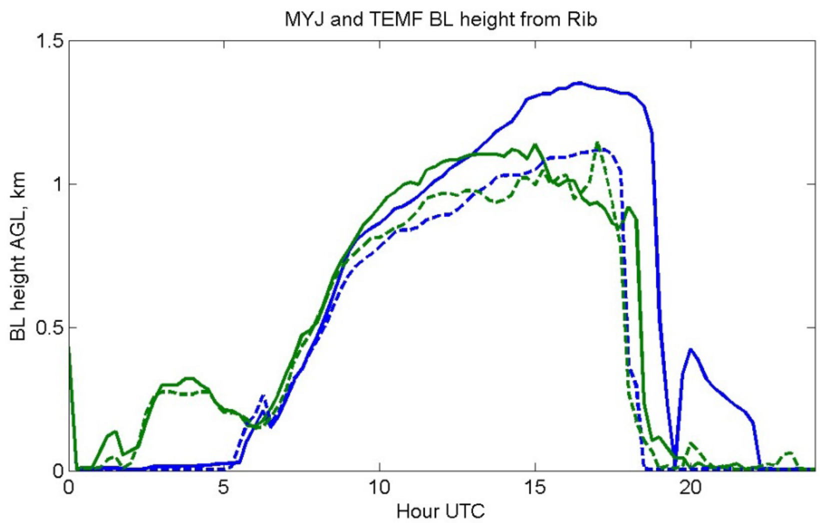

Figure 4: Boundary layer height diagnosed by bulk Richardson number. Blue = MYJ, green = TEMF, solid = slab, dashed = Noah LSM.

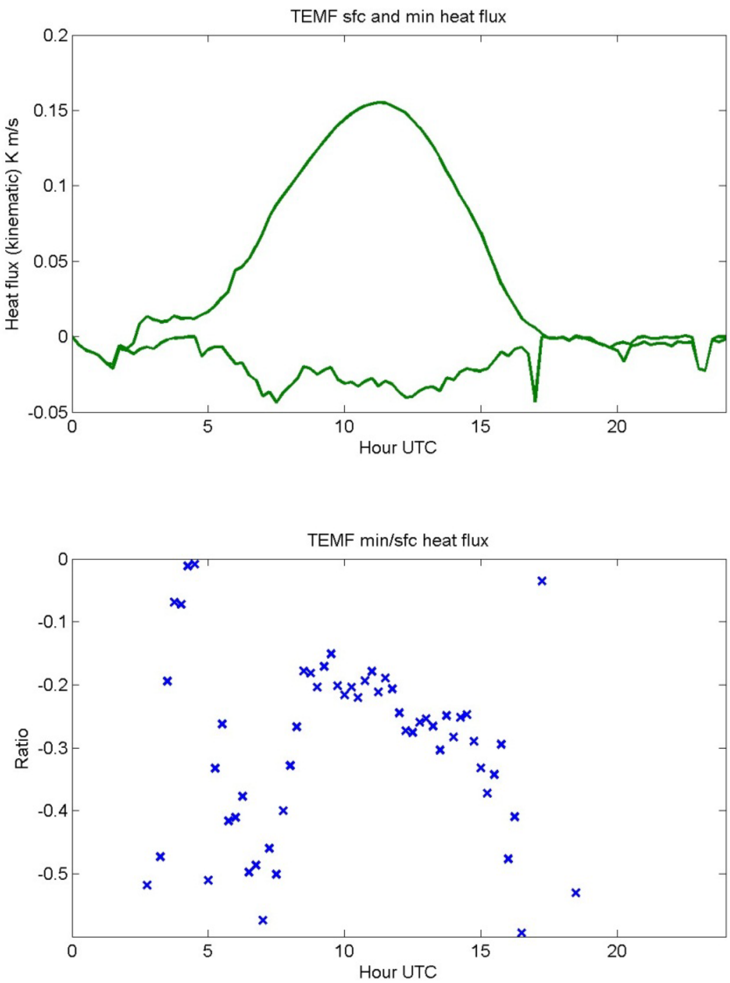

Figure 5: Surface and entrainment heat flux from TEMF (top), and their ratio (bottom) for the 30 June BLLAST case.

Sensible heat flux at the surface and its minimum in the profile are shown in figure 5, along with their ratio. TEMF has no explicit parameterization of entrainment. In an ideal (1D) situation, I expect the negative ratio to be large (much entrainment) during the morning transition (Angevine et al. 2001). Midday values should be between -0.2 and -0.4 or so. It is less clear what to expect in the afternoon, but in general, as the surface flux decreases, other processes become proportionally more important, and the magnitude of the ratio may increase. The ratios shown in the figure conform to these expectations.

The time-height behavior of the energy variables from the two PBL schemes with the Noah LSM is shown in figure 6. The color scales are the same for the two plots. MYJ has a minimum TKE of 0.1, while TEMF has no such floor. TEMF has some episodic non-zero turbulence at night, and there is at least general support in the data for this. The late afternoon decrease in the height and intensity of turbulence is earlier and smoother in TEMF.

4. Conclusions and recommendations

The TEMF PBL scheme in WRF shows a number of advantages over the existing schemes. TEMF has more ideal behavior in stable conditions, allowing flux magnitudes to decrease with stronger stability. In a stratocumulus boundary layer, TEMF allowed the correct boundary layer height to be maintained by cloud-radiation interaction. Entrainment at the PBL top conformed to general expectations, with more entrainment in the morning and afternoon and moderate values in daytime. Intermittent turbulence was allowed at night in the BLLAST case. Whether these advantages translate into generally improved simulations of real cases remains to be investigated.

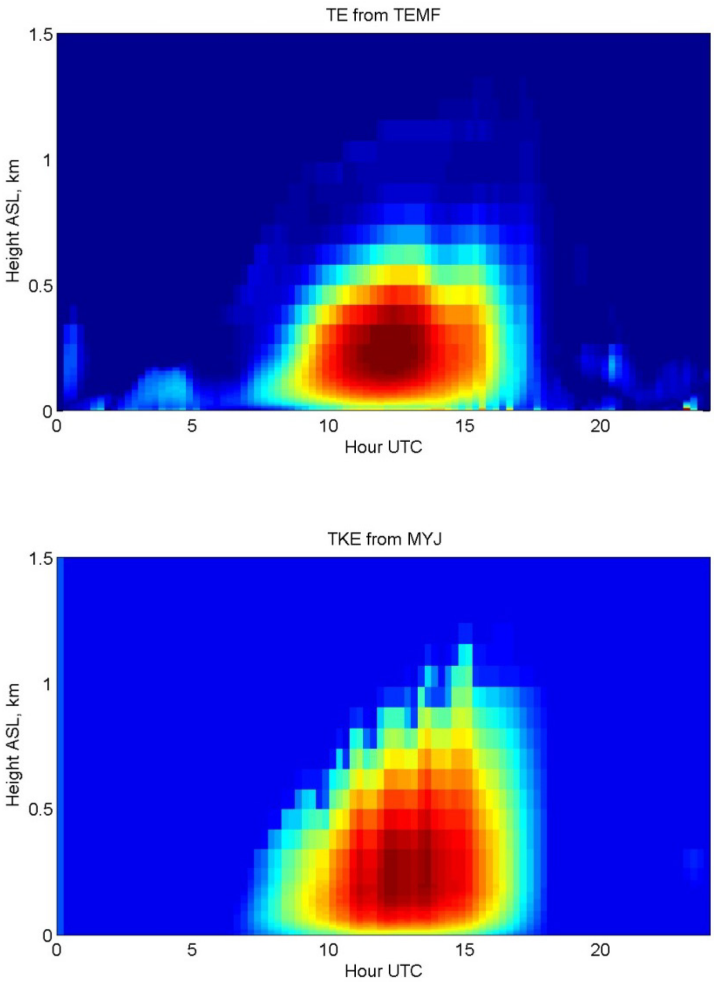

Figure 6: Energy variables in the 30 June BLLAST simulations. Top, TE from TEMF; bottom, TKE from MYJ.

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