9.13 TESTING NCEP OPERATIONAL SURFACE LAYER PARAMETERIZATIONS FOR STABLE CONDITIONS USING CASES-99 DATA

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1. INTRODUCTION

Impetus to extend operational forecasting capability beyond weather to air quality prediction has prompted an investigation at the National Center for Environmental Prediction (NCEP) of turbulence and boundary layer parameterizations used in its forecast models. The investigation focuses first on the parameterization of the stable boundary layer (SBL) since stable conditions are most conducive to air-pollution buildup, and also to direct efforts alongside those of the GEWEX GABLS project (Holtslag et al. 2003).

A central difficulty with effective SBL parameterization is the number of processes not represented in theoretical parameterizations that maintain or regenerate turbulence once it collapses in high static stability. Such processes are often associated with wave breaking, however their details are at present not well enough understood to have resulted in a theoretical extension to existing parameterizations to account for them. The need for extension, however, is recognized in large part from the runaway surface cooling and associated large negative mean biases of nighttime near-surface temperatures often found in weather and climate predictions when theoretical parameterizations are maintained. Empirical or heuristic extensions to enhance turbulent mixing (termed "enhanced" parameterizations) and hence warm nighttime near-surface temperatures have thus been employed, which have improved near-surface temperature forecast scores.

While the primary difficulty with enhanced parameterizations is their lack of theoretical basis, not much is also known of the details of their performance, for example with regard to specific classes of SBLs. The following reports on efforts to obtain such an understanding for the enhanced surface layer (SL) parameterizations used in the NCEP forecast models. We focus on evenings starting on 18, 19, 21 and 22 Oct. 1999 during the CASES-99 field experiment (Poulos et al. 2002). These nights were characterized by light yet non-zero turbulence and associated surface fluxes, with periods of stronger turbulence lasting on the order of hours. Such nights are similar to several others during the campaign. Two forecast variables are investigated: two-meter air temperature and surface heat flux. The procedure is similar to that carried out by Poulos and Burns (2003), who used CASES-99 observations over the entire campaign to drive two commonly used enhanced SL parameterizations and to compare the fluxes predicted with observations. Our study differs in that we 1) test the NCEP enhanced parameterizations as well as standard MO theory (theoretical, non-enhanced), 2) evaluate two-meter temperature as well as surface-layer heat flux and 3) focus on four nights rather than the entire campaign.

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2. SURFACE LAYER PARAMETERIZATIONS

Surface heat flux, H_s, is represented as

$$H_s = -\rho_a c_p u_* \theta_* , \qquad (1)$$

where ρ_a is the background air density (specified here as 1.23 kgm^{-3}) and c_p = 1004.7 $Jkg^{-1}K^{-1}$ is the specific heat at constant pressure. Surface friction velocity, u_*, and potential temperature scale, θ_*, are calculated from SL theory as

$$u_* = \frac{kU_h}{\ln(h/z_{0,m}) - \psi_m} \qquad (2)$$

$$\theta_* = \frac{k(\theta_h - \theta_0)}{\ln(h/z_{0,t}) - \psi_t} . \qquad (3)$$

Here, k = 0.4 is the Von Karman constant, U_h and θ_h are the mean wind speed and potential temperature at surface layer depth h, θ_0 is the surface potential temperature, $z_{0,m}$ and $z_{0,t}$ are the roughness lengths for momentum and heat, respectively, and ψ_m and ψ_t are stability functions for momentum and heat, respectively, which are given below. We take $z_{0,m}$ = $z_{0,t}$.

Three sets of ψ formulations are tested. The first is Monin-Obukhov (MO) theory,

$$\psi_m = -\beta_m \frac{(h - z_{0,m})}{L} \qquad (4a)$$

$$\psi_t = -\beta_t \frac{(h - z_{0,t})}{L} , \qquad (4b)$$

where the typical values β_m = β_t = 5 are employed (recent observations suggest a higher value for β_t) and L is the Monin-Obukhov length, given by

$$L = \frac{u_*^2 \theta_a}{k\, g \theta_*}, \qquad (5)$$

with g = 9.81 ms^{-2} the gravitational acceleration and θ_a a background value of θ, taken here as the average of θ_h and θ_0. These are theoretically based, containing no extensions to enhance turbulent mixing. The second set, employed in the NCEP regional ETA model, is (4a) and (4b) but with the maximum value

$$L = h \qquad (6)$$

employed when L, computed from model input values of U_h, θ_h and θ_0 in (5), exceeds h. This limitation is designed to prevent stability functions from becoming too largely negative, surface fluxes (through u_* and θ_*) from becoming too small and two-meter temperature too cold. The third set, employed in the NCEP global GFS model, is

$$\psi_m = -\left[x_m - x_{m,0} - \ln\left(\frac{1 + x_m}{1 + x_{m,0}} \right) \right] \qquad (7a)$$

$$\psi_t = -\left[x_t - x_{t,0} - \ln\left(\frac{1 + x_t}{1 + x_{t,0}} \right) \right], \qquad (7b)$$

where

$$x_m = \sqrt{1 + 2h/L}$$

$$x_{m,0} = \sqrt{1 + 2z_{0,m}/L}$$

with $x_t = x_m$ and $x_{t,0} = x_{m,0}$. While having the same effect as the limitation employed in the ETA, (7a,b) do so through continuous functions of h/L.

Diagnosis of two-meter temperature, θ_2, follows from SL theory as

$$\theta_2 = \theta_0 + \frac{\theta_*}{k}\left[\ln\frac{2}{z_{0,t}} - \psi_{t,2} \right], \qquad (8)$$

where $\psi_{t,2}$ is ψ_t evaluated at two meters, i.e. replacing h with 2 in (4a,b) and (7a,b). Plugging (3) into (8) after rearrangement then yields

$$\theta_2 = \chi\theta_h + (1 - \chi)\theta_0 , \qquad (9)$$

with

$$\chi = \frac{\ln\left[2/z_{0,t}\right] - \psi_{t,2}}{\ln\left[h/z_{0,t}\right] - \psi_t}.$$

3. DATA

Data used to drive and compare the predictions from these SL parameterizations were obtained from the ATD Integrated Surface Flux Facility (ISFF) operating during the CASES-99 campaign. These data are available online at http://www.atd.ucar.edu/rtf/projects/cases99/.

Observed triplets [U_h, θ_h, θ_0] drive predictions. Values of U_h and θ_h were those observed at the central tower. We present results first taking these at 10 meters and later at 5 meters. Values of θ_0 were taken as the average of measurements from three downward pointing radiometers (Burns et al. 2003) surrounding and located 100 meters within the central tower. Raw 5-minute data for each was averaged to 10 minutes to reduce fluctuations. A given (1800 LST to 0600 LST the next morning) thus contains 72 independent input triplets. Measured θ_2, to which predictions are compared, were taken from the same towers as the radiometer measurements, again averaging the three to a single value. Measured surface heat fluxes are discussed in Section 4. Further details on the ATD-ISFF data can be found at the above website as well as from Poulos and Burns (2003) and Burns et al. (2003). A value of $z_{0,m}$ = 3 cm ($z_{0,h} = z_{0,m}$ assumed) is employed, representative of conditions at the central tower.

A characterization of the four nights in terms of surface layer bulk Richardson number,

$$Ri_b = \frac{gh(\theta_h - \theta_0)}{\theta_a U_h^2} ,$$

is presented in Table 1. Tabulated is Ri_b computed assuming h = 5, 10 and 20 meters (data at 20 meters taken from the main tower). While differences exist depending on the height at which it is computed, for the most part $0.20 < Ri_b < 1$. This is an indication that, while weak, turbulence was non-zero during the majority of time during these nights. Hour-long or so events of stronger turbulence are generally associated with the periods of $Ri_b < 0.20$ tabulated, while periods of practically zero turbulence compose those of $Ri_b > 1$. A similar distribution appears in the data presented by Poulos and Burns (2003).

On an aside, a bias towards higher Ri_b for values less than 0.50 is seen as h increases from 5 to 10 m for all nights and for also 10 to 20 m for Nights 21 and 22, confirming similar observations noted by others of Richardson numbers being biased upwards as “grid” spacing increases. No such trend is seen, however, for $Ri_b > 0.50$, although the amount of data points in this range is less than below 0.50. The lack of trend could perhaps be expected since observations in high stability of characterized by more scatter.

Table 1. Values of surface layer bulk Richardson number (Ri_b) as computed at three heights (h) during four nights during the CASES-99 campaign.

Night	h(m)	Ri_b < 0.2	0.2 < Ri_b < 0.5	0.5 < Ri_b < 1.0	Ri_b > 1.0
18	5	23	27	21	1
	10	5	34	23	10
	20	7	36	22	7
19	5	22	28	21	1
	10	3	47	19	3
	20	3	43	19	7
21	5	28	16	15	13
	10	21	23	17	11
	20	13	35	19	5
22	5	49	18	5	0
	10	40	27	5	0
	20	37	32	3	0

4. RESULTS

Statistics of predicted minus observed θ_2 are presented in Table 2. Monin-Obukhov relationships, (4a,b), produce a cold bias for the nights, generally of ~ 1.5˚C but upward to over 3˚ C for Night 21. This is consistent with forecast applications employing these relationships, prompting, as mentioned in Section 1, the use of enhanced parameterizations. These results, however, emphasize that MO theory *by itself* causes a two-meter temperature cold bias, which is not as easily discernable from full model application results since these involve coupling to soil, radiation and outer layer PBL schemes.

It is seen that the NCEP enhanced parameterizations, i.e. the limit on L employed in the ETA model by (6) and the functions (7a,b) employed in the GFS, significantly improve biases for these nights. The GFS formulation, save for Night 22, in fact produces virtually no cold bias.

The standard deviations shown on the far right is thought to reflect, among other things, scatter among the individual measurement inputs and averaging uncertainty in arriving at our observed surface and two-meter temperature used in the comparison (see Section 3).

Surface layer heat flux, H_s, predicted from (1)-(3) is compared to turbulent heat fluxes observed at 1.5 and 10 meters from the main tower. The two observations are used to give a "consensus" observation, since while in theory fluxes should be constant within the surface layer in practice they are often not. We present the 10 meter flux also because of systematic errors in flux measurements below 5 meters (see Poulos and Burns 2003).

Plots of observed and predicted H_s employing h = 10 m are shown in Figures 1 for Nights 18 and 19 and Figure 2 for Nights 21 and 22. It is seen that the performance of the SL parameterizations is opposite that shown above for two-meter temperature – whereas MO theory produces a significant cold bias for two-meter temperature, it more accurately predicts the observed low surface heat fluxes than the enhanced formulations. A similar overprediction of H_s by enhanced formulations (different than the ones here) was found by Poulos and Burns (2003) for observations in the range 0.2 < Ri_b < 0.8.

Table 2. Two-meter temperature bias (predicted minus observed) computed for three surface layer models (Section 2) for four nights during CASES-99.

Night	Surface Layer Model	Bias (˚C)	Standard Deviation (˚C)
18	MO	-1.47	1.00
	ETA	-0.32	0.56
	GFS	-0.19	0.67
19	MO	-1.73	1.00
	ETA	-0.33	0.60
	GFS	-0.06	0.68
21	MO	-3.36	2.54
	ETA	-1.24	1.41
	GFS	-0.83	1.70
22	MO	-1.24	1.38
	ETA	-0.42	0.68
	GFS	0.06	0.74

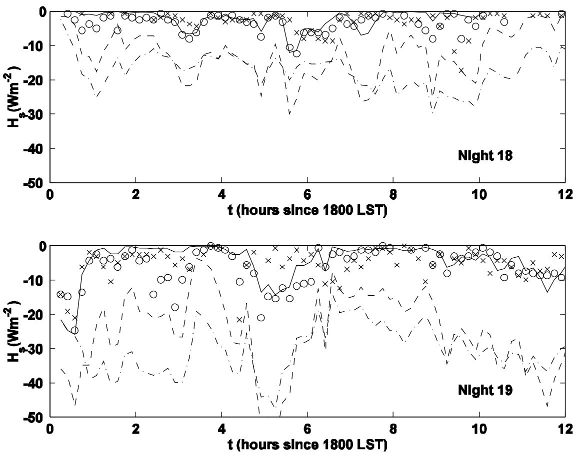

Figure 1. Observed ('o') and predicted (lines) surface heat flux versus time for Nights 18 and 19 of CASES-99. Solid, MO theory; dashed, GFS; dashed-dot, ETA. Predictions generated from meteorological input data at 10 m.

One possibility for the above discrepancy is that h = 10 m is too high to represent the typically shallow surface layers in the SBL. The above calculations but using h = 5 instead of 10 are presented in Table 3 and Figures 3 and 4. It is seen that while the differences among parameterizations are less than with the 10-meter results, the same basic behavior is maintained – MO theory, while underpredicting two-meter temperature, accurately predicts surface heat fluxes, and the enhanced GFS and ETA parameterizations, while accurately predicting two-meter temperatures, overpredicts surface heat flux.

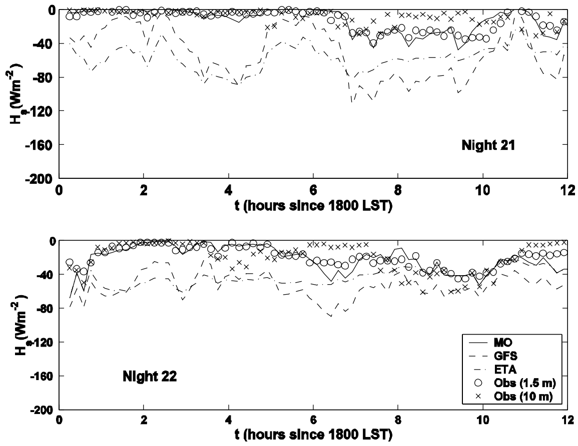

Figure 2. As Figure 1, but for Nights 21 and 22.

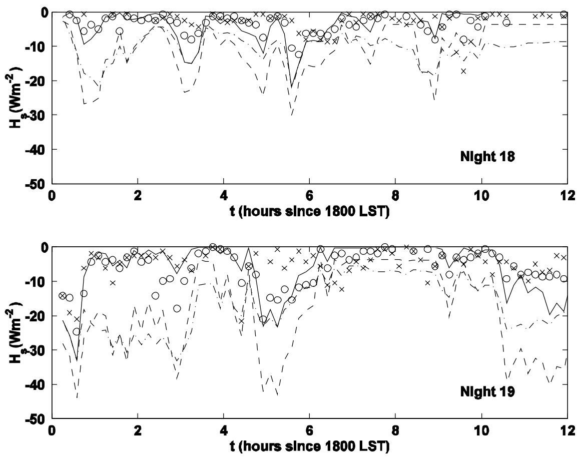

Figure 3. As Figure 1 but using 5-meter input temperature and wind speed.

5. CONCLUSION

The above findings pertain to four nights during CASES-99, and work would thus be needed to check if the they persist through similar nights both within and outside the CASES99 set. Assuming the results can be generalized, however, the inconsistency between two-meter temperature and surface heat flux predictions warrants a search for its reason. In particular, processes that affect mean temperature but not directly turbulent flux generation are suggested. One such process is radiative flux divergence, known to be important close to the ground and of emphasized importance during nights of high stability. Practically, the results suggest the possibility of

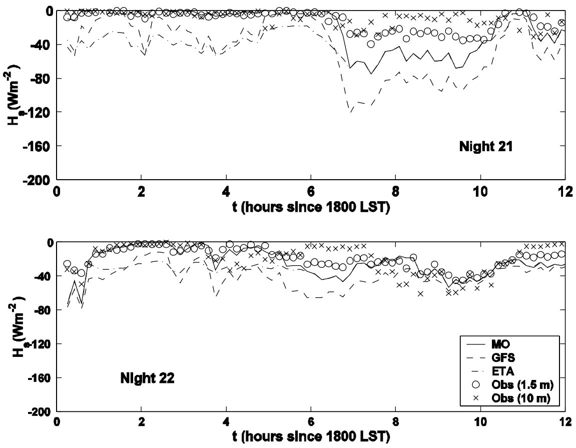

Figure 4. As Figure 3, but for Nights 21 and 22.

Table 3. As Table 2 but using 5-meter input temperature and wind speed.

Night	Surface Layer Model	Bias (˚C)	Standard Deviation (˚C)
18	MO	-1.07	0.78
	ETA	-0.57	0.47
	GFS	-0.34	0.50
19	MO	-1.35	0.66
	ETA	-0.76	0.36
	GFS	-0.44	0.44
21	MO	-2.27	2.03
	ETA	-1.15	1.09
	GFS	-0.66	1.19
22	MO	-0.96	0.98
	ETA	-0.63	0.55
	GFS	-0.28	0.51

using enhanced parameterizations only for two-meter temperatures while maintaining MO for fluxes, at least within a certain range of stability parameter.

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