Investigation of surface layer parameterization of the WRF model and its impact on the observed nocturnal wind speed bias:

Period of investigation focuses on the Second Texas Air Quality Study (TexAQS II) in 2006

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Executive Summary

This project investigates surface layer parameterization in the Weather Research and Forecasting (WRF) model during the Second Texas Air Quality Study (TexAQS II) period. The parameterization of energy fluxes from the surface layer significantly impacts simulated near-surface winds. Several recent studies on the meteorological features of the regions adjacent to the Gulf of Mexico using the WRF model have identified a frequent nocturnal wind speed over-prediction (e.g., Byun et al., 2008, Lee et al., 2010). Texas Commission on Environmental Quality (TCEQ) scientists also in several recent communications reported that the WRF model tends to over-predict the surface wind speed in eastern Texas in the evening hours, especially in coastal regions such as the Houston-Galveston-Brazoria (HGB) area. We have previously identified that a wind speed bias prevailed more noticeably when there was a high pressure system centered over the Louisiana/Mississippi/Arkansas states that was associated with easterly/southeasterly flow in the lowest hundreds of meters in Southeastern Texas (Lee et al., 2012; Ngan et al., 2013). This project builds on these findings to further examine the incorrect redistribution of kinetic energy from the nighttime residual layer to the surface.

The objectives of this project were three-fold: (1) to understand the sensitivities of the various surface layer (SL) schemes in the WRF model, especially the MM5 option based on the Monin-Obukhov similarity theory routinely used by TCEQ, (2) to investigate the temporal and spatial characteristics of exchange coefficients for heat and momentum of the scheme(s) through diagnosing intermediate variables/parameters in the parameterization schemes so as perhaps to hypothesize how they affect the accompanied planetary boundary layer (PBL) scheme that determines the wind speed, and (3) to relate how atmospheric stability regimes and important surface characteristics that influence sensible and latent heat fluxes contribute to the wind speed biases.

Multiple ten day simulations using the WRF model were performed between June 4 and 13, 2006 --- a period within the TexAQS-II field campaign that repeatedly showed the high wind speed bias problem during the evening hours. The following provides a chronology of major findings:

1. Simulations using a recent upgrade of the MM5 surface layer (SL) similarity scheme (Jiménez et al., 2012) generally showed significant improvement in reducing biases during the nighttime in the modeled friction velocity that is an important input to the PBL parameterization schemes. The upgrade extended the atmospheric stability regime applicability of the MM5 SL scheme by incorporating universal profile functions for vertical gradients of momentum and heat. The improvement expanded coverage for both highly stable and unstable atmospheric conditions, reduced the lower limit of friction velocity scale over land, and provided an option to account for thermal roughness length over land points (Dudhia 2012). We adopted this upgrade because our modeled results for friction velocity showed noticeable improvements although those for surface fluxes did not show as marked improvements.

2. We suggest that the most physically-based upgrades of the Land-Surface-Model(LSM)/SL-Similarity-Scheme/PBL-Model be used to investigate the low-level wind speed bias because these components are tightly coupled as inherited from the MM5 era such that few parameters are compensating for deficiencies of one another. Examples of these parameters are the bulk Richardson number values that define atmospheric regime cut-offs for similarity function parameterization and numerical values of some of the empirically determined parameters based on specific field campaigns. This decision was supported by evidence of significantly improved governing inputs to the PBL scheme, yet worsened 10 m wind speed biases; considering the SL scheme as a “stand-alone” module was not possible. In our newly proposed setup, along with the upgrade by Jiménez et al. (2012), we also replaced the MM5 5-layer soil thermal diffusion land surface model (LSM) with the NOAH LSM. NOAH is a physically based LSM that allows soil moisture nudging and easy incorporation of new time-varying input data and physics.

3. The NOAH LSM and the upgraded-MM5 SL scheme represented the best physically based surface physics option pair tested in this study and improved sensible heat flux biases in the late
afternoon over the University of Houston Coastal Center site by as much as 50%. Also the negative bias of the sensible heat flux during the nighttime was reduced in the simulation that utilized the NOAH LSM. Moreover, the previously modeled abrupt drop in wind speed between 1800 and 1900 CST averaged over all 46 Continuous Air Monitoring Sites (CAMs) in the HGB area was largely removed. However, it is discouraging that the over-estimation of 10 m wind speed was aggravated.

4. In theory if one achieves significant improvement in the simulation of the sensible heat flux with non-degraded performance for the latent heat and momentum fluxes, one would also conjecture improvement in the predictions of low-level wind speed. Nonetheless, the model simulations did not support this conjecture. This result suggests that the MM5 5-layer soil thermal diffusion LSM is better tuned for the MM5 SL scheme. Without re-optimizing the values of the tunable parameters this physics option pair may not improve WRF’s performance for the targeted modeled fields.

5. We further attempted to identify tunable parameters that could be tuned to optimize the model performance with respect to the low-level wind speed prediction. It was concluded that:
   (a) A formal mathematical approach based on multiple criteria algorithms such as those by Gupta et al. (1999) should be employed in the simultaneous optimization of the numerical values of those parameters applicable to various seasons and climate conditions of interest, and
   (b) More frequent utilization of observed soil moisture should be used to nudge the surface heat and/or moisture fluxes towards reality to allow the LSM-SL option pair to better capture the decoupling of the nocturnal boundary layer and the vertical distribution of wind speeds (Wilczak et al., 2009).
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1. Introduction

The Weather Research and Forecasting Advanced Research-WRF (WRF-ARW or abbreviated as WRF hereafter) model (Shamarock et al., 2008) frequently over-estimates near surface wind speeds during nighttime hours in the states around the Gulf of Mexico (e.g., Byun et al., 2008 and Lee et al., 2010). This has important consequences on inaccurate predictions of wind force on structures, wind turbine electricity production efficiency (Storm and Basu 2010) and transport and concentration of air pollutants (Ngan et al., 2012). Although it is plausible that the advection and planetary boundary layer (PBL) schemes in the WRF model are directly responsible for the determination of the wind speeds simulation there, the specific locality and temporal characteristics of the wind speed biases in the Gulf of Mexico regions entail additional investigation on the most tunable parameters in the determination of these nocturnal low level winds. The Monin-Obukhov surface layer (SL) similarity scheme is used in the WRF model to provide linkage between the model’s land surface and PBL parameterization schemes. It governs the calculation of friction velocity and exchange coefficients for momentum, heat and moisture. These parameters enable the calculation of the surface heat and moisture fluxes in the Land Surface Model (LSM) that feed the PBL schemes as bottom boundary conditions and thus contributes to the schemes’ accuracies in predicting low level winds. Furthermore, the surface layer similarity scheme involves a few empirically determined tunable parameters lending itself to the focus of this study.

The surface layer is a rather thin layer, typically equal to about one tenth of the PBL height, across which the state variables such as wind speed and potential temperatures experience the largest vertical gradients. The surface layer similarity scheme provides universal vertical gradient profile functions for momentum and heat within this layer. This study focuses on investigating this similarity scheme and the suitability of some of their empirically derived parameters for the Houston-Galveston-Brazoria (HGB) area.

The goal of this project is to understand the characteristics of the nocturnal wind bias problem in the WRF meteorological model and aim to: (1) understand the sensitivities of the various surface layer schemes in the WRF model, especially the MM5 option routinely used by TCEQ that is based on the Monin-Obukhov similarity theory, (2) investigate the temporal and spatial characteristics of exchange coefficients for heat and momentum of the scheme by outputting intermediate variables in the computation so as to hypothesize how the scheme affects the accompanied PBL scheme in contributing to the wind speed biases, and (3) relate how atmospheric stability regimes and important surface characteristics that influence sensible and latent heat fluxes contribute to the wind speed biases.

Rates of momentum and heat fluxes derived by the surface layer model are significantly dependent on the land surface model (LSM) chosen. Jiménez et al. (2012) suggested that the U.S. National Centers for Environmental Prediction; Oregon State University; Air Force; Hydrological Research Laboratory (NOAH) (Ek et al. 2003, Chen and Dudhia 2001) LSM and its more physically based parameterization such as those in evapotranspiration and runoff processes may have the potential to resolve further the wind bias problem. The NOAH LSM’s capability to allow soil moisture nudging also provides an advantage in addressing the wind bias problem. Another conclusion of this study is a possible future work involving the NOAH LSM option and a mathematical approach of a multiple-criteria optimization scheme (Sen et al., 2001) to determine the desired range of values of the tunable parameters in the SL and LSM parameterization schemes to minimize biases of the predicted state variables. Finally a summary is provided at the end of this report.
2. Survey of the different surface layer similarity schemes in WRF

The surface layer schemes in the WRF model provide exchange coefficients for heat and momentum to the LSM, and friction velocities to the PBL computational modules. In essence, the SL schemes provide the parameterization linkage for the dynamic and thermal atmospheric phenomena between land and atmosphere. Namely; it provides exchange coefficients to LSMs, friction velocity and surface fluxes over water points to PBL schemes. There are specific recommendations on how to configure the LSM-SL-PBL scheme-sets (Dudhia 2012). In this study we use the MM5 5-layer soil thermal diffusion LSM due to its relevance to the previous and current Texas Commission for Environmental Quality (TCEQ) projects on model wind bias studies. By the same token we focus more on the pairing of the fifth-generation Pennsylvania State University—National Center for Atmospheric Research Mesoscale Model (MM5) SL similarity scheme (Zhang and Anthes 1982) with the Yonsei University (YSU) PBL scheme (Hong et al., 2006).

For the sake of understanding the parameterization sensitivity of the Monin-Obukhov-similarity-theory based SL schemes and its impact on surface momentum and heat fluxes, we conducted a survey on all such SL schemes in the WRF model. There are five Monin-Obukhov-similarity-theory based SL schemes in the WRF model version 3.4.1 (Dudhia 2012). Although we report on all these similarity theory based SL schemes, we focus more on three configuration choices of surface layer similarity scheme and PBL scheme pairs provided in the meteorological model WRF version 3.4.1: (1) The fifth-generation Pennsylvania State University—National Center for Atmospheric Research Mesoscale Model (MM5) surface layer similarity scheme (Zhang and Anthes 1982) with the Yonsei University (YSU) PBL scheme (Hong et al., 2006), (2) Same as (1) but with modification of the MM5 surface layer scheme in accordance with Jiménez et al. (2012) to include extreme stability regimes, and (3) The Eta surface layer similarity (Janjić 1990) with the Mellor-Yamada-Janjić (MYJ) PBL scheme (Janjić 2001).

2.1 MM5 Surface Layer Scheme (sf_sfclay_physics=1)

The MM5 SL scheme designated as sf_sfclay_physics=1 in the WRF physics option is based on the Monin-Obukhov similarity theory (Monin and Obukhov 1954). The theory gives profile functions for mean wind speed, $\phi_m$, and potential temperature, $\phi_h$, within the surface layer as:

$$\phi_m \left( \frac{z}{L} \right) = \frac{kz}{u_*} \frac{\partial U}{\partial z} \tag{1}$$

$$\phi_h \left( \frac{z}{L} \right) = \frac{kz}{\theta_a} \frac{\partial \theta}{\partial z} \tag{2}$$

Where $\frac{z}{L}$ represents the Monin-Obukhov stability parameter, defined as

$$\frac{z}{L} = k \frac{g}{\theta_a} \frac{\theta_a}{u_*^2} \tag{3}$$
and \( k \) is von Kármán’s constant, \( u_* \) is friction velocity, \( z \) is height above surface, \( \bar{U} \) is mean wind speed, \( \theta_* \) is surface temperature scale, and \( \theta \) is potential temperature, \( g \) is gravitational acceleration, and \( \theta_a \) is potential temperature of air in the surface layer.

Kinematic fluxes of momentum, \( \tau \); sensible heat, \( H \); and latent heat, \( LH \), at the atmosphere-surface interface are respectively given as follows:

\[
\tau = \rho u_*^2 = \rho C_d \bar{U}^2 \quad (4)
\]

\[
H = -\rho c_p u_* \theta_* = -\rho c_p C_h \bar{U} (\theta_a - \theta_g) \quad (5)
\]

\[
LH = L_e \rho u_* q_* = L_e \rho M C_q \bar{U} (q_g - q_a) \quad (6)
\]

Where, \( \rho \) is air density in the surface layer; \( c_p \) is specific heat capacity at constant pressure; \( \bar{U} \) is wind speed in the lower layer enhanced by a convective velocity according to Beljaars (1995) and a sub-grid velocity according to Mahrt and Sun (1995). \( L_e \) is the latent heat of vaporization; \( M \) is soil moisture; \( q_* \) is saturated specific humidity availability; \( \theta_g \) is potential temperature of air at ground level; \( q_g \) and \( q_a \) are specific humidity of air in ground level and in the surface layer; and \( C_d, C_h \) and \( C_q \) are respectively bulk transfer coefficient (sometimes also called bulk exchange coefficient; e.g., Smedman et al., 2007) for momentum, heat and moisture.

Integrating Eqs. (1) and (2) with respect to height, \( z \), one can obtain:

\[
\bar{U} = \frac{u_*}{k} \left[ \ln \left( \frac{z}{z_0} \right) - \psi_m \left( \frac{z}{L} \right) + \psi_m \left( \frac{z_0}{L} \right) \right] \quad (7)
\]

\[
(\theta_a - \theta_g) = \frac{\theta_*}{k} \left[ \ln \left( \frac{z}{z_0} \right) - \psi_h \left( \frac{z}{L} \right) + \psi_h \left( \frac{z_0}{L} \right) \right] \quad (8)
\]

Where \( z_0 \) is roughness length, \( \psi_m \) and \( \psi_h \) are respectively similarity functions for momentum and heat as follows:

\[
\psi_m (\xi) = \int_0^{\xi} \left[ 1 - \phi_m (\xi) \right] \frac{d\xi}{\xi} \quad (9)
\]

\[
\psi_h (\eta) = \int_0^{\eta} \left[ 1 - \phi_h (\eta) \right] \frac{d\eta}{\eta} \quad (10)
\]
Where the variables of integration are $\zeta = z/L$, and $\eta = z \Pr / L$; $\Pr$ denotes the turbulent Prandtl number. These similarity functions $\psi_m$ and $\psi_h$ may take up easier forms via variable transformation such as one below suggested by Panofsky (1963):

$$\phi^4 - \gamma \left[ \frac{z \Pr}{L} \right] \phi^3 = 1$$

(11)

Herein $\gamma$ is a constant determinable from observation.

By substituting Eq. (7) into Eq. (4); and by neglecting the contribution of $\psi_m(z_0/L)$; one can obtain the bulk transfer coefficient for momentum:

$$C_d = \frac{k^2}{\ln \left( \frac{z}{z_0} \right) - \psi_m \left( \frac{z}{L} \right) \ln \left( \frac{z}{z_0} \right) - \psi_m \left( \frac{z}{L} \right)}$$

(12)

In like manner, by substituting Eqs. (7) and (8) into Eq. (5); and by neglecting the contributions of $\psi_m(z_0/L)$ and $\psi_h(z_0/L)$, one can obtain the bulk transfer coefficient for heat:

$$C_h = \frac{k^2}{\ln \left( \frac{z}{z_0} \right) - \psi_m \left( \frac{z}{L} \right) \ln \left( \frac{z}{z_0} \right) - \psi_h \left( \frac{z}{L} \right) \ln \left( \frac{z}{z_0} \right) - \psi_h \left( \frac{z}{L} \right)}$$

(13)

For moisture, the formulation of Carlson and Boland (1978) was followed. The authors introduced a viscous sub-layer of height $z_v$, where $z_v = 0.01 m$ over land and $z_v = z_0$ and assumed $\psi_{moisture} = \psi_h$, and assumed that the methodology to derive the bulk transfer coefficient for heat such as that in Eq. (13) above was applicable, they obtained the bulk transfer coefficient for moisture as follows:

$$C_q = \frac{k^2}{\ln \left( \frac{z}{z_0} \right) - \psi_m \left( \frac{z}{L} \right) \ln \left( \frac{\rho c_p k u z}{c_s z_v} + \frac{z}{z_v} \right) - \psi_h \left( \frac{z}{L} \right)}$$

(14)

Where $c_s$ is the effective heat transfer coefficient resulted from non-turbulent processes.

The integrated similarity functions are calculated with respect to four stability regimes (Zhang and Anthes, 1982) defined by the bulk Richardson number, $R_d$:
\[ R_{ib} = \frac{g}{\theta_a} z \left( \frac{\theta_{va} - \theta_{vg}}{U^2} \right) \]  

(15)

Where \( g \) is the gravitational acceleration, \( \theta_{va} \) and \( \theta_{vg} \) are the virtual potential temperature of the air in the surface layer, and at ground surface, respectively. The four stability regimes and their corresponding similarity functions and their respectively ranges of \( R_{ib} \) suggested (Zhang and Anthes 1982, Arya 1988, Jiménez et al. (2012)) are:

\[ \psi_m = \psi_h = -10 \left( \frac{z}{z_0} \right) \]  

--- stable regime, when \( R_{ib} \geq 0.2 \)  

(16)

\[ \psi_m = \psi_h = -5R_{ib} \frac{\ln \left( \frac{z}{z_0} \right)}{1.1 - 5R_{ib}} \]  

--- damped mechanical turbulent regime, when \( 0 < R_{ib} < 0.2 \)  

(17)

\[ \psi_m = \psi_h = 0 \]  

--- neutral regime, when \( R_{ib} = 0 \)  

(18)

\[ \begin{cases} 
\psi_m = 2\ln \left( \frac{1 + x}{2} \right) + \ln \left( \frac{1 + x^2}{2} \right) - 2\tan^{-1} x + \frac{\pi}{2} \\
\psi_h = 2\ln \left( \frac{1 + x^2}{2} \right) 
\end{cases} \]  

--- free convection regime, when \( R_{ib} < 0 \)  

(19)

Where \( x = \left[ 1 - 16 \left( \frac{z}{L} \right) \right]^{1/4} \).

This MM5 SL option has been commonly used for meteorological modeling at TCEQ. It serves as the “baseline” option for comparison purposes in this study. A few of the parameters, such as \( z_0 \) and \( z/L \) will be further studied.

2.2 Modified MM5 SL in accord to Jiménez et al. (2012) (sf_sfclay_physics =11)

The base-line MM5 SL scheme (sf_sfclay_physics =1) described in the previous section had their tunable parameters derived from a measurement campaign in Kansas, USA (Izumi 1971). Specific threshold values of some of the parameters and range of applicability of the original scheme was addressed by Jiménez et al. (2012):

(a) Originally minimum friction velocity was set at 0.1 m s\(^{-1}\). In this new option this minimum value is reset to 0.001 m s\(^{-1}\) --- such low friction velocity occurs occasionally during night time (Shin and Hong 2011).
(b) It incorporated highly unstable atmospheric regimes after formulation suggested by Fairall et al. (1996): For unstable regimes, the similarity function that is between a Monin-Obukhov type similarity profile and a profile resulting from pure convection suggested by Fairall et al. (1996) was used.

\[
\psi_m = \frac{\psi_{Kh,m}\left(\frac{z}{L}\right) + \left(\frac{z}{L}\right)^2 \psi_{Ch,m}\left(\frac{z}{L}\right)}{1 + \left(\frac{z}{L}\right)^2}
\]  

(20)

Eq. (20) is a direct quotation of Eq. (17) from Jiménez et al. (2012). It derives a similarity function by adding a weighed contribution from a Monin-Obukhov type surface layer similarity, \(\psi_{Kh,m}\) and that from pure convection, \(\psi_{Ch,m}\).

(c) It incorporated highly stable atmospheric regime after Cheng and Brutsaert (2005): For stable regimes, the following integrated similarity function after Cheng and Brutsaert (2005) was used.

\[
\psi_m = -a \ln \left\{ \frac{z}{L} + \left[ 1 + \left(\frac{z}{L}\right)^b \right]^{\frac{1}{b}} \right\}
\]  

(21)

\[
\psi_h = -c \ln \left\{ \frac{z}{L} + \left[ 1 + \left(\frac{z}{L}\right)^d \right]^{\frac{1}{d}} \right\}
\]  

(22)

where \(a=6.1, b=2.5, c=5.3,\) and \(d=1.1\). Cheng and Brutsaert (2005) have empirically tuned some of these parameters in the above similarity functions in accordance with the Cooperative Atmosphere-Surface Exchange Study CASE-99 (Poulos et al., 2002).

(d) The neglected term of \(\psi_m\left(z_0/L\right)\) and \(\psi_h\left(z_0/L\right)\) in the derivation of the bulk exchange coefficients were re-instated (See Eqs. (20)-(22) of Jiménez et al., (2012)): This rectified two of the limitations of the base-line MM5 SL scheme in the unstable regime in the previous section; namely: Firstly \(\ln(z/z_0) - \psi_h(z/L) \geq 2\) imposed to avoid a “too high” value of \(C_h\) in Eq. (13) was removed. The inclusion of contributions from \(\psi_m\left(z_0/L\right)\) and \(\psi_h\left(z_0/L\right)\) in Eqs. (7) and (8) successfully prevents the possibility of \(R_h\) and \(z/L\) resulting in opposing signs. Secondly, the brute force limitation of \(\psi_m \leq 0.9 \ln(z/z_0)\) and \(\psi_h \leq 0.9 \ln(z/z_0)\) imposed to prevent “too high” exchange coefficient values is no longer necessary as the gentler gradient of the integrated similarity function including those neglected terms make it extremely rare to attain such high exchange coefficients.
2.3 Janjić SL scheme (sf_sfclay_physics=2)

The surface layer scheme (Janjić 2001) is based on the similarity theory (Monin and Obukhov, 1954). This scheme is used in conjunction with the Mellor-Yamada-Janjić (MYJ) PBL level 2.5 closure scheme. The Beljaars (1995) correction is applied in order to avoid singularities related to the turbulent kinetic energy production and dissipation equation under free convection and vanishing wind speed conditions. With this correction, a portion of the surface buoyance flux is converted into kinetic energy of unorganized flow near the surface assuring that the friction velocity, \( u_* \), is never zero. Over water surfaces a viscous sublayer is parameterized explicitly following Janjić (1994). Over land, the scheme accounts for the effects of a viscous sub-layer through variable roughness height for temperature and humidity as proposed by Zilitinkevitch (1995). With this parameterization, the temperature and humidity roughness height \( z_{oT} \) is defined via roughness height for momentum, \( z_{oM} \):

\[
z_{oT} = z_{oM} \exp\left(-k\alpha \text{Re}^{\gamma}\right)
\]  

(23)

where \( \alpha \) is a tunable empirical constant, \( \text{Re} = z_{oM} (u_*/\nu) \) is the Reynolds number, and \( \nu \) is the molecular viscosity for momentum. For similarity functions, the scheme uses function following Paulson (1970) for over land and following Lobocki (1993) for over the ocean.

2.4 GFS accompanied SL scheme (sf_sfclay_physics=3)

The GFS SL scheme should be used in conjunction with the GFS PBL scheme. The GFS PBL scheme is based on a so-called “nonlocal K” theory approach which accounts for the non-local transport through the inclusion of the counter-gradient fluxes in a vertical diffusion algorithm where the PBL height is diagnosed to constrain a prescribed vertical profile of vertical diffusivity within the height (Hong and Pan 1996). For many years the default GFS PBL scheme option has been referred to as the “Medium-Range Forecast (MRF)”. For convenient reference, the turbulence diffusion equation that governs the GFS PBL scheme (Hong and Pan 1996) is included herein:

\[
\frac{\partial \bar{C}}{\partial t} = \frac{\partial}{\partial z} \left[ K_{ec} \left( \frac{\partial \bar{C}}{\partial z} - \gamma_c \right) \right]
\]

(24)

where \( \bar{C} \) is a prognostic variable, \( K_{ec} \) is eddy diffusivity, \( \gamma_c \) denotes nonlocal counter-gradient contributions, and \( h \) is PBL height within which the equation is applicable defined as the height in which the turbulent mixing diminishes beyond a certain threshold.

The lowest model layer is assumed to be the surface layer and the Monin-Obukhov similarity profile relationship is applied to obtain the surface stress and sensible and latent heat fluxes (e.g., Eqs. (4)-(6)). The formulation was based on Miyakoda and Sirutis (1986). A bulk aerodynamic formula is used to calculate the fluxes once the bulk transfer coefficients have been obtained. Thermal roughness over the ocean is based on a formulation derived from the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) field campaign (Zeng et al, 1998). Land surface evaporation is comprised of three components: direct evaporation from the soil and from the canopy, and transpiration from the vegetation. The parameterization of these three components follows Pan and Mahrt (1987).
2.5 Quasi-normal scale elimination (sf_sfclay_physics=4)

Since WRF version 3.1 a SL-PBL scheme set named Quasi-Normal Scale Elimination (QNSE) has been made available following Sukoriansky et al. (2005). The authors used a spectral closure model of stably stratified turbulence to develop a turbulence kinetic energy-dissipation ($K$–$\varepsilon$) model suitable for applications to the atmospheric boundary layer. Starting with the primitive equations describing the dynamic and thermal states of the atmosphere for all length scales, the authors proceeded by bundling up and replacing the smallest scale mode representations with their ensemble-averaged quasi-normal statistics via a so-called scale elimination step (Sukoriansky et al., 2005). Upon the completion of scale elimination, the approach yields eddy viscosities and eddy diffusivities suitable to be used in determining the turbulent mixings within the PBL --- referred to as the QNSE PBL scheme. Sukoriansky et al emphasized that the QNSE PBL scheme must be paired up with a QNSE-derived SL scheme for consistency in formulation derivation and field data used for parameter optimization. The revised QNSE SL scheme is based on the Monin-Obulkov similarity theory with the CASES-99 field experiment as one of the major data sets that provided input to optimize the parameterization scheme. The following summarize the formulation and coefficients used in the SL scheme:

\[
L = \frac{u_z^2}{k\beta \theta} = \frac{z \alpha_M^2(Ri)}{R_i \alpha_H(Ri)} \quad (25)
\]

\[
u_1 = \frac{u_z}{k} \int_{z_0}^{z_*} \frac{dz}{z \alpha_M} \quad (26)
\]

\[
\theta_1 = \theta_0 + \frac{\theta_0}{k} \int_{z_0}^{z_*} \frac{dz}{z \alpha_H} \quad (27)
\]

\[
u_1 = \frac{u_z}{k} \left( \ln \frac{z_1}{z_0} + c_u \frac{z_1}{L} + ... \right) \quad c_u = 2.25 \quad (28)
\]

\[
\theta_1 = \theta_0 + \frac{\theta_0}{1.4k} \left( \ln \frac{z_1}{z_0} + c_\theta \frac{z_1}{L} + ... \right) \quad c_\theta = 2.04 \quad (29)
\]

Where \( \beta = \frac{\theta}{g} \), \( \alpha_M = \frac{K_M}{K_0} \), \( \alpha_H = \frac{K_H}{K_0} \), \( R_i \) is gradient Richardson number, \( z_1 \) is height of first model layer, and \( K_0 \) is eddy viscosity at \( R_i = 0 \); i.e., neutral flow condition.

It is worthy to note that the QNSE SL-PBL scheme pair performed well in very stable conditions in the Nordic regions. For instance, under extremely cold conditions at the Sodankyla station, Finland, where meteorological models often erred grossly in predicting much too warm near-surface temperature, as much as 20°C warm-biases. This new scheme-pair rectified much of that problem.

2.6 MYNN SL scheme (sf_sfclay_physics=5)

The Mellon-Yamada-Nakanishi-Niino (MYNN) PBL scheme is rather similar to the approach taken in MYJ PBL scheme. The MYNN SL scheme must be used in conjunction with the MYNN PBL scheme. It has the option to be more sophisticated than MYJ scheme as it can be configured with level 2.5 as well as 3.0 closures. Nakanishi et al. (2001) used a database of large-eddy simulation (LES) for dry atmospheric boundary layers under various stratification conditions to improve both the closure models applicability to
such conditions as well as eliminating the singularity problem. Nakanishi and Niino (2004) introduced a partial condensation scheme after Sommeria and Deardroff (1977) to improve the precipitation forecast. They also tuned model constants for the MYNN PBL scheme and added a diagnostic equation for the turbulent length scale, \( l \). Herein we repeat some of the equations in their 2004 paper for the sake of easy reference:

\[
\frac{1}{l} = \frac{1}{l_s} + \frac{1}{l_t} + \frac{1}{l_b}
\]

\[(30)\]

\[
l_s = \begin{cases} 
  k z \left(1 + \alpha_5 \frac{z}{L}\right)^{-1} & 0 \leq \frac{z}{L} < 1 \\
  k z \left(1 - \alpha_4 \frac{z}{L}\right)^{0.2} & \frac{z}{L} < 0
\end{cases}
\]

\[(31)\]

\[
l_t = \alpha_1 \int_{z=0}^{h} zdz
\]

\[
l_b = \frac{q}{N} \left[ 1 + \alpha_3 \left( \frac{q_c}{l/N} \right)^{1/2} \right]
\]

\[(32)\]

\[(33)\]

Equation (30) assures an upper bound in \( l \). Equation (31) gives length scale for surface layer, \( l_s \), where \( \alpha_4 = 100, \alpha_5 = 2.7 \). Similarly, Eqs. (32) and (33) give length scale for turbulence \( l_t \) and buoyance \( l_b \), respectively, where \( \alpha_4 = 0.23, \alpha_2 = 1, \alpha_3 = 5 \), and \( q \) is twice the turbulent kinetic energy, \( q_c \) is a turbulent velocity scale proportional to \( w_* \), and \( N \) is the Brunt Väiälä frequency.

The MYNN SL is also based on the Monin-Obukhlov similarity theory and the steps linking it to the MYNN PBL scheme is akin to that of MYJ SL – MYJ PBL pair. The soil-surface temperature is predicted by the force restore method after the soil heat flux is obtained from the surface energy-balance equation, and the soil-surface specific humidity is estimated with an effective evaporation rate of 0.6.

The above 5 different options for the SL schemes exhaust the WRF-ARW choice theoretically based on the Monin Obukhov similarity theory. This study focuses further on the options: \((sf_sfclay_physics=1)\) and \((sf_sfclay_physics=11)\) as they provided the premises of this project that aims to identify tunable parameters (e.g., Foken 2006) that are empirically determined based on field data stipulated in Table 2.1 that may be significantly responsible for the nocturnal low-level wind speed biases after sunset in the HGB area. In the following section we elaborate on the model runs attempted to evaluate for such tunable parameters that may significantly impact the redistribution of kinetic energy from the residual layer to the surface.
Table 2.1 Field data used in determining the empirical parameters in the surface layer (SL) schemes studied

<table>
<thead>
<tr>
<th>Section: name and Ref.</th>
<th>Description</th>
<th>Field Date (Ref.)</th>
<th>Data characteristics (Ref.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 MM5 (Zhang and Anthes 1982)</td>
<td>Thermal-diffusion</td>
<td>Kansas (Izumi 1971)</td>
<td>Kansas (July-August 1968) over grass prairie</td>
</tr>
<tr>
<td>2.2 MM5 modified (Jiménez et al., 2012)</td>
<td>Expanded MM5 SL (Section 2.1) with added capability to handle extreme meteorological regimes</td>
<td>Kansas (Izumi 1971), CASE-99 (Blumen et al., 1999) and TOGA COARE (Webster and LuKas 1992)</td>
<td>CASE-99 Kansas (October 1999) used by Cheng and Brutsaert 2005; TOGA COARE Western Pacific (Nov 1992 - Feb 1993) used by Fairall et al., 1996</td>
</tr>
<tr>
<td>2.3 Eta (Janjić 2001)</td>
<td>In conjunction with level 2.5 Mellor-Yamada-Janjić PBL closure</td>
<td>Kerang and Hay (Swinbank and Dyer 1968)</td>
<td>Southern New South Wales, Australia (1962-1964)</td>
</tr>
<tr>
<td>2.4 GFS (Hong and Pan 1996)</td>
<td>In conjunction with MRF PBL --- nonlocal scheme</td>
<td>TOGA COARE (Webster and LuKas 1992)</td>
<td>TOGA COARE Western Pacific (Nov 1992 - Feb 1993)</td>
</tr>
<tr>
<td>2.5 QNSE (Sukoriansky et al., 2005)</td>
<td>In conjunction with QNSE PBL</td>
<td>CASES-99 (Blumen et al., 1999, Poulos et al., 2002)</td>
<td>CASE-99 Kansas (October 1999)</td>
</tr>
<tr>
<td>2.6 MYNN (Nakanishi et al., 2001)</td>
<td>In conjunction with MYNN PBL</td>
<td>Wangara (Clarke et al., 1971)</td>
<td>Melbourne, Australia (July-August 1967)</td>
</tr>
</tbody>
</table>

3. Model Rerun, Configuration and Intermediate Diagnostics

There have been two revisions to the YSU PBL scheme since WRF version 3.2 to fix bugs in the program. Both of the revisions deal with stable atmospheric conditions. The first introduced an adjustment of convective velocity scale that results in reduced mixing in the upper layers of the stable layer. The second reduced the minimum turbulence eddy diffusivity in the stable layer. Throughout this study WRF version 3.4.1 was used as it superseded the previous versions.

3.1 Model Configuration

The model geometric and physics package configuration used in this study is nearly identical to that used in the previous TCEQ-funded wind-bias project (Lee et al., 2012). There are two main differences in its execution: (a) the version of the WRF meteorological model: version 3.4.1 is used instead of 3.2 used in the previous project, (b) only the large wind-bias period between June 4 and June 12, 2006 was rerun to provide the basis for this study.

For the sake of completeness the main simulation specifications are stipulated as follows: The modeling domain structure consists of nested domains of different resolutions: a coarse grid domain (36-km cell size, named as ‘NA36’) that covers the continental United States, a regional domain (12-km cell size, named as ‘SUS12’) over Texas and her neighboring Gulf states, and a fine domain (4-km cell size, named as ‘TX04’) covering the eastern Texas area. These domains are shown in Figure 3.1. The initial and boundary conditions for WRF originated from the National Centers for Environmental Prediction (NCEP) North American Mesoscale (NAM) 3 hourly analyses while the sea surface temperature (SST) was updated daily by the NCEP real-time global sea surface temperature analysis in 0.5 degree grid spacing. The SUS12 domain was nested down from the NA36 model results, and likewise the TX04 domain was initialized by nesting down from the SUS12 results. Surface analysis and observational nudging were not
used in the simulation, but grid nudging was operated in TX04 domain as used in the coarse domains. The physics options and model configuration used in the WRF simulation are listed in Table 3.1.

Figure 3.1 WRF domains used for model simulations in the three different spatial resolutions: 36-km (NA36), 12-km (SUS12) and 4-km (TX04).

### Table 3.1 Model configurations used in this study.

<table>
<thead>
<tr>
<th>Domain name</th>
<th>NA36</th>
<th>SUS12</th>
<th>TX04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>36 km</td>
<td>12 km</td>
<td>4 km</td>
</tr>
<tr>
<td>Domain coverage</td>
<td>Continental US</td>
<td>Texas &amp; adjoined states</td>
<td>eastern Texas</td>
</tr>
<tr>
<td>Horizontal grid</td>
<td>162 x 128</td>
<td>174 x 138</td>
<td>216 x 288</td>
</tr>
<tr>
<td>Initialization</td>
<td>NAM + NCEP daily SST</td>
<td>2-way nesting</td>
<td></td>
</tr>
<tr>
<td>Microphysics</td>
<td>WSM5\textsuperscript{a}</td>
<td>WSM6\textsuperscript{b}</td>
<td></td>
</tr>
<tr>
<td>Cloud scheme</td>
<td>KF\textsuperscript{c}</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Radiation scheme</td>
<td>RRTM\textsuperscript{d} for longwave radiation</td>
<td>MM5 (Dudhia)\textsuperscript{e} for shortwave radiation</td>
<td></td>
</tr>
<tr>
<td>PBL scheme</td>
<td>YSU\textsuperscript{f} scheme</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land surface model</td>
<td>5-layer soil thermal diffusion model\textsuperscript{g}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nudging</td>
<td>3D grid nudging (no nudging of mass fields within PBL)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} WRF Single-Moment 5-class (Hong et al., 2004). \textsuperscript{b} WRF Single-Moment 6-class (Hong and Lim, 2006). \textsuperscript{c} Kain and Fritsch scheme (Kain, 2004). \textsuperscript{d} Rapid Radiative Transfer Model scheme (Mlawer et al. 1997). \textsuperscript{e} Dudhia (1989). \textsuperscript{f} Yonsei University scheme (Hong et al., 2006). \textsuperscript{g} 5-layer soil thermal diffusion model (Grell et al., 1994).
3.2 Observational data for evaluation

The model results were evaluated against Continuous Air Monitoring Site (CAMS) observational data. In this study, we focus on the Houston-Galveston-Brazoria (HGB) area. Within the HGB area, wind profiler was operated by the Cooperative Agency Profilers (CAP, https://madis-data.noaa.gov/cap/) at La Porte (LPTTX) which was paired with CAMS site C35. The University of Houston Coastal Center (UHCC) was a continuous monitoring station operated by University of Houston to measure meteorological parameters including temperature, wind, precipitation and fluxes. It was located southeast of the Houston metropolitan area and about 15 miles away from the Gulf of Mexico. Friction velocity and other flux data including latent heat flux and sensible heat flux were measured at UHCC. Data are available at 10-minute interval for fluxes and at 1-minute frequency for regular meteorological variables. Momentum flux was measured by a 3-D sonic anemometer Model RM Ying 8100 at 10 m and 28 m above ground level (AGL). The locations of the monitoring stations are shown in Figure 3.2.

Figure 3.2 CAMS stations map color coded with 5-selected regions. The number of stations in each region is printed next to the sector’s label.

4. Parameters predicted by the WRF surface layer schemes

There are four variables in the YSU-PBL scheme that are directly linked to the boundary forcing from the MM5 surface layer similarity scheme:

\[
\frac{\partial C}{\partial t} + \frac{\partial}{\partial z} (\Gamma C) = \frac{\partial}{\partial z} \left[ K_c \left( \frac{\partial C}{\partial z} - \Gamma c \right) - (\Gamma C) h \left( \frac{z}{h} \right)^{3/2} \right] \quad -- (34)
\]

\[
\theta_r(h) = \theta_w + \theta_r \left[ a \left( \frac{w' \theta'}{w_0} \right) \right] \quad -- (35)
\]
\[ w_s = (u_s^2 + \phi_m kw_s^2 z / h)^{1/3} \] -- (36)

Namely: (1) the gradient adjustment term \( \gamma \) that account for non-local mixing of PBL shown in Eq. (34) (also see Eq. 2 in Hong et al., 2006), (2) the temperature excess term \( \theta_f \) shown in the right hand side of Eq. (35) due to surface buoyancy flux; where \( \theta_s \) is virtual potential temperature. Here again \( h \) is PBL height, and the subscripts 0 and a represent at surface and at first model layer height, respectively; \( a \), the coefficient in the last term, is set equal to 0.68, (3) the vertical diffusivities, \( Kc \), is proportional to the mixed layer velocity scale \( w_s \) as given in Eq. (36) (also see Eq. A2 and A12 in Hong et al., 2006), where \( w_{sb} \), is the convective velocity scale for moist air, and (4) the non-dimensional stability function \( \phi_m \).

At the outset of Section 3 we presented the reasons to rerun the model with WRF version 3.4.1. Figure 4.1 shows the modeled diurnal evolution of the 10 meter wind speed averaged over the grid cells that contain one or more CAMS monitors in the HGB area. Verification was made against the corresponding measurements averaged over the study period. During the daytime hours all three WRF simulations captured the 10 meter wind speed reasonably correctly (Fig. 4.1). However, the prediction of the 10 m wind speed using the new WRF version 3.4.1 continued to exhibit over-estimation between sunset and early morning of the next day, although in much diminished magnitudes. The figure shows that at 0000 CST when the over-estimation peaked, the over-estimation derived from the WRF version 3.2 prediction of 1.2 m s\(^{-1}\) was reduced to 0.2 m s\(^{-1}\) compared to the measured speed of 1.6 m s\(^{-1}\). The MM5 5-layer soil thermal diffusion LSM model (referred to as the slab LSM model), may not have correctly parameterized the transition of the surface momentum and heat fluxes. This could cause an erroneously rapid decrease of low level wind speed in the early evening as clearly shown at 1900 CST in the wind speed evolution as simulated by using the slab LSM model in conjunction with: (slab1) the MM5 SL scheme with WRF version 3.4.1 (also see Section 2.1), (slab11) same as (slab1) but with the modified MM5 SL scheme (Jiménez et al. (2012), and (slab1v32) same as (slab1) but with WRF version 3.2 (Fig. 4.1).
Figure 4.1 Verification of modeled 10 m wind speed averaged over grid cells where a CAMS monitor resides see Figure 3.2 for HGB sites) compared to the measurement average over June 4–13, 2006 for: (slab1) using MM5 SL with WRF version 3.4.1, (slab11) using the modified MM5 SL (Jiménez et al., 2012) with WRF version 3.4.1, and (slab1-v32) using MM5 SL with WRF version 3.2.

4.1 Output $\frac{z}{L}$ each time step

We analyzed the stability regimes pertinent to the UHCC site. We tried two approaches for the output of $\frac{z}{L}$. The first attempt was to modify the segment of the code where it was derived. We simply added a “print statement” to screen-dump its value at every time step in module sfclay.F that performs the surface similarity parameterization calculations. The calculation of $\frac{z}{L}$ was based on Eq. (7) of Holtslag and Eq. (1) of De Bruin (1988) and Launiainen (1995). Table 4.1 shows some of the results for UHCC. We noticed that there was a strong tendency for $\frac{z}{L}$ to give the "zero" value as noted by Jiménez et al. (2012).
Table 4.1 Sample per time-step screen-dump of $z/L$ for spatial point around UHCC

<table>
<thead>
<tr>
<th></th>
<th>0.0000000E+00</th>
<th>0.0000000E+00</th>
<th>0.0000000E+00</th>
<th>0.0000000E+00</th>
<th>0.0000000E+00</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
</tr>
<tr>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
</tr>
<tr>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
</tr>
<tr>
<td>0.0000000E+00</td>
<td>-1.154630</td>
<td>-1.236989</td>
<td>-1.431963</td>
<td>-1.654521</td>
<td>-1.732578</td>
</tr>
<tr>
<td></td>
<td>-1.732578</td>
<td>-1.490933</td>
<td>-1.516289</td>
<td>-1.914787</td>
<td>-2.033314</td>
</tr>
<tr>
<td></td>
<td>-1.807323</td>
<td>-1.852601</td>
<td>-2.434674</td>
<td>-2.317992</td>
<td>-2.245106</td>
</tr>
</tbody>
</table>

The second approach was to activate the output switch for $z/L$ for its hourly output. We achieved this by modifying the “registry” as follows: (1) insert variable “ZOL” to the registry file, (2) specify its dimensionality, i.e., “ij” as a 2 dimensional variable, (3) specify its unit, i.e., “m” as standing for meters, and (3) specify output switches, i.e., “rh” as standing for “restart” and “history” file options.

The hourly output of $z/L$ in the content of the hourly output-files agreed with those in the “screendump” files and was mostly the “zero” value.

We also proceeded to re-run WRF version 3.4.1 using a recent update in the MM5 surface layer similarity parameterization modified by Jiménez et al. (2012). It is labeled as “option 11”. It differs from “option 1” with a broadened applicability range for highly unstable and stable meteorological conditions, and provided an option to account for thermal roughness length over land points (Dudhia 2012). Option “11” was shown to improve the bulk transfer coefficients of momentum, heat and moisture (Jiménez et al., 2012).

Over the various CAMS sites, we investigated modeled and measured friction velocity, stability parameter and roughness length. Figure 4.2 shows the results of modeled friction velocity, $u_*$ (m s$^{-1}$) for the period June 4-13, 2006, at the UHCC station with: surface layer scheme (red) MM5 SL, and (blue) modified MM5 SL (Jiménez et al. 2012). Comparing friction velocity predictions using the two SL options: option=1 and option=11, prediction from the latter option generally showed larger friction velocities at sunset (Fig. 4.2). Larger friction velocity can be advantageous for retarding low level wind speed and could reduce the near surface wind speed over estimation.

Figure 4.2 shows the results of modeled surface latent heat flux (Watt m$^{-2}$) for the period June 4-13, 2006, at the UHCC station with surface layer scheme (red) MM5 SL, and (blue) modified MM5 SL (Jiménez et al. 2012). Figure 4.3 shows the surface latent heat flux over the same period with hardly any departure of modeled values except on June 12 2006. The resemblance between the modeled momentum fluxes for the predictions using the two SL schemes is also strikingly alike (Figure 4.4) except on June 12 2006 when the wind fields were the most calm within the HGB area during the study period.
Figure 4.3 Verification of model result for friction velocity, $U_*$ (m s$^{-1}$) for the period June 4-13, 2006, at the UHCC station with: surface layer scheme (red) MM5 SL, and (blue) modified MM5 SL (Jiménez et al. 2012).

Figure 4.4 Verification of model result for surface latent heat flux (Watt m$^{-2}$) for the period June 4-13, 2006, at the UHCC station with surface layer scheme (red) MM5 SL, and (blue) modified MM5 SL (Jiménez et al. 2012).
Figure 4.4 Verification of model result for momentum exchange coefficient (kg m$^{-3}$) for the period June 4-13, 2006, at the UHCC station with surface layer scheme (red) MM5 SL, and (blue) modified MM5 SL (Jiménez et al. 2012).

4.2 NOAH Land Surface Model Simulation

Basing on the future work recommendation of Jiménez et al. (2012), we replaced the MM5 5-layer soil thermal diffusion LSM with the NOAH LSM and repeated the extra intermediate variable output step in Section 4.1. Figure 4.5 shows sensible heat flux verification and demonstrated substantial (up to 50%) reduction in mid-day high biases achieved by using the NOAH LSM.

Figure 4.5 Verification of model result for surface sensible heat (Watt m$^{-2}$) for the period June 4-13, 2006, at the UHCC station when using: (slab1) slab LSM and MM5 SL, (slab11) slab LSM and modified MM5 SL (Jiménez et al., 2012), (noah1) NOAH LSM and MM5 SL, and (noah11) NOAH LSM and modified MM5 SL.

An important rationale to resort to these more physically-based upgrades of the Land-Surface-Model(LSM)/SL-Similarity-Scheme option pair to evaluate the 10 m wind speed bias is that these modules have been too tightly coupled as inherited from the MM5 era. A few parameters within the modules are compensating for deficiencies from one another. Examples of these parameters are the bulk Richardson number values defined atmospheric regime cut-offs for similarity function parameterization.
and numerical values of some of the empirically determined parameters based on specific field campaigns. This decision to deviate partially from our original objectives (2) and (3) is supported by evidence in the significantly improved governing inputs to the PBL scheme, yet worsened 10 m wind speed biases. Pursuing objectives (2) and (3) by considering the SL scheme as a “stand-alone” module is not doable. In our newly proposed setup above we upgraded MM5 SL with modification by Jiménez et al. (2012), we also replaced the MM5 5-layer soil thermal diffusion land surface model (LSM) with the NOAH LSM. The NOAH LSM is a much more physically based LSM than the MM5 slab LSM.

5. Quality Assurance/Quality Control Procedures

This project was established upon the QA Categories III which was listed in the quality assurance project plan (QAPP) document submitted along with the work plan in January 2013. Modeling domains shown in Section 3 were identical as TCEQ’s WRF model configuration. The simulation used the “namelist.wps” and “namelist.input” files (control file for running WPS and WRF, respectively) downloaded from TCEQ. The WRF run encountered no errors during the simulation. The CAMS stations data in METSTAT ASCII format was downloaded from TCEQ ftp site. An IDL subroutine was programmed to visualize and compute the statistical analyses shown in the following sections.

The UHCC data were obtained from the UH Institute for Multi-dimensional Air Quality Studies) IMAQS measurement team through the personal contact with Prof. Bernhard Rappenglueck, who is the one of the co-PI of the Houston-Network of Environment Towers (H-NET) project (http://www.hnet.uh.edu/about.php). The data was archived in ASCII format. An IDL program was used to read the files and extracted the corresponding model output for the comparisons. There was no missing data throughout the study period. The wind profiler data, was collected through the Meteorological Assimilation Data Ingest System (MADIS, http://madis.noaa.gov/) which was developed by NOAA/OAR/ESRL/GSD to integrate quality control and distribute observations from NOAA and non-NOAA organizations. The Data was archived in NetCDF formatted files that were downloaded through the ftp site with user account and password granted by MADIS. The data availability of La Porte site was good even though there were occasionally some missing data. There was no long-term missing data during the study period which could limit the analysis. As end users for the data, we would not be in a position to validate the data. But, by comparing the observed data to model output, no suspicious sample was detected.

6. Results

Recently there were two thorough WRF modeling studies on applying different PBL scheme options in WRF to identify the best PBL option in the HGB area (Hu et al., 2010) and in the Gulf states (Yerramilli et al., 2010). They agreed with the customary practice of TCEQ in selecting YSU as one of the preferred PBL schemes producing the least biases in 2 meter temperature and 10 m wind.

In Sections 3 and 4 above we employed the following three modeling advances aiming to rectify the modeled low level wind speed biases in the HGB area during nighttime in the summer: (1) WRF version 3.4.1 which included two revisions in the YSU PBL scheme, (2) a modified option of the MM5 SL scheme according to Jiménez et al. (2012), and (3) NOAH, a more sophisticated LSM to provide bottom boundary conditions for the PBL scheme. We incorporated these advances incrementally to examine the evolutions of a few low level wind simulation parameters throughout the period between 0000 UTC June 4 to 0000 UTC June 13 2006 – a period within the TEXSAQS II campaign that WRF showed strong low level wind speed high biases at night. The general outcome from these advances is mixed and did not drastically improve the wind speed biases.
6.1 WRF Version 3.4.1.

There are two revisions in the YSU PBL scheme from the WRF older version --- version 3.2. Both of the fixes deal with the stable atmospheric conditions. The first introduces an adjustment of convective velocity scale that results in reduced mixing in the upper layers of the stable layer. The second reduces the minimum turbulence eddy diffusivity in the stable layer. WRF version 3.2 was used in our previous TCEQ-funded project (Lee et al., 2012), thus rerunning WRF with version 3.4.1 became necessary. Hereafter the WRF version 3.4.1 simulation result was presented except when specifically qualified otherwise. The rerun covered June 4 to June 13, 2006. Figure 4.1 shows that the over-estimations of the night time 10 m wind speed persisted, although diminished even with the rerun results. The maximum study-period averaged over-estimation of 10 meter wind speed at 2100 CST was reduced by 55% due the version upgrade from a high bias of 1.1 m s\(^{-1}\) to 0.5 m s\(^{-1}\) when verified against the observed speed of 2.3 m s\(^{-1}\).

6.2 Adopt Surface Layer scheme option 11 after Jiménez et al. (2012)

In WRF version 3.4.1 a new SL scheme (sf_sfclay_physics =11) was made available according to Jiménez et al. (2012) (see also Section 2.2). It is based on the MM5 SL scheme (Section 2.1). The major achievement of this new scheme is the inclusion of treatment for extreme meteorological regimes. The recommendations of Fairall et al. (1996) for extremely unstable conditions and that of Cheng and Brutsaert (2005) for extremely stable conditions were adopted. Figure 4.1 shows that the maximum study-period averaged over-estimation of 10 meter wind speed was at 2100 CST. It was increased by 40% compared with that by the original scheme from a high bias of 0.5 m s\(^{-1}\) to 0.7 m s\(^{-1}\) when verified with the observed speed of 2.3 m s\(^{-1}\). Figure 4.2 shows verification comparison of friction velocity at UHCC between results using the MM5 SL and the modified MM5 SL scheme. The high biases at night predicted by the original scheme were substantially reduced for four nights out of the 10 day study period, as the modified scheme allowed the cut-off of \(u^*\) to be lowered by two orders of magnitude to 0.001 m s\(^{-1}\). Figure 4.3 shows verification comparison for surface exchange coefficients for heat. The schemes performed comparably, although it may be argued that the spikes on 11\(^{th}\) and 12\(^{th}\) of June were better captured by the modified scheme.

Figure 6.1 shows verification over UHCC for: (a) 2 meter temperature and (b) 10 meter wind speed. There was no obvious superiority in prediction by the modified MM5 SL scheme. There was no distinctive difference in performances by the two SL options for 2 meter temperature. Figure 6.1b shows that the wind speed high biases at UHCC were aggravated by the modified scheme at night between 2000 CDT to the next day 600 CDT. This may point to a possible compensating error in determining the empirical constants such as \(\gamma\) in Eq. 11. However, the modified scheme according to Jiménez et al. (2012) is scientifically more versatile to include both the extremely stable and unstable atmospheric regimes and realistically more accurate to reflect frequently observed \(u^*\) as low as 0.001 m s\(^{-1}\).
Figure 6.1 Verification of model result for June 4-13, 2006 when using the MM5 SL scheme (red) and the modified MM5 SL (Jiménez et al., 2012) (blue) at the UHCC station for: (top) 2 meter temperature (°C), and (bottom) 10 m wind speed (m s⁻¹)

6.3 Replace MM5 5-layer soil thermal diffusion (slab) LSM by NOAH LSM

Many studies dealing with low level wind speed prediction performance of WRF recommended a sophisticated LSM such as Jiménez et al. (2012) that concerned Iberian, Spain (Jiménez et al., 2010), Yerramilli et al. (2010) that concerned the Gulf states, and Wilczak et al. (2009) that concerned Southeastern TX. The YSU PBL has the option to couple with the NOAH LSM, which is a more physically based LSM scheme than the slab LSM scheme customarily used by TCEQ scientists. The NOAH LSM has an obvious advantage over the slab LSM by allowing more frequent updates in land surface and vegetative parameters as well as a physical model for evapotranspiration and runoffs. We have replaced the slab LSM with the NOAH LSM in the physics options (see Table 2.1).

Figure 4.4 shows the sensible heat flux verification comparison between predictions by the standard and the modified MM5 SL schemes when coupled to either the slab or the NOAH LSM. It demonstrates that a substantial (around 50%) reduction in mid-day high biases was achieved by using the NOAH LSM, regardless of which SL scheme was used. Figure 6.2 shows verification for predictions using the standard MM5 SL scheme coupled with the two LSMs against measurement averages over the 46 CAMS sites.
within the HGB area. Figure 6.2 a and b show verification over the grid cell averages for cells where a CAMS monitor resides compared with CAMS monitor measurement averages, using the slab LSM (red) and using the NOAH LSM (blue) for: (a) 2 meter temperature, and (b) 10 meter wind speed, respectively. By using the NOAH LSM, the 2 m temperature under-estimation at night time was significantly reduced (by as much as 1.5 °C on June 10) for all days in the study period. However it did not always reduce the persistent over-estimation for the day time maxima (improved 5 days out of 10 days in the study period). On the other hand for 10 meter wind speed predictions shown in Fig. 6.2 b, it showed worsen performance by the prediction using the NOAH LSM as it aggravated over-estimation at around 1900 CST on 5 days: 4th, 7th, 8th and 9th of June, out of the 10 day study period (also see Figure 6.3).

Figure 6.3 shows the modeled and observed diurnal evolution of the 10 m wind speed averaged over the 43 CAMS sites within the HGB area. The run that employed the NOAH LSM actually aggravated the wind speed biases. However, the sharp temporal gradient caused by the modeled abrupt drop in wind speed between 1800 and 1900 CST was largely removed. Figure 6.4 demonstrates the prediction verification for 10 meter wind speed over the UHCC for the two SL schemes (Section 6.2) and the two LSM (Section 6.3) combinations. The prediction that used the NOAH LSM performed slightly worse than that with the slab LSM. Finally Figure .5 shows a verification comparison for 50 m level wind speed at La Porte. The prediction that used the NOAH LSM did considerably better than the one that used the slab LSM during the mid to late evening hours yet with no performance degradation for other hours. The maximum reduction in the bias between 2200 and 2300 CST by using the NOAH LSM was about 0.5 m s$^{-1}$ from 1.5 m s$^{-1}$ when using the slab LSM versus the observed 10 m wind speed of 7.5 m s$^{-1}$ on June 6 2006.
Figure 6.2 Verification of modeled 2-D fields averaged over grid cells where a CAMS monitor resides compared to the measurement average (see Figure 3.2 for HGB sites) over June 4–13, 2006, when using the slab LSM (red) and the NOAH LSM (blue) for: (top) 2 meter temperature (°C), and (bottom) 10 m wind speed (m s⁻¹).
Figure 6.3. Verification of modeled 10 m wind speed (m s\(^{-1}\)) averaged over grid cells where a CAMS monitor resides compared to the measurement average (see Figure 3.2 for HGB sites) over June 4–13, 2006 for: (OBS) observation, and for prediction when applying: (slab1) slab LSM, (slab11) modified MM5 SL (Jiménez et al., 2012); and slab LSM, (noah1) MM5 SL and NOAH LSM, and (noah11) modified MM5 SL and NOAH LSM.

Figure 6.4 Comparison of model result for 10 meter wind speed (m s\(^{-1}\)) for the period June 4-13, 2006, at the UHCC station for (OBS) Observation, and for prediction when applying: (slab1) slab LSM, (slab11) modified MM5 SL (Jiménez et al., 2012) and slab LSM, (noah1) MM5 SL and NOAH LSM, and (noah11) modified MM5 SL and NOAH LSM.
Figure 6.5 Comparison of model result for 50 meter wind speed (m s⁻¹) for the period June 4-13, 2006, at the La Porte station for (OBS) Observation, and for prediction when applying: (slab1) the slab LSM, (slab11) modified MM5 SL (Jiménez et al., 2012); and slab LSM, (noah1) MM5 SL and NOAH LSM, and (noah11) modified MM5 SL and NOAH LSM.

7. Summary and Future Work

In this study, we aimed to diagnose and remedy the WRF modeled wind speed high biases of nocturnal low level winds in the Houston-Galveston-Brazoria (HGB) area. The advection and PBL modules in the WRF physics package are directly attributable to wind speed predictions. A previous TCEQ funded wind-biases project (Lee et al., 2012) showed some of the characteristics of the temporal distribution of the wind speed biases around sunset in clear sky days such as those between June 4 and June 13, 2006 over the HGB area. Their report showed evidence that the discrepancy in modeling the collapse of the convective PBL was likely a primary cause for the wind speed biases. The sunset time instance represents an abrupt cut off of solar radiation. The rapid growth of the nocturnal boundary layer (NBL) resulting from cooling of surface from emissivity of long wave radiation alters the vertical transfer of momentum and heat. Eventually the remnant turbulence from the convective PBL forms the residual layer aloft detaches itself from the NBL below. However the WRF model apparently showed some deficiency in simulating this transition for the HGB area.

All PBL schemes in the WRF model depend on a land surface model (LSM) to provide bottom boundary conditions for momentum, heat and moisture fluxes. Customary, TCEQ uses the MM5 5-layer soil thermal diffusion (slab) model as its LSM option to complement it with the fifth-generation Pennsylvania State University—National Center for Atmospheric Research Mesoscale Model (MM5) surface layer (SL) similarity scheme (Zhang and Anthes 1982) to provide the PBL scheme with friction velocities. Thus the LSM-SL-PBL triplet with each of its components contributes strongly to the forcing of the PBL processes.

We discussed some of these PBL schemes based on their tight links with the SL schemes within WRF. We also noted that the SL schemes may provide an opportunity to optimize some of the empirical parameters that were derived from a few rather old field measurements (see Table 2.1). For the MYJ, GFS, QNSE, MYNN similarity SL schemes they can only be applied to their unique corresponding PBL schemes. Similarly such “proprietary” linkage exists for the preferred LSM options (Dudhia 2012). With the YSU PBL scheme as our preferred PBL scheme as discussed in the beginning of Section 6, the
possible SL options are the MM5 SL scheme (Section 2.1) and the modified MM5 SL scheme (Jiménez et al., 2012) (Section 2.2). The LSM options available for both of these pairs are the slab LSM and the NOAH LSM.

We devised and implemented a three-tiered nesting domain WRF model sensitivity experiment to investigate the four possible LSM-SL-PBL triplets. Section 4.1 focused on SL scheme model performance. Figure 4.1 shows that the daily maximum bias at 2100 CST for the 10 meter wind speed was increased by 40% when verified with the modified MM5 SL scheme with respect to that by the original SL scheme. Figure 4.2 shows the comparison for friction velocity at UHCC between predictions using the two SL schemes. The high biases at night predicted by the original scheme were substantially reduced for four nights out of 10 nights in the study period. Figure 4.3 shows comparison for surface exchange coefficients for heat at UHCC. The predictions using the two SL schemes performed comparably. Figure 6.1 shows comparisons for 2 meter temperature and 10 meter wind speeds at UHCC. There is no distinctive difference in performance for the 2 meter temperature predictions (see Fig. 6a). Figure 6.1b shows that the wind speed high biases at UHCC were aggravated at night between 20:00 to the next day 6:00 CDT.

However, the modified scheme according to Jiménez et al. (2012) is scientifically more versatile to include both the extremely stable and unstable atmospheric regimes and is realistically more accurate to capture frequently observed $u_*$. It is hypothesized that the tunable parameters, such as $\gamma$ in Eq. (11) that was derived for specific field data primarily for Kansas data (Izumi 1971), were more tuned to the standard MM5 SL scheme. They did not account for newer data sets for extreme atmospheric conditions such as CASE-99 (Cheng and Brutsaert 2005) and TOGA COARE (Fairall et al., 1996) used in the modified SL scheme. As a result, the performance for 10 m wind speed prediction may deteriorate due to the inconsistencies.

Many recent studies aimed to improve WRF modeling fidelity for near surface wind speed pointed out the important contribution of the model’s LSM component (Jiménez et al., 2010; Yerramilli et al., 2010; and Wilczak et al., 2009). The NOAH LSM allows frequent updates in land surface and vegetative parameters as well as physical models for evapotranspiration and runoffs. Figure 6.2 shows the verification comparison between predictions from using the slab and NOAH LSMs and the CAMS site averaged measured values. The 2 meter temperature (Fig. 6.2a), simulation using the NOAH LSM reduced both day time hot biases and early morning cold biases. On the other hand, for 10 meter wind speed predictions (Fig. 6.2b), it worsened over-estimation during the early evening hours (also see Figure 6.3). However, the discrepancy caused by the modeled abrupt drop in wind speed between 1800 and 1900 CST was largely removed. Figure 6.4 shows the sensible heat flux verification comparison and demonstrated substantial (up to 50%) reduction in the mid-day high biases by using the NOAH LSM. For instance, on June 6th 2006, the mid-day sensible heat flux over estimation of 140 w m$^{-2}$ was reduced to 70 w m$^{-2}$ out of a flux of 160 w m$^{-2}$ measured at UHCC. Figure 6.4 demonstrates the verification comparison for 10 meter wind at UHCC. The prediction that used the NOAH LSM did slightly worse than that with the slab LSM during the early evening hours throughout the 10 day study period. Figure 6.5 showed the verification comparison for 50 m level wind speed at La Porte. The prediction using the NOAH LSM did considerably better than when using the slab LSM especially during the mid to late evening hours. Therefore, the modeling sensitivity experiments converge to recommend the more physically based NOAH(LSM)-Modified-MM5(SL)-YSU(PBL) triplet as the physics option to address the low level wind speed biases at night in the HGB area.

The important rationale to resort to these more physically-based upgrades of the Land-Surface-Model(LSM)/SL-Similarity-Scheme option pair to evaluate the 10 m wind speed bias is that these modules have been too tightly coupled as inherited from the MM5 era. A few parameters within the modules are compensating for deficiencies from one another. Examples of these parameters are the bulk Richardson number value defined atmospheric regime cut-offs for similarity function parameterization and numerical values of some of the empirically determined parameters based on specific field campaigns. This decision to deviate partially from original objectives (2) and (3) is supported by evidence in the
significantly improved governing inputs to the PBL scheme, yet worsened 10 m wind speed biases. Pursuing objectives (2) and (3) by looking at the SL scheme as a “stand-alone” module was not possible. In our newly proposed setup above we upgraded MM5 SL with modification by Jiménez et al. (2012). We also replaced the MM5 5-layer soil thermal diffusion land surface model (LSM) with the NOAH LSM. The NOAH LSM is a much more physically based LSM than the MM5 slab LSM.

Based on this work we seek guidance for future work. We did an additional literature survey to identify systematic ways to tune parameters in a multivariate problem. This is particularly relevant to the NOAH LSM and the modified MM5 SL parameterization schemes in WRF. Gupta et al. (1999) pioneered a multi-criteria optimization methodology to derive optimally tuned parameters for a LSM for a global model. Sen et al., (2001) further developed the methodology with a preference hierarchy based multi-criteria calibration algorithm and applied it successfully to a version of the Biosphere-Atmosphere Transfer Scheme. We believe that these methodologies can efficiently optimize tunable parameters in the NOAH and SL schemes for resolving the modeled wind biases. Secondly, we believe that utilization of additional observed soil-moisture data can nudge the modeling of the surface layer de-coupling more accurately thus facilitate the correct capturing of the vertical momentum fluxes and vertical wind profiles during the sunset hours.

8. References


Lee, P., F. Ngan and H. C. Kim, 2012: Investigation of nocturnal surface wind bias by the Weather Research and Forecasting (WRF)/ Advanced Research WRF (ARW) meteorological model for the


