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MODIFICATION OF THE YONSEI UNIVERSITY BOUNDARY LAYER SCHEME IN THE WRF MODEL FOR STABLE CONDITIONS

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Abstract: The stable stratified atmospheric boundary layer continues to pose challenges for Numerical Weather Prediction and Climate models. Existing parameterizations cannot adequately capture the depth of the Planetary Boundary Layer (PBL), low-level jets and nocturnal near surface temperature because of their poor representation of turbulent fluxes, especially in mountainous terrain. In addition, small scale processes such as collisions between katabatic and valley flows which produce intense mixing, strong vertical velocities and a rapid drop in temperature are distributed in space and time and are unable to be captured. These interactions between flows of different scales, in general, can contribute significantly to sub-grid, short-lived, intense turbulence events, spasmodically producing high fluxes over short periods. Such vigorous mixing episodes need to be included in meso-scale models in order to improve their performance, especially in dealing with near surface flows.

High-resolution numerical calculations were performed using the Weather Research and Forecasting (WRF) model to test its ability to predict mountain weather. Data from two comprehensive field experiments conducted under the aegis of Mountain Terrain Atmospheric Modelling and Observations (MATERHORN) Program (www.nd.edu/~dynamics/materhorn) were used in this study. Different PBL options available in the WRF model were tested and evaluated for stable conditions. The Yonsei University (YSU) PBL scheme was modified and implemented in WRF. The performance of the modified and original YSU scheme, were compared. Preliminary results show that the modified version is more capable of predicting the velocity of the observed low-level jet, which was consistently over-predicted by the original version.

Further data processing and analysis is under way. The objective is to develop better parameterizations for turbulent fluxes in the complex terrain leading to improved predictability of local scale air flow. This work is a contribution in this direction and numerous applications follow from this research including air quality modelling and aviation.

Key words: *Boundary layer parameterization, Modification of existing PBL scheme, Turbulence in complex terrain, Mountain numerical modelling, WRF model evaluation.*

INTRODUCTION

One of the goals of the on-going Mountain Terrain Atmospheric Modelling and Observations Program MATERHORN (www.nd.edu/~dynamics/materhorn) is to identify and understand the deficiencies – structural, physics and dynamics in meso-scale models and improve model predictions. The stable stratified atmospheric boundary layer continues to pose challenges for Numerical Weather Prediction and Climate models. The turbulence parameterization constitutes the most critical part of turbulent-flow simulations. Existing parameterizations cannot adequately capture the depth of the Planetary Boundary Layer (PBL), low-level jets and nocturnal near surface temperature because of their poor representation of turbulent fluxes, especially in mountainous terrain. Boundary layer parameterizations work fairly well down to a one-kilometre grid size. When the grid size becomes smaller, the applicability of these schemes becomes questionable. Small scale processes such as collisions between katabatic and valley flows which produce intense mixing, strong vertical velocities and a rapid drop in temperature are sporadically distributed in space and time and cannot be captured with a grid resolution of one-kilometre or larger. But these interactions between flows of different scales, in general, can contribute significantly to sub-grid, short-lived, intense turbulence events, that produce high fluxes over short periods. Such energetic mixing episodes need to be included in meso-scale models, especially for near surface flows.

High-resolution runs (with 500 m resolution) of the Advanced Research version (ARW-WRFv3.4.1.) of the Weather Research and Forecasting model (http://www.mmm.ucar.edu/wrf/users) were completed to test the abilities of the code for mountain terrain numerical modelling. Data from two MATERHORN field campaigns were used for verification. The capabilities and limitations of different PBL options available in the WRF model was investigated and compared against these meteorological data. The Monti et al. (2002) parameterization of the eddy diffusivities of momentum and heat for the stable lower atmosphere has been implemented in the Yonsei University (YSU) scheme. A unique aspect of this parameterization is the stability dependence of the turbulent Prandtl number that allows momentum to be transported by internal waves, while heat is diffused by turbulent eddies, which are suppressed due to stable stratification; thus the momentum diffuses faster than heat.

MODEL SET UP

Model domains

Four nested domains of 32, 8, 2 and 0.5 km grids were based on a Lambert Projection cantered at 113^{O}W, 40^{O}N (located in Utah, USA). The experimental domain was the Dugway Proving Ground (DPG) - U.S. Army facility, located in the Great Salt Lake Desert, and is surrounded on three sides by mountain ranges. Our special interest was focused on the interaction between the down-slope flow from the isolated topographic peak Granite Mountain (GM), and valley flows. The outcomes presented in the paper are only from the innermost domain with 0.5x0.5 km grids. The vertical grid was setup with 50 terrain following (eta) levels. More points were employed in the lowest part of the PBL to increase the vertical resolution in the stable boundary layer. The initial and boundary conditions for the ARW-WRF are based on the NCEP Final Operational Model Global Tropospheric Analyses (http://rda.ucar.edu/datasets/ds083.2/).

In 2012, the land-cover and terrain elevation dataset was updated based on the newer 33-category National Land Cover Database (NLCD) dataset (Fry et al., 2011). The new land-cover increased the area defined as playa. The soil-texture class is defined by a 16-category United States Geological Survey (USGS) dataset, which is also modified to include playa, white sand, and lava soil texture classes. The updated database was used together with a new parameterization of soil thermal conductivity in the Noah land-surface model for silt loam and sandy loam soils proposed by Massey et al. (2013) that provide significant nocturnal temperature bias reduction.

Modelling periods

This case study covers six Intensive Operational Periods (IOP) with quiescent large-scale conditions (defined as a period where the wind speed is less than 5 m/s at 700 mb). Every IOP covers 24 hours or more, four IOPs were conducted in September and October 2012 and the other two in May, 2013. It was important to isolate local land-atmosphere processes under stable conditions. In order to perform a proper model experiment, sufficient spin-up time (12 hours or more, depending on the starting time for the different IOPs) was taken into account.

Physical options

The physics package (WRF-ARW V3: User's Guide, 2008, 2012) includes: Lin et al. microphysics scheme, the Rapid Radiative Transfer Model (RRTM) longwave radiation parameterization, Dudhia shortwave radiation parameterization, Noah Land Surface Model, and Cumulus Parameterization: Kain-Fritsch scheme for 32km grid and Grell-Devenyi ensemble scheme for 8km grid only. Several of the available planetary boundary layer (PBL) schemes in ARW-WRF version 3.4.1 were compared. These are: Yonsei University (YSU), Asymmetric Convective Model (ACM2), Mellor-Yamada-Janjic (MYJ), Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN), Bougeault-Lacarrère (BouLac), and Quasi-Normal Scale Elimination (QNSE).

Modification of YSU schemes for stable conditions

The advantages of YSU scheme is that this scheme is simple, well evaluated for different conditions, computationally inexpensive and better in predicting convective boundary layer than the local closure schemes. The YSU scheme uses identical profile functions for momentum and heat for stable conditions, assuming that the turbulent Prandtl number (Prt) is a constant. The experimental data of Strang and Fernando (2001), and Monti et al. (2002) showed that both momentum and heat diffusivities are stability (i.e. gradient Richardson Number) dependent. Monti et al. (2002) suggested a new parameterization for eddy diffusivities under stable conditions. An advantage of this parameterization is the implementation of a stability varying Prt that allows momentum to be transported from a specific region by the internal waves, while heat is diffused by turbulent eddies, which are suppressed due to stable stratification. In this work, the same parameterization has been implemented in YSU schemes of ARW-WRFv3.4.1 and the model results were compared with results from the other PBL schemes.

MODELING RESULTS AND DISCUSSION

Numerical simulations were performed for six IOP cases using described above six PBL schemes and the modified YSU scheme called YSUmod. Different statistical measures were calculated for the entire IOPs period using data from Tethered-balloon soundings at Sagebrush site located east of GM and centrally in the main valley. This site was in the path of the nocturnal meso-scale drainage flows over the Dugway Valley, and at times was influenced by slope flows from different directions. The statistics were calculated for four IOPs by matching up level from the Tethered-balloon profiles and interpolated to the closest model level. The Root Mean Square Error (RMSE), Normalized Mean Error (NME) and Index of Agreement (IA) are listed in Table 1. The Index of Agreement is developed by Willmott (1981) as a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all.

Table 1. Summary of statistical measures: RMSE, NME and IA

	Temperature			**Wind speed**			**Wind direction**		
	RMSE (^{0}C)	**NME (%)**	**IA**	**RMSE (ms^{-1})**	**NME (%)**	**IA**	**RMSE (deg)**	**NME (%)**	**IA**
ACM2	1.93	10.29	0.97	2.40	65.33	0.46	105.83	36.91	0.65
BouLag	1.86	9.70	0.97	1.89	52.68	0.49	108.75	37.60	0.64
MYJ	1.74	9.21	0.97	2.25	58.91	0.48	109.27	38.63	0.63
MYNN	1.88	9.56	0.97	2.23	58.08	0.48	107.86	37.49	0.64
QNSE	1.63	8.67	0.98	2.12	55.78	0.47	117.53	40.69	0.61
YSU	2.12	10.73	0.96	2.20	57.79	0.46	115.55	40.75	0.61
YSUmod	2.49	11.33	0.94	1.90	53.44	0.52	109.13	37.77	0.64

The RMSE for temperature is less than 2.5 degrees with an index of agreement more than 0.94 and NME less than 11%. All of the schemes had similar IA values. The wind speed IA ranged from 0.46 to 0.52 and the direction from 0.61 to 0.65. The wind speed is the most challenging to predict under the quiescent conditions because small differences induce big errors for weak winds. The modified YSU scheme performed the best for the wind speed, increasing the index of agreement from 0.46 to 0.52 and reducing NME from 58% to 53%. Improvement for wind direction in comparison with the original scheme is also substantial with IA from 0.61 to 0.64 and NME from 41% to 38%. The main reason for the worst agreement of YSU and YSUmod with the temperature observations close to the ground is related mainly to the surface layer parameterization. The surface layer schemes calculate friction velocities and exchange coefficients that enable the calculation of surface heat and moisture fluxes by the land-surface models. These fluxes provide a lower boundary condition for the vertical transport in the PBL schemes. The YSU and YSUmod PBL were coupled with revised MM5 surface layer scheme (Jiménez and Dudhia, 2012). The related near-surface flow was dominated by the katabatic wind, which could not have been described properly by Monin–Obukhov theory. Grisogono et al. (2007) show that for sufficiently stratified flows over moderately sloped surfaces, Monin–Obukhov scaling is inadequate for describing the basic PBL dynamics, which is often governed by katabatic and drainage flows. The authors compared the Monin–Obukhov length (L_{MO}) with the height of the low-level katabatic jet estimated from the Prandtl model for simple sloped flows. For moderate and steeper slopes (more than 5 degrees), sufficiently stratified flows with Prandtl number larger than 1 are inevitably susceptible to more momentum than heat mixing, and then the height of the low-level katabatic jet is less than the Monin–Obukhov length. In such flows, L_{MO}

is too large to represent the near-surface fluxes induced by the low-level katabatic jet. The lower boundary conditions for the vertical transport are coming from the surface layer. The errors propagate above this layer leading to an increase of temperature at the closest to the ground model levels.

An example of vertical profiles of temperature, wind speed, and wind direction is shown in Figure 1. The YSUmod shows very good performance for the vertical profile within the nocturnal PBL including temperature, except the lowest levels affected by inconsistency with the PBL-surface layer. If the PBL-surface layer consistency is not enforced, the near-surface temperature turns out to be too warm and the warm bias increases with strength of stratification.

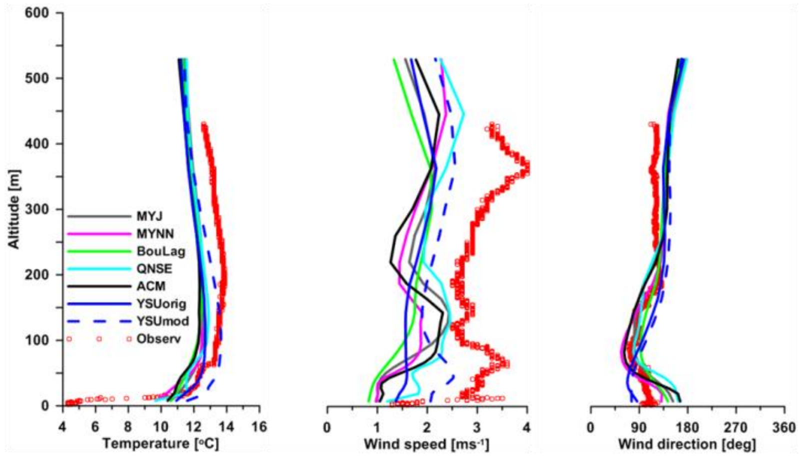

Figure 1. Vertical profiles comparison between different PBL schemes for October 18, 2012, 22.03-22.28 local time.

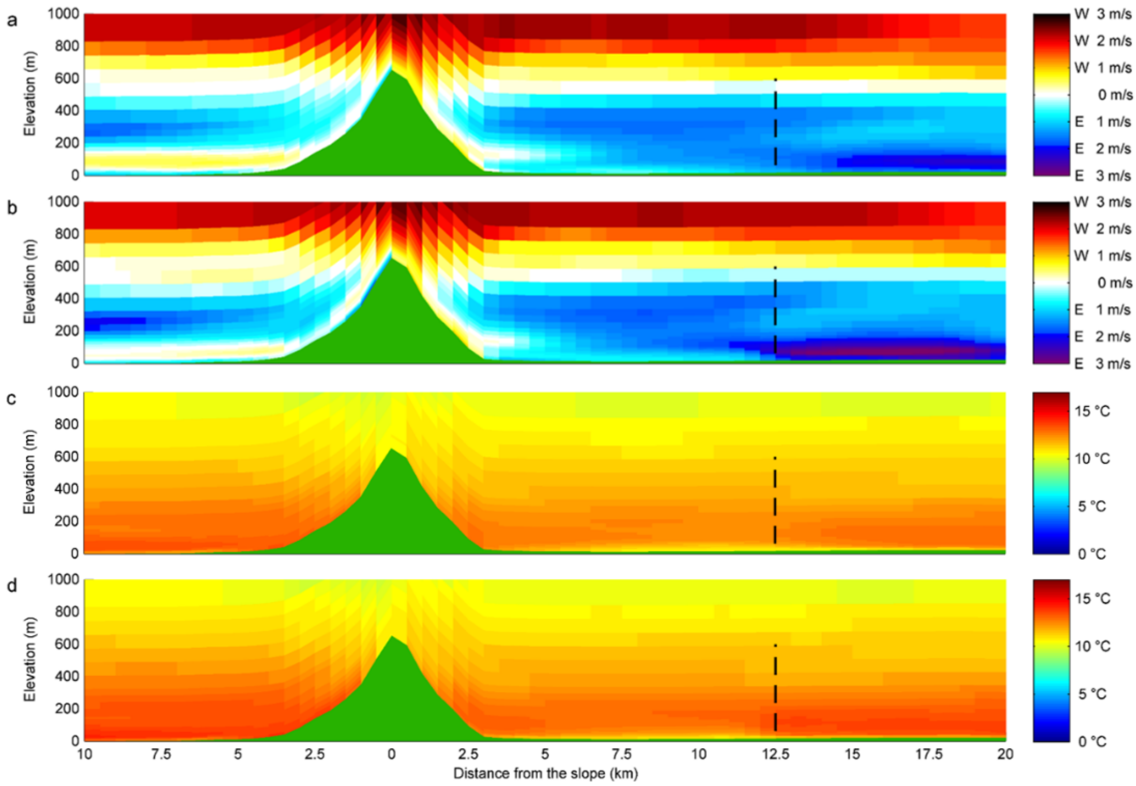

Figure 2. Vertical cross-section comparison for along slope velocity component (a, b) and temperature (c, d) between YSU (a, c) and YSUmod (b, d) for October 18, 2012, 22.20 local time. The dashed line corresponds to Sagebrush location of Balloon profile; W and E indicate western and eastern wind directions.

The along slope velocity component and temperature vertical cross-sections are shown for the original and the modified YSU schemes in Fig. 2. The down-slope flow penetrates deeply inside the field from the west site of the GM. The valley flow suppresses the down-slope flow on the eastern slope forming front of interaction when the flow reverses. The modified YSU increases the maximum speed from 2 to 3 ms^{-1} inside the valley; temperature within 300 m above the ground is also in better agreement with observations.

CONCLUSIONS

This work was conducted under the MATERHORN Program to understand the ability of WRF model to predict near surface flow and temperature for stable conditions in mountain terrain. Six different PBL schemes were evaluated against observations and compared with the modified YSU scheme. All of the schemes over-predict the minimum temperature inside the "valley cold pool" and could not capture well the low-level jet and vertical layering in the stratified layer. The preliminary results show better performance of the modified YSU scheme for the velocity profile within the PBL. The surface layer parameterizations contributed to near-surface variability, affecting the closest PBL layers and inducing errors to PBL mixing with the lower boundary condition. Further data processing and analysis is under way. The objective is to develop better parameterizations for turbulent fluxes in the complex terrain leading to improved predictability of local scale air flow. A new vertical scaling for the lower part of very stable PBL expected to be offered and implement into the surface layer.

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REFERENCES

Dimitrova, R., Z. Silver, H.J.S. Fernando, L. Leo, S. Di Sabatino, C. Hocut and T. Zsedrovits, 2014: Intercomparison between different PBL options in WRF model: modification of two PBL schemes for stable conditions. *Pross. of 94th AMS Annual Meeting*, 2-6 February, 2014, Atlanta, Georgia.

Fry, J., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold and J. Wickham, 2011: Completion of the 2006 national land cover database for the conterminous United States, *PE&RS*, **77**, 858-864.

Grisogono, B., L. Kraljević and A. Jerîčević, 2007: The low-level katabatic jet height versus Monin–Obukhov height, *Q J R Meteorol Soc*, **133**, 2133–2136.

Jiménez, P. A. and J. Dudhia, 2012: Improving the representation of resolved and unresolved topographic effects on surface wind in the wrf model. *J Appl Meteorol Clim*, **51** (2), 300–316.

Massey, J., W. J. Steenburgh, S. W. Hoch and J. C. Knievel, 2013: Sensitivity of near-srface temperature forecasts to soil properties over a sparsely vegetated dryland region. *J Appl Meteorol Clim*, in press

Monti, P., H. J. S. Fernando, M. Princevac, W. C. Chan, T. A. Kowalewski and E. R. Pardyjak, 2002: Observations of flow and turbulence in the nocturnal boundary layer over a slope. *J Atmos Sci*, **59**, 2513–2534.

Strang, E. J. and H. J. S. Fernando, 2001: Vertical mixing and transports through a stratified shear layer, J Phys Oceanogr, **31**, 2026-2048.

Willmott, C. J., 1981: On the validation of models. *Physical Geography*, **2**, 184–194.

WRF-ARW V3: User's Guide, 2008, updated 2012: *NCAR technical note*, NCAR/TN–475+STR, Boulder, Colorado, USA.