UNCLASSIFIED

WRF Forecast Sensitivity of Wave-Turbulence Interactions to Initialization Strategy and PBL Physics in the Stable Boundary Layer

Astrid Suarez[1], Dave Stauffer[1], Brian Gaudet[1] , Aijun Deng[1], Larry Mahrt[1] and Nelson Seaman[1]

[1]Department of Meteorology, Pennsylvania State University, PA, USA

14th Annual WRF Users' Workshop
June 24-28, 2013

Introduction

- Under clear skies and weakly-forced synoptic conditions at night, radiative cooling contributes to the development of the stable boundary layer (SBL)

- The SBL is characterized by strong static stability and weak, intermittent, turbulent mixing

- Turbulence in the SBL can be generated by submeso motions, nonstationary shear events with time scales on the order of one to tens of minutes and horizontal scales ranging from the turbulent scales to the meso-gamma scales (~2 m to 2 km)

- Submeso motions, can result in the enhanced dispersion of pollutants near the surface, the meandering transport of plumes, and the temporary coupling of the SBL with the residual layer

- Gravity waves are an important submeso mechanism

- Research has been conducted in order to understand the production and/or modulation of turbulence by gravity waves in the SBL, where gravity waves are often observed

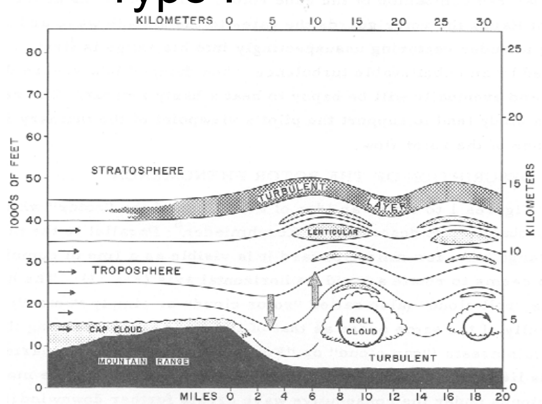
Introduction (Cont.)

- Waves can control both the production and/or destruction of turbulence through the modification of momentum and thermal fluxes and nonlinear phenomena such as wave breaking, rotor circulation and wave-wave interactions

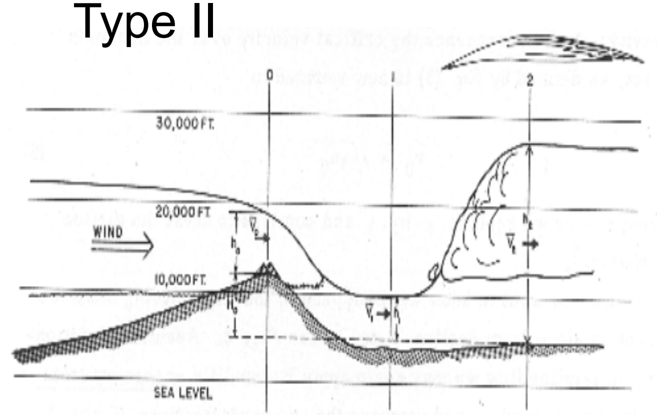
- Two types of rotor circulations have been identified in the atmosphere:
  - *Type I*: characterized by moderate or severe turbulence, where the rotor circulation becomes collocated beneath the resonant wave crest
  - *Type II*: characterized by severe to extreme turbulence associated with high amplitude waves

- Despite their relevance for the study and modeling of the SBL, the impact of this wave-induced circulation on the surface cold pool has been largely ignored

Type I



Type II



PENNSTATE 1855

Introduction (Cont.)

- Observations from the Rock Springs network (in Central Pennsylvania) and WRF forecasts are used to identify cases exhibiting these two types of wave circulation

- The sensitivity of WRF model forecasts to initialization strategy and to planetary boundary layer (PBL) physics is examined for these case studies

- Three initialization strategies, including free-forecasts and four dimensional data assimilation experiments, are examined

- Four PBL parameterizations currently available in WRF V3.3.1 are tested

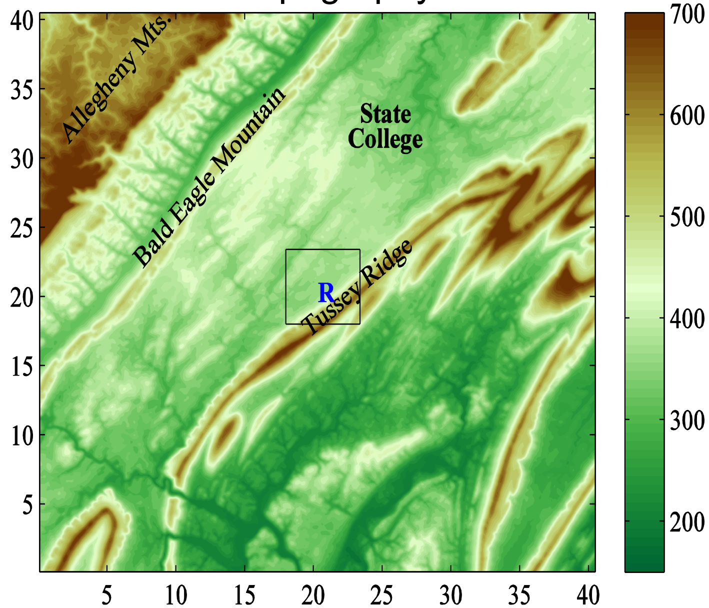
- WRF forecasts are verified against Rock Springs network observations

- The feasibility of the WRF model to forecast these complex wave-turbulence interactions is assessed through the analysis of filtered temperature (TEMP) and wind speed (WSP) fields

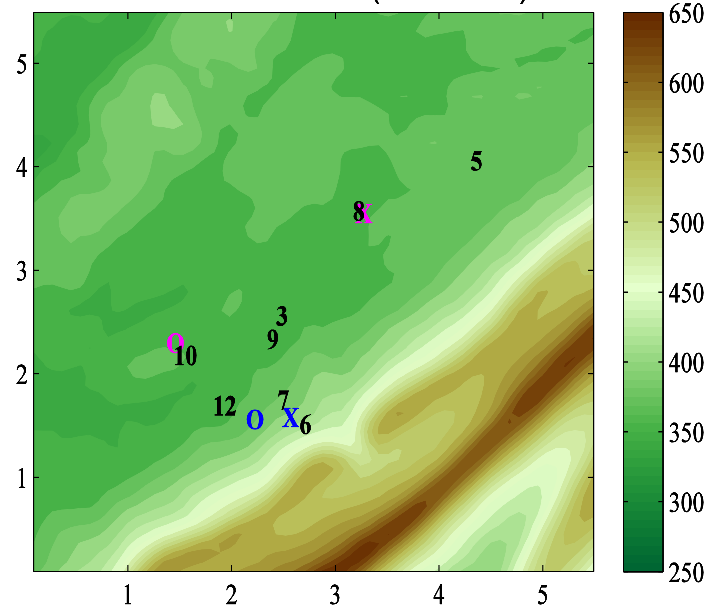
Rock Springs, PA Observing Network

- Observations from a surface network located near Rock Springs, PA USA are used for the study of the SBL and wave-turbulence interactions
- The network consists of two SODARs and an array of 2-, 10-, and 50-m towers equipped with
  - Rapid response 2-D (T, u, v) and 3-D sonic anemometers (T, u, v, w)
  - Thermistors (T)

Local Topography



Site IDs and SODAR (X and O) Locations



Description of Cases

- Six case studies, presenting gravity waves generated by both Allegheny Mts. and Tussey Ridge, are investigated
    - 14 April 2011 (APR14)
    - 16 September 2011 (SEP16)
    - 06 November 2011 (NOV06)
    - 04 December 2011 (DEC04)
    - 24 August 2011 (AUG24)
    - 13 November 2011 (NOV13)

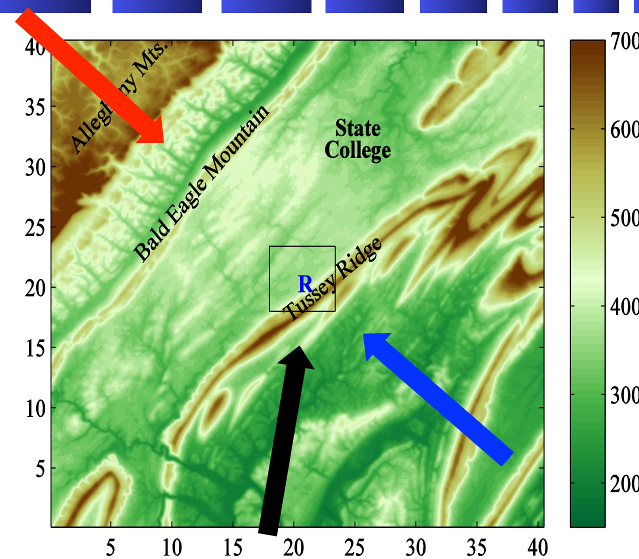
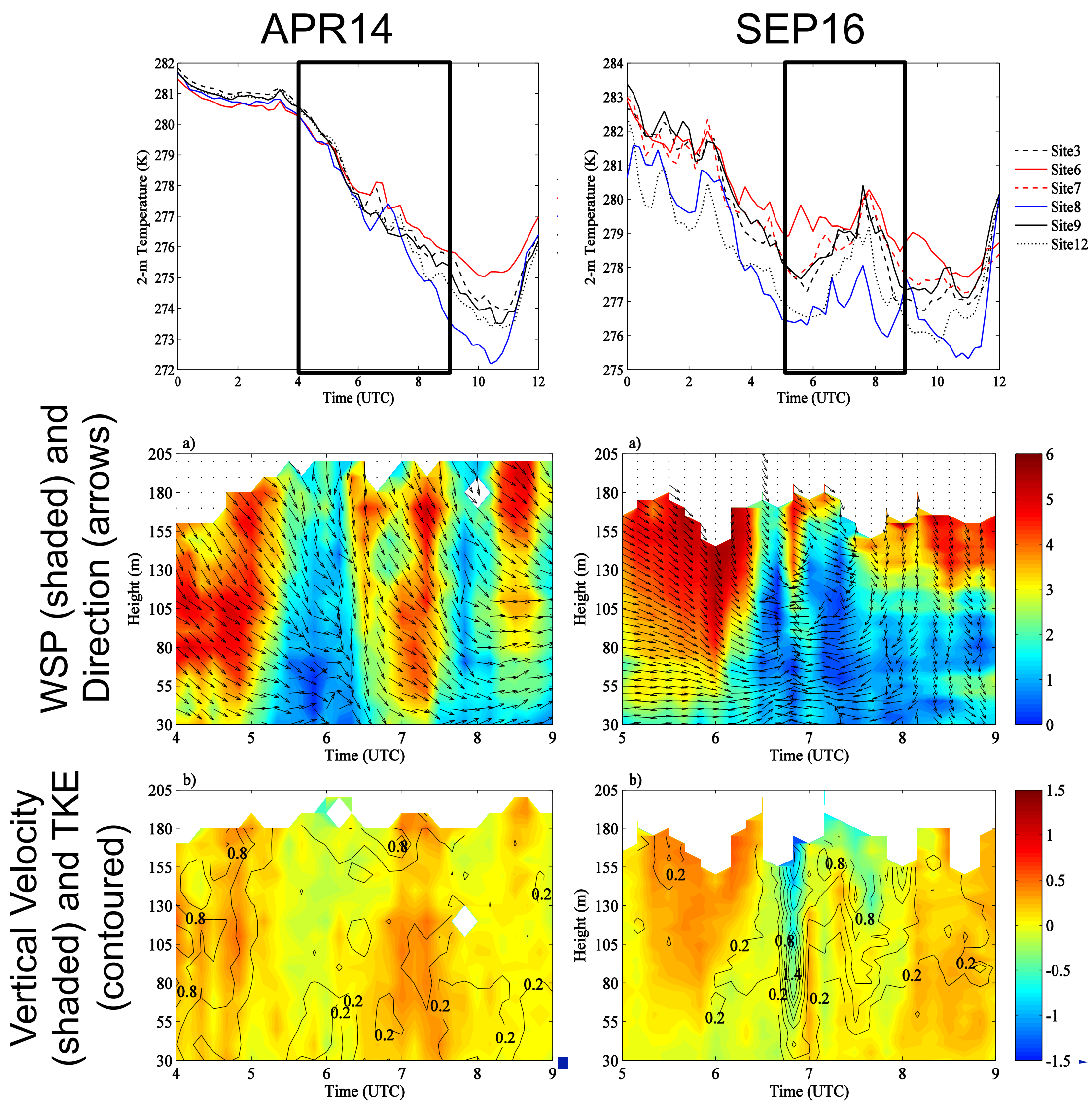


Table 1. Summary of Case Studies

CASES	WIND DIRECTION (Surface)	DIRECTIONAL SHEAR (Surface-850 hPa)	SOURCE	WAVE TYPE
APR14	NW	45	Allegheny Mts	Resontant Lee Wave/ Type I
SEP16	NW	45		
NOV06	SE	90	Tussey Ridge	Resontant Lee Wave/ Type I
DEC04	SE	90		
AUG24	S	45	Tussey Ridge	Downslope Windstorm/Type II
NOV13	SW	45		

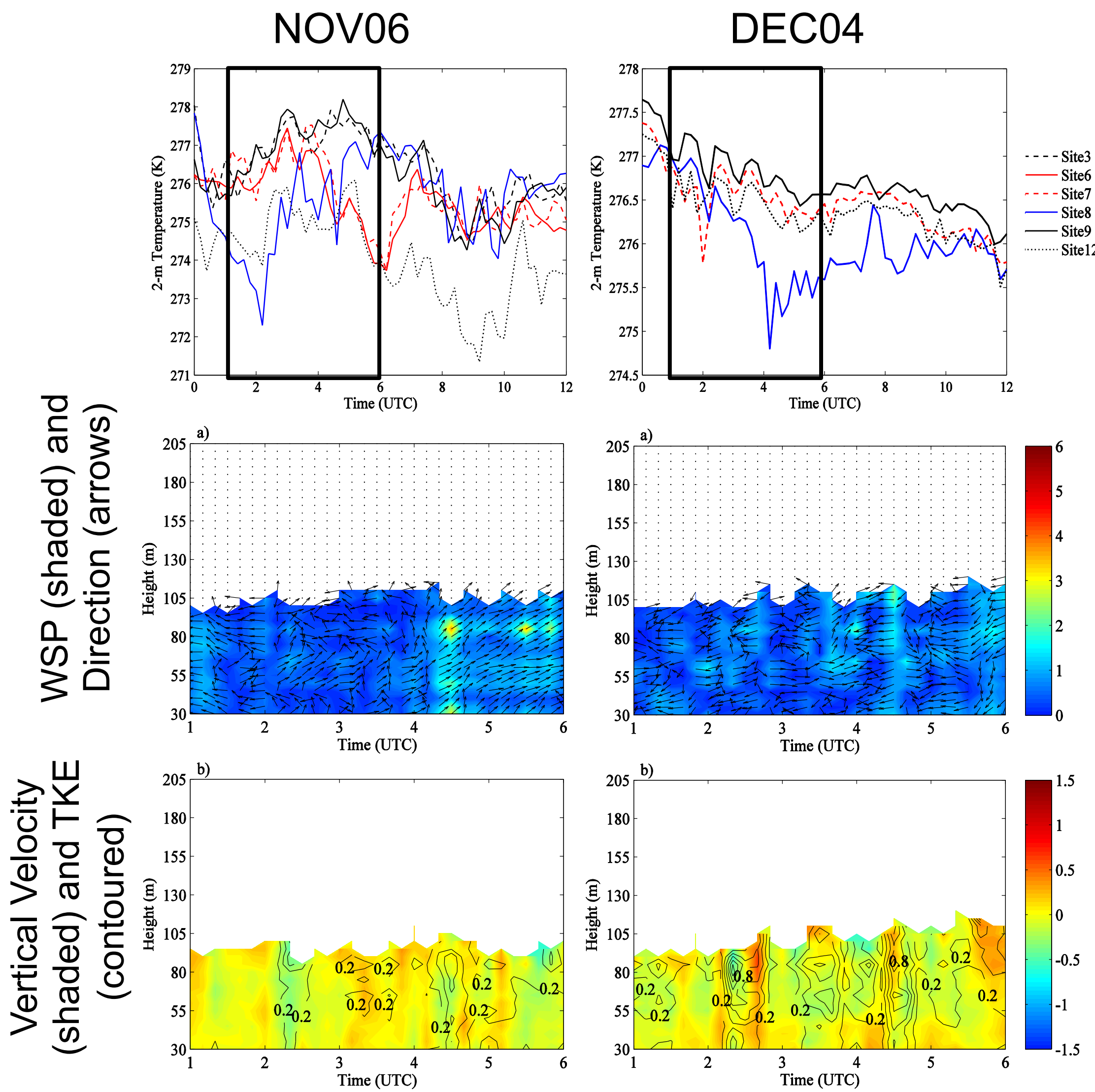
Description of Cases:
Network Measurements for APR14 and SEP16

- TEMP fluctuations of ~1-2 K through the night are observed at all sites
- Fluctuations are associated with wind directions shifts from NW to N and NW to E and weak WSPs
- The onset of these fluctuations are accompanied by changes in vertical motions and enhanced turbulent kinetic energy (TKE)
- TEMP, WSP and wind direction fluctuations suggest the presence of a Type 1 rotor circulation
- This can be the result of resonant lee waves excited by the Allegheny Mts.



Description of Cases:
Network Measurements for NOV06 and DEC04

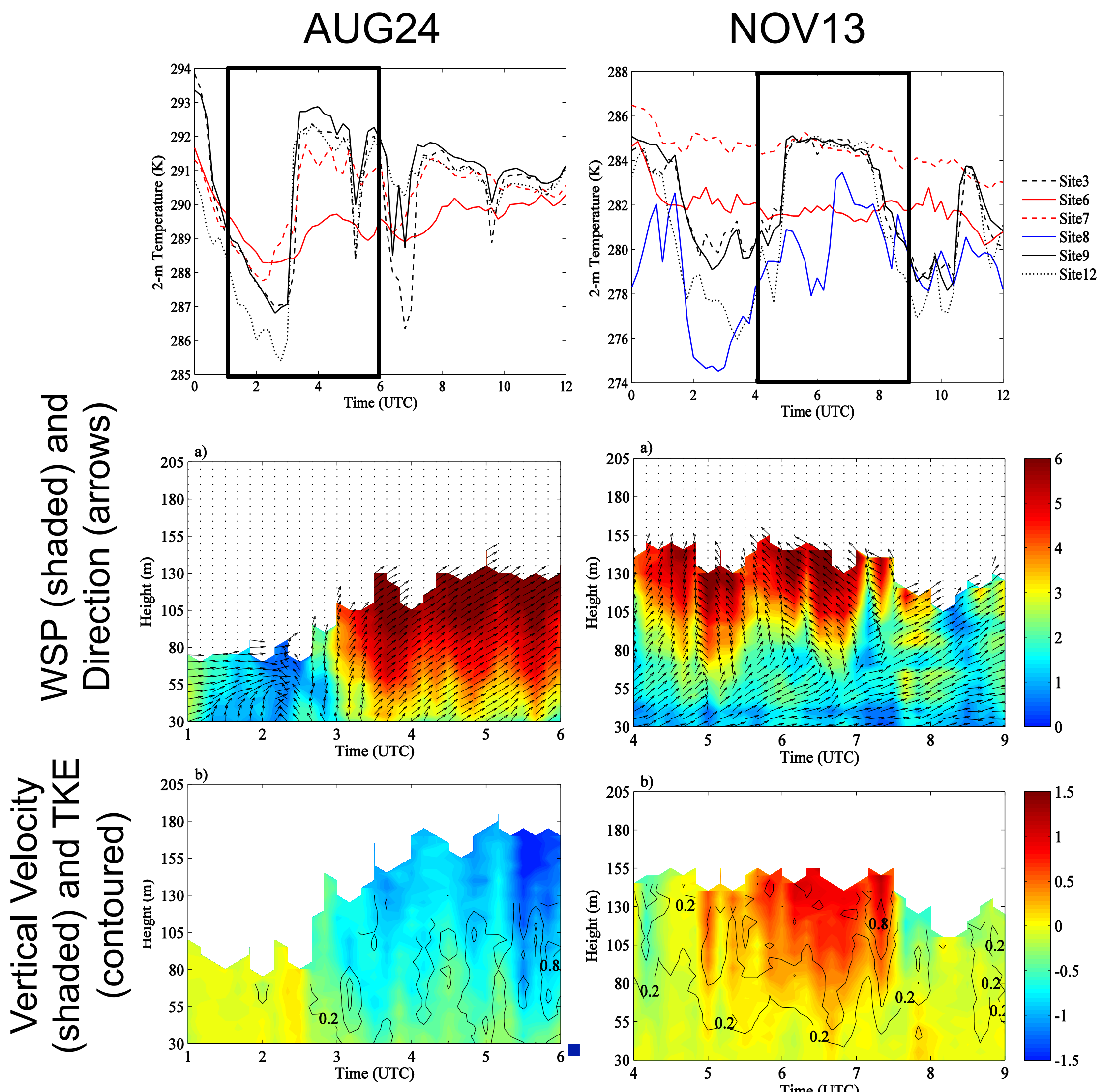
- TEMP fluctuations, of up to 3-4 K over 1 h, near the slope of Tussey Ridge and within the cold pool are observed
- Weaker, high-frequency fluctuations are present at Site 3, 7, and 9
- WSP of less than 2 m s^{-1} are observed throughout the night
- Wind direction shifts from SW to E are associated with downward vertical motions and enhanced TKE generation from 30 to 90 m AGL
- Type I rotor circulation generated by trapped waves excited by Tussey Ridge are hypothesized to affect the network through the night



Description of Cases:

Network Measurements for AUG24 and NOV13

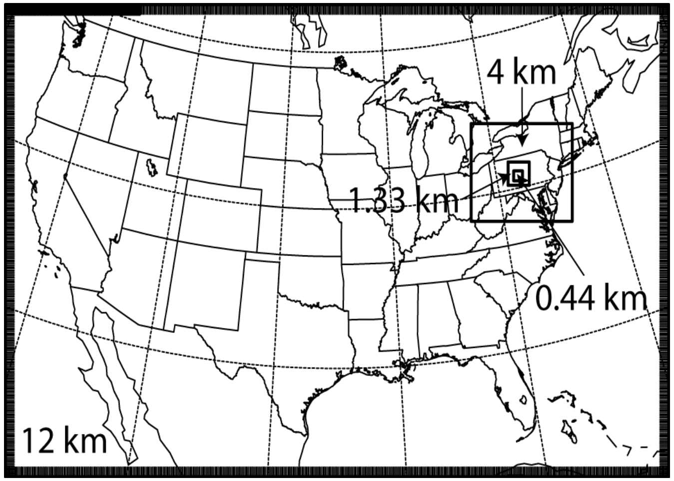
- Step-like TEMP changes of 5-7 K over 10s of min are observed for sites located lower in the valley
- The onset of the fluctuations is associated with increasing WSPs of up to 6 m s^{-1} and wind direction shifts from SW
- For AUG24 (SODAR located on the slope), downward motions associated with the downward branch of a lee wave is observed
- For NOV13 (SODAR located in the valley), upward motion associated with the upward branch of the lee wave is present
- Both cases present large TKE generation during the events

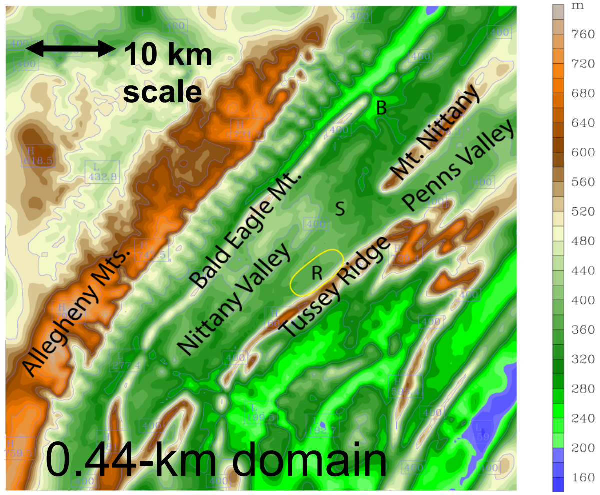


UNCLASSIFIED

WRF Configuration

- WRF Version 3.3.1
- Four one-way nested domains: 12, 4, 1.33, and 0.44 km
- GFS 0.5˚x0.5˚ or pre-forecast data assimilation initialization
- WSM 3-class microphysics
- RRTM longwave / Dudhia shortwave radiation (5 min updated frequency)
- Kain-Fritsch cumulus parameterization on 12-km domain only
- Noah LSM with MODIS land use
- Model output every 1 h, 1 h, 12 min, and 12 min for the 12-, 4-, 1.33-, and 0.44-km domains
- High frequency output (10 s) available over a small region encompassing the Rock Springs network





WRF Experiments:
Initialization Strategy

- Three initialization strategies are tested:
  - ***CTRL***: a 12-h forecast initialized at 0000 UTC from GFS
  - ***BSL***: a 24-h forecast initialized from GFS 12 h prior to 0000 UTC (1200 UTC)
  - ***FDDA***: a 12-h forecast following a 12-h four-dimensional-data-assimilation, pre-forecast period initialized at 1200 UTC from GFS

- During the pre-forecast:
  - Stauffer and Seaman (1994) multi-scale FDDA with analysis nudging of GFS analysis data is performed in the 12-km domain (Deng et al. 2009)
  - Observation nudging is also applied for all domains, over all levels, to constrain local aspects of the WRF forecasts to:
    - World Meteorological Organization (WMO) observations
    - Rock Springs observations (Site 3 temperature and wind)

WRF Experiments:
Initialization Strategy

- The CTRL, BSL, and FDDA initialization strategies are tested for all six case studies

- The experiments are conducted using the modified Mellor-Yamada-Janjic (MYJ) PBL parameterization coupled with the NCEP Eta model surface layer scheme (Janjic 2002), as described by Seaman et al. (2012)

    - *background mixing is reduced from 0.1 to 0.01 $m^2\ s^{-2}$*

Table 2. Initialization Strategy Experiments

CASE	CTRL *Initialized at 0000 UTC*	*BSL* *Initialized 12 h prior to 0000 UTC*	*FDDA* *12-h pre-forecast period*
APR14	APR14_MYJ_CTRL	APR14_MYJ_BSL	APR14_MYJ_FDDA
SEP16	SEP16_MYJ_CTRL	SEP16_MYJ_BSL	SEP16_MYJ_FDDA
NOV06	NOV06_MYJ_CTRL	NOV06_MYJ_BSL	NOV06_MYJ_FDDA
DEC04	DEC04_MYJ_CTRL	DEC04_MYJ_BSL	DEC04_MYJ_FDDA
AUG24	AUG24_MYJ_CTRL	AUG24_MYJ_BSL	AUG24_MYJ_FDDA
NOV13	NOV13_MYJ_CTRL	NOV13_MYJ_BSL	NOV13_MYJ_FDDA

WRF Experiments:
PBL Parameterization

- Four PBL parameterization/schemes currently available in WRF are tested:
    1) modified MYJ
    2) Yonsei University (YSU; Hong et al. 2006)
    3) Quasi-normal Scale Elimination (QNSE; Sukorianky et al. 2005)
    4) Mellor-Yamada-Nakanishi-Niino (MYNN; Nakanishi and Niino 2004)

- All experiments are conducted using the FDDA initialization strategy previously discussed

- Three cases, presenting the three gravity-wave types, are examined. These include SEP16, NOV06, and NOV13

Table3. PBL Physics Sensitivity Experiments

PBL Scheme	SFC Scheme	SEP16	NOV06	NOV13
MYJ	Eta	SEP16_MYJ_FDDA	NOV06_MYJ_FDDA	NOV13_MYJ_FDDA
MYNN	Eta	SEP16_MYNN_FDDA	NOV06_MYNN_FDDA	NOV13_MYNN_FDDA
QNSE	QNSE	SEP16_QNSE_FDDA	NOV06_QNSE_FDDA	NOV13_QNSE_FDDA
YSU	MM5	SEP16_YSU_FDDA	NOV06_YSU_FDDA	NOV13_YSU_FDDA

WRF Experiments:
Verification Strategy

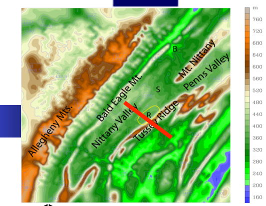
- Rock Springs observations are used to verify model predictions of gravity waves in the 0.444-km WRF domain
- Spectral decomposition is applied to the observations and model predictions in order to evaluate the model's ability to forecast motions at various scales
- Following Gaudet et al. (2008), the evaluation of the model is separated into a low-frequency, "deterministic" component and a high-frequency, non-deterministic component
- The spectral distribution is determined by applying a 2-h running mean average filter to both observed and modeled fields
    - Verification of low-frequency components (greater than 2 h) is conducted by computing mean absolute error (MAE) and mean error (ME)
    - Verification of high-frequency components (less than 2 h) is conducted by examining the mean amplitude distributions within the network
- This verification strategy is applied to TEMP and WSP

Initialization Strategy

PENNSTATE

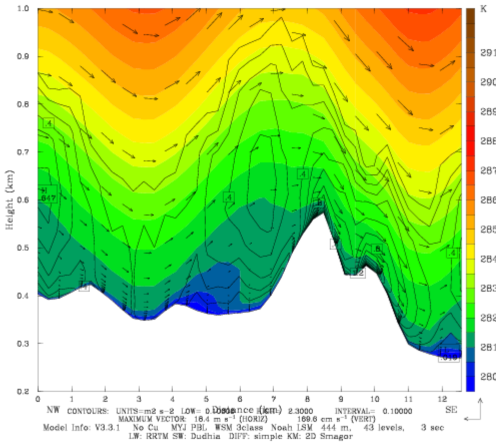
1855

Model-Predicted Wave-Turbulence Interactions over the Rock Springs Network

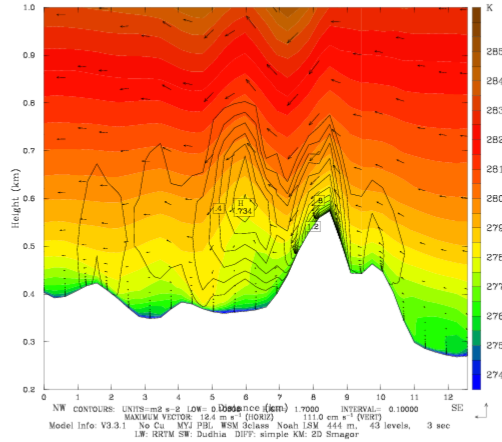


10 km scale

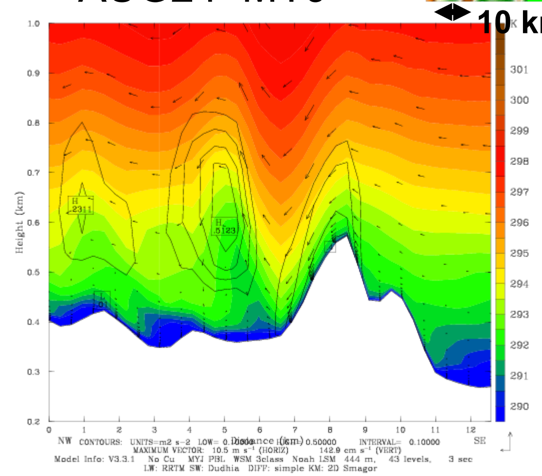
APR14_MYJ



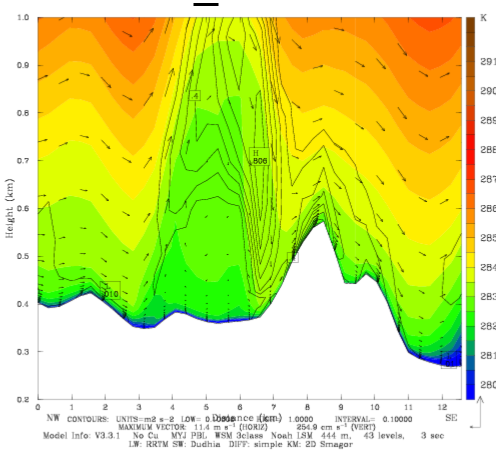
NOV06_MYJ



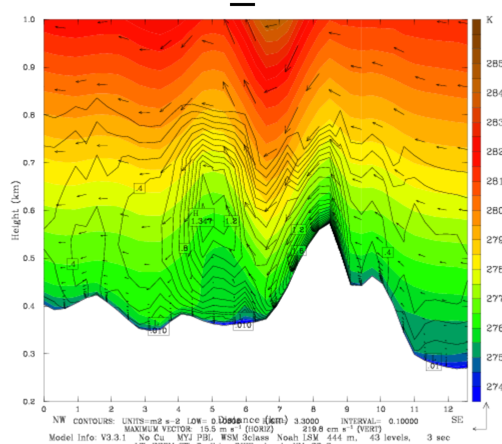
AUG24 MYJ



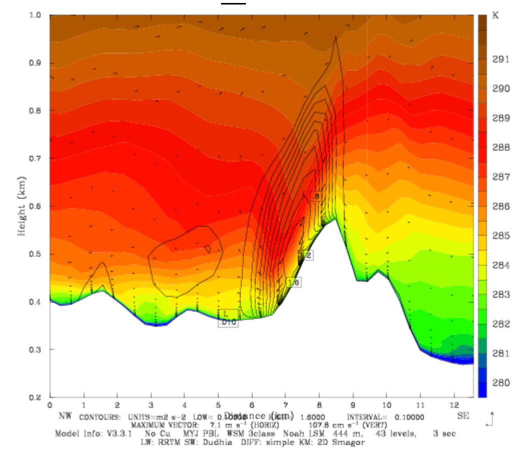
SEP16_MYJ



DEC04_MYJ

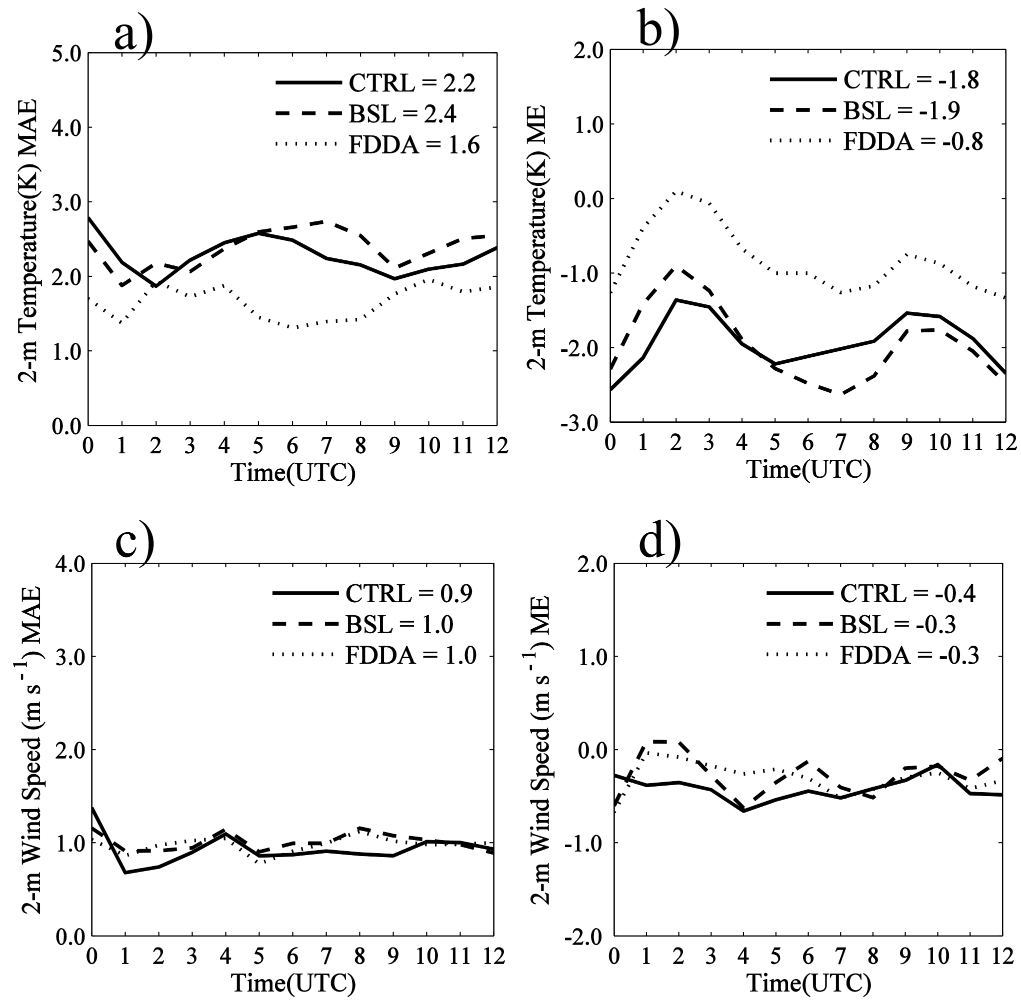


NOV13_MYJ



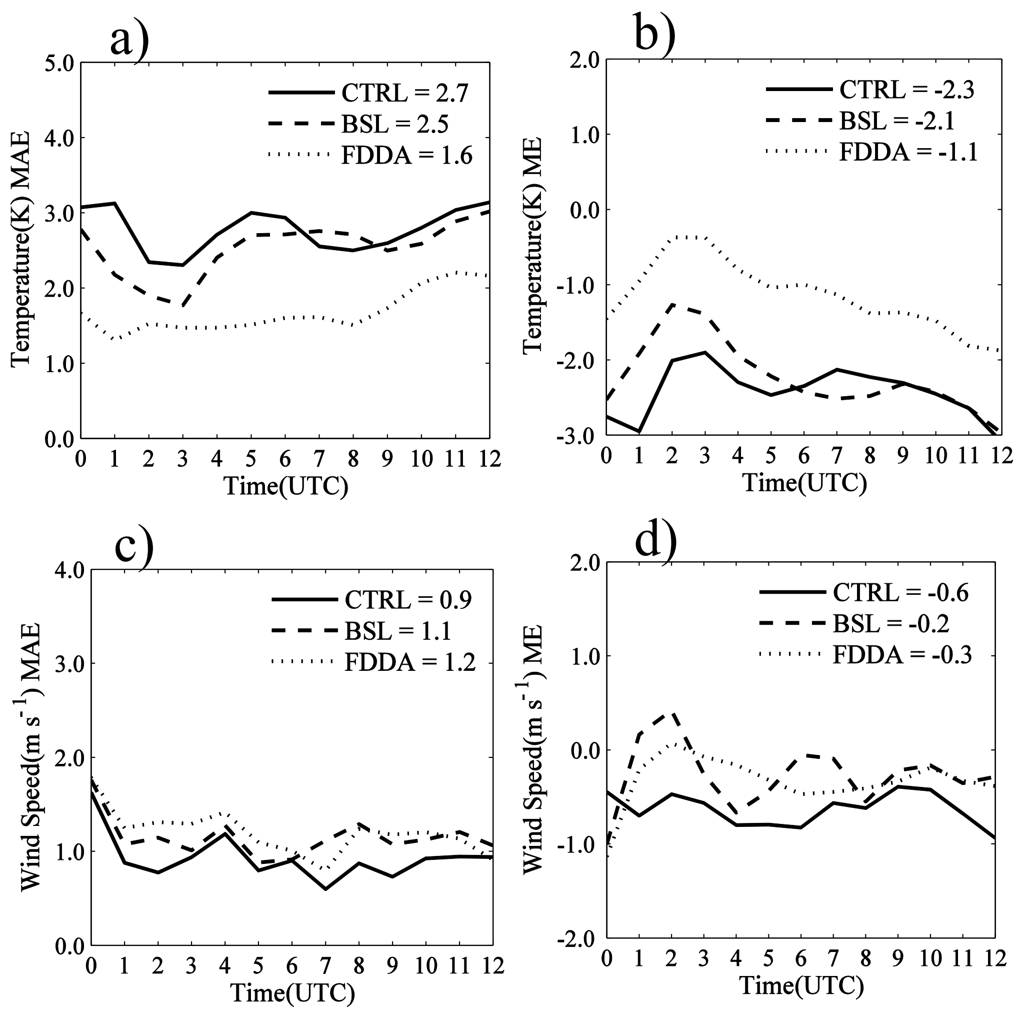
Initialization Strategy:
Verification of 2-m TEMP and WSP over the Network

- FDDA produces the best initial conditions (0000 UTC) for 2-m TEMP over the network, and the lowest 2-m TEMP MAE and ME over all experiments
- FDDA also produces the best initial conditions for the 2-m WSP
- 10-h averaged WSP MAE (0.9 to 1.0 m s^{-1}) and ME (-0.3 to -0.4 m s^{-1}) for all initialization strategies are statistically similar



Initialization Strategy:
Verification of 9 and 17-m TEMP and WSP over the Network

- At 9 and 17 m AGL, the FDDA still has a statistical advantage over CTRL and BSL when forecasting TEMP
- The FDDA produces 10-h MAE and ME up to 1 K smaller than other initialization strategies
- CTRL and BSL have cold biases greater than 2 K through the night
- CTRL produces the smallest WSP MAE, but it has the largest WSP biases
- At these levels, BSL and FDDA perform comparably when forecasting WSP
- All the experiments slightly under-predict WSPs at these levels



Initialization Strategy:
2-m TEMP Fluctuations between 12 min and 2 h

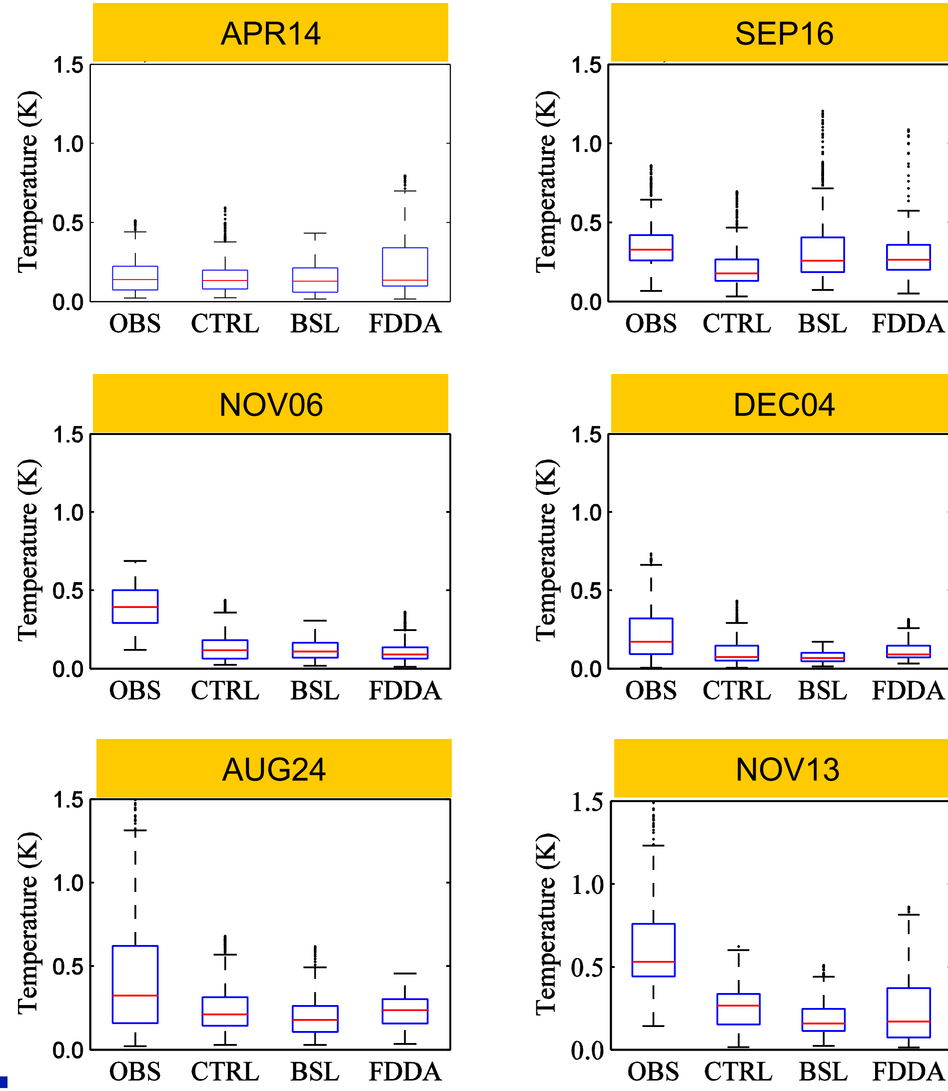
- For APR14, FDDA produces larger than observed 2-m TEMP fluctuations. CTRL and BSL seem to better forecast the fluctuations for this event.

- For SEP16, BSL and FDDA better predict 2-m TEMP fluctuations than CTRL

- For NOV06 and DEC04, all of the initialization strategies produce TEMP fluctuations smaller than those observed.

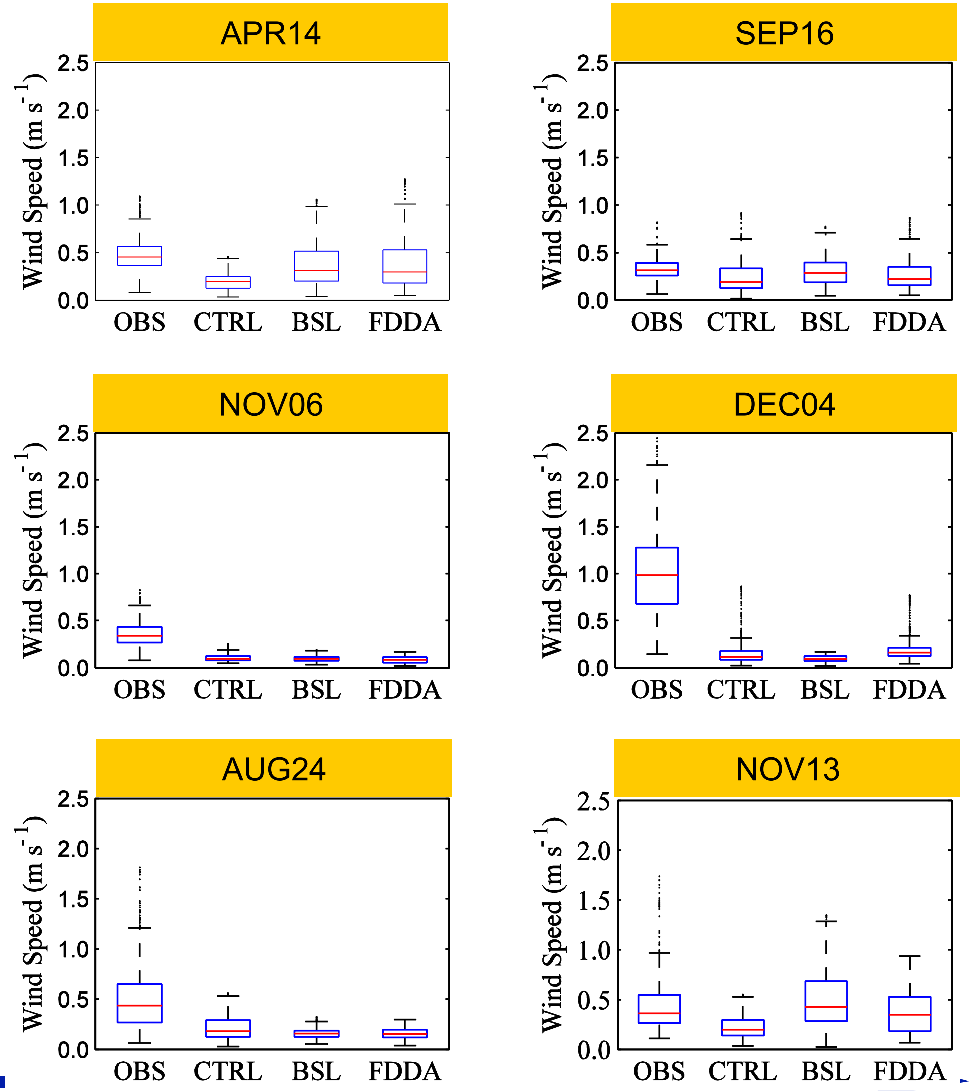
- For AUG24, all of the experiments perform comparably. FDDA median is closer to those observed.

- For NOV13, FDDA produces a larger range of fluctuations with amplitudes larger than those forecasted by CTRL and BSL.



Initialization Strategy:
2-m WSP Fluctuations between 12 min and 2 h

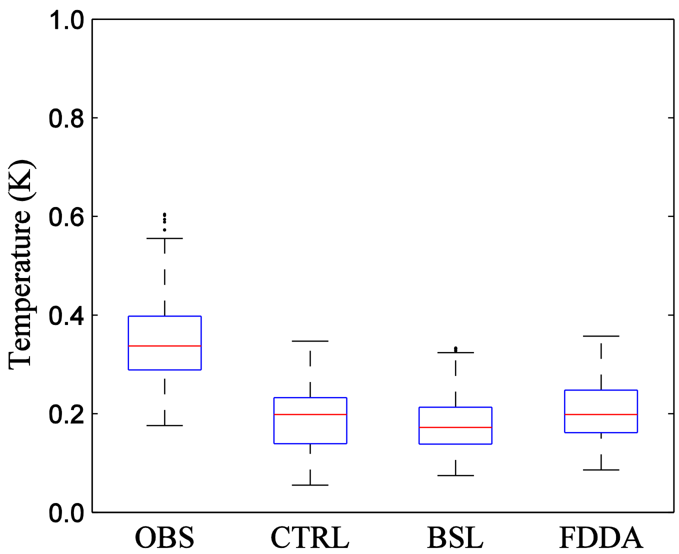
- For APR14, CTRL under-predicts the amplitude of WSP fluctuations
- For SEP16, all of the schemes forecast similar spread. However, BSL and FDDA better match the observed median
- All of the PBL schemes forecast much weaker WSP fluctuations than observed for NOV06, DEC04, and AUG24
- For NOV13, FDDA has an advantage forecasting the amplitude of WSP fluctuations over the CTRL and BSL
- For this case, BSL produce slightly larger than observed fluctuations within the network

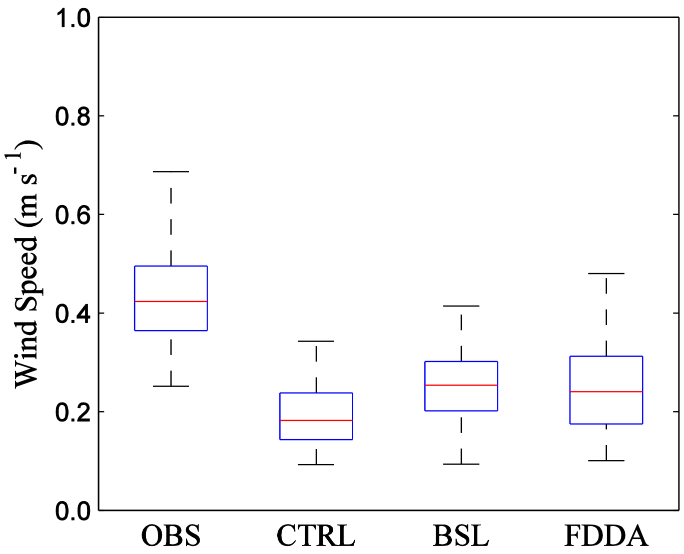


UNCLASSIFIED

Initialization Strategy:
TEMP and WSP Fluctuations for All Cases

- Over all cases, all of the initialization strategies forecast TEMP and WSP fluctuations weaker than observed
- FDDA has a small advantage forecasting TEMP and WSP fluctuations over the other initializations
- CTRL produces much weaker WSP fluctuations than observed over all experiments





PBL Parameterization

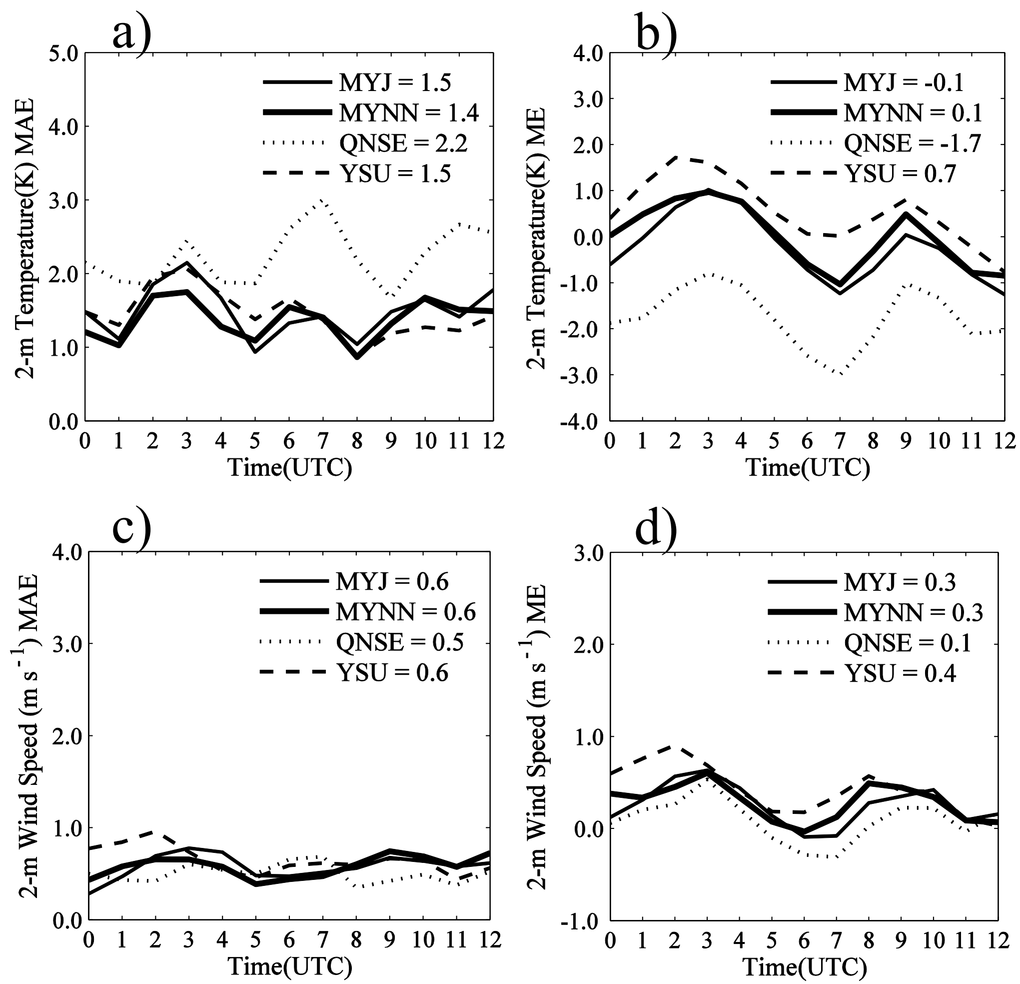
PBL Parameterization:
Verification of 2-m TEMP and WSP

- The QNSE has a large cold bias for all experiments (initial cold bias of ~ 2 K) and YSU has the largest warm bias (0.7 K)

- The MYJ and MYNN have near zero 10-h averaged TEMP bias

- Similar 2-m WSP MAE for all parameterizations

- The MYJ, MYNN and YSU have positive WSP biases of 0.3, 0.3, and 0.4 m s^{-1} respectively, while the QNSE has a slight advantage at 0.1 m s^{-1}

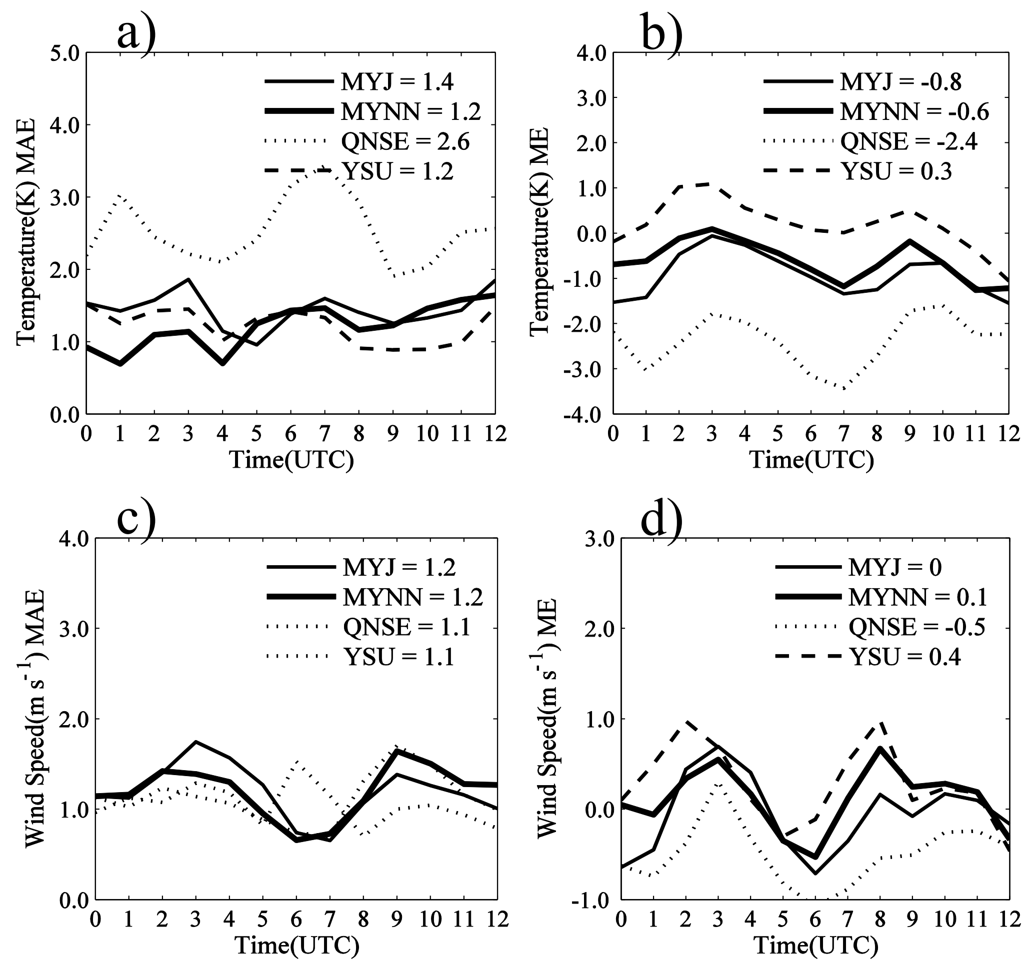


PENNSTATE

1855

PBL Parameterization:
Verification of 9 and 17-m TEMP and WSP

- The QNSE continues to have a large MAE and ME with a cold bias of 2.4 K through the night
- MYNN and YSU have a small advantage (0.2 K) over MYJ forecasting TEMP at 9 and 17 m AGL for 10-h averages
- All of the PBL schemes have similar WSP MAE (1.1 to 1.2 m s^{-1})
- MYJ and MYNN have near zero biases in WSP
- QNSE has negative WSP biases of 0.5 m s^{-1}
- YSU has a positive WSP bias of 0.4 m s^{-1}



PENNSTATE

1855

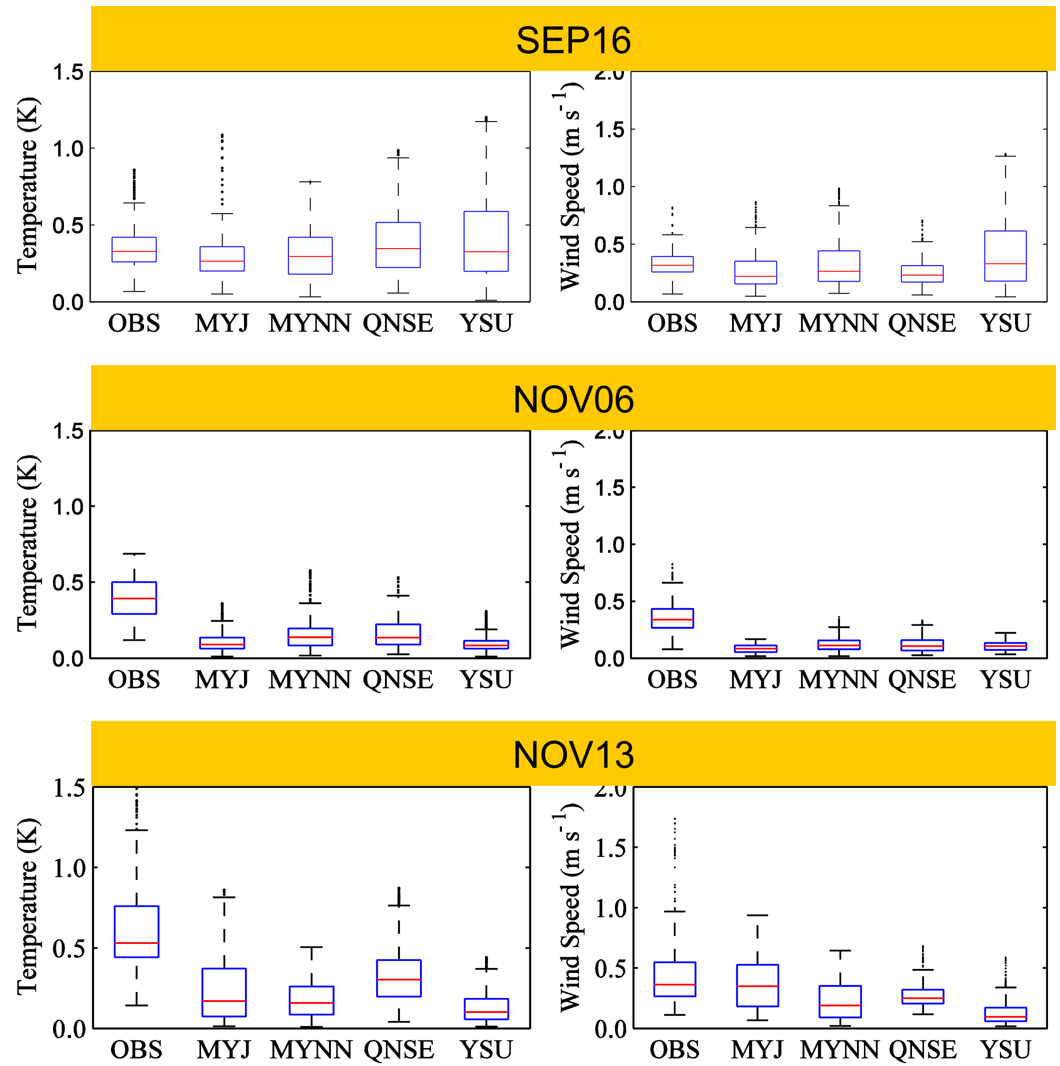
PBL Parameterization:

2-m TEMP and WSP Fluctuations between 12 min and 2 h

- For SEP16, all experiments produce comparable fluctuations to those observed. MYJ and MYNN produce fluctuations closer to observed for TEMP, while the QNSE and YSU over-predict the amplitude of 2-m TEMP.

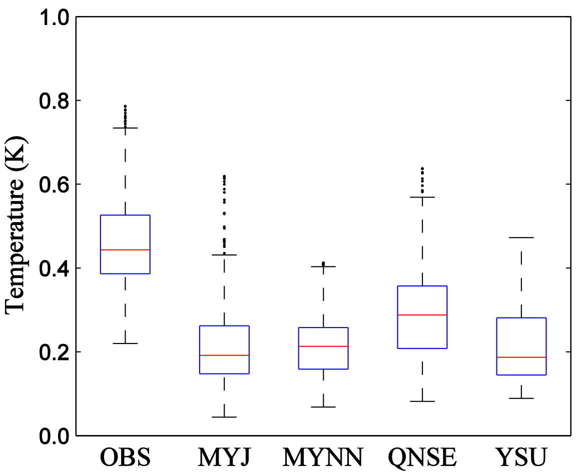
- For NOV06, all the experiments under-predict the fluctuations. The MYNN and QNSE produce larger TEMP fluctuations than MYJ and YSU

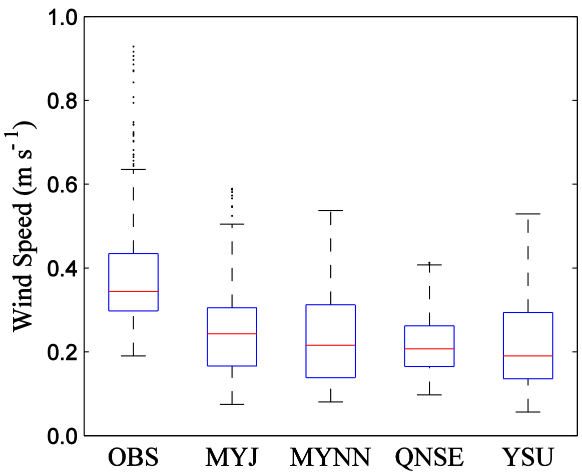
- For NOV13, the MYJ and QNSE seem to have a slight advantage when forecasting TEMP. MYJ produces the best WSP forecast for this case



PBL Parameterization:
Mean TEMP and WSP Fluctuations for All Cases

- Overall, all of the PBL schemes under-predict 2-m TEMP and WSP fluctuations, but there are some advantages for the TKE-based schemes
- The YSU has some disadvantages forecasting TEMP and WSP fluctuations since it over-predicts fluctuations for SEP16 and largely under-predicts fluctuations for NOV06 and NOV13
- QNSE has some advantages when forecasting 2-m TEMP fluctuations over other schemes
- Although the medians are similar, the MYJ and MYNN produce a spread of WSP fluctuations more consistent with observations than the QNSE





Conclusions:
Initialization Strategy

- All of the initialization strategies forecast the complex wave-turbulence interactions for the case studies. This includes the production of Type I and Type II rotors as hypothesized from observations (not shown)

- All of the strategies forecast similar wave structures; however, they differ in the specific wave characteristics such as amplitude, frequency, wavelength, and transitions (not shown)

- FDDA strategy has some advantages when forecasting TEMP and WSP for both low- and high-frequency motions

- FDDA produces TEMP MAEs less than 1.6 K and TEMP ME less than 1.1 K at all levels (2, 9 and 17 m AGL)

- All the initialization strategies perform comparably for low-frequency WSP forecasts

- Nevertheless, FDDA produces slightly more realistic WSP fluctuations than the other initialization strategies for four out of the six cases examined

Conclusions:
PBL Parameterization

- For low-frequency, deterministic motions, the MYJ, MYNN and YSU perform comparably for TEMP, while the QNSE has a large cold bias that results in poor MAE and ME
- The QNSE poor temperature forecasts can be a result of using the scheme during the daytime (where this scheme has been shown to have some difficulties)
- All of the schemes perform comparably when forecasting WSP
- Overall, all of the PBL schemes under-predict 2-m TEMP and WSP fluctuations, but there are some advantages for the TKE-based schemes
- QNSE has some advantages when forecasting TEMP fluctuations over the other schemes; while MYJ and MYNN perform better than QNSE and YSU when forecasting WSP fluctuations for SEP16 and NOV13
- Deterministic accurate predictions of submeso motions (i.e., the timing and detail structure of temperature and wind fluctuations) is very difficult if not impossible
- Stochastic methods for representing the effect of submeso motions should be investigated

Thank you

Acknowledgements

- This research was funded by DTRA Grant No. HDTRA1-10-1-0033 under the supervision of John Hannan and Anthony Esposito.
- Funding for sodars and additional tower instrumentation were provided by the US Army Research Office by DURIP Grant No. W911NF-10-1-0238 under the supervision of Walter Bach.

PENNSTATE

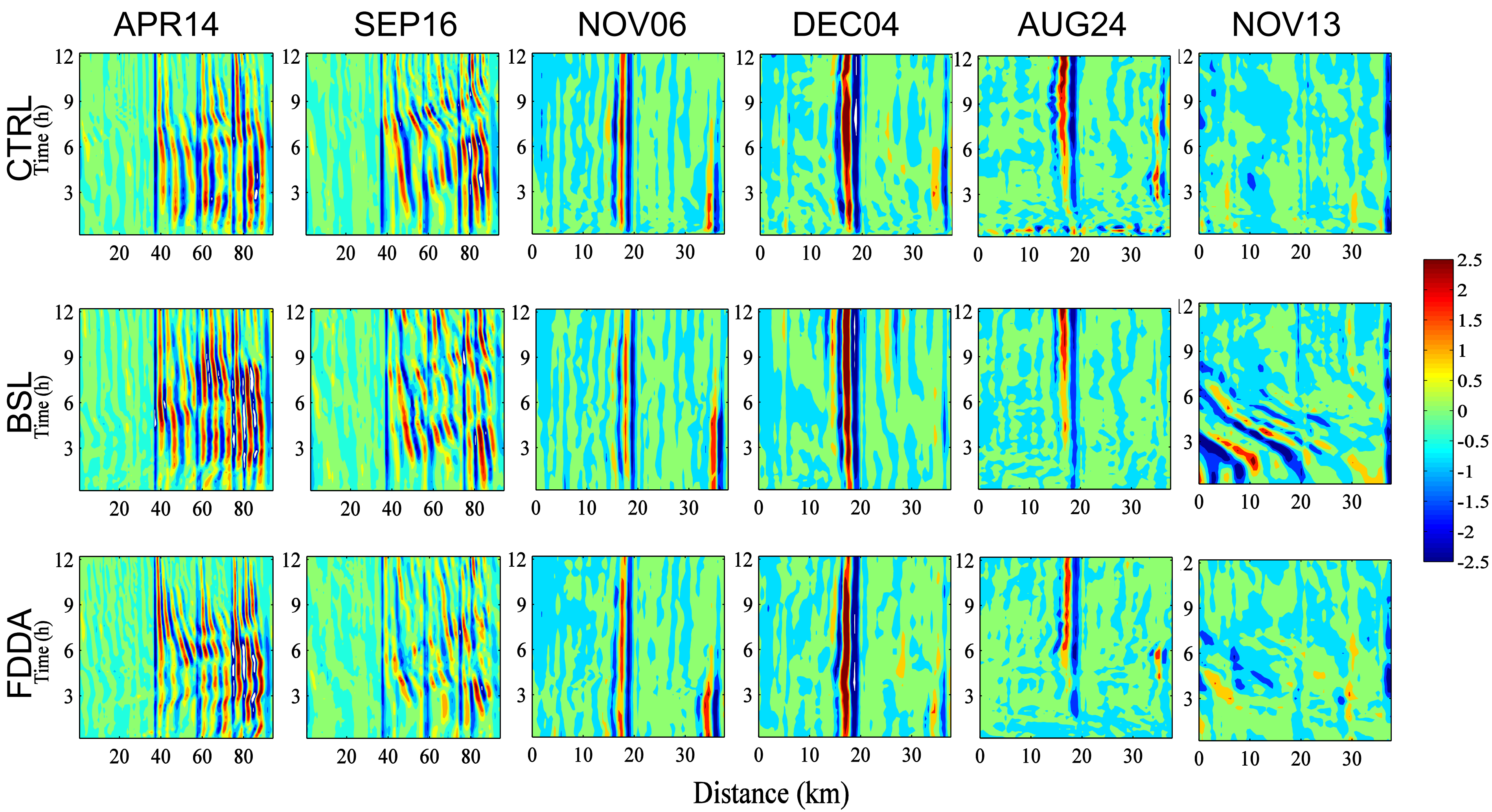
1855

References

- Deng, A., D. Stauffer, B. Gaudet, J. Dudhia, C. Bruyere, W. Wu, F. Vanderberghe, Y. Liu, and A. Bourgeois, 2009: Update on WRF-ARW end-to-end multi-scale FDDA system. 10th WRF Users' Workshop, NCAR, 23-26 June, Boulder, CO., 1.9.14
- Gaudet, B.J., N.L. Seaman, D.R. Stauffer, S. Richardson, L. Mahrt and J.C. Wyngaard, 2008: Verification of WRF-predicted mesogamma-scale spectra in the SBL using a high-frequency filter decomposition. Preprints, *9th WRF Users' Workshop,* Boulder, CO, NCAR/MMM, P8.1
- Hong, Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly Weather Review*, 134, 2318-2341.
- Janjic, Z.I., 2002: Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model, NCEP Office Note, No. 437, 61.
- Nakanishi, M. and H. Niino, 2004: An improved Mellor-Yamada level-3 model with condensation physics: Its design and verification. *Boundary Layer Meteorology*, 112, 1-31.
- Seaman, N.L., B.J. Gaudet, D. R. Stauffer, L. Marht, S.J. Richardson, J.R. Zielonka, and J.C. Wyngaard, 2012: Numerical prediction of the submesoscale flow in the nocturnal boundary layer over complex terrain. *Mon. Wea. Review*, 140, 956-997.
- Stauffer, D.R., and N.L. Seaman, 1994: Multiscale four-dimensional data assimilation. *Journal of Applied Meteorology*, 33, 416-434.
- Sukoriansky, S., B. Galpering, and V. Perov, 2005: Application of a new spectral theory of stable stratified turbulence to the atmospheric boundary layer over sea ice. *Boundary-Layer Meteorology*, 117, 231-257.

Supplemental Material

Initialization Strategy:
Hovmoller Diagrams for All Exp.

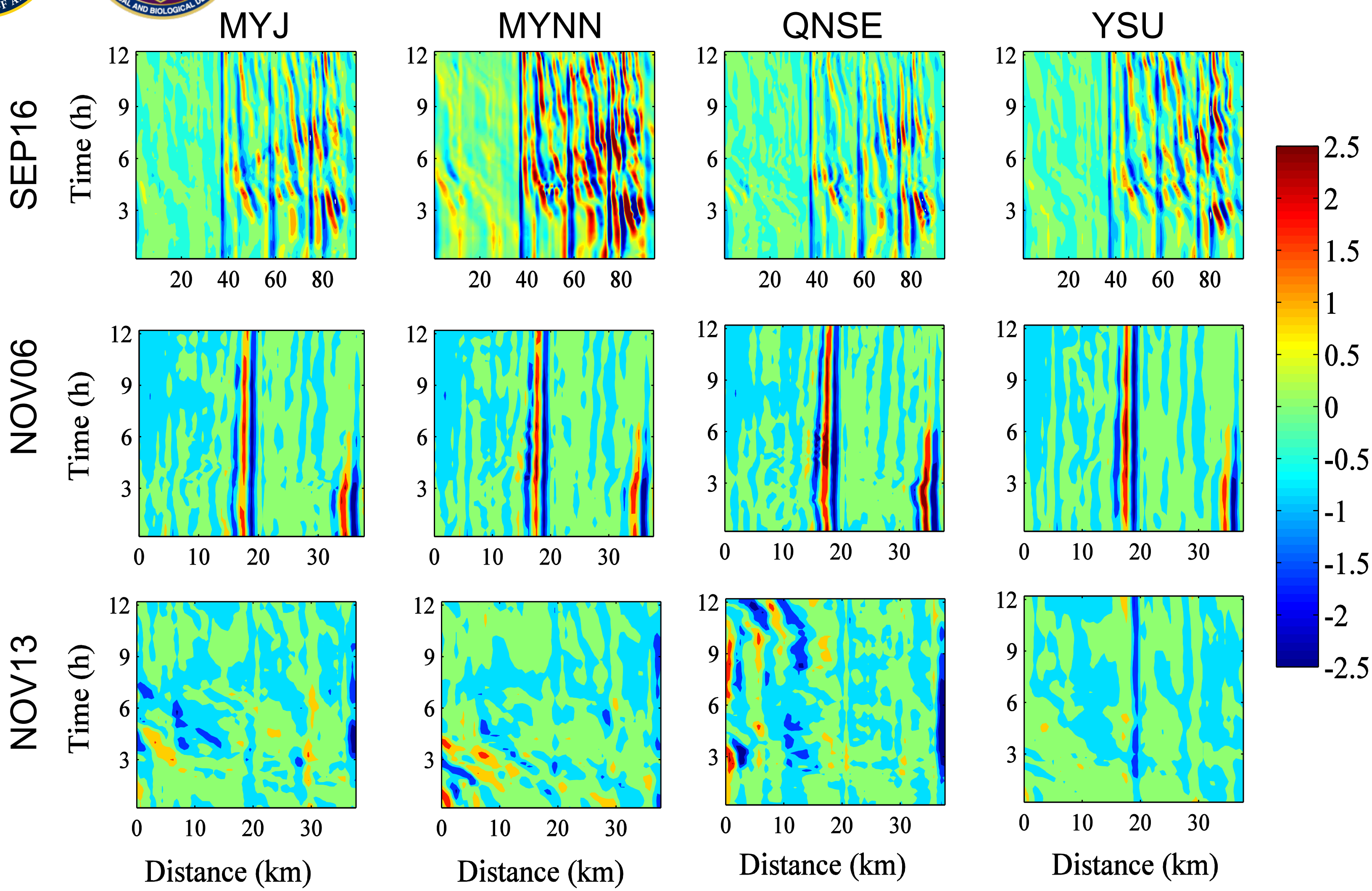


Distance (km) Distance (km) Distance (km)

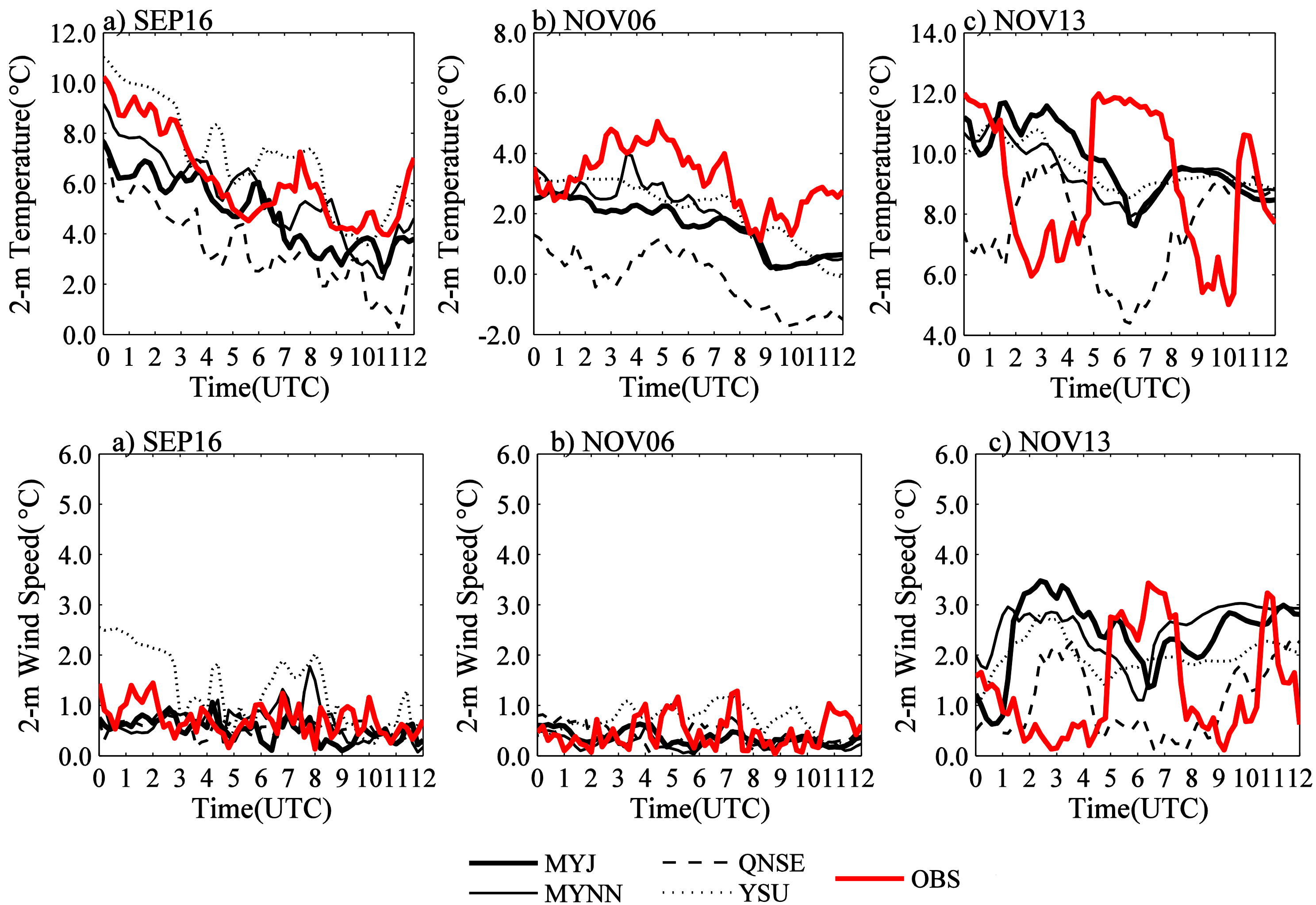
PENNSTATE

1855

PBL Parameterization:
Hovmoller Diagrams for All Exp.



PBL Parameterization:
TEMP and WSP at Site 9



Wave-Turbulence Interaction for AUG24_MYJ:
Potential Temperature (shaded) and TKE (contoured)

- Trapped wave modes, resembling a hydraulic jump, over the Rock Springs network