Model-Physics and Data-Assimilation Sensitivity Studies for High Resolution Modeling of the Stable Boundary Layer

Brian P. Reen¹, David R. Stauffer¹, Brian J. Gaudet¹, Nelson L. Seaman¹, Astrid Suarez¹, Scott J. Richardson¹, Larry Mahrt², and Joshua D. Hoover¹

¹ Dept. of Meteorology, Penn State University
² COAS, Oregon State University

12th Annual WRF Users’ Workshop
Paper 5.6
22 June 2011
Boulder, CO
Background

- Stable boundary layers (SBLs) are difficult to predict well since weak forcing can result in very shallow SBLs (of order 1-10 m) with weak winds with highly variable directions influenced by waves, shallow drainage flows, etc.

Observed 1-minute 9-m Wind at Central PA Site on 4-5 September 2009
Goals

• Project Goal: To understand and predict the structure and variability of stable boundary layers (SBLs) to improve predictions of atmospheric transport and dispersion (AT&D)

• Presentation Goal: Investigate sensitivity of SBL model results to:
  - Radiation update frequency / slope shading effects
  - Land-Surface Model (LSM)
  - Initial conditions
Topography of Central PA
Based on DoD DTED-1 90-m Terrain Dataset

Field Site:
Extensive PSU-owned agric. land at Rock Springs, PA

A = University Park Airport (KUNV)
S = State College
R = Rock Springs
Rock Springs Observing Network
Showing Topography of Nittany Valley & Tussey Ridge

2 sodars are currently operational within the Rock Springs Observing Network
WRF-ARW Grid Configuration

- WRFv3.3 configured with nested domains with 12-, 4-, 1.33-, and 0.44-km horizontal grid spacing. Sub-kilometer horizontal resolution needed to resolve fine-scale terrain important for shallow SBL flows and AT&D.

\[
\begin{align*}
\text{u, v, T, q} & \quad 68 \text{ m} \\
p, w, \text{TKE} & \quad 47 \text{ m} \\
& \quad 33 \text{ m} \\
& \quad 24 \text{ m} \\
& \quad 17 \text{ m} \\
& \quad 13 \text{ m} \\
& \quad 10 \text{ m} \\
& \quad 8 \text{ m} \\
& \quad 6 \text{ m} \\
& \quad 4 \text{ m} \\
& \quad 2 \text{ m} \\
& \quad 0 \text{ m}
\end{align*}
\]

- Very high vertical resolution near the surface to resolve shallow SBL and gravity-driven slope flows (2 m spacing through lowest 10 m).
WRF-ARW Physics

- WRFV3.3 using:
  - MYJ TKE scheme – modified to use lower background TKE (0.01 instead of 0.10 J kg$^{-1}$) to better resolve low TKE SBL
  - Noah land surface model
  - RRTM longwave / Dudhia shortwave radiation
    - 5-minute update frequency
    - Use slope and terrain shading effects on 1.33- and 0.44-km domains
  - WRF Single-Moment 3-class microphysics – focus here is on case with no precipitation and limited clouds
  - Kain-Fritsch cumulus parameterization on 12-km domain only
This presentation will focus on Sites 6 and 9/10. Note that elevation of Site 6 (416 m) is ~50 m higher than Site 9 (368 m) and they are ~900 m apart (slope=5%).

Locations of Obs Tower Sites

Nittany Valley

Tussey Ridge (~650 m)
Internal waves and other submeso motions cause intermittent turbulence near the surface.

Shallow gravity-driven drainage flow overrides coldest air on valley floor, gradually filling Nittany Valley.

Very light omni-directional winds in cold pool.

(Adapted from Mahrt et al., Tellus 2010)
Initial Conditions

- GFS surface field at 0.5-degree (~55 km) cannot represent 0.444-km scale fields

1-minute observations and 10-second model output used to adequately sample the data and both are 30-minute averaged to smooth high-frequency variations

Site 9 2-m Temperature

- Sunset: ~2337 UTC
- Sunrise: ~1041 UTC

5 September 2009
Improving Initial Conditions

- To allow model to spinup meteorology consistent with terrain on 0.444-km domain
  - model started 12 hours earlier (12 UTC)
  - Daytime portion of run (12 – 00 UTC) uses coarser vertical resolution to
    minimize risk of numerical issues during the more strongly forced convective
    boundary layer

\[ \begin{align*}
  & u, v, T, q \quad 68 \text{ m} \\
  & p, w, TKE \quad 47 \text{ m} \\
  & \text{D A Y} \quad 33 \text{ m} \\
  & \text{N I G H T} \quad 33 \text{ m} \\
\end{align*} \]

Use similarity theory to adjust 9 m winds to 7, 5, 3, and 1 m

Interpolate / Extrapolate Using Altered Version of VINTERP
Improving Initial Conditions

• Initializing model 12 hours earlier at 12 UTC significantly improves conditions at 00 UTC.

• 2-m diagnostic temperature plotted for consistency between day and night periods with differing near-surface vertical resolution.

Sunset: ~2337 UTC
Sunrise: ~1041 UTC

5 September 2009
Physics Sensitivity -- LSM

- At this valley location and in this case, the Noah LSM predicts cooling better than the simpler thermal diffusion method just prior to 00 UTC
- Thermal diffusion remains too warm until morning
- Near morning, fog in both experiments inhibits warming

Site 9 2-m Temperature

Sunset: ~2337 UTC
Sunrise: ~1041 UTC
5 September 2009
Fog in LSM Experiments

- Fog prevents model from warming sufficiently after sunrise
- No moisture measurements available at Rock Springs for this case

Site 9 at 1130 UTC (30-minute averaged)

Sunset: ~2337 UTC
Sunrise: ~1041 UTC

5 September 2009
Physics Sensitivity – Slope / terrain shading

- Inclusion of terrain slope and terrain shading effects in radiation calculations have very little effect.
- Location in valley northwest of southwest-northeast oriented mountain would suggest largest effect near sunrise (1042 UTC).
- Fog minimizes any potential effect.
Physics Sensitivity – Slope / terrain shading

- Site 6 is on the slope and so more likely to be affected by terrain radiation effects
- However little effect seen at site 6
- There is a slight decrease in warming (up to 0.4 C in unaveraged data) during the morning
- Other slopes in 0.444-km domain are ~1 C cooler with slope / terrain shading at ~1148 UTC

Sunset: ~2337 UTC
Sunrise: ~1041 UTC
5 September 2009
Physics Sensitivity – Radiation Update Interval

- Changing the interval between radiation updates to 30, 10, 5, and 1 minute updating has largest effect near sunset and between 09 and 12 UTC
- Cooling near sunset inhibited somewhat with use of 30-minute update and best with 1-minute update
- Timing of cooling/fog around 09 UTC sensitive to update interval

Site 9 2-m Temperature

Sunset: ~2337 UTC
Sunrise: ~1041 UTC

5 September 2009
Physics Sensitivity – Radiation Update Interval

Site 9
No averaging

• Time evolution of vertical profile shown for 30 and 1 minute radiation updating between 0800 UTC and 1130 UTC

• Cooling/fog occurs ~0900 UTC for 1-minute radiation update but ~1130 for 30-minute radiation update

• Tradeoff between CPU use and accuracy (changing from 30 to 1 minute radiation updating increased runtime by ~6%)
Improving initial conditions – use of observations

- Standard WMO observations and site 9 observations used to enhance analysis of initial conditions using OBSGRID at 12 UTC
- On 0.444-km domain only one WMO observation available (KUNV)
- Inclusion of obs improves temperature in first couple hours and slightly improves 10-11 UTC
Data Assimilation

- Since the period of interest for the SBL is 00 UTC to 12 UTC, we investigate use of nudging throughout the 12-h daytime period as a pre-forecast.
- Surface and 3D analysis nudging applied to 12-km domain to prevent large-scale features from drifting.
- Observation nudging applied to all domains:
  - Temperature, moisture, and winds at all levels.
  - Standard WMO obs and Rock Springs site 9:
    - Rock Springs uses 1-hourly, 30-minute averaged surface temperature and winds.
Obs Nudging Weights

- Surface observations use default vertical weighting:
  - If PBL top at or below first full level above surface (Regime 1) then full weighting through 50 m and a vertical rampdown in the next 50 m
  - If PBL depth above first full level above surface (Regime 4) then full weighting through the PBL top and a vertical rampdown in the next 50 m
- Surface observation horizontal weighting
  - 12- and 4-km domains – 67 km (100 km [OBS_RINXY] * 0.67 [SFCFACR])
  - 1.33-, and 0.444-km domains – 13.4 km (20 km [OBS_RINXY] * 0.67 [SFCFACR])
    - Avoid KUNV obs on plateau from influencing Rock Springs 20 km to the southwest in the valley since errors are unlikely to be correlated
- Horizontal spreading limited by terrain using MM5 methodology (SFC_SCHEME_HORIZ) (bug-fixed)
Data Assimilation -- Temperature

- Nudging (dynamic initialization) shows slight improvements at some times (e.g., ~23 UTC)
- Nudging results in insufficient cooling overnight at this site, but the lack of fog appears consistent with observations and allows more realistic warming at end of forecast

Site 9 2-m Temperature

Sunset: ~2337 UTC
Sunrise: ~1041 UTC

5 September 2009
Data Assimilation – Wind Speed

- During the daytime, nudging shifts time of wind peak by 1-2 hours (but note errors are < 1 m/s)
- Nudging improves forecast wind speed during the beginning of the nighttime period

Site 9 9-m Wind Speed (2-hour average)

Sunset: ~2337 UTC
Sunrise: ~1041 UTC
5 September 2009
Nudging (dynamic initialization) improves wind direction during afternoon.

Strong improvement in forecast wind direction during early portion of nighttime period.
Conclusions

• 12-h pre-forecast allows model to spinup meteorology more consistent with local terrain from coarse ~55-km GFS initial conditions
• Use of Noah appears to better handle evening cooling than simpler thermal diffusion
• Fog formation time is sensitive to radiation update frequency
• Limited sensitivity to slope terrain and shading radiation effects
• Use of obs in objective analysis of initial state (OBSGRID) mainly improves results within a couple hours of model start time
• Preliminary nudging strategy in a pre-forecast for this case shows mixed results. Special local data currently limited to single surface site and no moisture data.
Future Work

- Use additional observations for initial conditions and nudging: additional sites at Rock Springs, additional vertical levels at Rock Springs, moisture from sensor on newly obtained sodar, other sites?
- Test methodology for additional cases
- Create objective verification over multiple Rock Springs obs sites
- Investigate longer pre-forecast to allow more spinup for LSM fields
- Refine obs nudging strategy for this high-resolution simulation
Future Work

• Extend evaluations up to ~ 150-250 m with new PSU Sodar instruments provided by Army Research Office (ARO) Defense University Research Instrumentation Program (DURIP)

• Investigate effect of improved NWP on atmospheric transport and dispersion forecasting
Acknowledgements

- Defense Threat Reduction Agency under DTRA Grant No. HDTRA1-10-1-0033 under the supervision of Dr. John Hannan.
Nocturnal gravity-driven drainage flow modulated by transient submeso motions

Conceptual model:
Shallow gravity-driven drainage flow overrides coldest air on valley floor, gradually filling Nittany Valley.

Courtesy Larry Mahrt, 2010
The Noah Land-Surface/Canopy Model in WRF

Noah Schematic

- Configuration of Noah in the SBL version of WRF seeks to reduce biases in low-level wind speeds and temps through improved modeling of surface fluxes.

From Noah tutorial by F. Chen.