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Numerical Prediction of Mesogamma-Scale Wind Meandering in the Nocturnal Stable Boundary Layer

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Sponsor: Defense Threat Reduction Agency

Objectives and Methodology

- **Background:** Most NWP models poorly predict conditions in the stable boundary layer (SBL)

- **Objectives:**
  - **Understand physical processes** controlling SBL growth and structure in complex environments.
  - **Identify model resolution and physical requirements** to predict wind fluctuations responsible for stable plume meandering.
  - **Validate and/or improve WRF parameterizations** for sub-kilometer predictions of SBL.

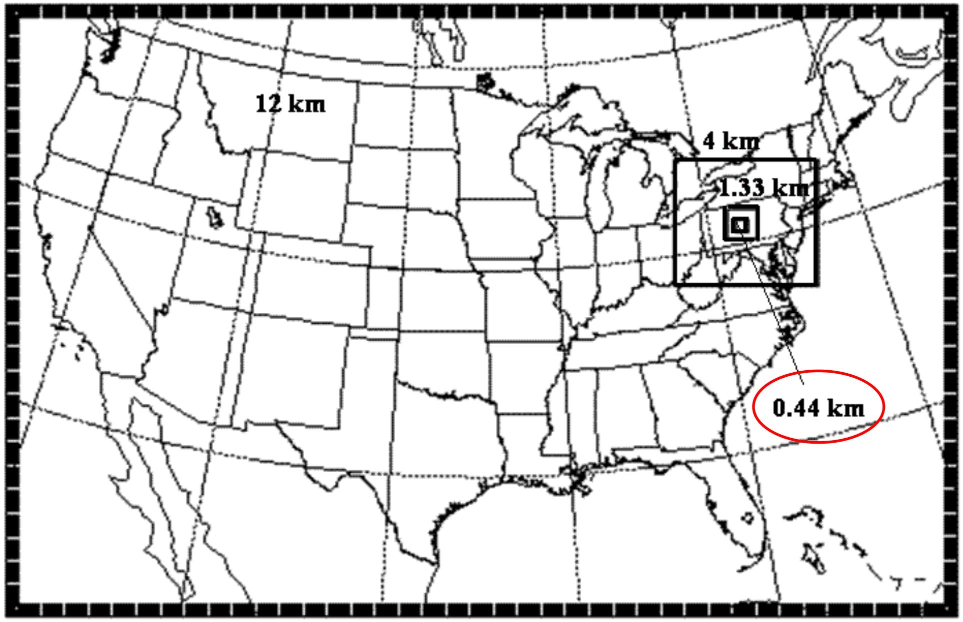
Methodology:

- Conduct "scoping" field study to obtain data on SBL evolution.
- Evaluate sub-kilometer WRF-ARW predictions of SBL.
- As necessary, modify SBL parameterizations.

WRF-ARW Horizontal Grid

- **WFR-ARW configured with 4 nested domains.**

Domain No.	Horiz. Res. (km)	No. of Points
1	12.0	421 X 271
2	4.0	193 X 169
3	1.333	121 X 121
4	0.444	151 X 151



ARW output saved at local field network sites at 10-sec frequency, averaged to 1 min.

- All inner grids use one-way nested grid interfaces.
- 12-h nocturnal forecasts take ~6 h on sixteen 3.0 GHz CPUs.

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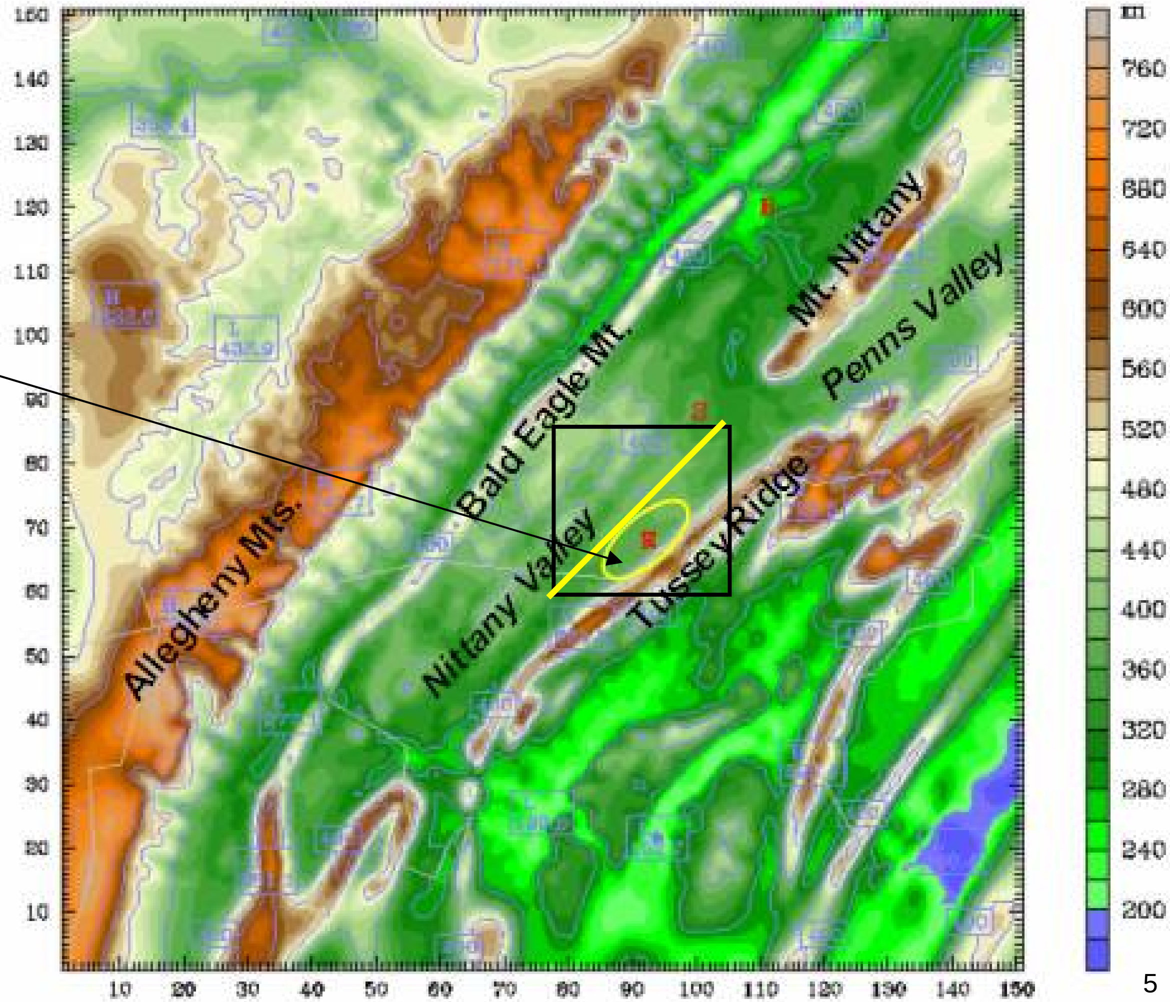
444-m Innermost ARW Domain

(DTED-1 Terrain Database, ~90 m Resolution)

Terrain (m) shown on color bar at right;
(R = Rock Spring, S = State College, B = Bellefonte)

Field Site (ellipse):

Extensive PSU-owned agricultural land at Rock Spring, PA



- **Sub-kilometer resolution is necessary to resolve fine-scale terrain important for shallow SBL flows.**
- **Small box shows sub-domain for detailed diagnosis.**
- **Gold line indicates location of cross section.**

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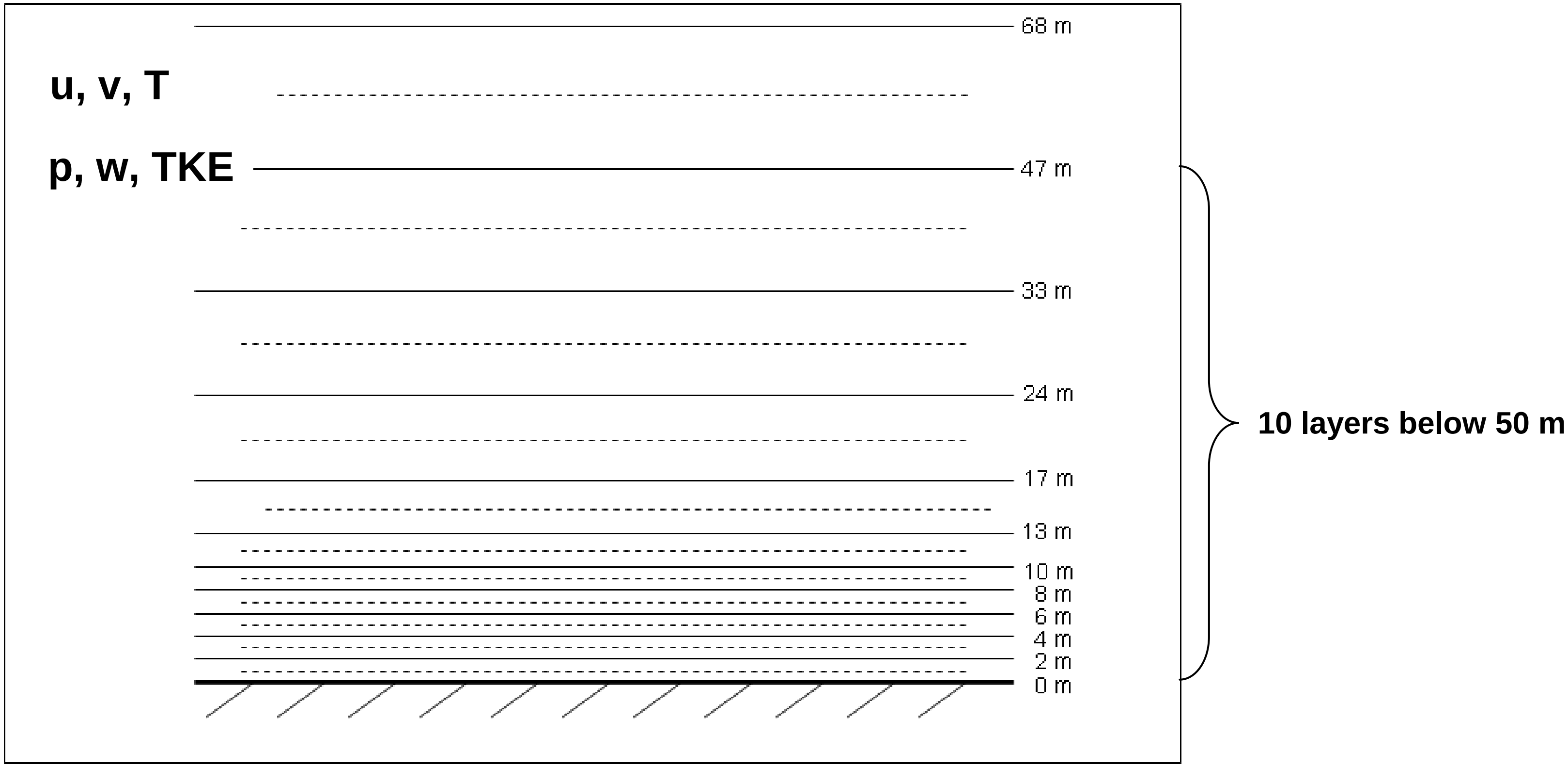
WRF-ARW Vertical Grid

- WRF-ARW is configured with 43 layers; Model top is at 50 hPa.
- Lowest five layers are 2 m thick, gradually increasing upwards.
- 10 layers below 50 m AGL.



Fast-Response Instrumentation 10-m Towers at Rock Spring, PA

Campbell 107 Thermistor

Vaisala WS425
2-D Sonic Anemometer
Threshold: ~0.05 ms^{-1}
Sampling rate: 1 Hz → 20 Hz

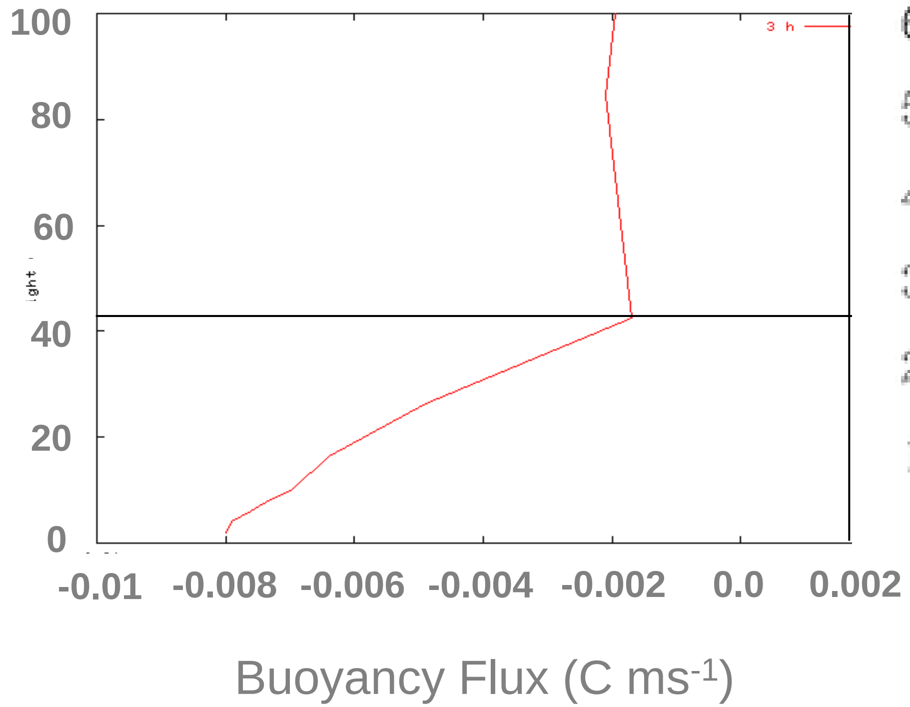
Tussey Ridge in background

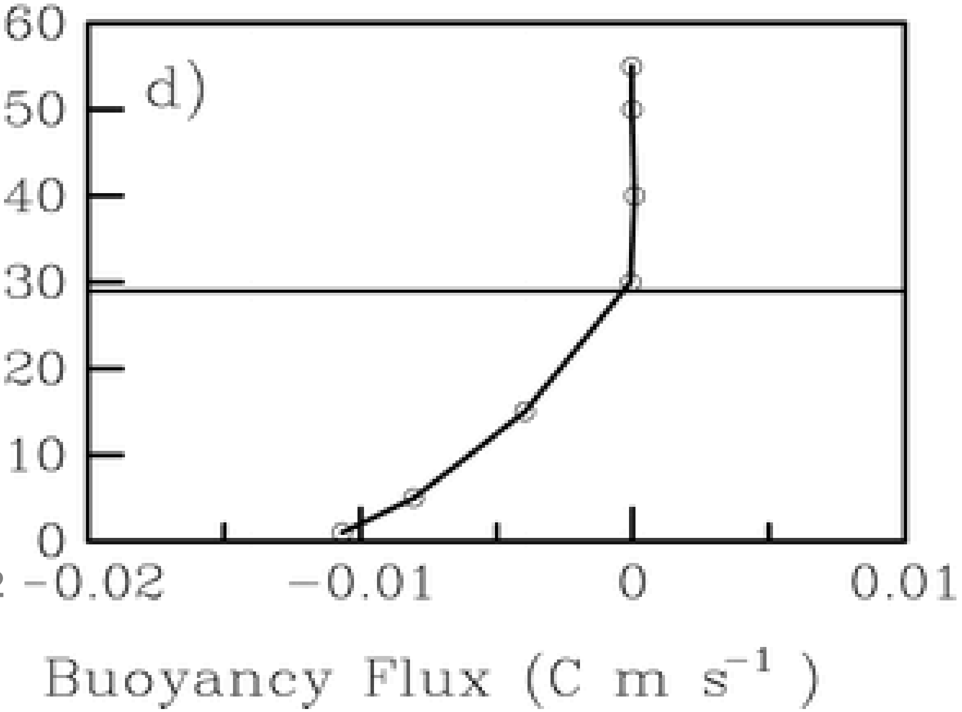
Data recorder / transmitter with solar-rechargeable battery pack

Preliminary Modeling Results

MYJ Scheme: Predicted Vertical Structure of SBL

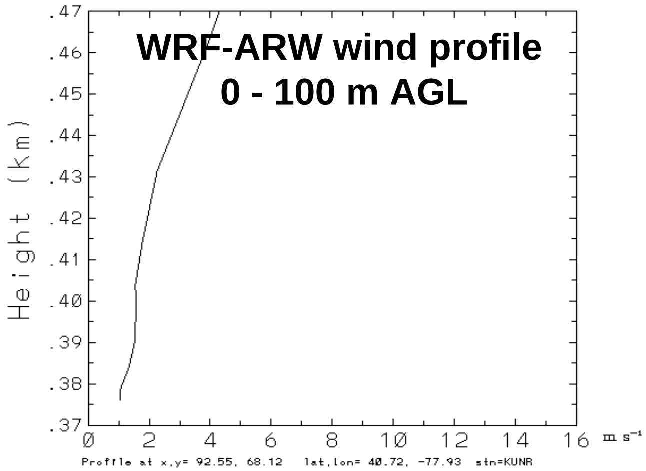
Mellor-Yamada-Janjic Predicted buoyancy flux profile **0300 UTC, 10 Sept. 2007** **Rock Spring, PA**	1-h avg'd. observed buoyancy flux profile **CASES99, 18 Oct. 1999** **Vickers and Mahrt (2004)**



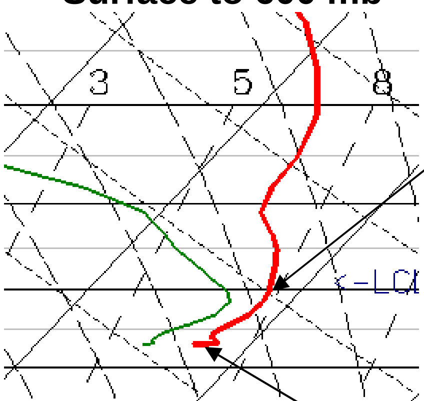


Predicted Vertical Structure

14 Nov. 2007, 08 UTC



WRF-ARW Skew-T, log p profile
Surface to 600 mb

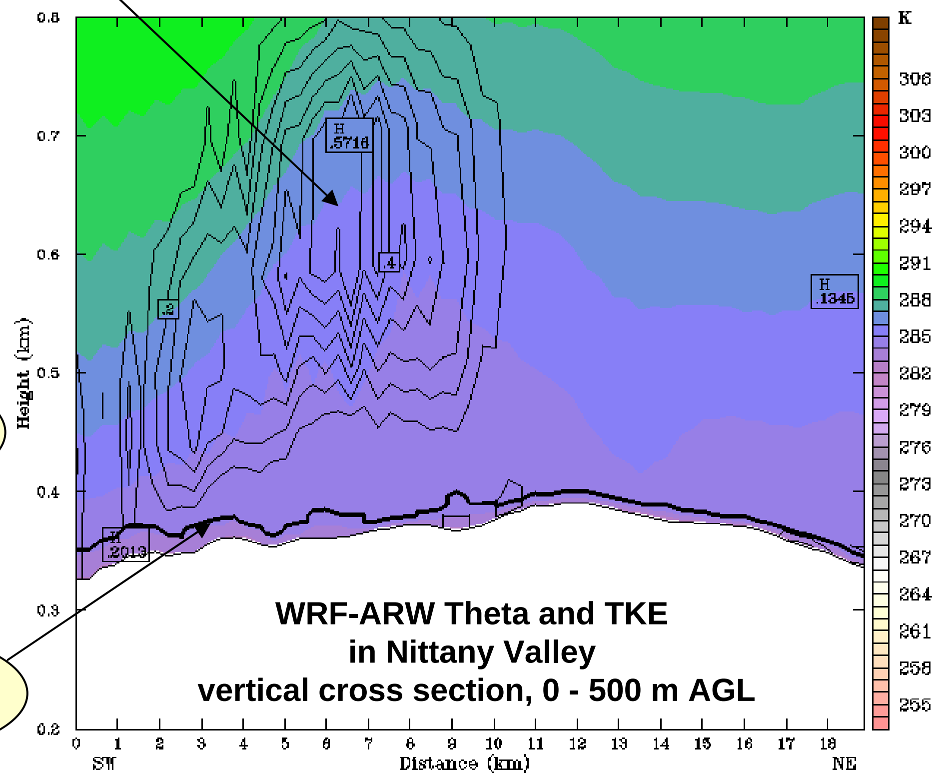


Shallow SBL ~ 20 m depth

Strong TKE in LLJ aloft

Post cold-front inversion layer

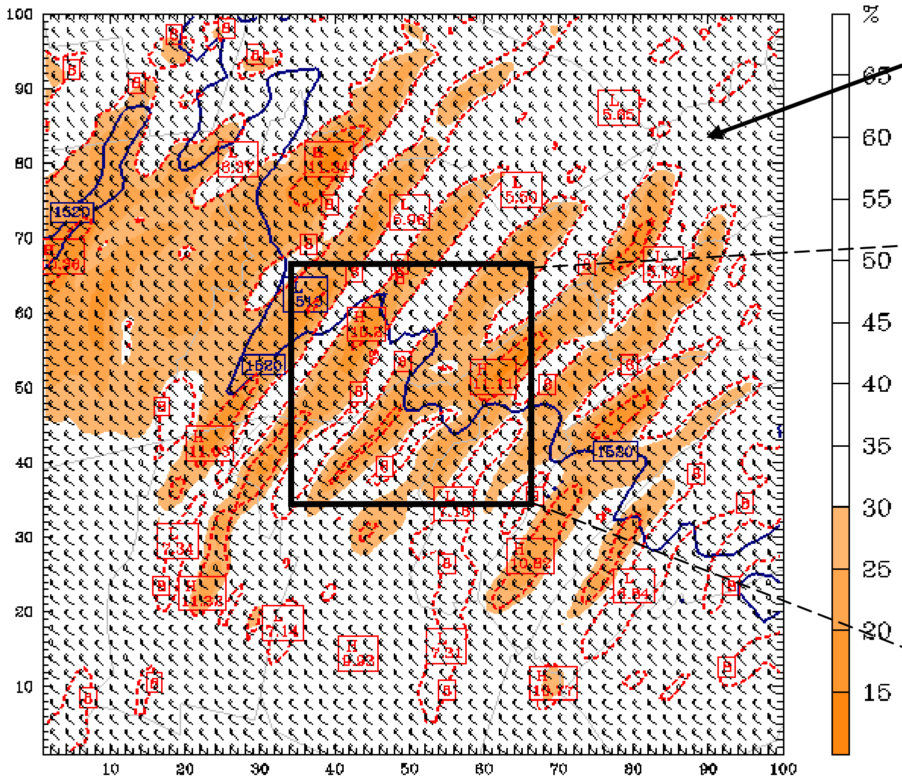
Diagnosed SBL(x,y) Depth



Internal Gravity-Waves

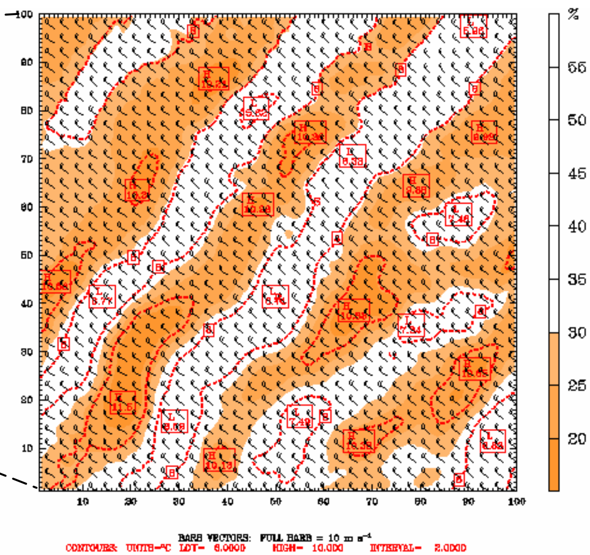
Wind, Geopotential Height and Relative Humidity (color fill) at 850 mb, 0900 UTC, 18 Aug. 2007

100 X 100 point sub-domain of 1.33-km grid



Northwesterly wind field aloft generates lee-wave train downwind of Allegheny Mts.

100 X 100 point sub-domain of 0.444 km grid



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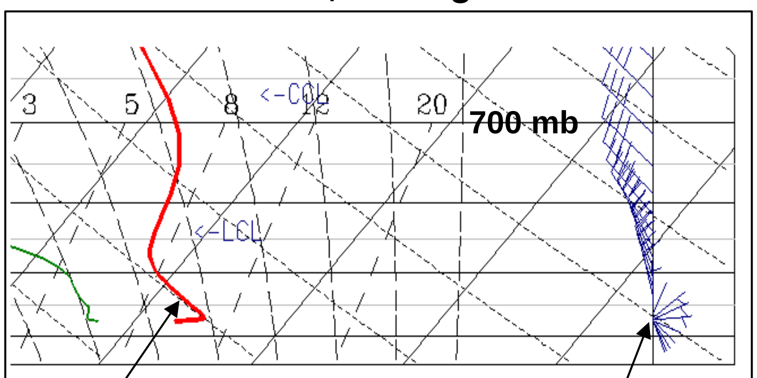
Vertical Cross Section in Nittany Valley Showing Internal Gravity Waves

18 August 2007 Case, 0900 UTC

Synoptic wind direction:
Northwesterly above 900 mb.

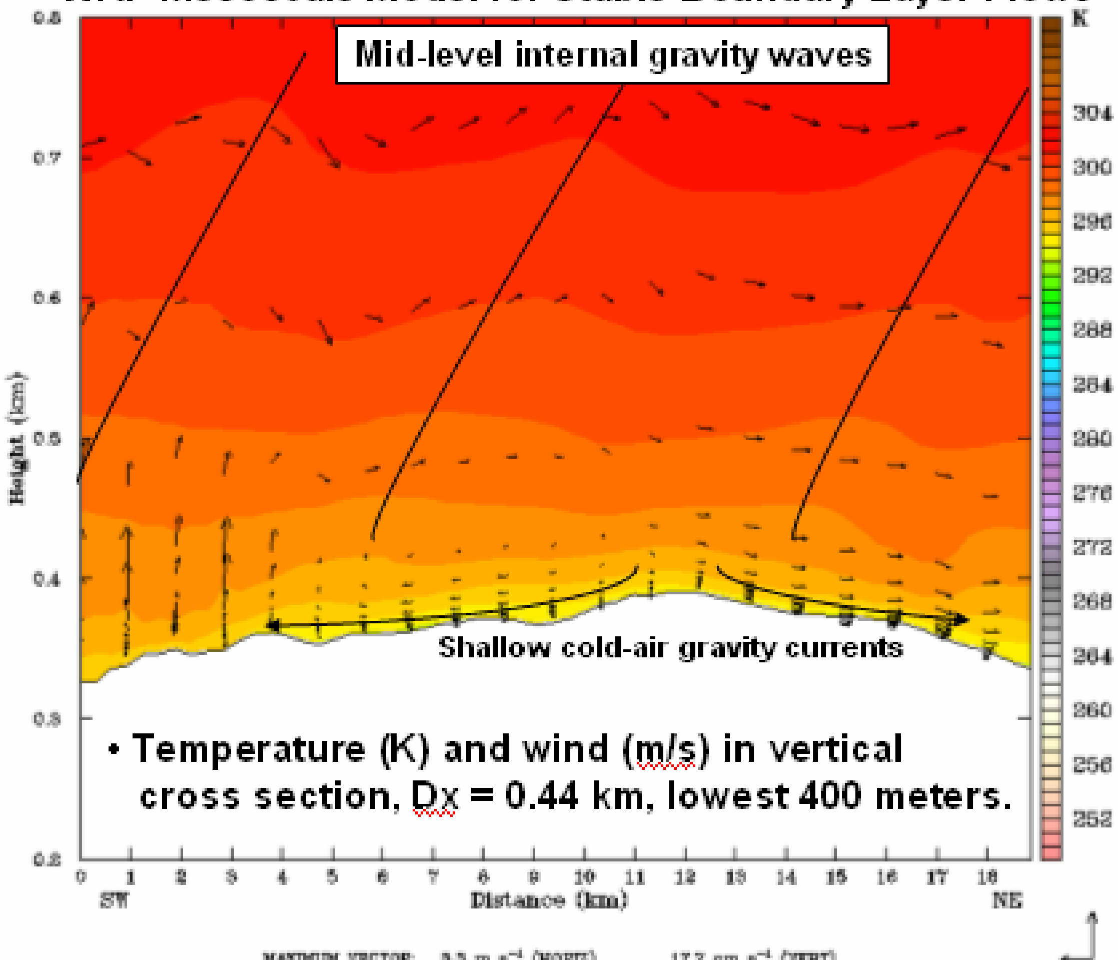
ARW fcst. sounding, Rock Spring, PA
0900 UTC, 18 August 2007



Residual elevated mixed layer aloft, above shallow SBL inversion

Large directional wind shear above SBL

WRF Mesoscale Model for Stable Boundary Layer Flows

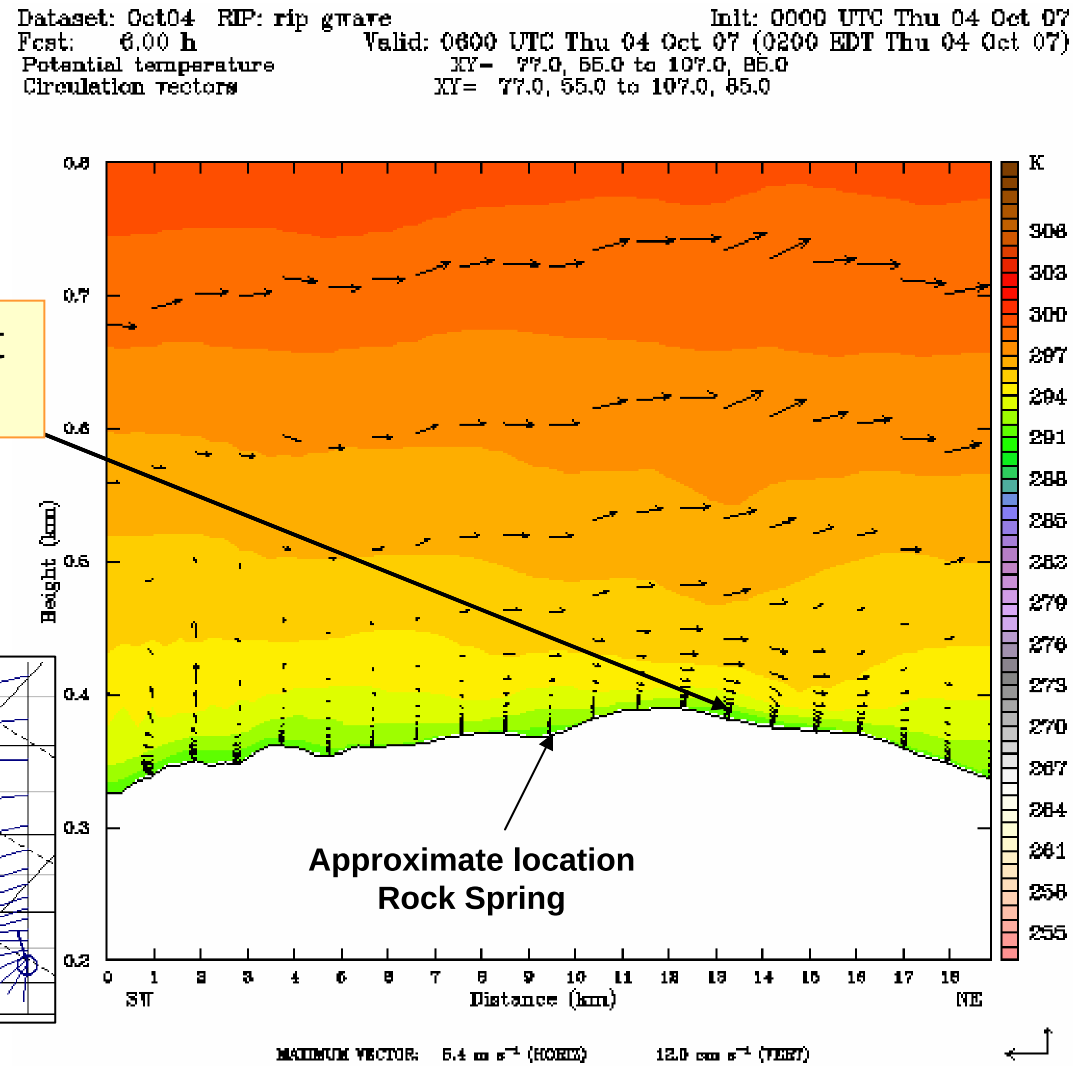


Internal Gravity Waves in Nittany Valley Cross Section

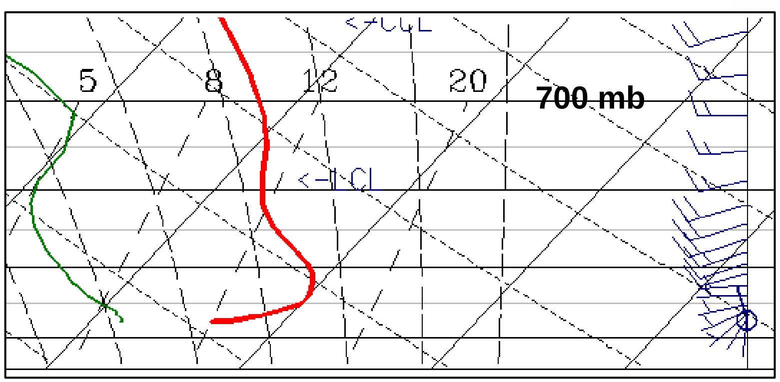
4 October 2007 Case

Synoptic wind direction:
West-southwesterly above 900 hPa

Transient gravity waves aloft perturb winds in SBL



ARW fcst. sounding, Rock Spring, PA 0900 UTC, 4 October 2007



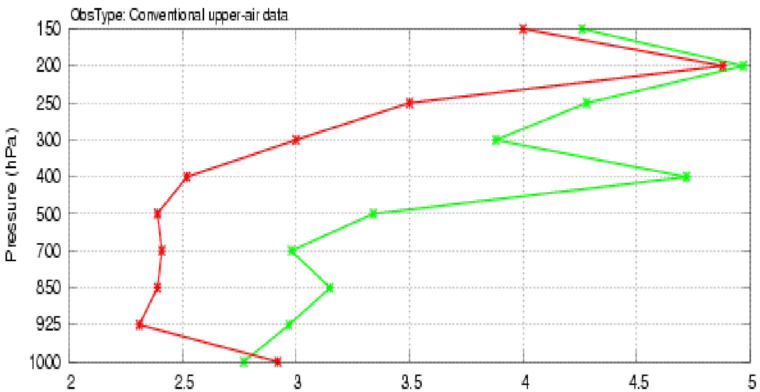
Objective Verifications

12-km & 4-km WRF-ARW RMSE & Bias

30 March – April 30, 2008

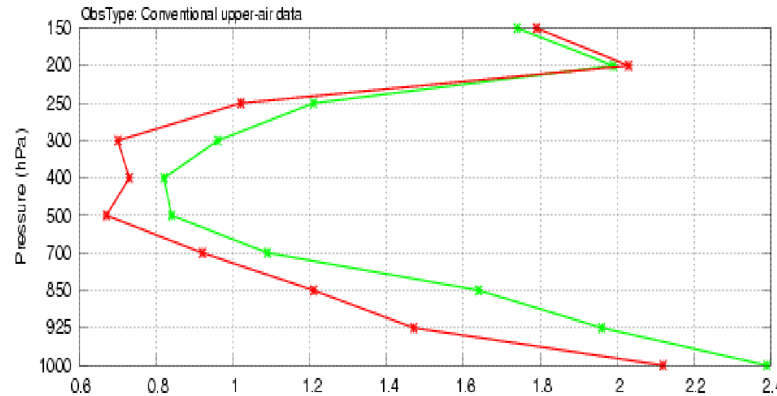
12-km: (green)
4-km: (red)

Wind speed at 1200UTC

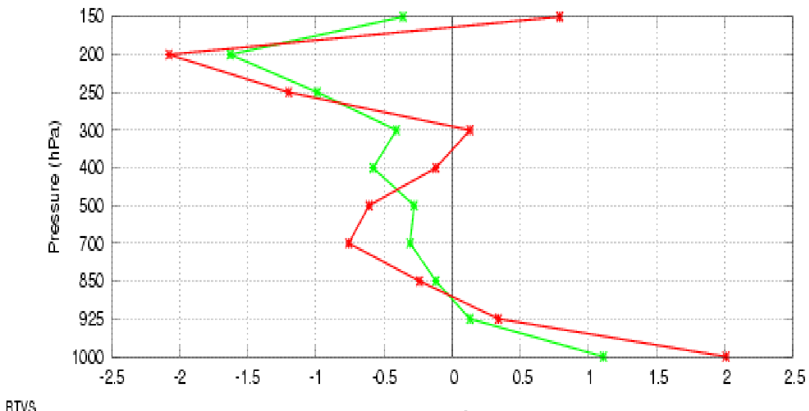


RMSE (ms^{-1}) vs. Pressure

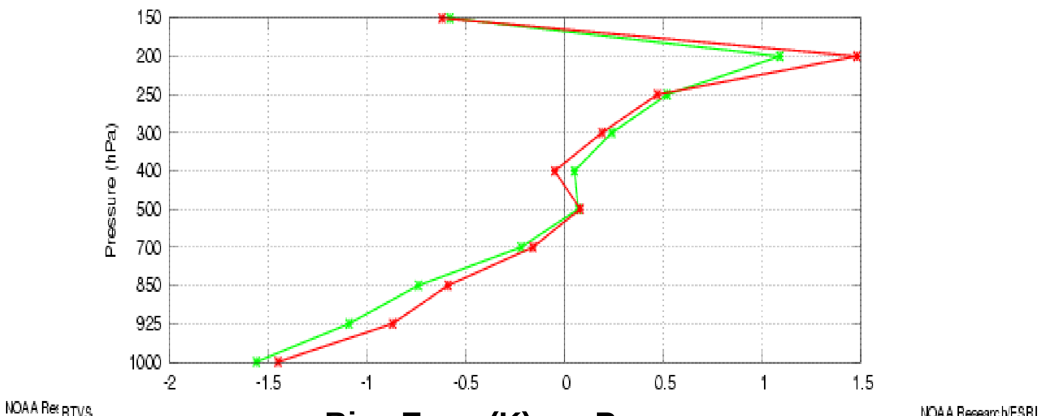
Temperature at 1200UTC



RMSE (K) vs. Pressure



Bias Error (ms^{-1}) vs. Pressure



Bias Error (K) vs. Pressure

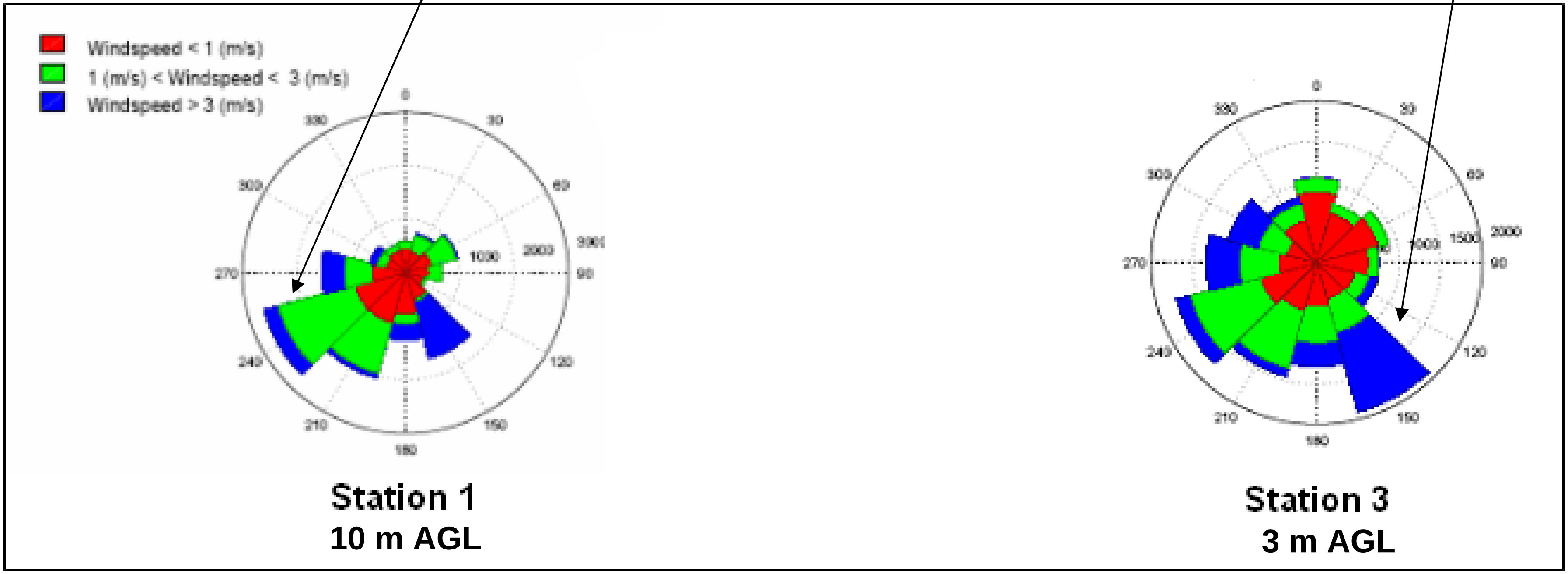
MET software provided by DTC

Observed Nocturnal Wind Roses

Rock Spring, PA, 4-25 October 2007

Site 1: Dominant west-southwesterly terrain-channeled wind at 10 m AGL.

Site 3: Shallow south-southeasterly drainage wind from Tussey Ridge at 3 m AGL



• Towers 1 and 3 are located ~0.75 km from the base of Tussey Ridge.

Idealized Streamlines in Nittany Valley

0.444-km sub-domain

• *Mean wind aloft from west-southwest*

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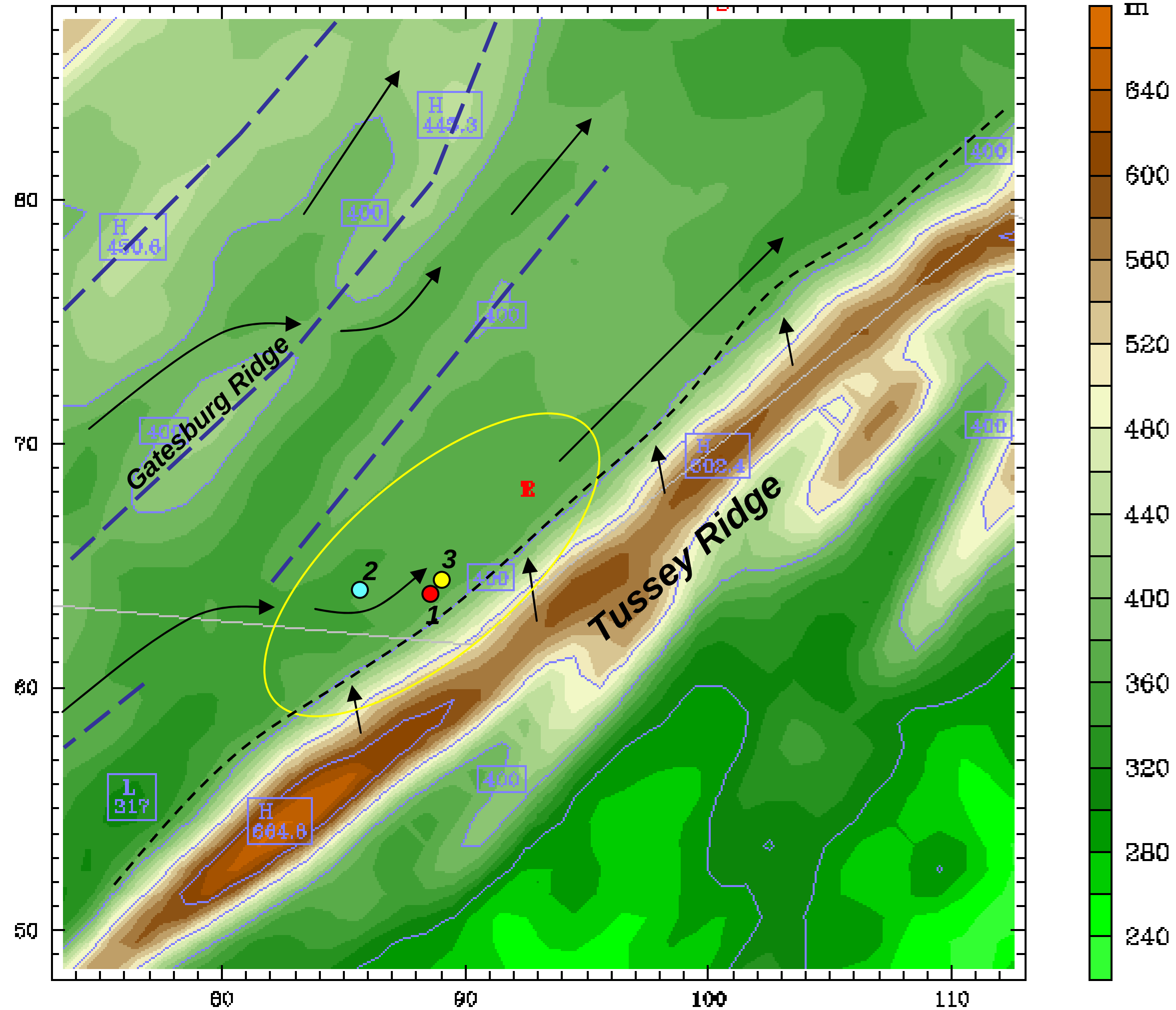
- Site 1
- Site 2
- Site 3

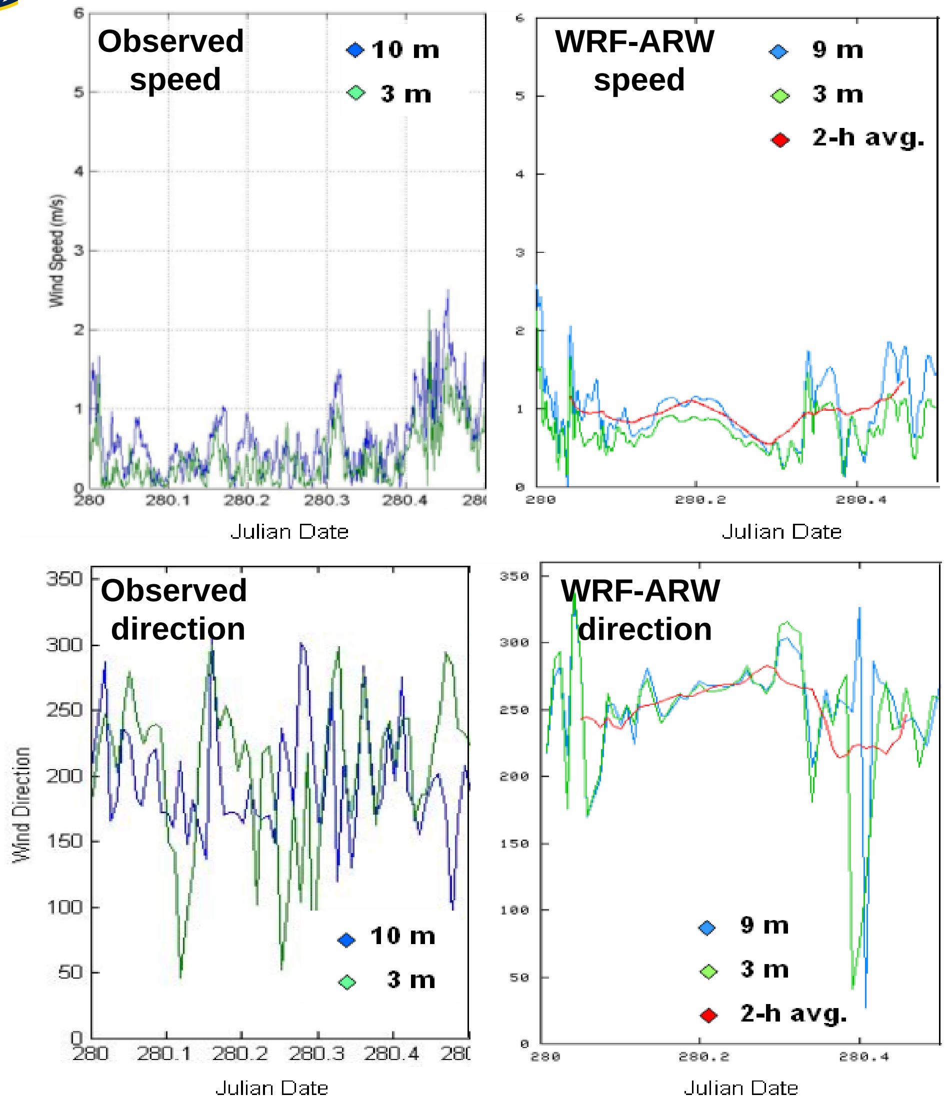
Axis of low ridges in Nittany Valley.

Approximate convergence zone between Tussey Mt. drainage wind and channeled Nittany Valley wind.

3 km



7 Oct. 2007 Case
One-Minute Time Series



Evaluation Method: *(Gaudet 2008, P8.2)*

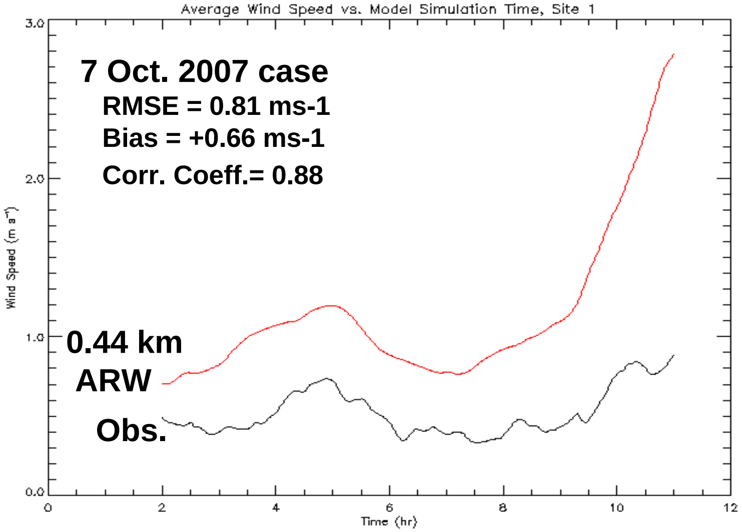
Decompose time series into components:

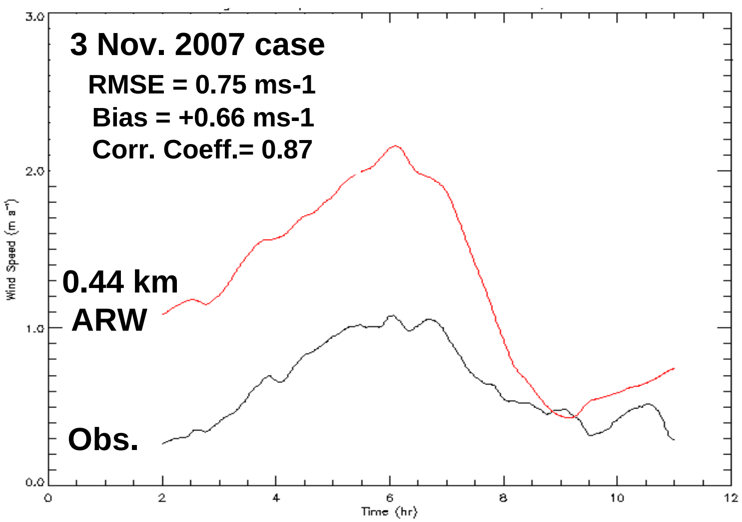
- **low frequencies → Deterministic**
- **high frequencies → Non-deterministic**

WRF-ARW winds in SBL exhibit…

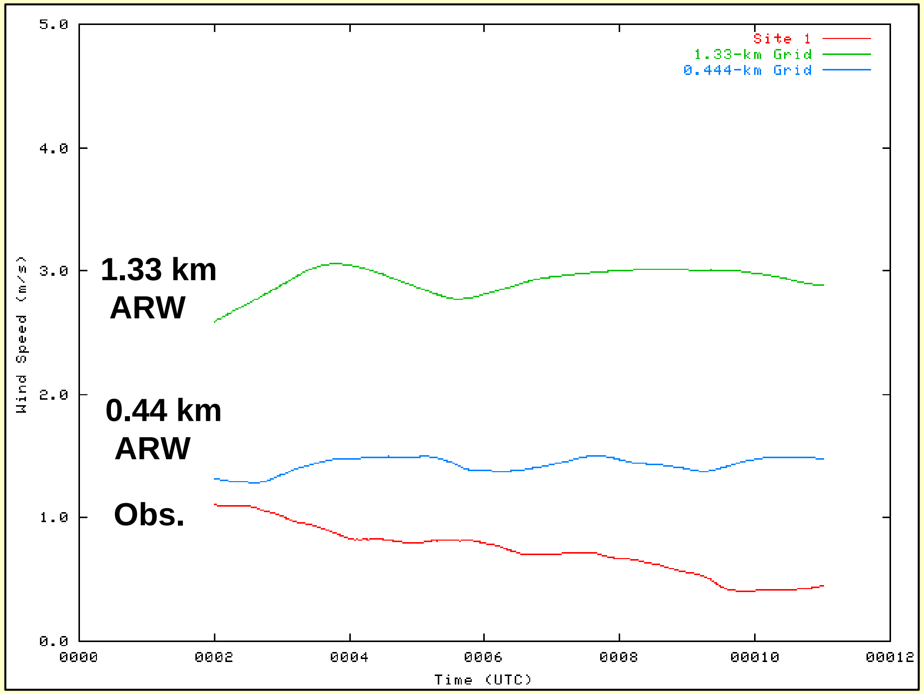
- **Speed shear in 1-10 m layer.**
- **Intermittent bursts of higher speeds with periodicity similar to obs'd. (~0.3-2.0 h).**
- **Direction fluctuations with periodicity similar to obs'd. (~0.5-2.0 h)**
- **Mean direction bias of ~ +40 deg. (westerly), possibly due to failure of 444-m grid to fully resolve local hills in Nittany Valley (see slide 16).**

Low-Frequency* Wind Speed
9-m AGL, Site 1





16-Case Composite, Autumn 2007



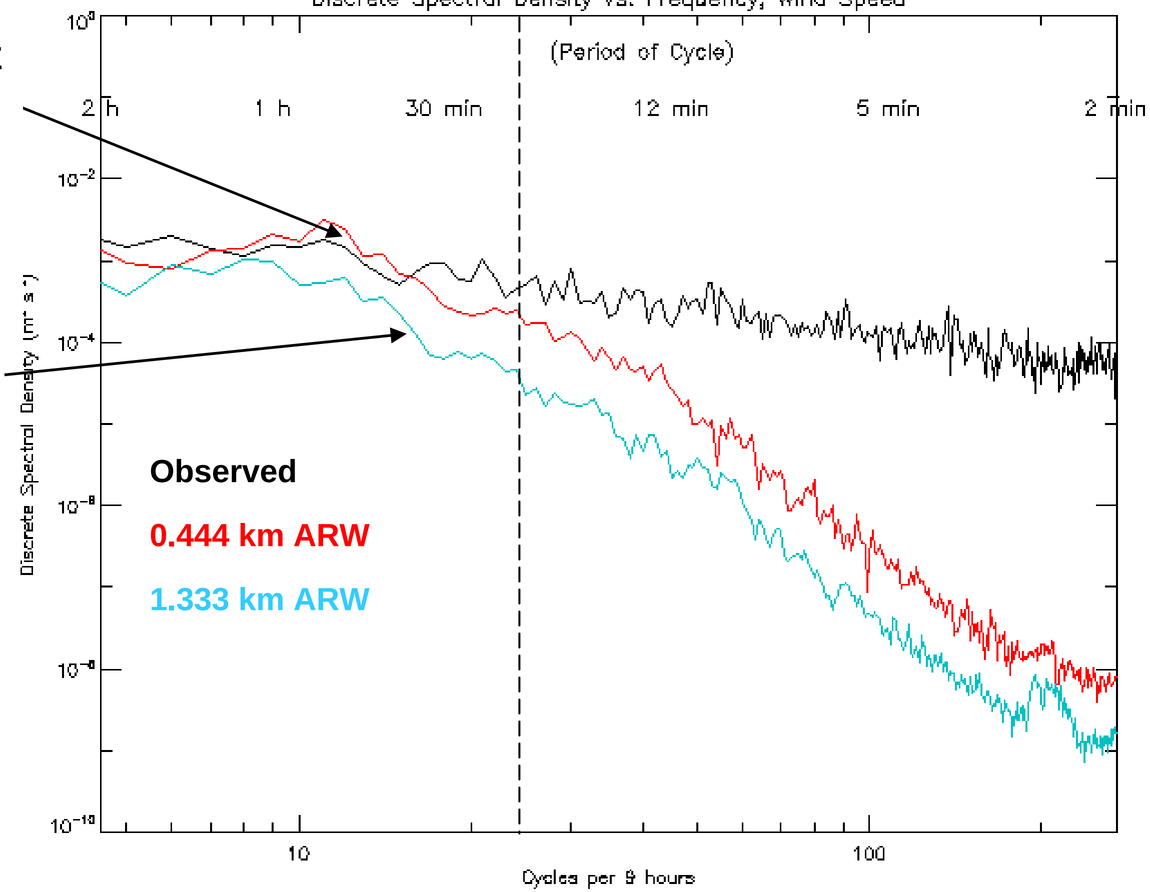
****2-h Running Average* filter is applied to each time series to remove non-deterministic high frequencies < 20 min.*

High–Frequency Kinetic Energy Spectra in SBL

Gaudet et al. (2008), poster P8.1

- **0.444 km: ARW KE ~ Obs'd KE for freq. 0.3 – 2.0 h**
- **1.333-km KE ~ 1/3 x 0.444-KE**

9-m AGL, Site 1

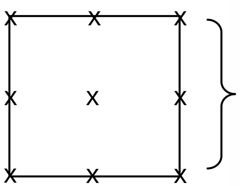


Meandering Trajectories in Nittany Valley

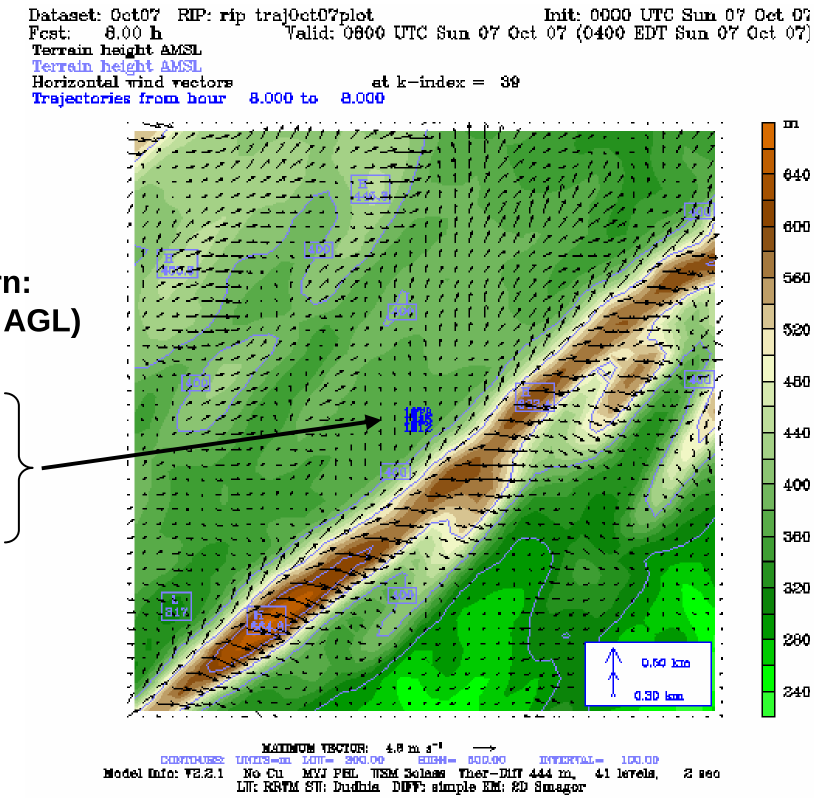
Released at 5m AGL on 444-m Sub-Domain

0800-1200 UTC, 7 Oct. 2007 | **0800-1200 UTC, 6 May 2008**

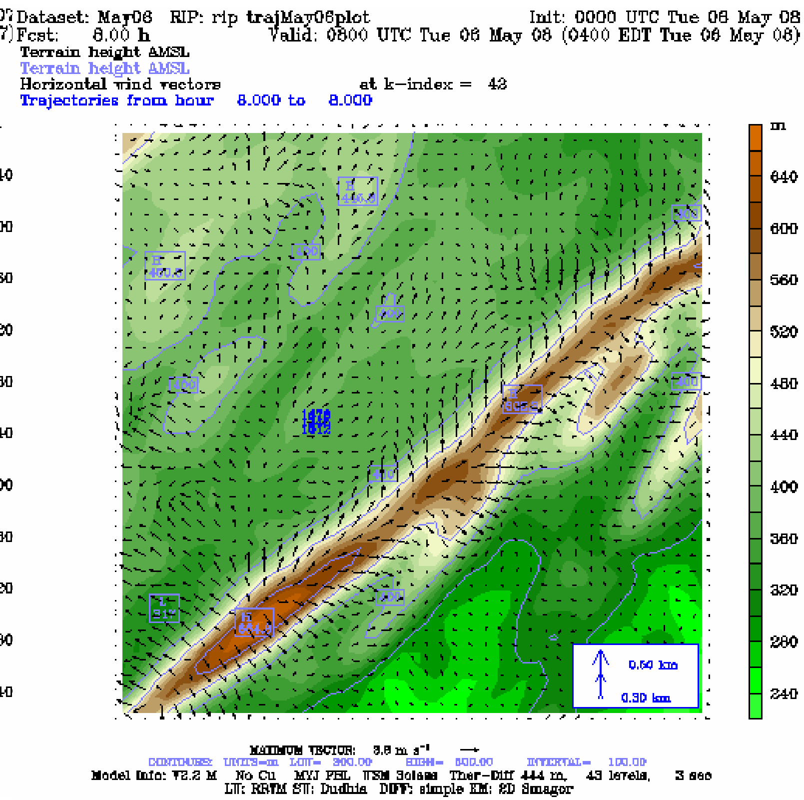
Release pattern:
(9 parcels at 5 m AGL)



1 Dx
(444 m)



Sinuous, high-dispersive plume



Looping, low-dispersive plume

Next Steps

- **Expand field network.**
  - Completed 2nd phase, May 2008.
  - Future: Add remote sensing instruments.
- **Continue analysis of local observations.**
  - Study interactions of downslope flows, valley channeling, etc.
- **Study processes affecting stable meandering.**
  - Internal gravity waves
  - LLJ shear, intermittent turbulence bursts
- **Extend modeling to include QNSE SBL.**

Summary

- **Sub-kilometer ARW with MYJ scheme simulates qualitative vertical structure of the SBL.**
  - Negative buoyancy flux profile (shallow layer).
  - Intermittent turbulence from LLJ to surface (deep layer).
- **Predicted wind speed errors reveal model has skill in SBL.**
  - Low-frequency components have small RMSE and some pos. bias.
  - High-frequency KE spectrum simulated well for 20-120 min. range.
- **Sub-mesoscale wind fluctuations appear forced by cold-air drainage, internal gravity waves, and turbulence in LLJ.**
- **High-resolution models may be able to predict some important characteristics of stable meandering critical for better forecasting of plume behavior in SBL.**

Questions?

Backups

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Strategy for WRF Vertical Grid Configuration

- **Ultra-high resolution WRF grid…**
  - **scales comparably** to resolutions commonly used for convective PBLs:

Convective PBL depth, Z_i:	**Z_i ~ 1250 m**	
Grid Resolution:	**Dx = 12 km →**	**~10 x Z_i**
	Dz = 50-200 m →	**~0.04-0.16 x Z_i**
Stable PBL depth, h:	**h ~ 40 m**	
Grid Resolution:	**Dx = 444 m →**	**~10 x h**
	Dz = 2-14 m →	**~ 0.05-0.35 x h**

  - **allows application** of existing "ensemble-type" mesoscale PBL schemes to predict shallow SBLs.
    - **Mellor-Yamada-Janjic turbulence scheme is used in this study.**
    - **Grid does NOT scale well for convective boundary layers.**
  - **is applied** for running daily 12-h forecasts.
    - **Model begins at 0000 UTC; runs for nocturnal period only, with Dt = 2 s.**
    - **Runs in ~9 h on four nodes of a Linux cluster at PSU (4 CPUs per node).**

Verification of WRF-Predicted Temps. vs. Obs. at Rock Spring, PA

7 October 2007

Initial condition has cold bias:

WFR initial conditions (Sept-Oct) had a strong cold bias apparently caused by an interpolation error in GFS analyses at 00 UTC. WRF requires several hours to recover. Error was corrected by NCEP in mid-October 2007.