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

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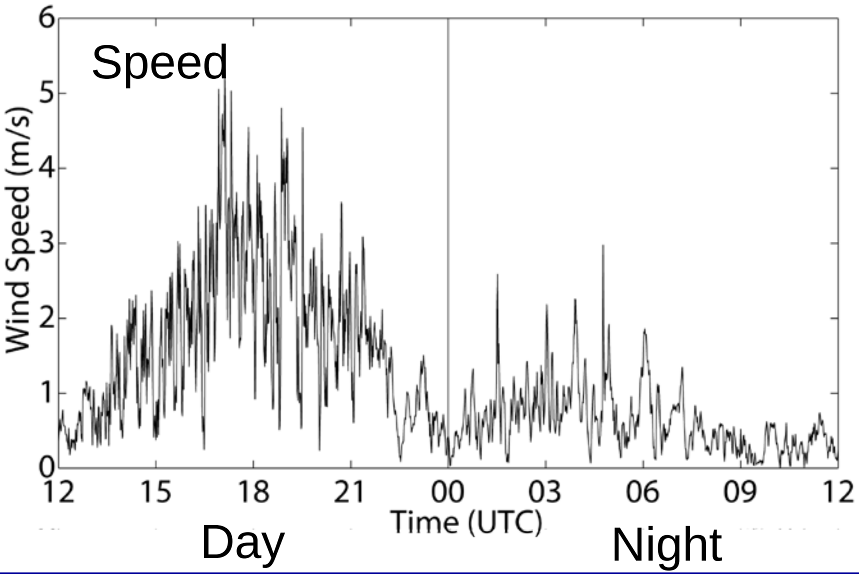
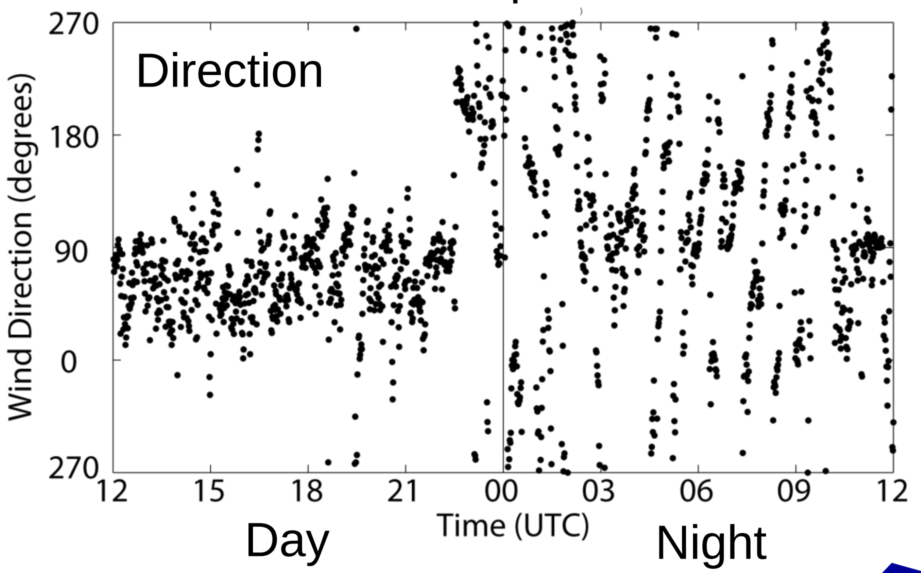
Background

- 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



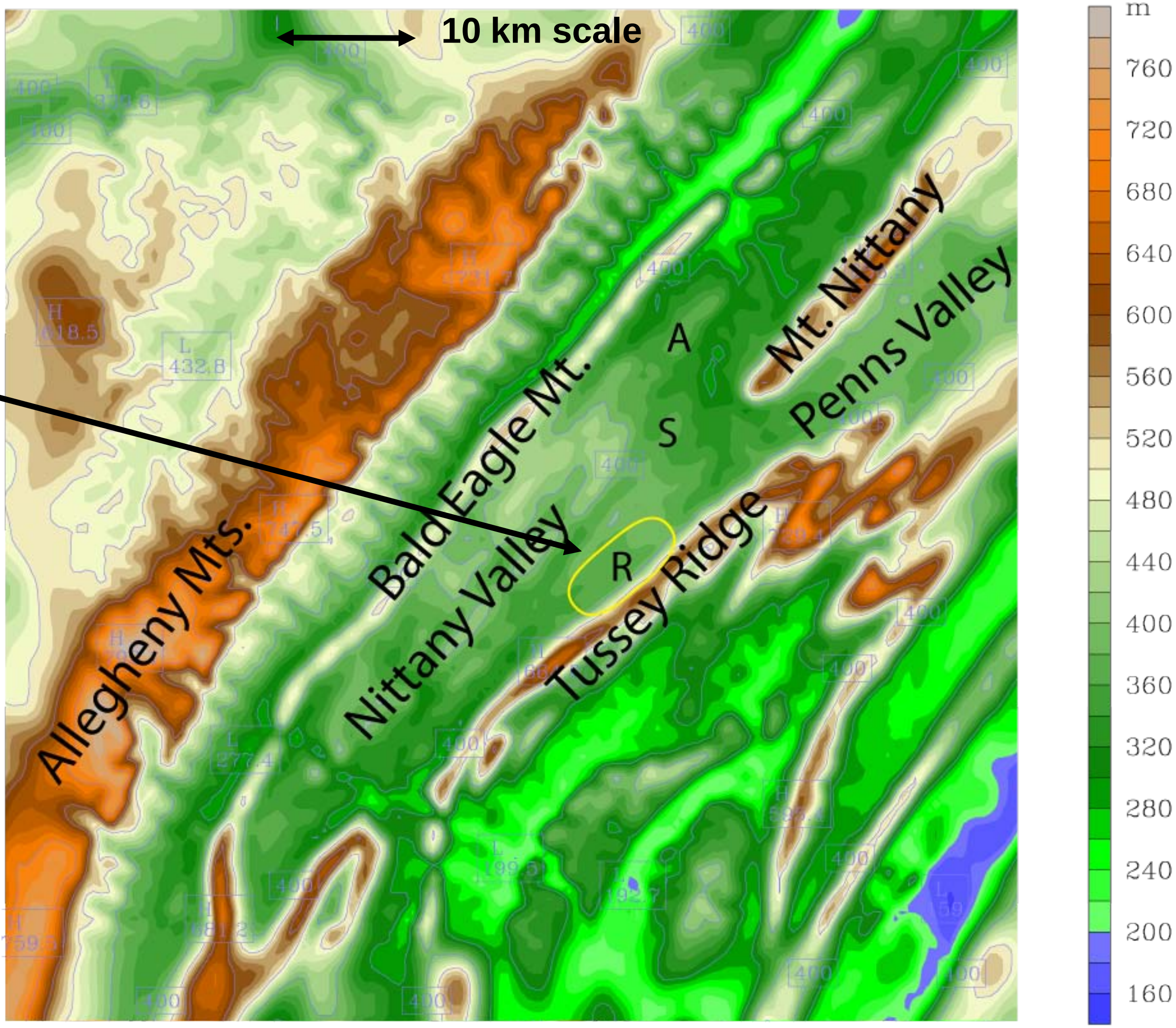


Goals

- 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

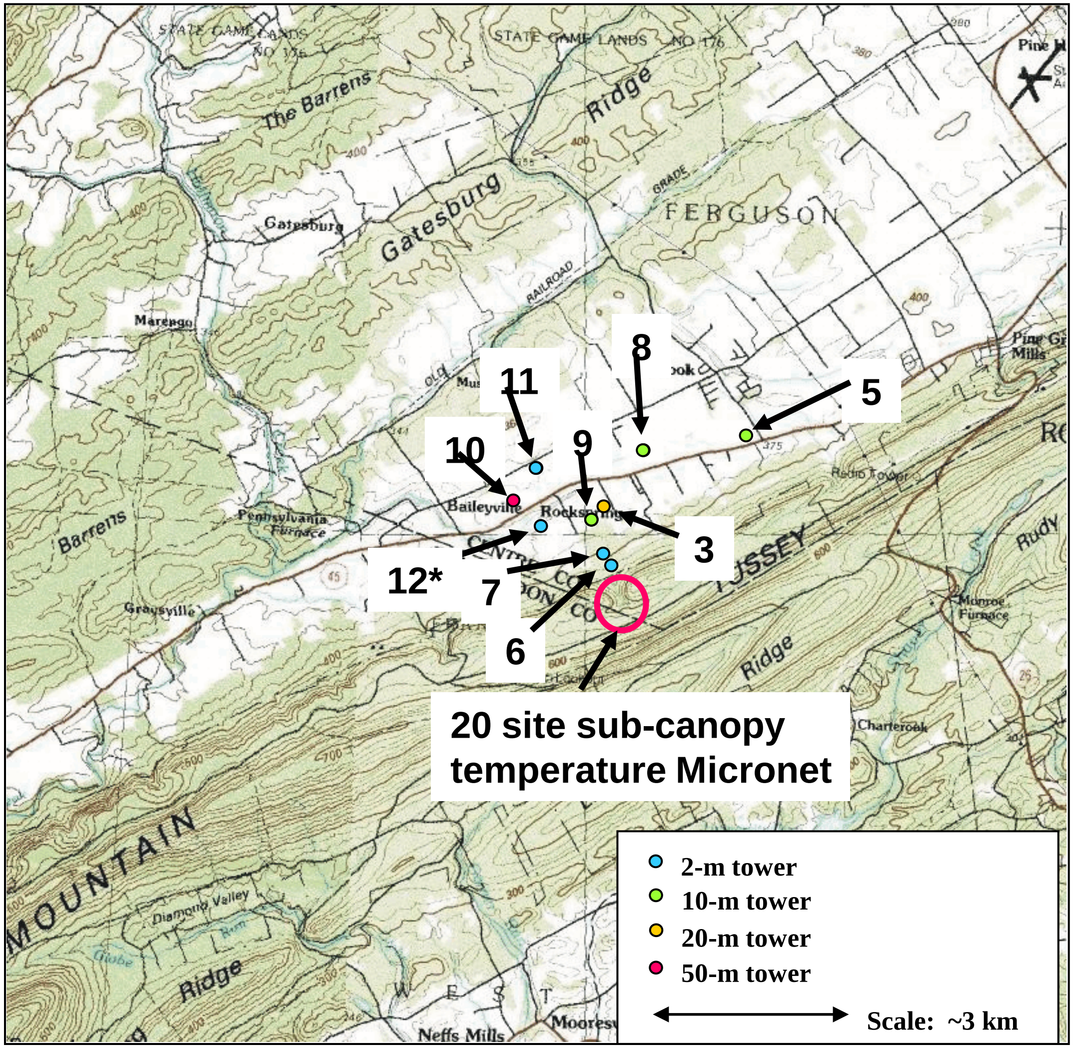


Field Site:

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

A = University Park Airport (KUNV)
S = State College
R = Rock Springs

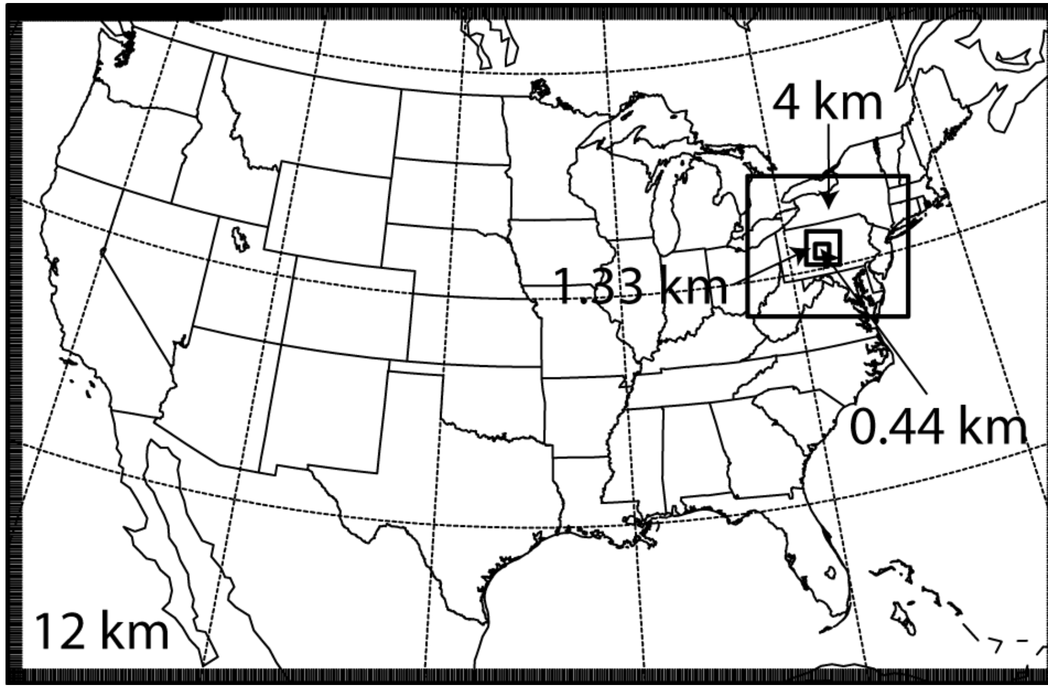
Rock Springs Observing Network
Showing Topography of Nittany Valley & Tussey Ridge

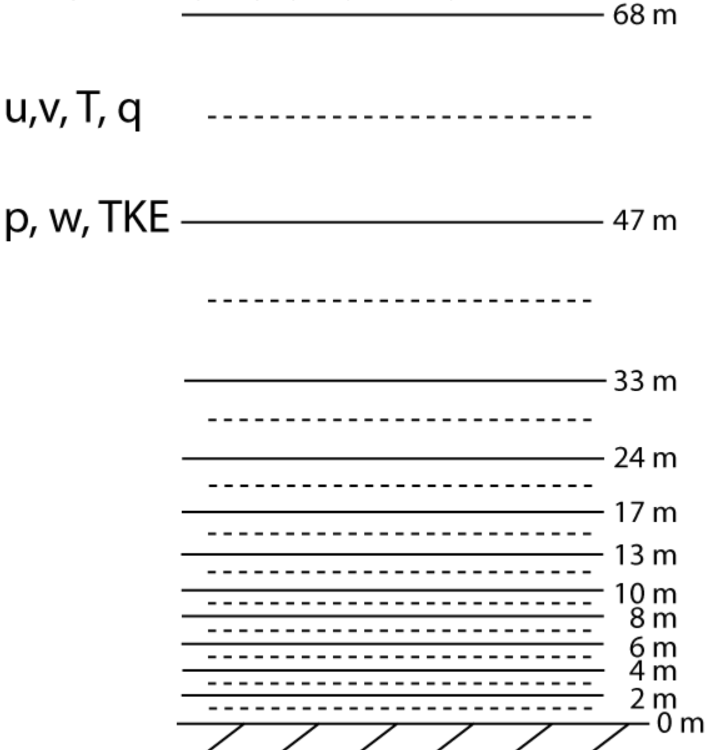


2 sodars are currently operational within the Rock Springs Observing Network

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.





- 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

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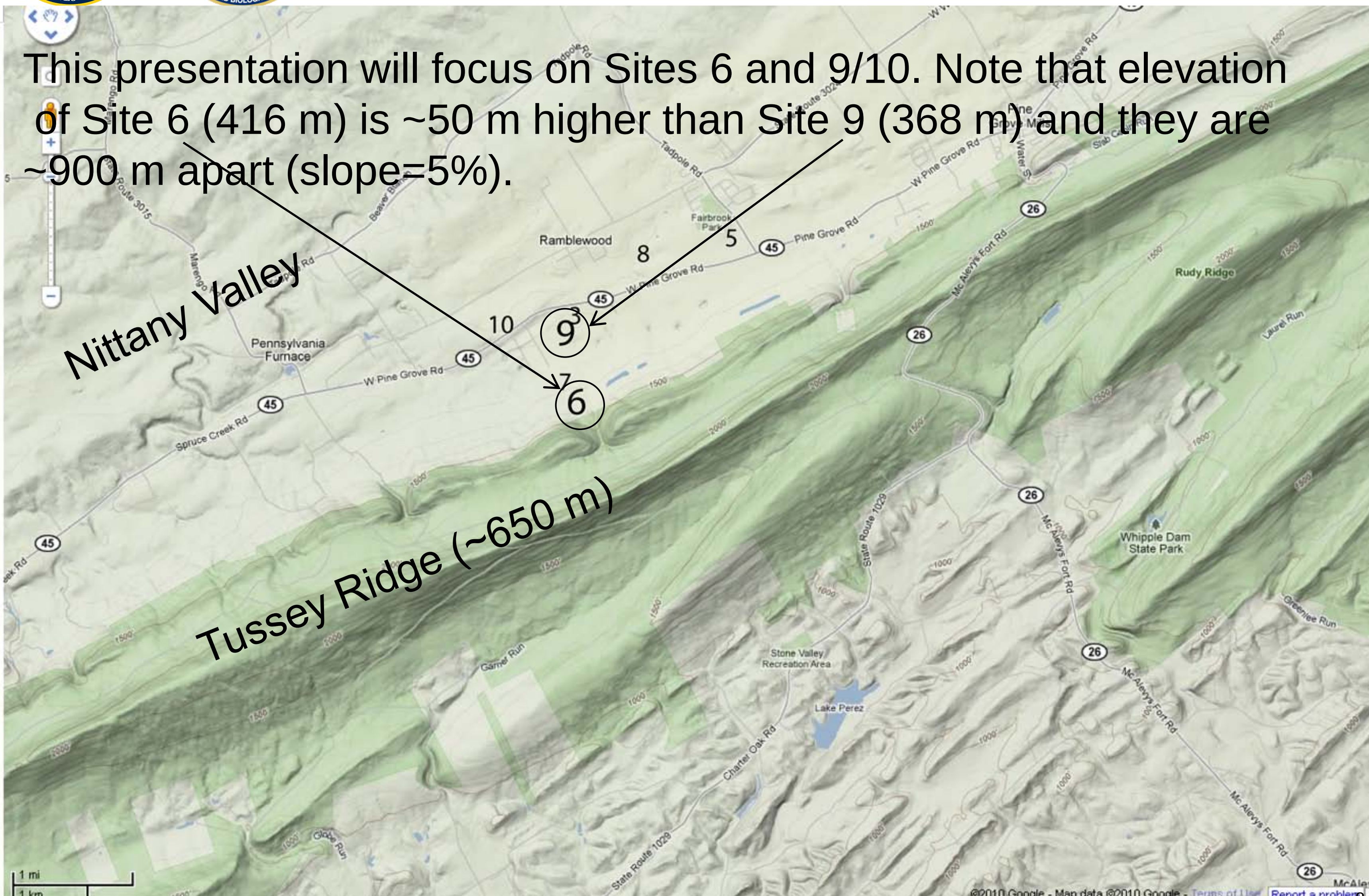
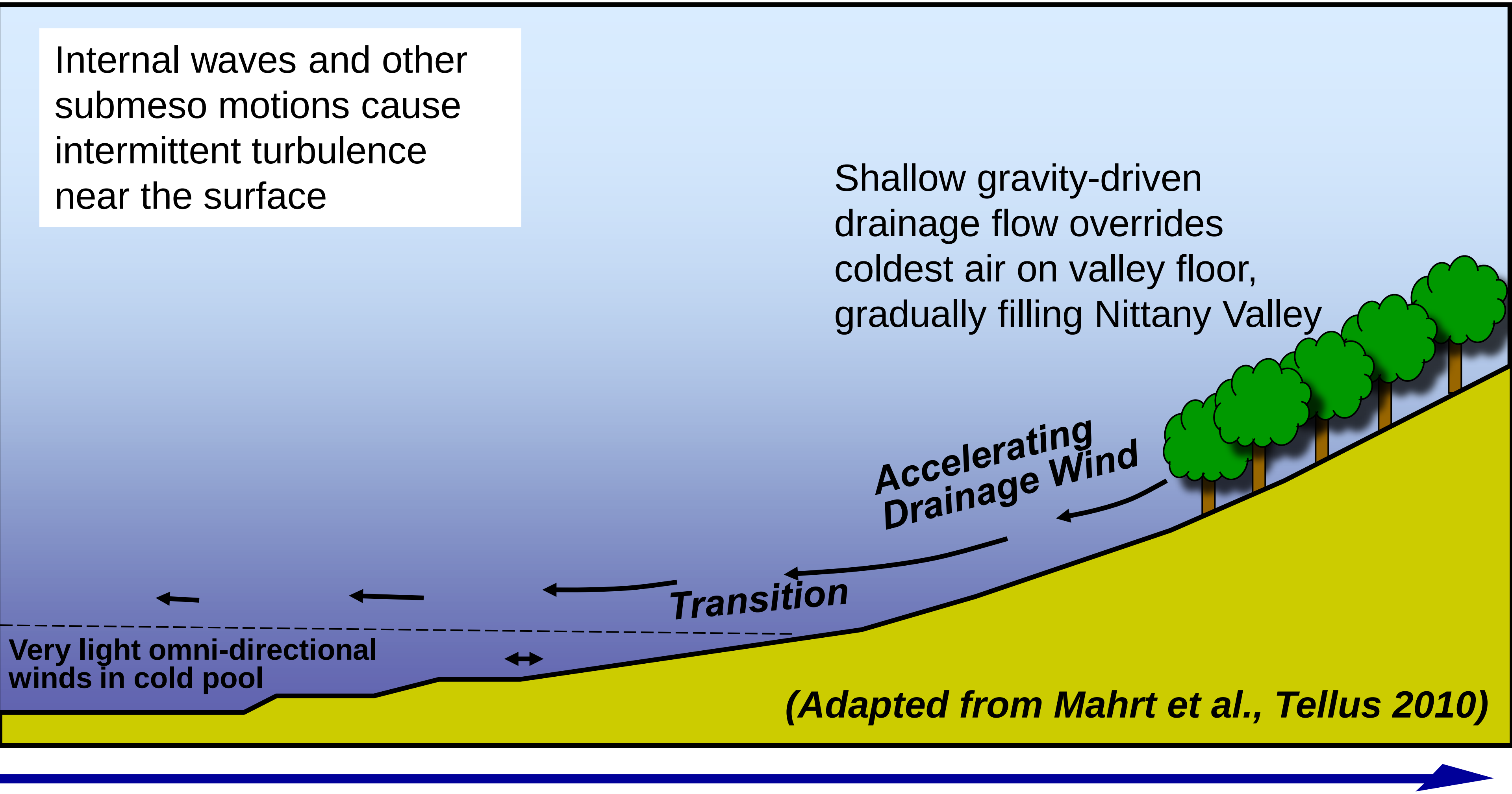
Locations of Obs Tower Sites

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%).



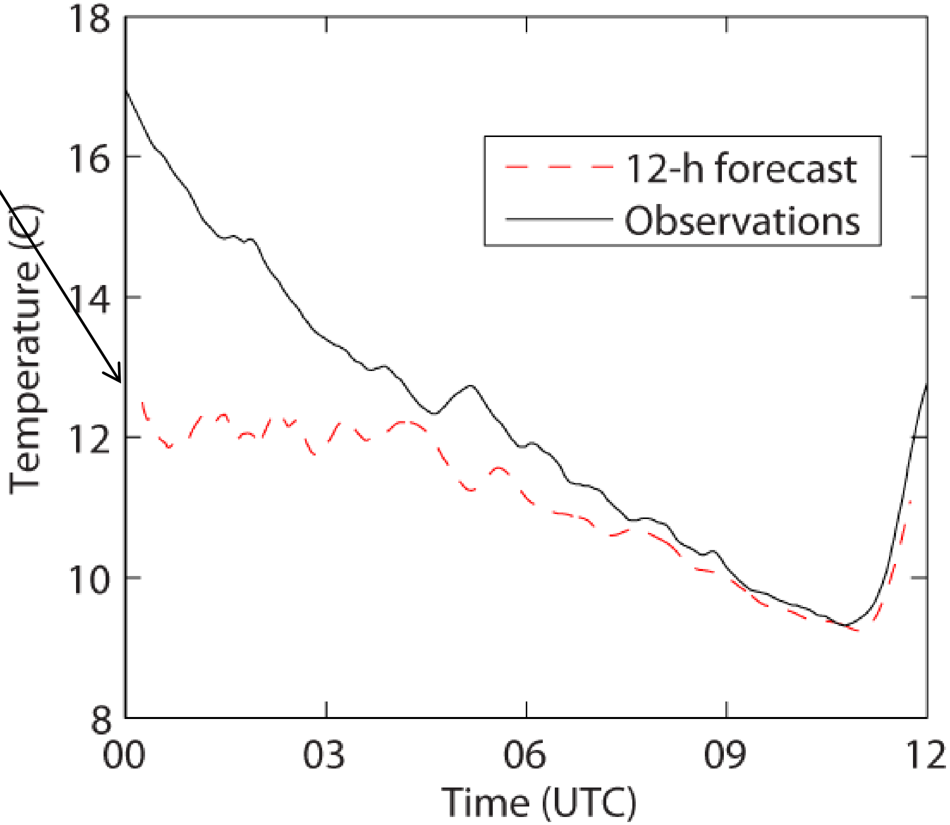
Conceptual Model of Nocturnal Flow Regimes For Valleys with Weak Down-valley Terrain Slopes



Initial Conditions

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

Site 9 2-m Temperature



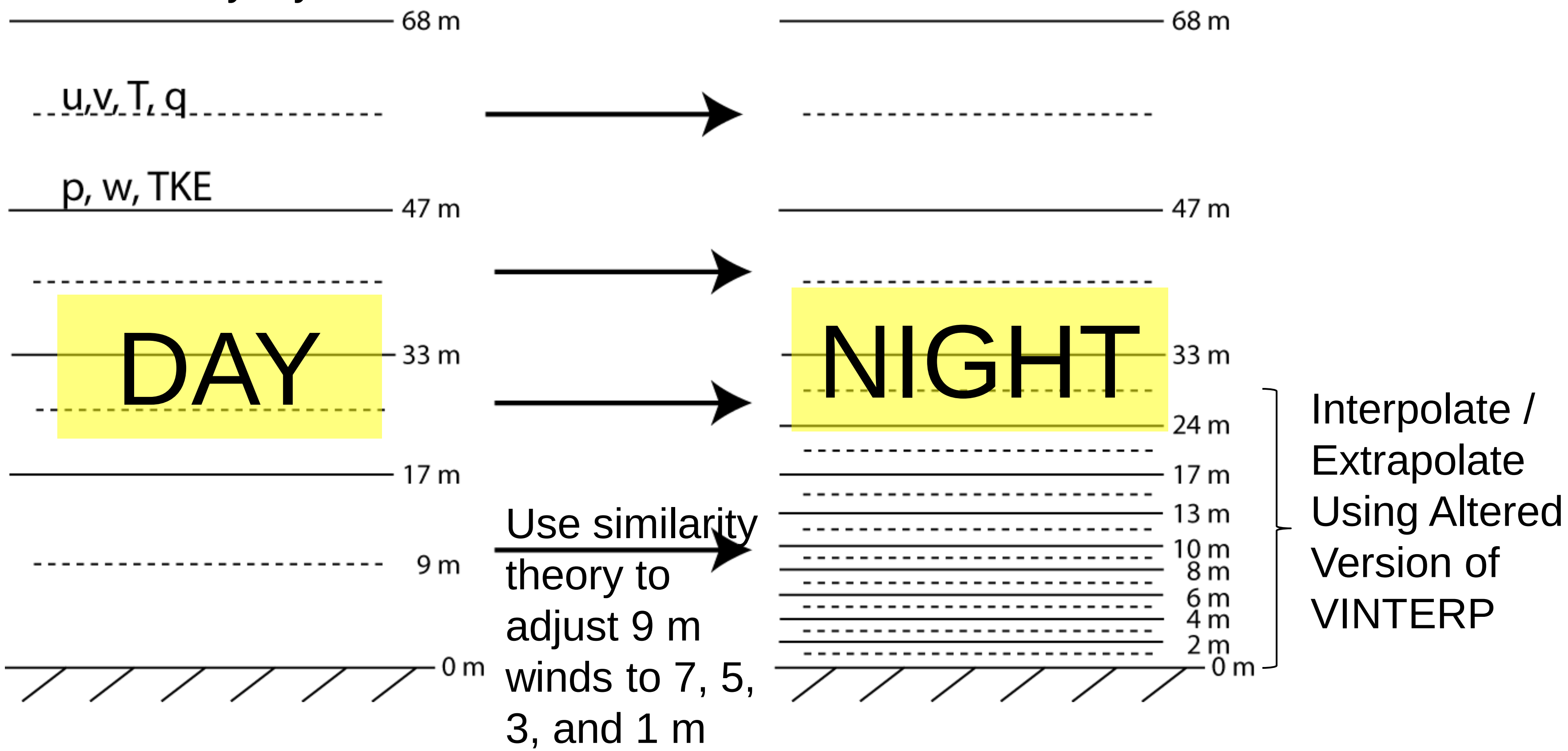
1-minute observations and 10-second model output used to adequately sample the data and both are 30-minute averaged to smooth high-frequency variations

Sunset: ~2337 UTC
Sunrise: ~1041 UTC

5 September 2009

Improving Initial Conditions

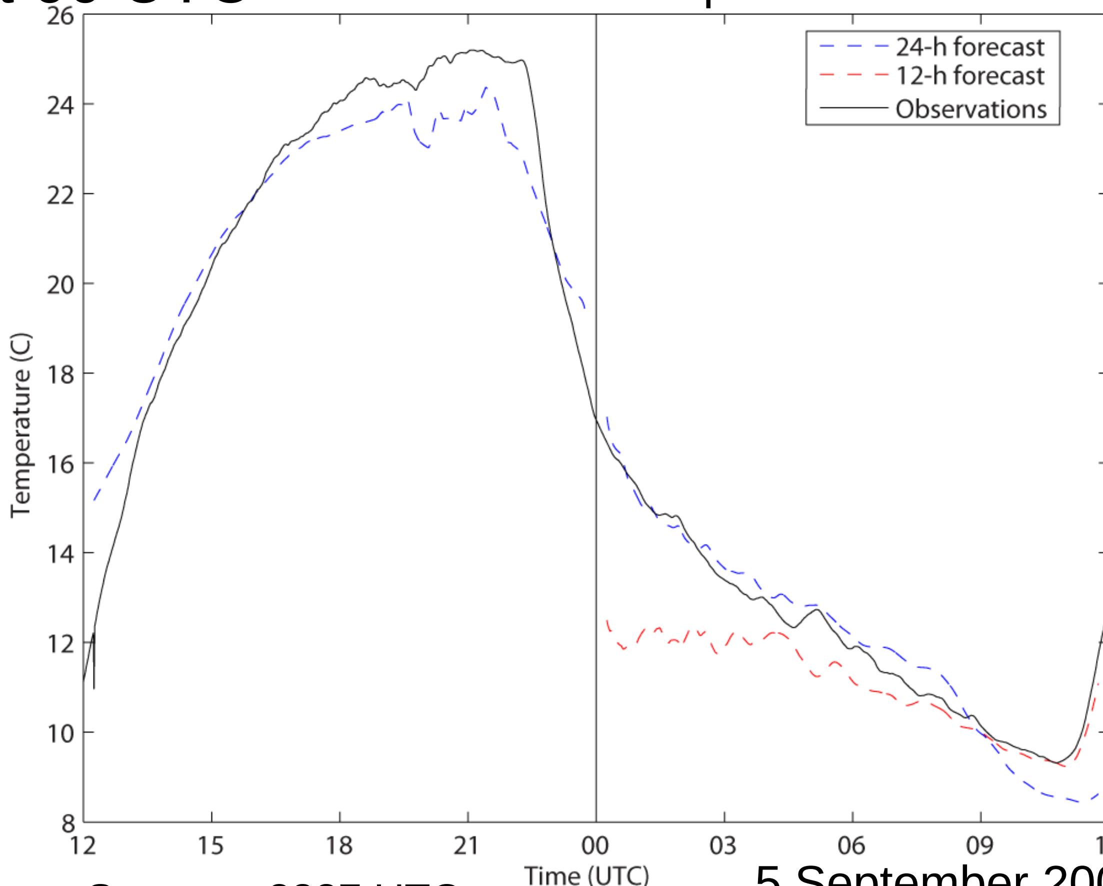
- To allow model to spinup meteorology consistent with terrain on 0.444-km domain model started 12 hours earlier (12 UTC)
  - Daytime portion of run (12 – 00 UTC) uses coarser vertical resolution to minimize risk of numerical issues during the more strongly forced convective boundary layer



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

Site 9 2-m Temperature



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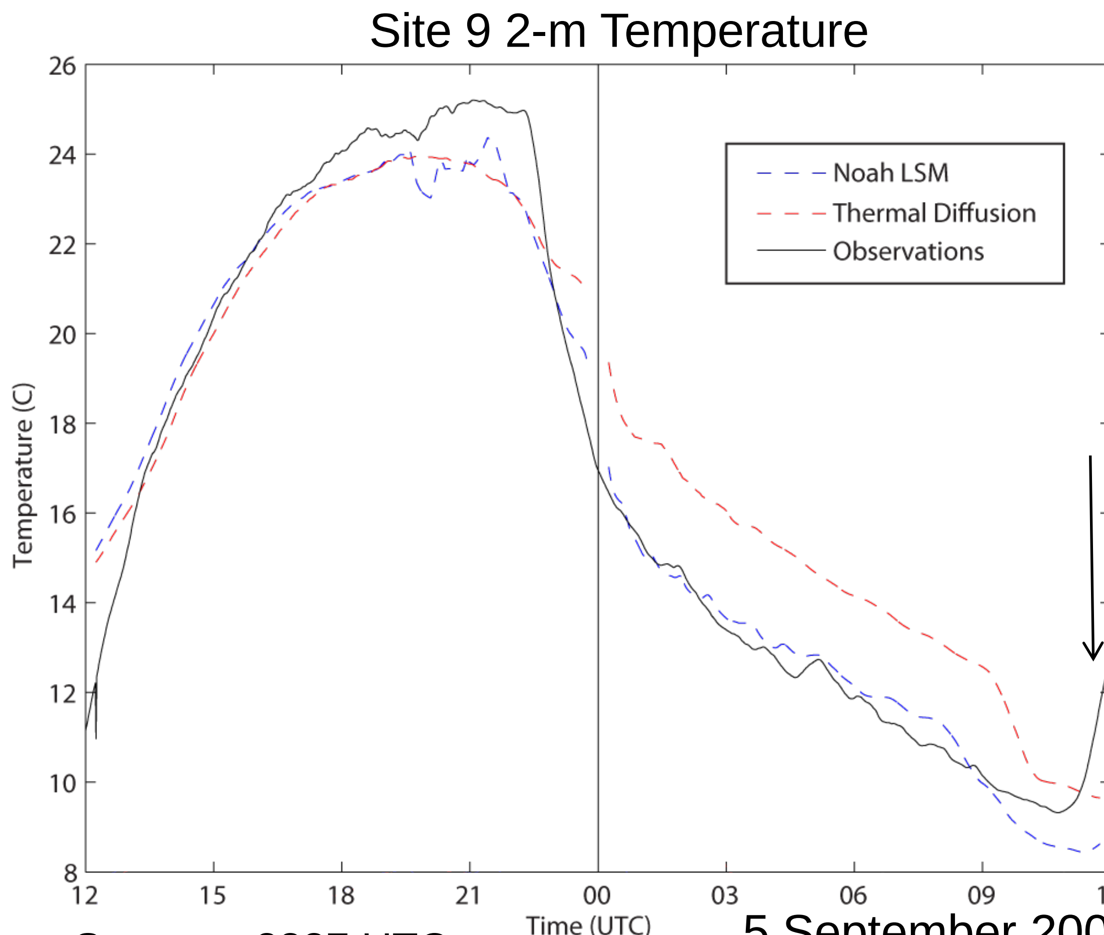
Physics Sensitivity -- LSM

- 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



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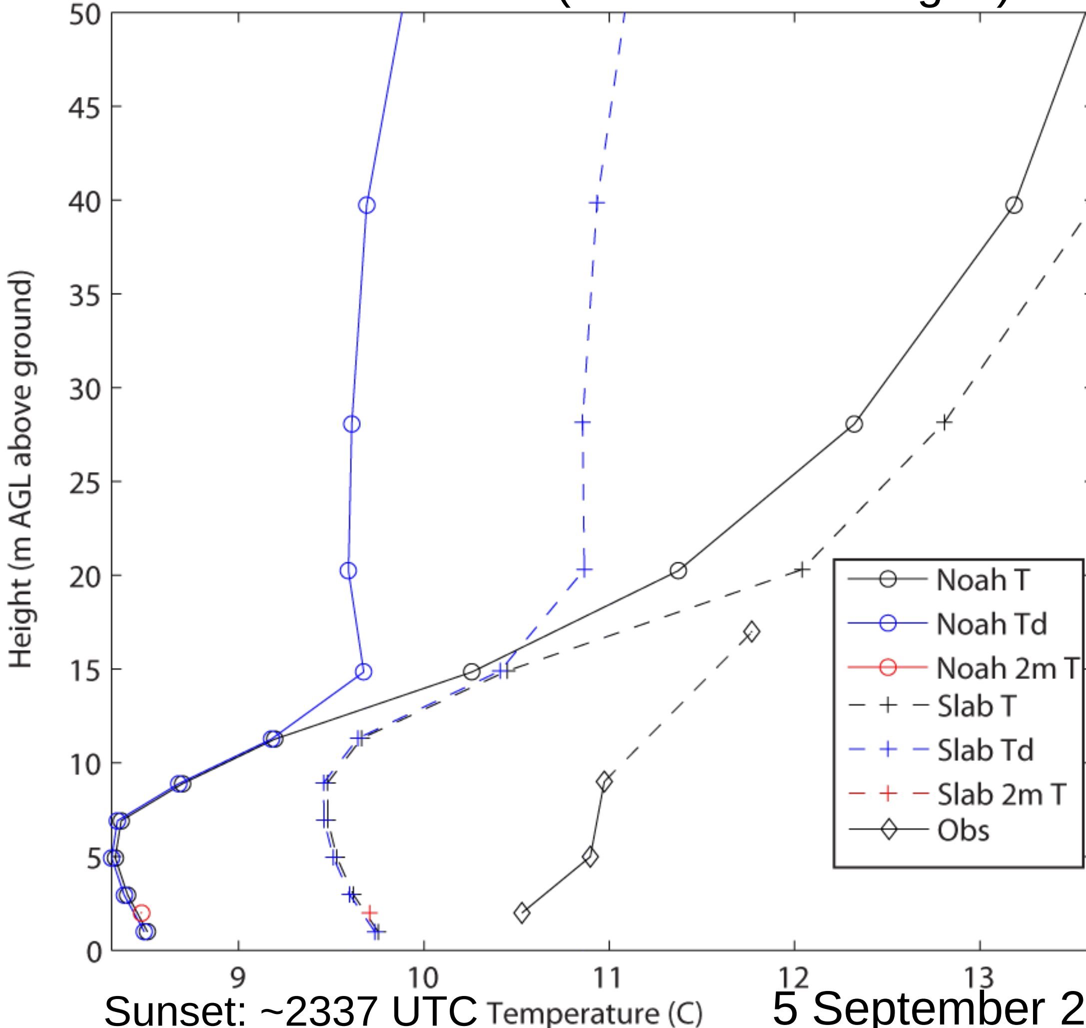
Fog in LSM Experiments

- 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

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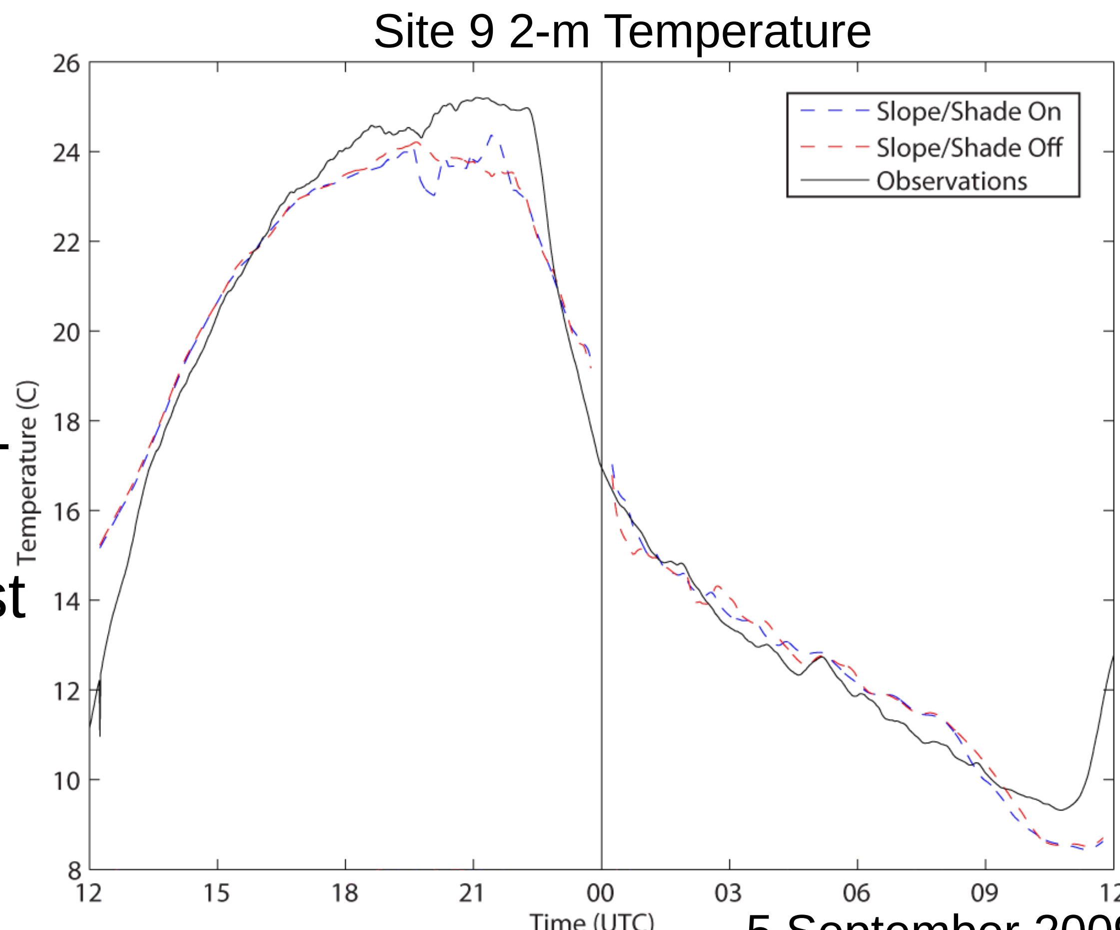
Physics Sensitivity – Slope / terrain shading

- 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



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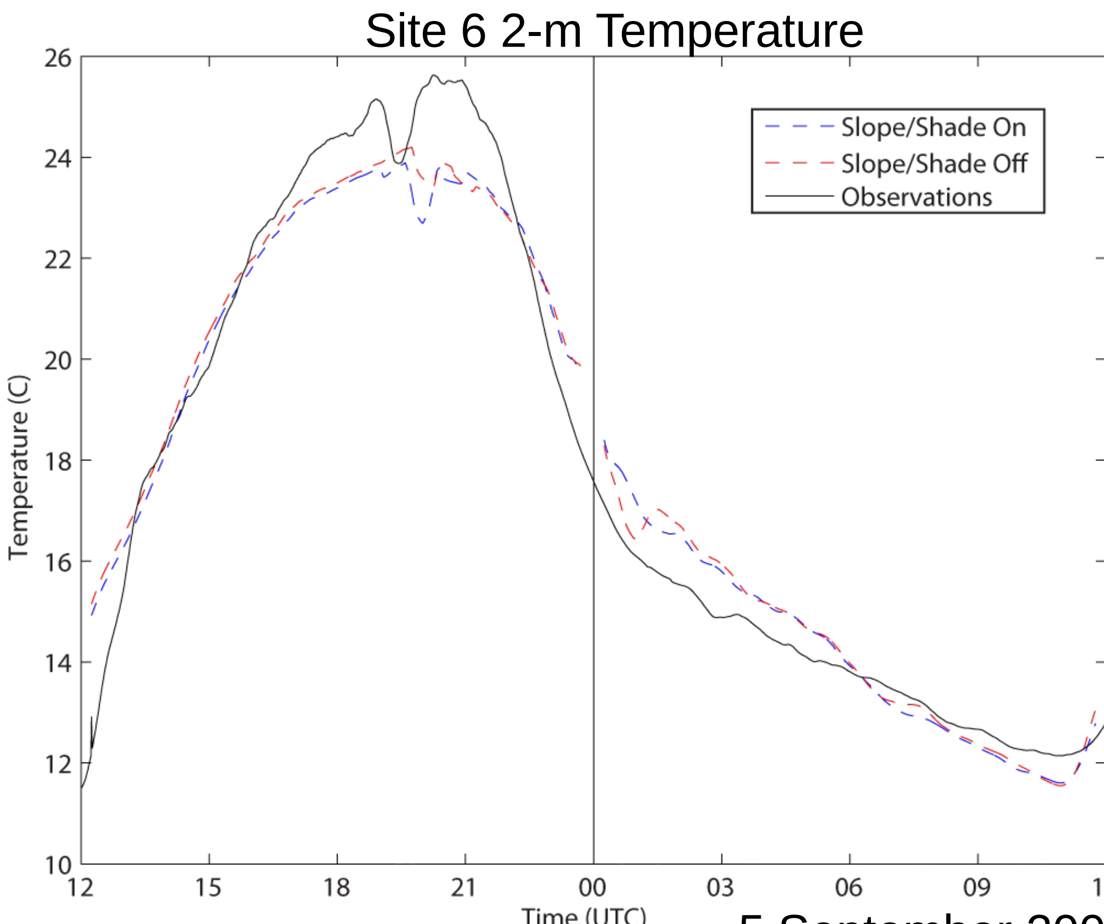
Physics Sensitivity – Slope / terrain shading

- 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



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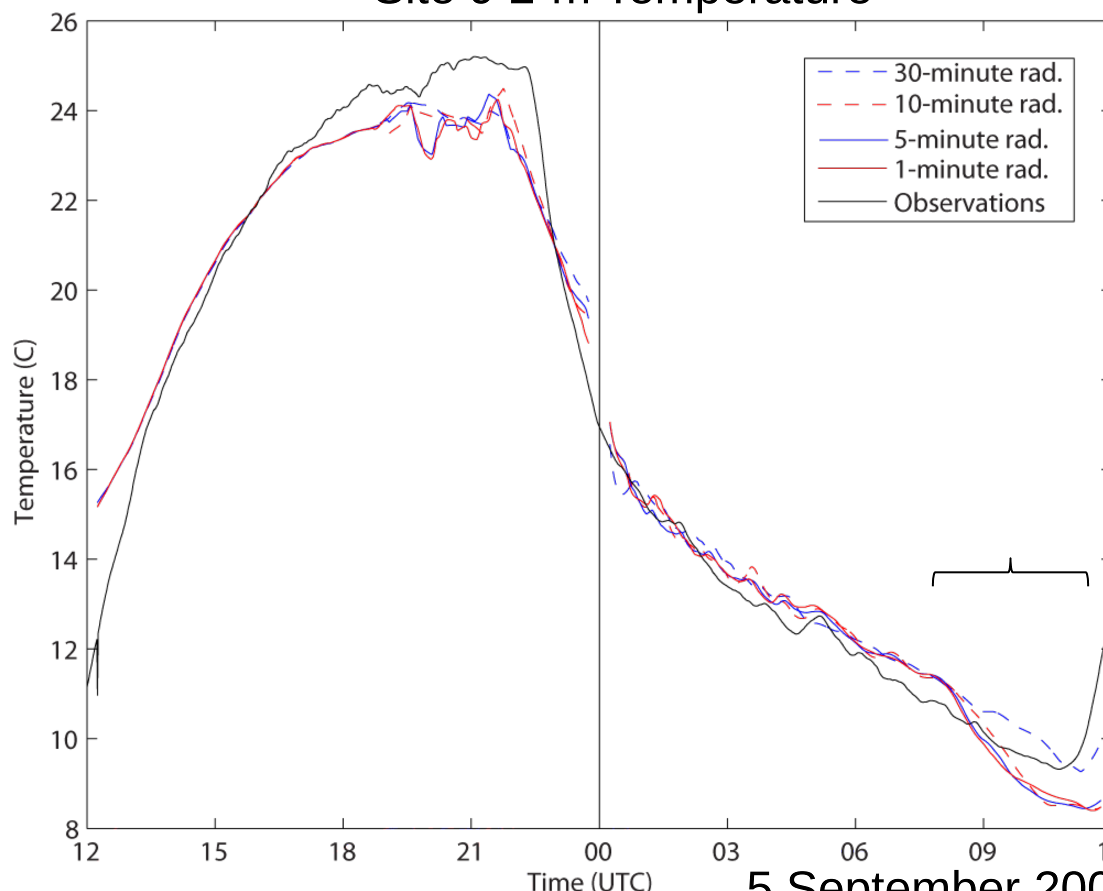
Sunset: ~2337 UTC

Sunrise: ~1041 UTC

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



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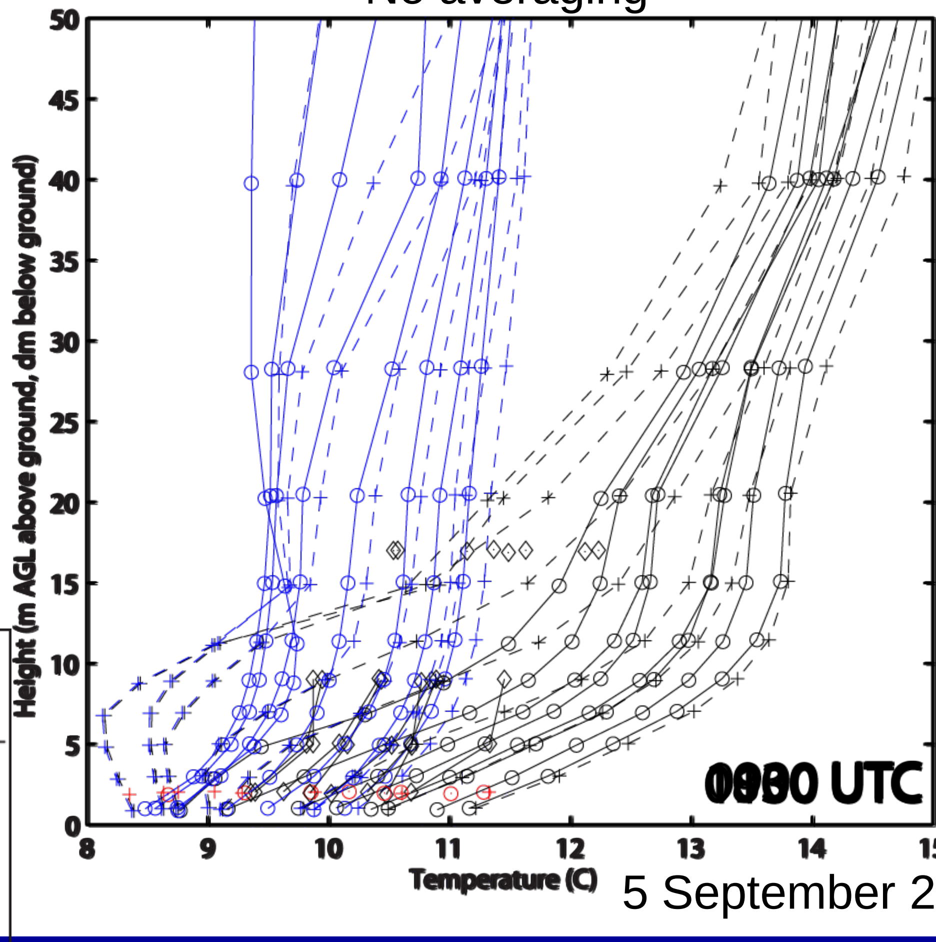
Sunset: ~2337 UTC

Sunrise: ~1041 UTC

Physics Sensitivity – Radiation Update Interval

- 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%)



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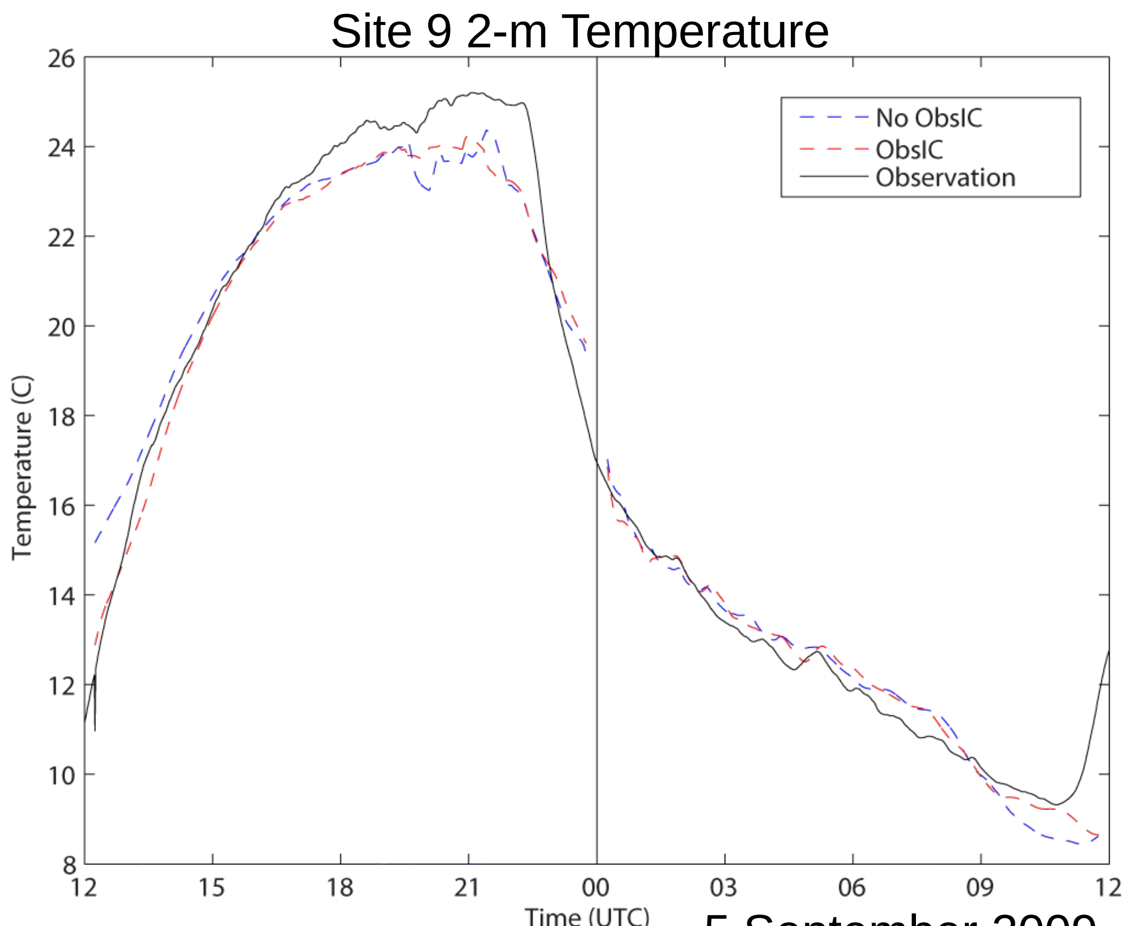
Improving initial conditions – use of observations

- 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



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Data Assimilation

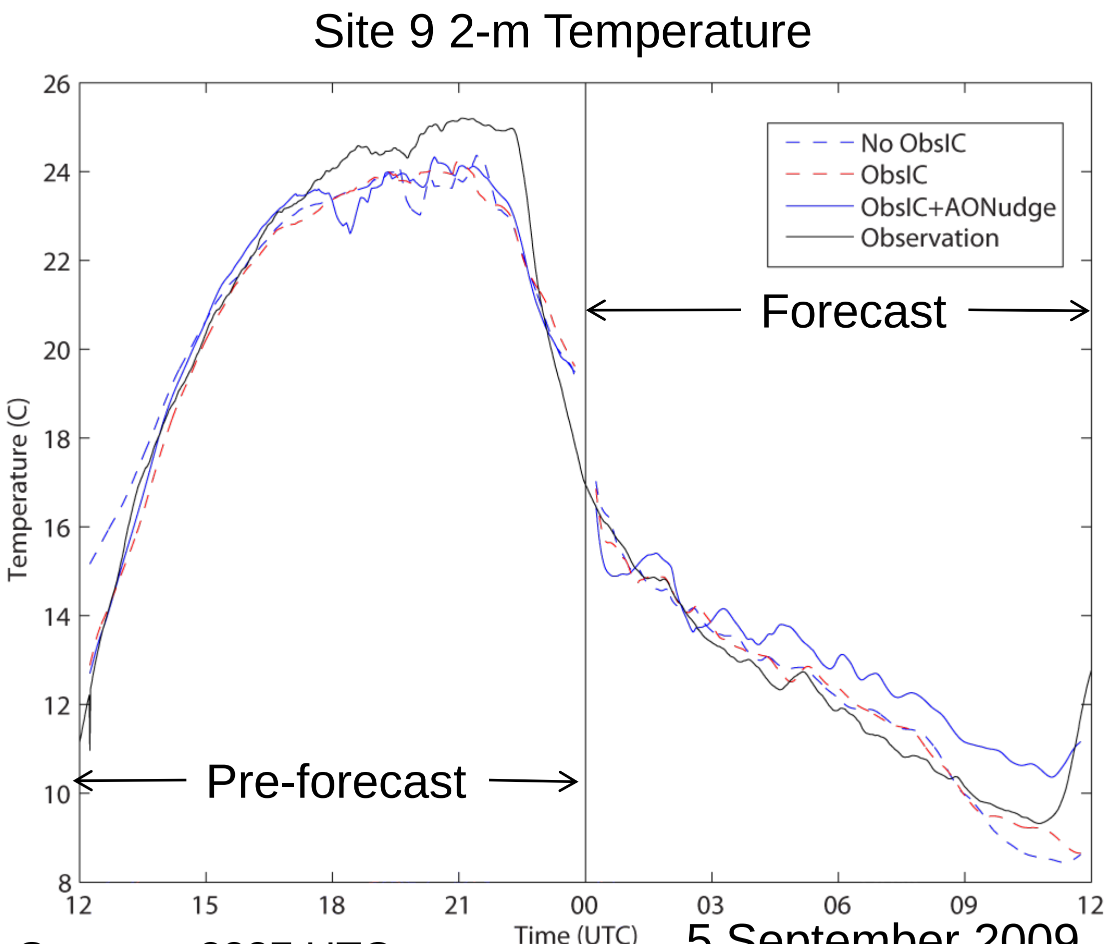
- Since the period of interest for the SBL is 00 UTC to 12 UTC, we investigate use of nudging throughout the 12-h daytime period as a pre-forecast
- Surface and 3D analysis nudging applied to 12-km domain to prevent large-scale features from drifting
- Observation nudging applied to all domains
  - Temperature, 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



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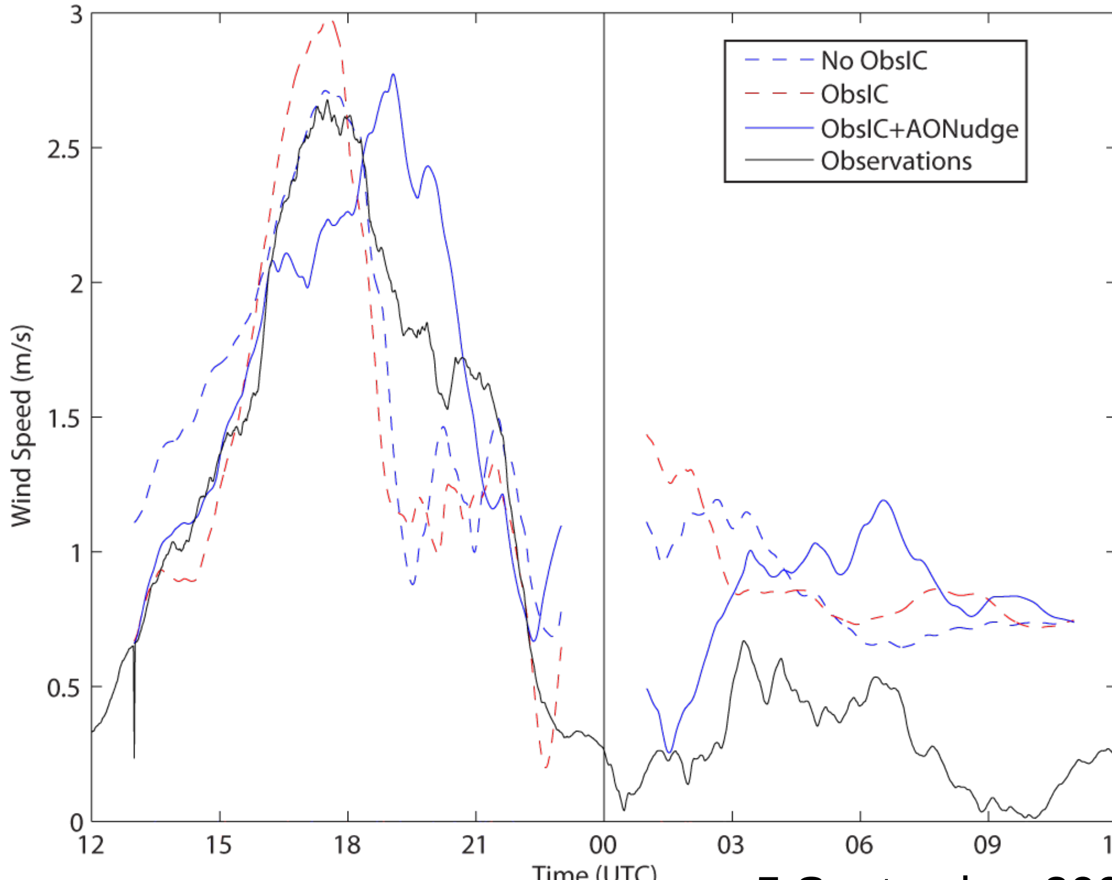
Data Assimilation – Wind Speed

- 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)



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Sunset: ~2337 UTC

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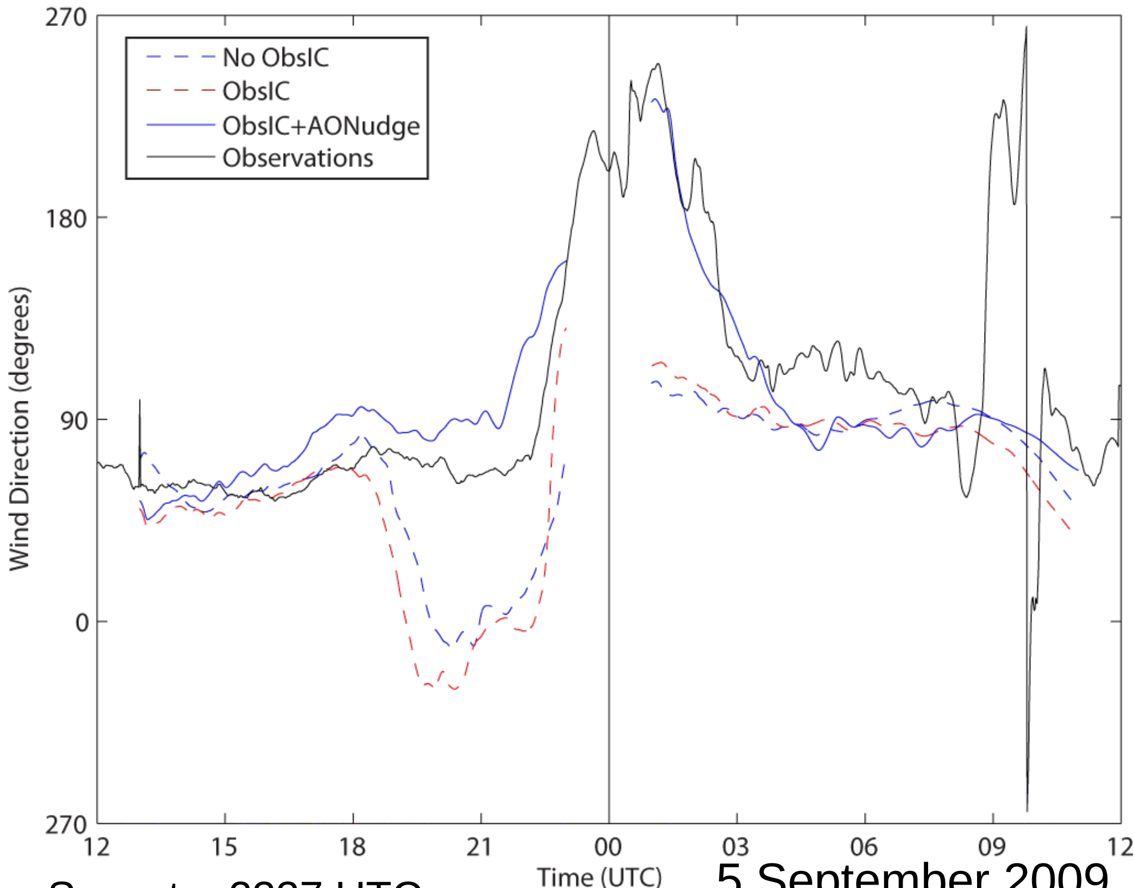
Data Assimilation – Wind Direction

- Nudging (dynamic initialization) improves wind direction during afternoon
- Strong improvement in forecast wind direction during early portion of nighttime period

Site 9 9-m Wind Direction of Mean Wind
(2 hour average)



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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

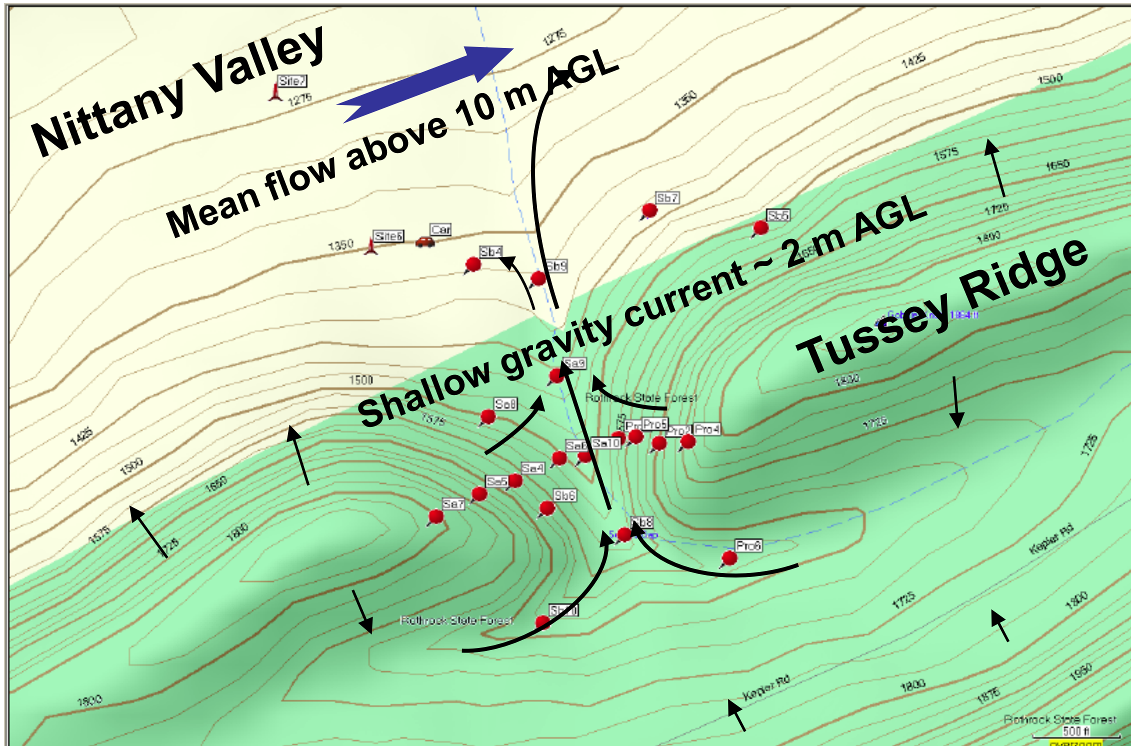
Future Work

- 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

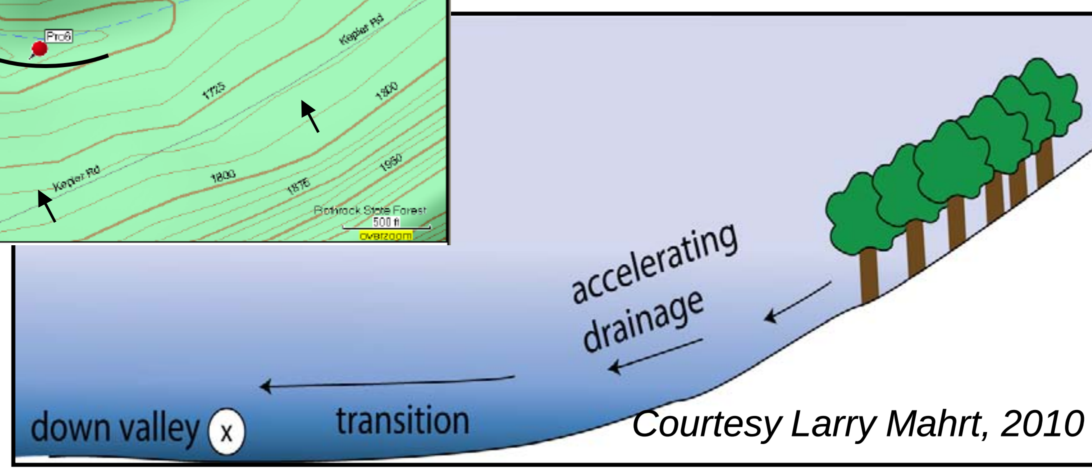
- Defense Threat Reduction Agency under DTRA Grant No. HDTRA1-10-1-0033 under the supervision of Dr. John Hannan.

Nocturnal gravity-driven drainage flow modulated by transient submeso motions



Conceptual model:

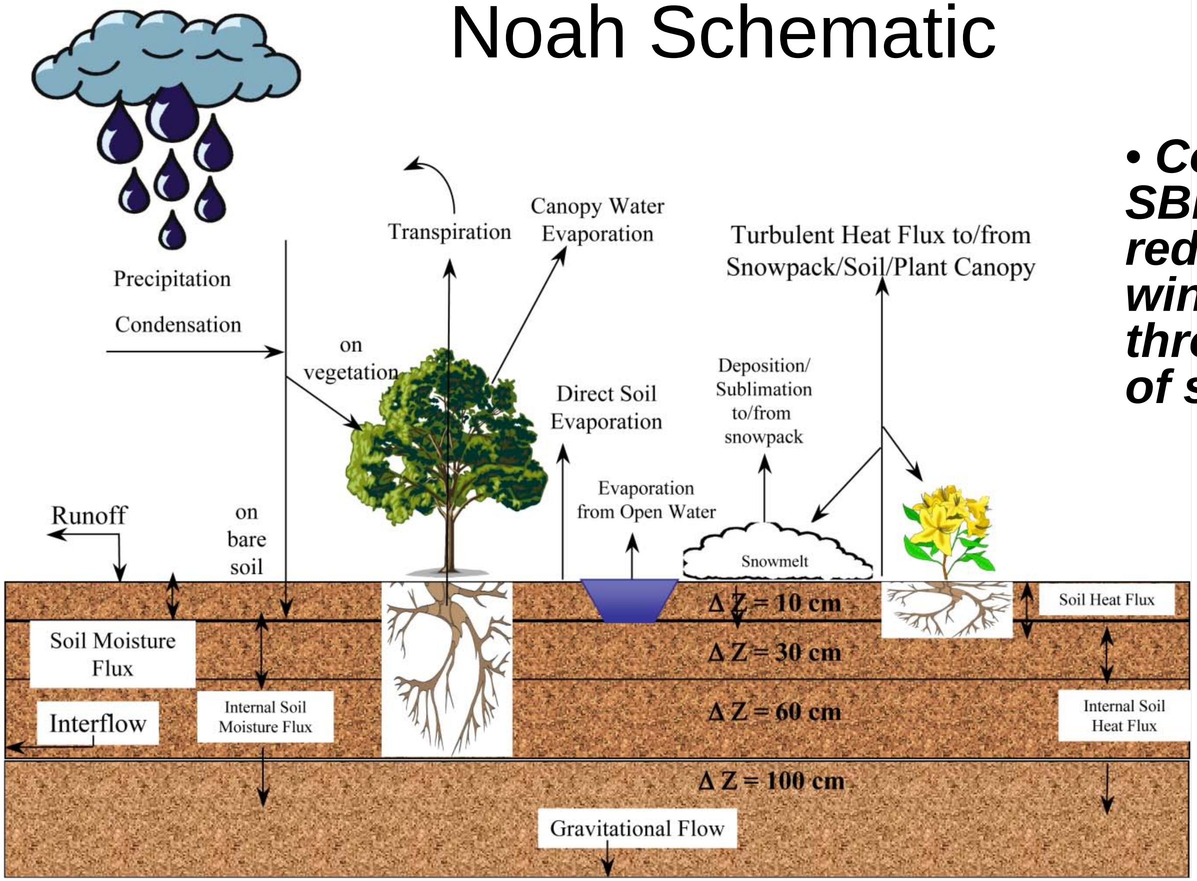
Shallow gravity-driven drainage flow overrides coldest air on valley floor, gradually filling Nittany Valley.



Courtesy Larry Mahrt, 2010

The Noah Land-Surface/Canopy Model in WRF

Noah Schematic



From Noah tutorial by F. Chen.

- ***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.***