Analysis and Simulation of a Cold-Air Pool and High Wintertime Ozone Episode in Utah's Uintah Basin

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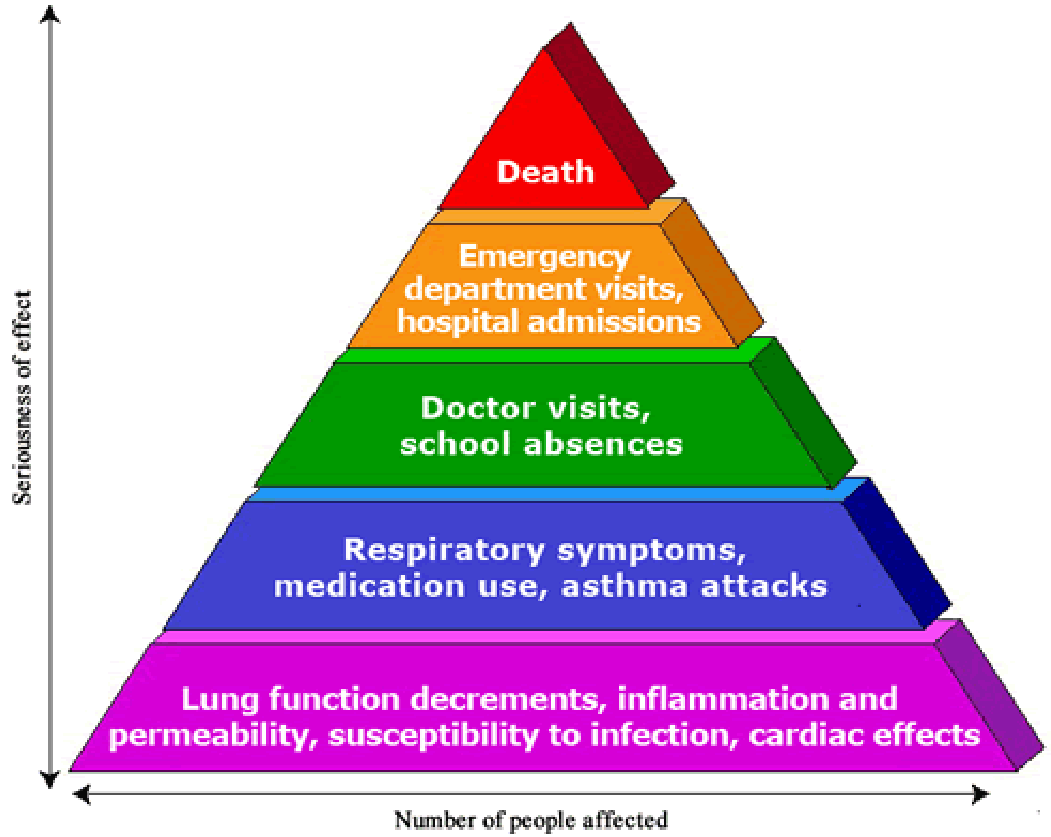
Overview

- Background & Motivation
- Research Questions
- Model Setup & Modifications
- Evolution of 1-6 Feb 2013 Cold-Air Pool
- Base Run & Sensitivity Studies
- Flow Features in the Basin
- Ozone & Air Quality
- Conclusions & Future Work

Background - Ozone & Health

- Surface ozone is a significant health hazard to humans
  - Respiratory irritation and inflammation
  - Aggravated asthma
  - Long-term lung damage
  - Increased hospital admissions and ER visits
  - Increased mortality



- Younger adults more sensitive than older adults

- Background levels typically 20-45 ppb (U.S. EPA 2006)

- EPA National Ambient Air Quality Standard (NAAQS) is 75 ppb for an 8-hour average

U.S. EPA: http://www.epa.gov/apti/ozonehealth/population.html

Background - Ozone in Rural Basins

- **2005 - High wintertime ozone concentrations first analyzed in Upper Green River Basin, WY (Schnell et al. 2009)**
  - **2008 - Several instances where ozone exceeded 100 ppb**
- **2009 - High ozone levels first detected in Uintah Basin**
- **2012 - WY counties designated as non-attainment areas**

Upper Green River and Uintah Basins share many characteristics:

- **Extensive oil & gas operations**
- **Frequent winter snow cover**
- **Similar climate and vegetation**

Study finds oil and gas causing pollution problem in eastern Utah

Environment » $5M Uinta Basin study IDs causes of winter pollution, but leaders aren't quite ready to act.

By Judy Fahys | The Salt Lake Tribune
First Published Feb 19 2013 06:56 pm • Last Updated Feb 20 2013 03:25 pm

2013 Uintah Basin Winter Ozone Study

Draft Final Report
2013 Uinta Basin Winter Ozone Study

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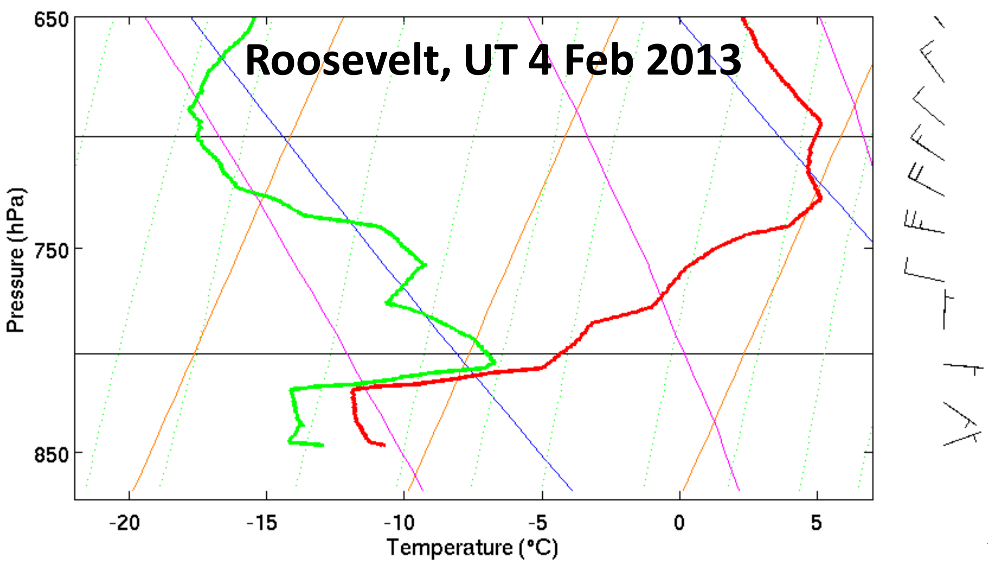
- NOAA/CSD
- NOAA/PMEL
- NOAA/ESRL
- Environment Canada
- Utah State University
- University of Utah
- University of Colorado CIRES
- University of Wyoming
- Karlsruhe Institute of Technology
- Environ
- Alpine Geophysics
- Science & Technology Corporation

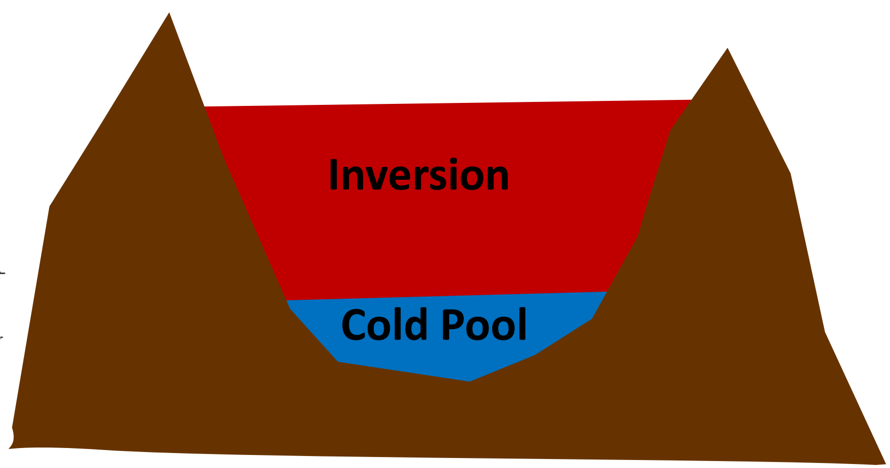
2013 Uintah Basin Winter Ozone Study

Photos: Erik Crosman

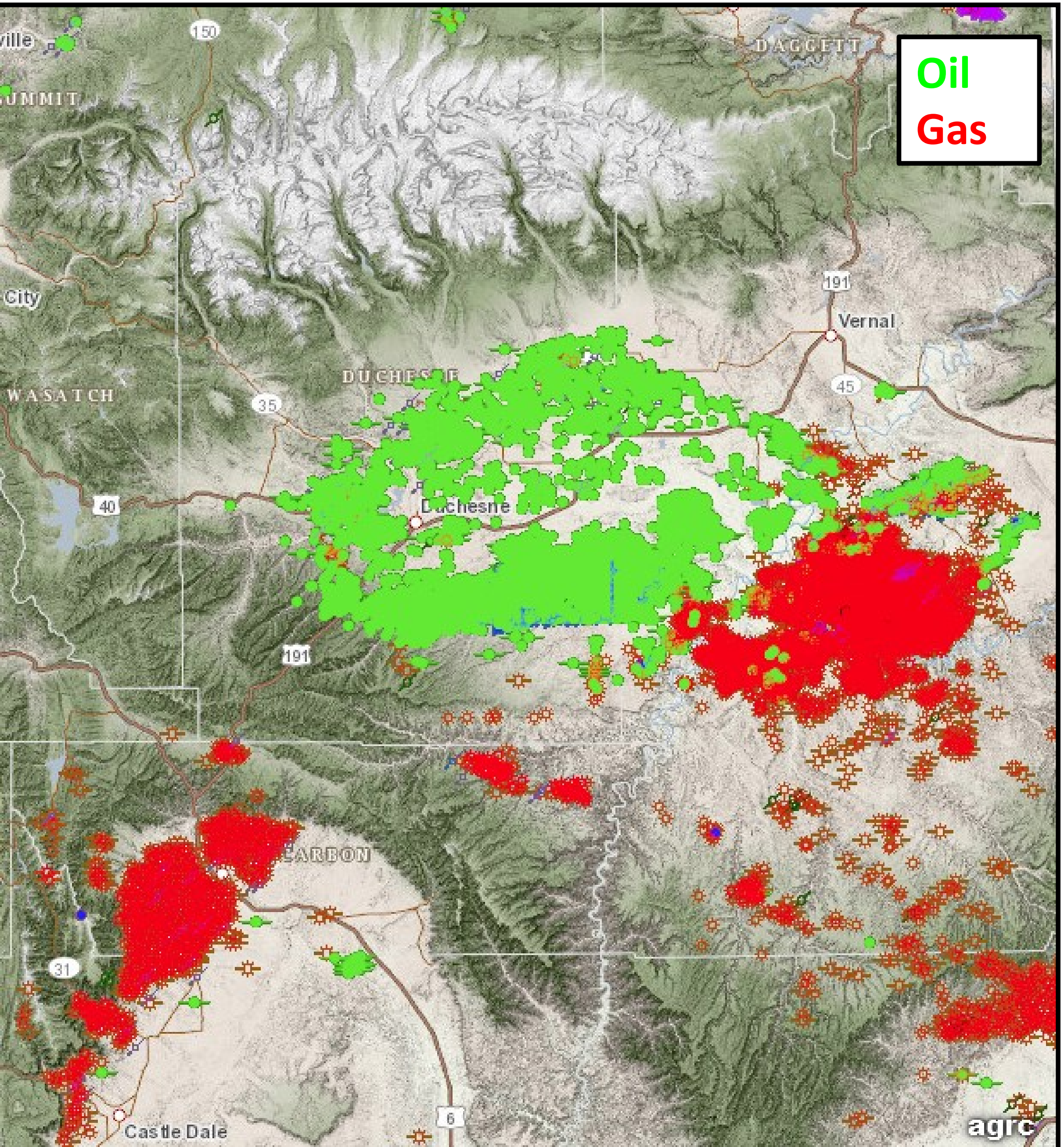
Background - Cold-Air Pools (CAPs)

- Stagnant, stable layer of air confined in a topographical depression with warmer air typically aloft (Lareau et al. 2013)
- Diurnal or persistent
  - Solar heating insufficient to destroy low level volume of cold air
- Onset coincident with mid-level warming, removed by mid-level cooling (Reeves and Stensrud 2009)
- Many studies link persistent CAPs to poor air quality
  - Malek et al. 2006, Silcox et al. 2012, Whiteman et al. 2014
  - Whiteman et al. 2001, Lareau et al. 2013, Lareau and Horel 2014





Uintah Basin



- Large (~15,000 km^2) and bowl-like basin ringed by mountains
- Over 500 m of relief from basin center to ridgelines
- 9,400 oil & gas producing wells in March 2014
- Over 3,600 permits for additional wells since Jan 2012

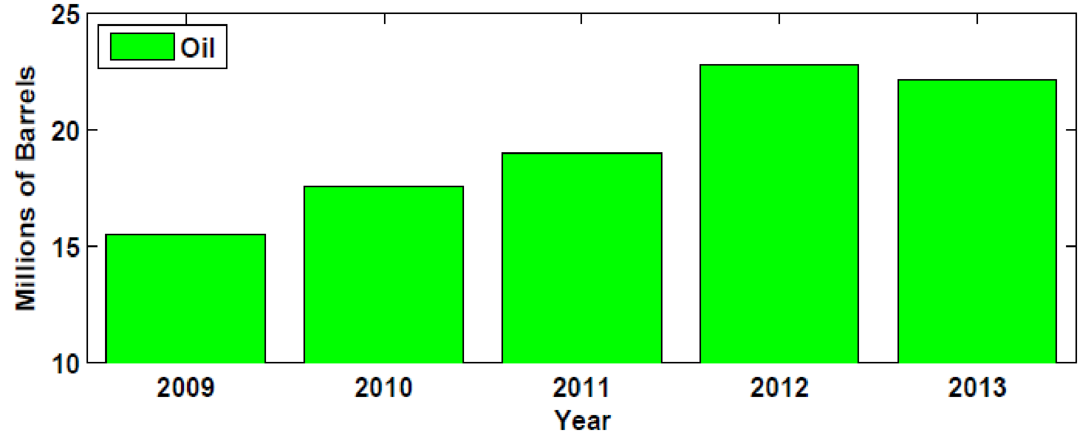
Courtesy of Utah Division of Oil, Gas, and Mining

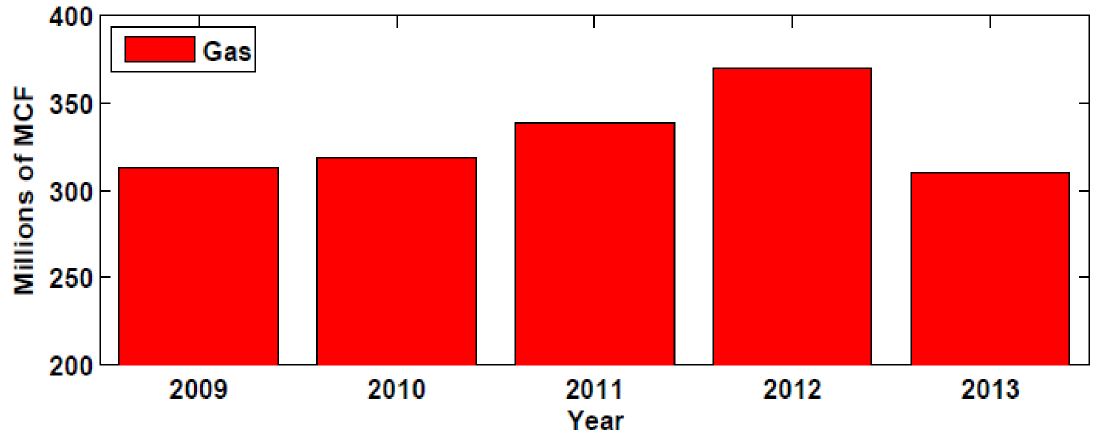
Fossil Fuel Production

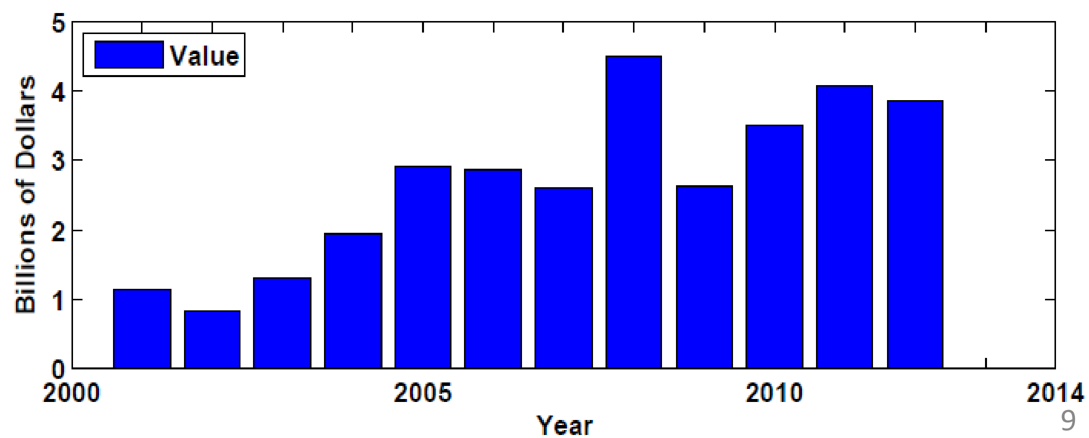
- Notable increase in drilling since 2009

- 60% of local economy tied to oil & gas industry (Salt Lake Tribune 2013)

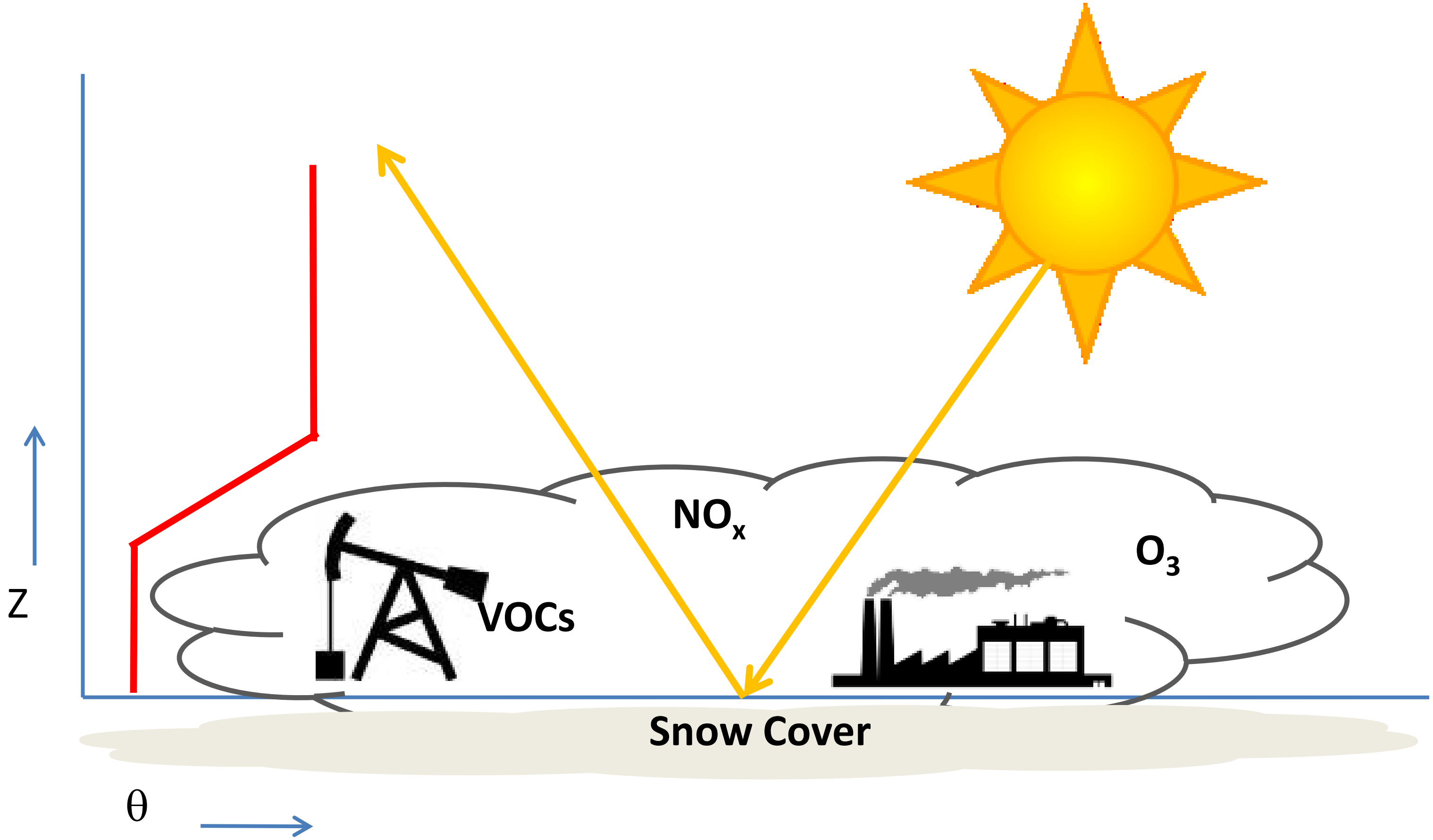
- Increasing trend expected to continue







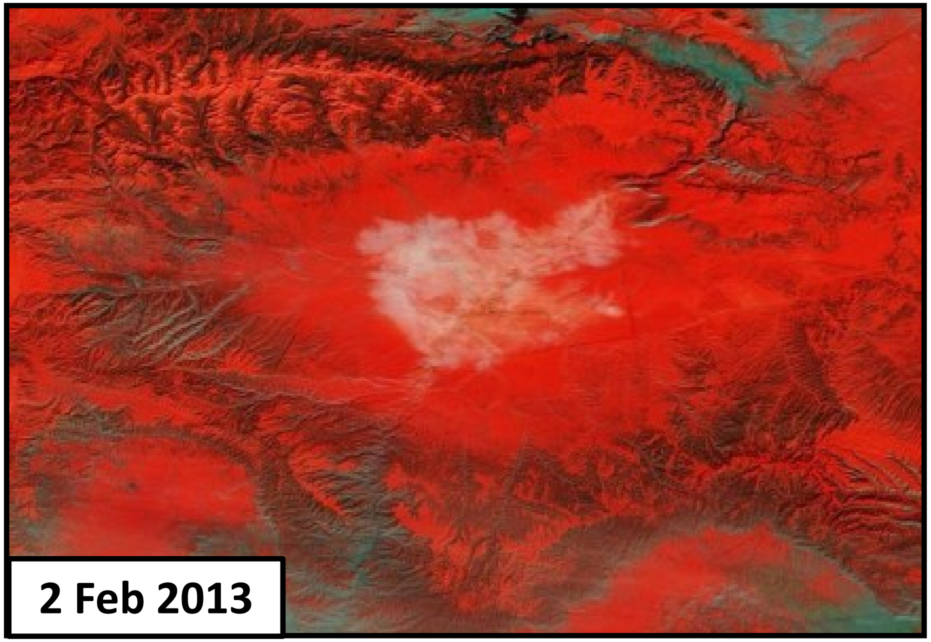
Winter Ozone Production



- Snow cover aids formation of strong CAPs under upper ridging
- Pollutants trapped near surface in stagnant conditions
- High-albedo snow increases actinic flux and enhances photolysis rates to ~50% greater than summer (Schnell et al. 2009)

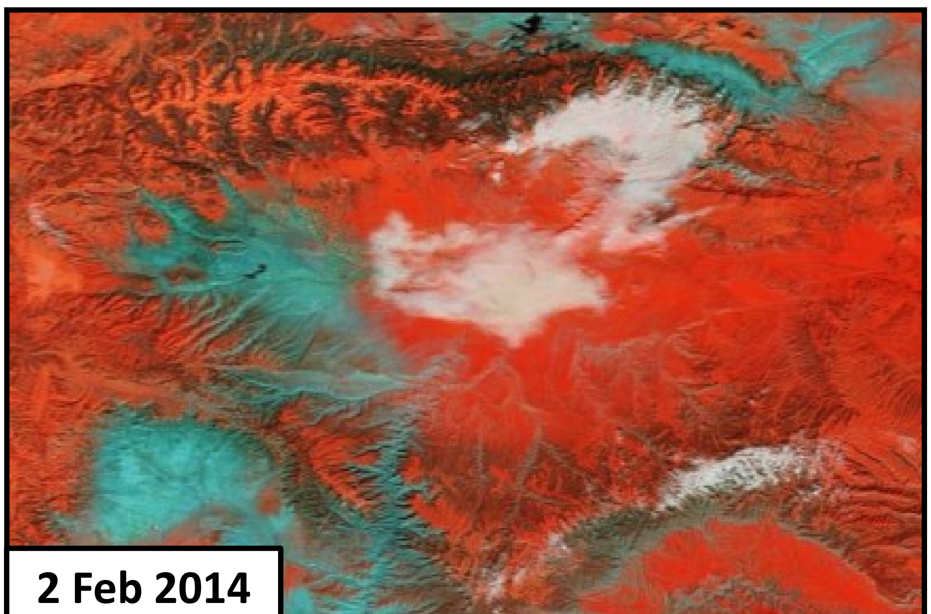
  → Rapid ozone production

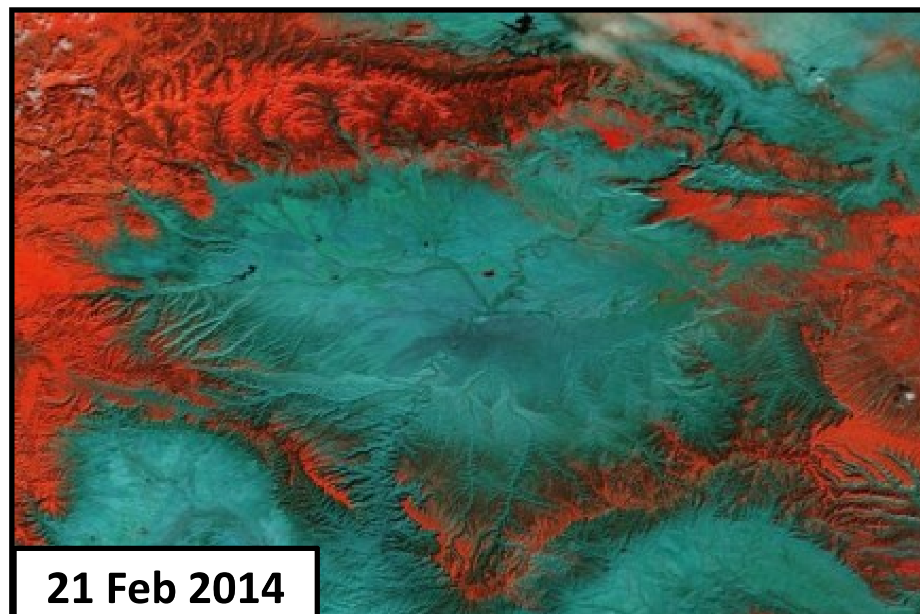
Snow Cover Variations…



- Large year-to-year variations in snow cover
- Depends on if snow from early-winter storms can be sustained into February

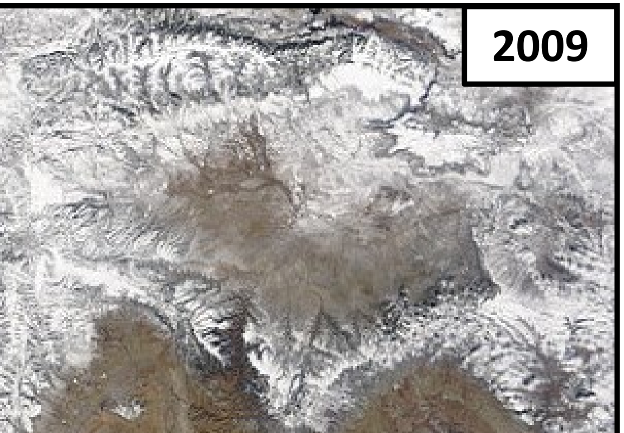
Courtesy NASA SPoRT program





…Set to Ozone Expectations

NAAQS exceedance days at Ouray:



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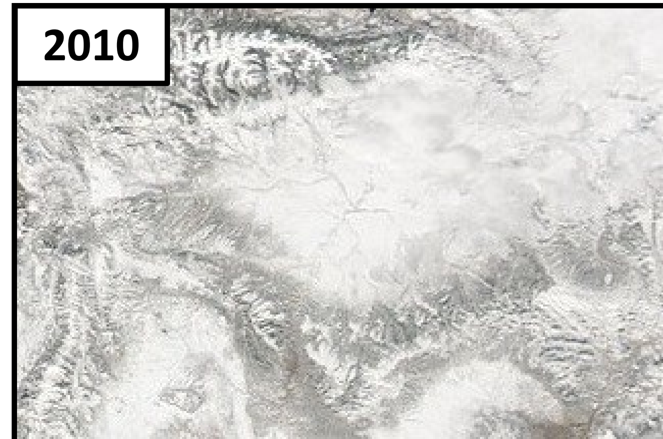

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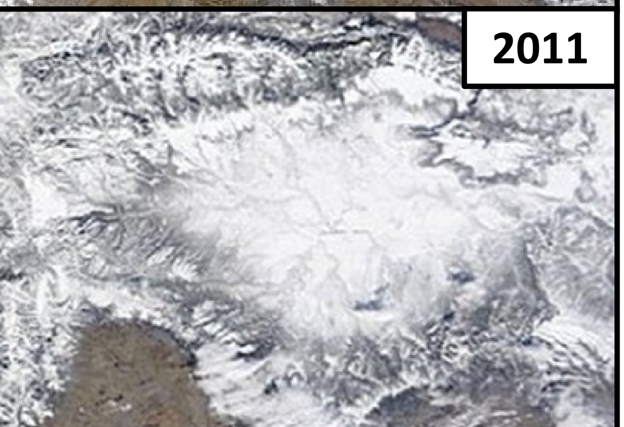

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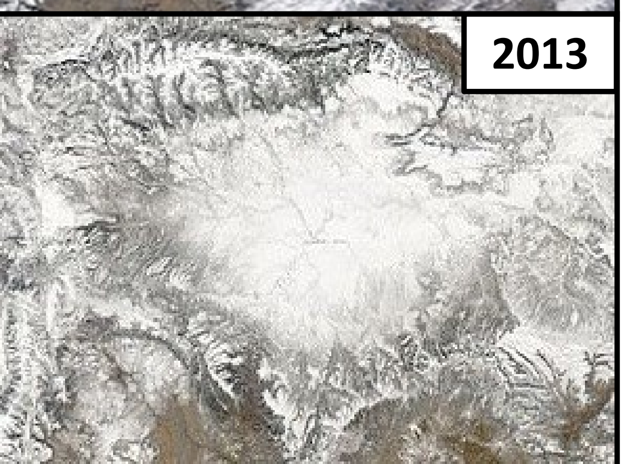

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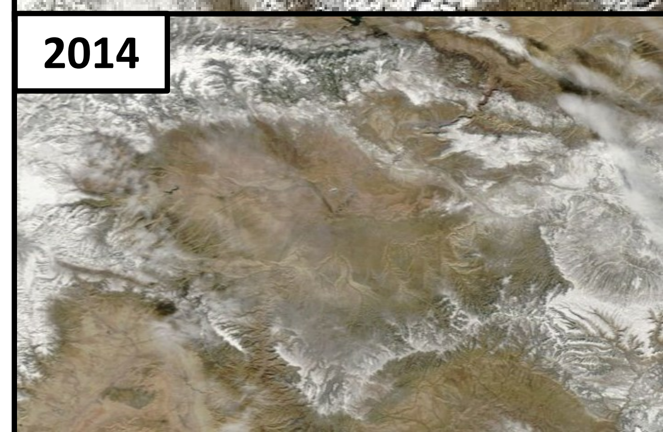

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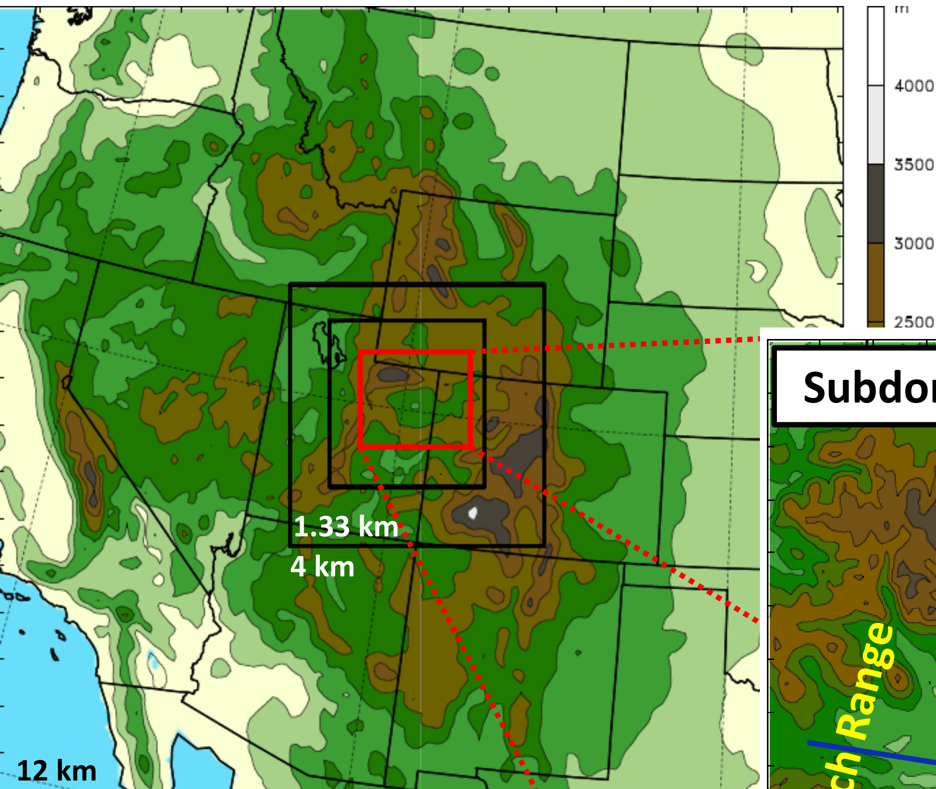
2013 Uintah Basin Winter Ozone Study

Research Questions

- ***What is the sensitivity of simulated CAP structure and evolution to cloud microphysics?***
- ***How do snow cover variations affect CAP simulations and structure?***
- ***What are the important wind flow regimes in the Uintah Basin CAP? Can they be diagnosed by mesoscale modeling and how might they affect air quality in the basin?***
- ***What is the influence of snow cover on simulated air quality in the Uintah Basin?***

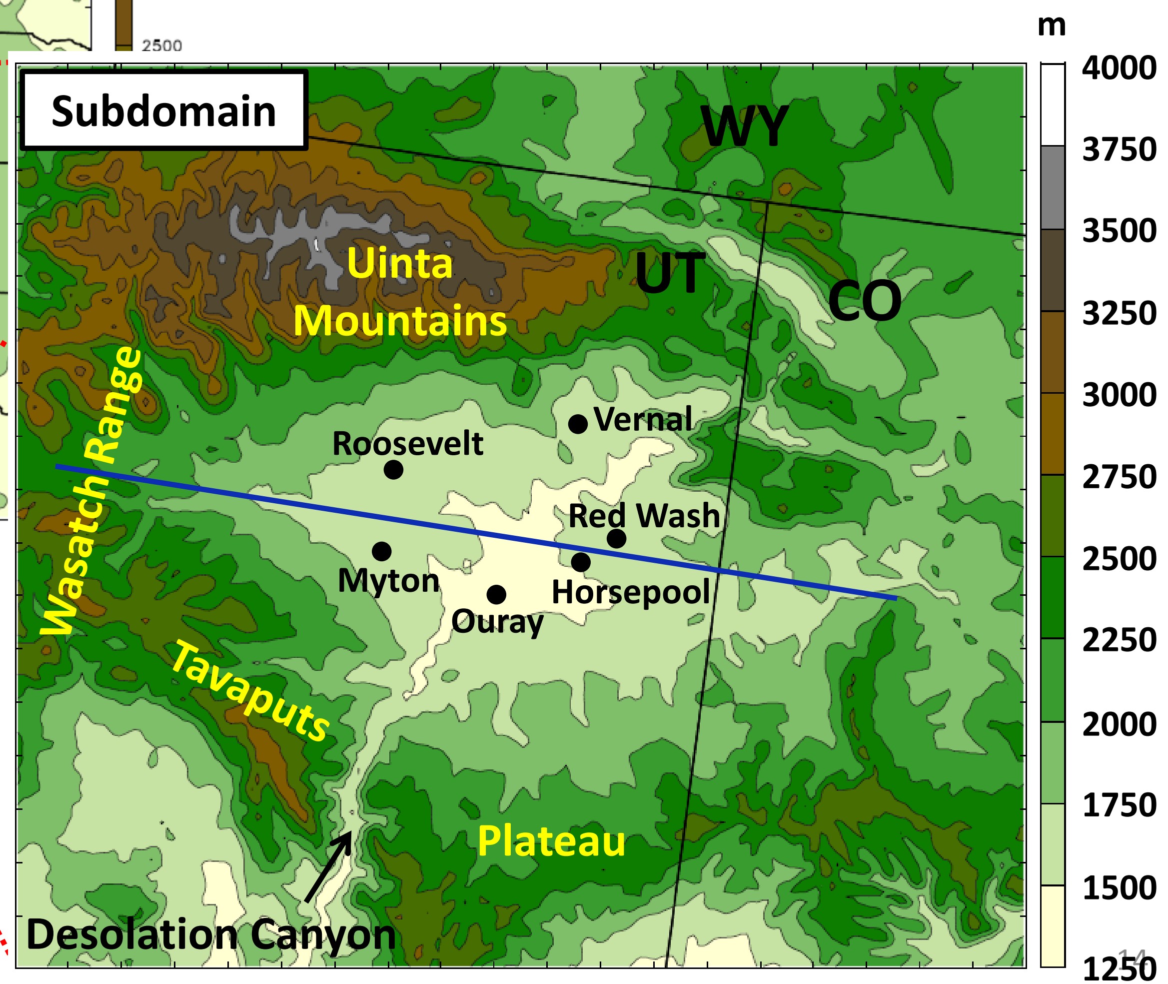
Model Setup & Domains

Outer Domain



WRF-ARW v3.5

- NAM analyses for initial & lateral BC
- 41 vertical levels
- Time step = 45, 15, 5 seconds
- 1 Feb 0000 UTC to 7 Feb 0000 UTC 2013



Parameterizations:

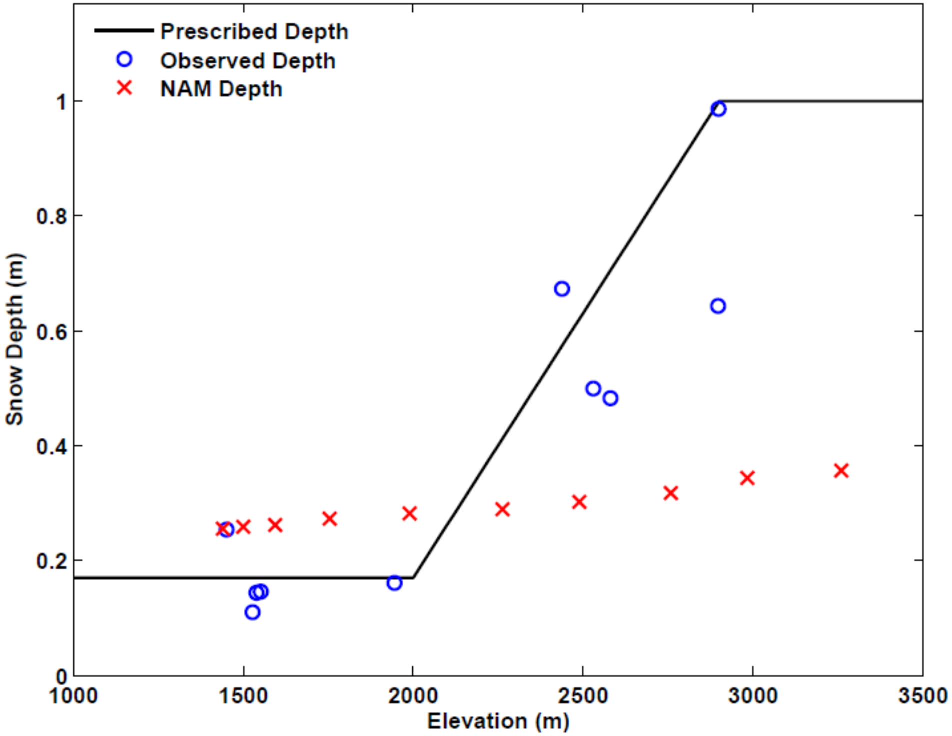
- Microphysics: Thompson
- Radiation: RRTMG LW/SW
- Land Surface: Noah
- Planetary Boundary Layer: MYJ
- Surface layer: Eta Similarity
- Cumulus: Kain-Fritsch (12 km domain)
- Landcover/Land use: NLCD 2006 (30 m)

WRF Modifications

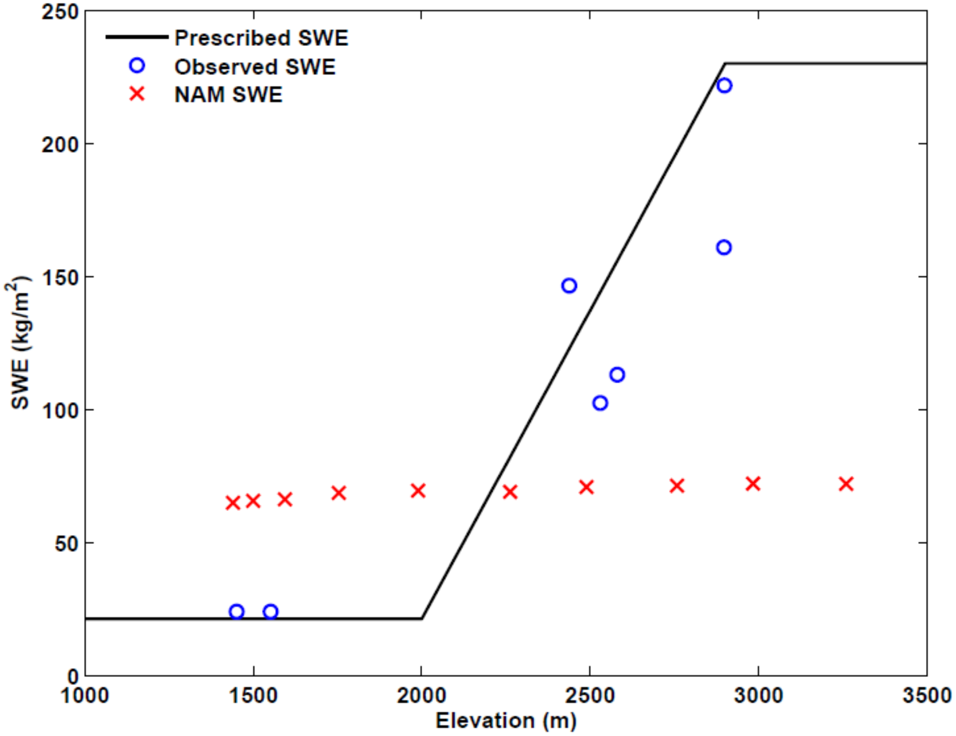
- Idealized snow cover in Uintah Basin and mountains
- Snow albedo changes
- Edited VEGPARM.TBL

} Allows model to achieve high albedos measured in basin

Snow Depth



Snow Water Equivalent



WRF Modifications

- Idealized snow cover in Uintah Basin and mountains
- Snow albedo changes
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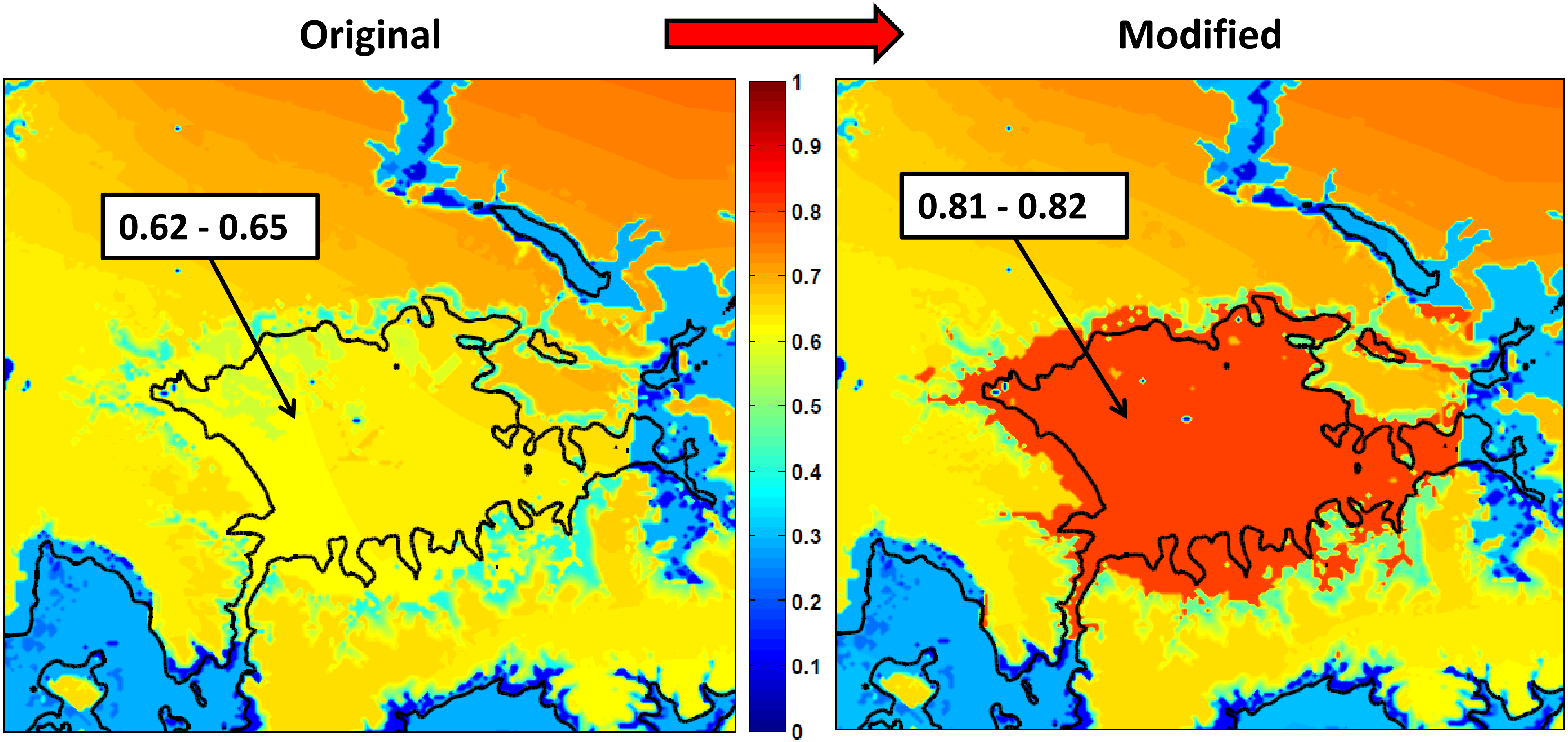
Allows model to achieve high albedos measured in basin

Photos: Erik Crosman

Albedo Changes

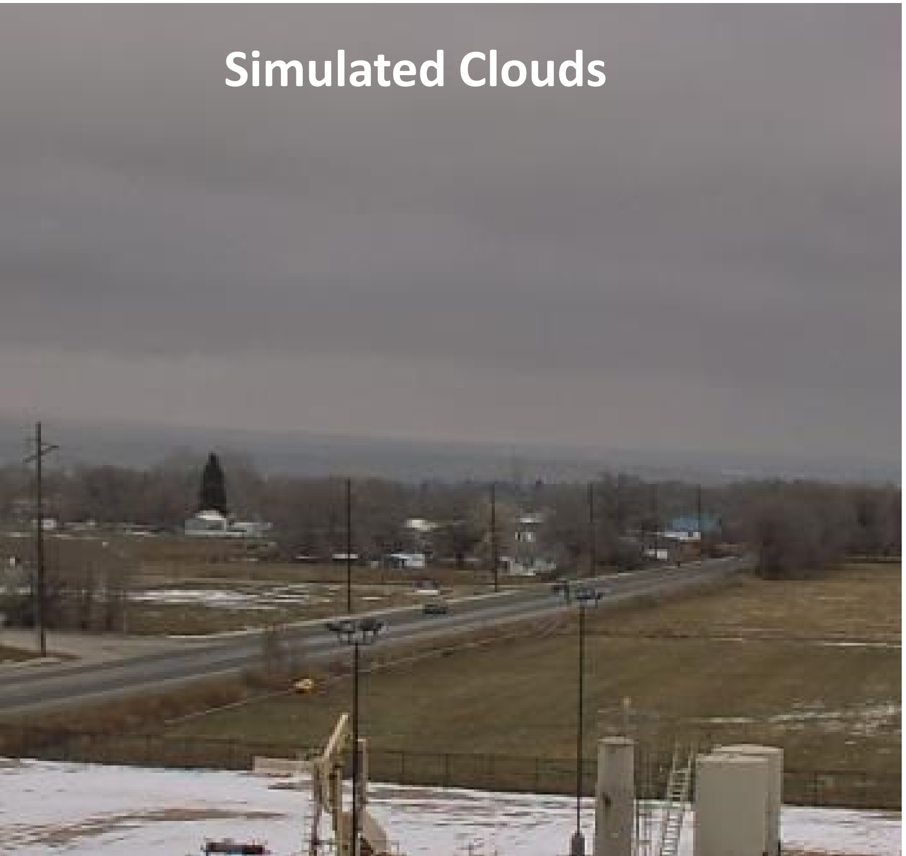


- 0.82 is average albedo measured at Horsepool during 2013 Uintah Basin Winter Ozone Study

WRF Modifications

- Microphysics modifications (Thompson) in lowest 15 model layers (~500m):
  - Turned off cloud ice sedimentation
  - Turned off cloud ice autoconversion to snow

    → Results in ice-phase dominated low clouds/fog vs. liquid-phase dominated



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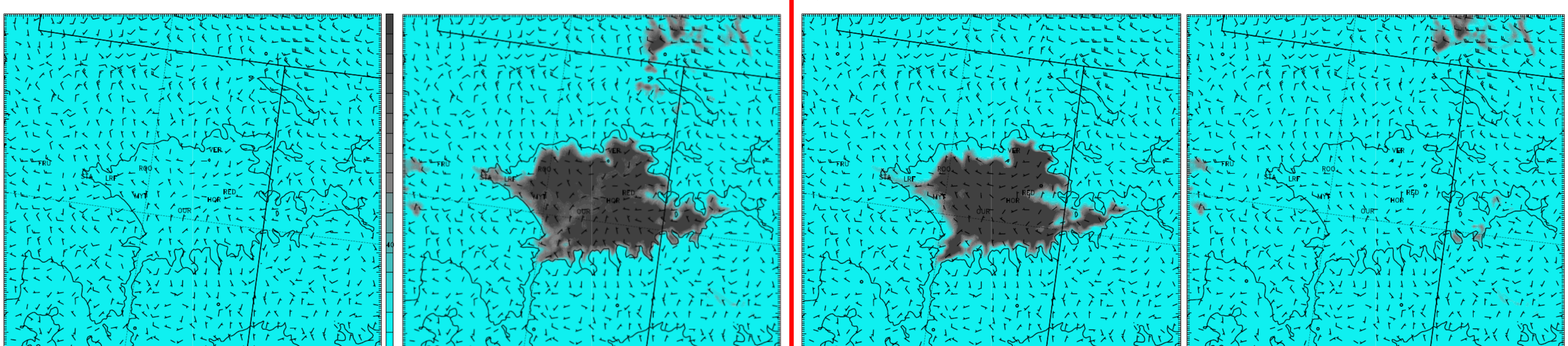
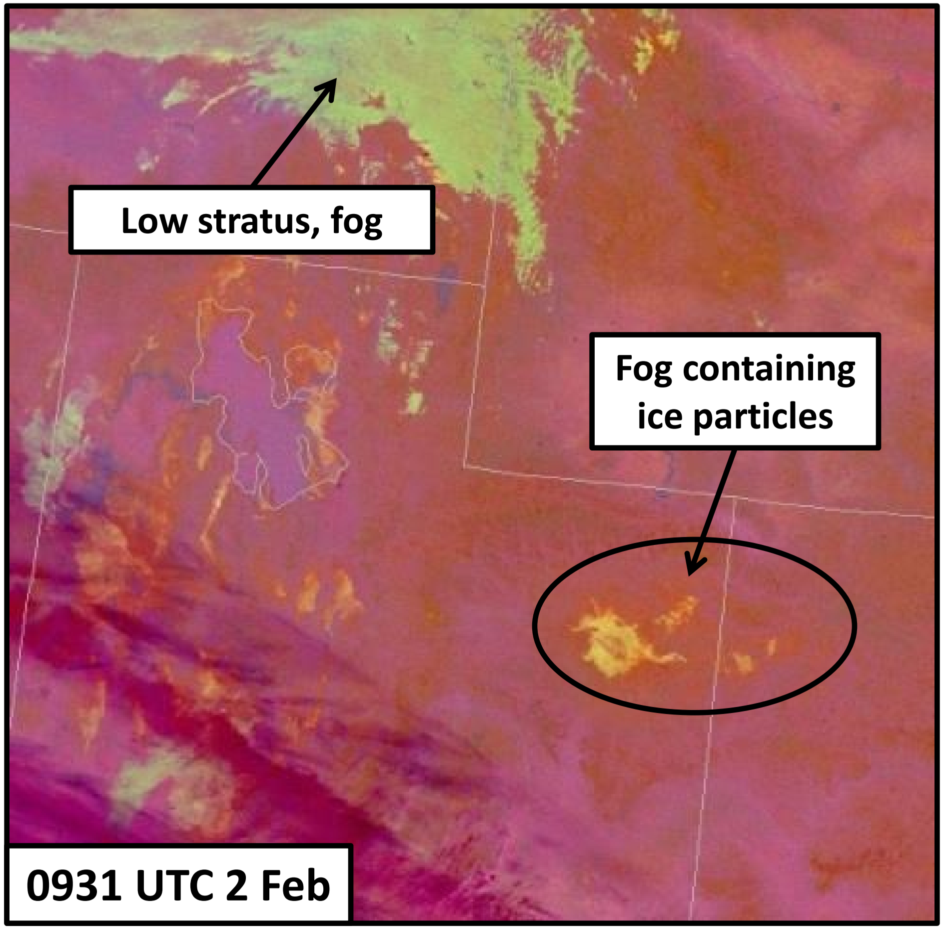
Before | **After**



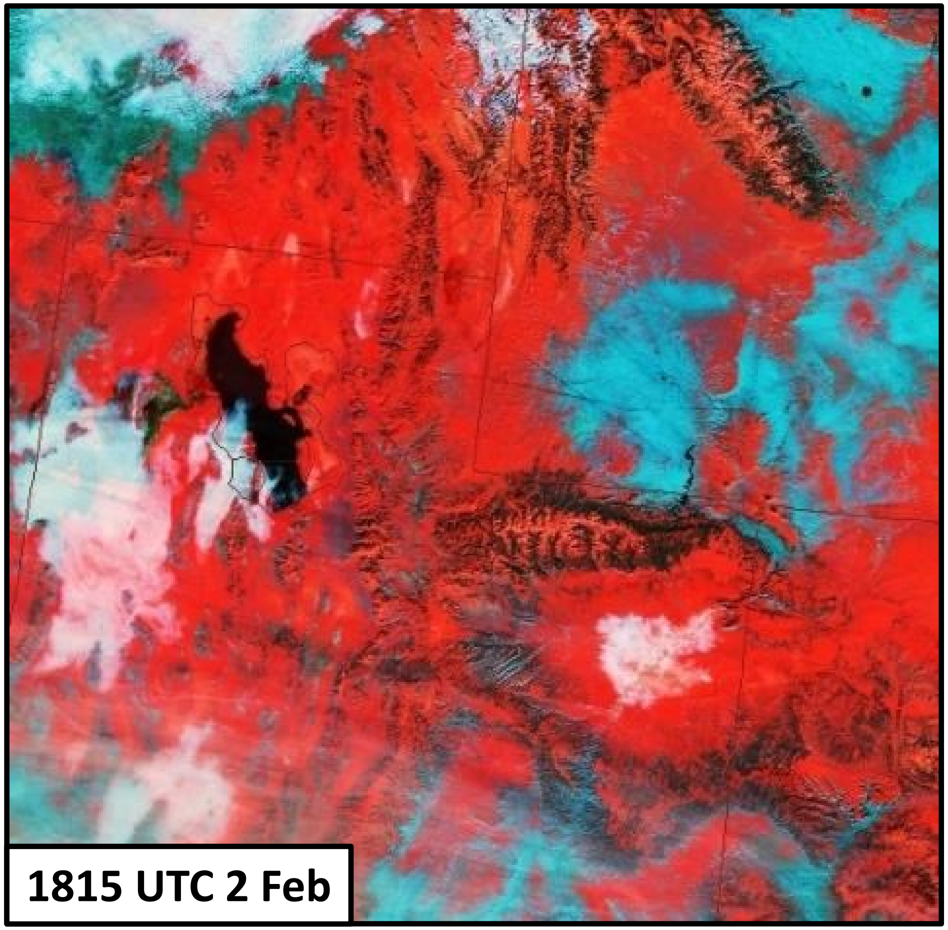
Cloud Ice | **Cloud Water** | **Cloud Ice** | **Cloud Water**

Satellite Imagery

VIIRS Nighttime Microphysics RGB



MODIS Snow-Cloud



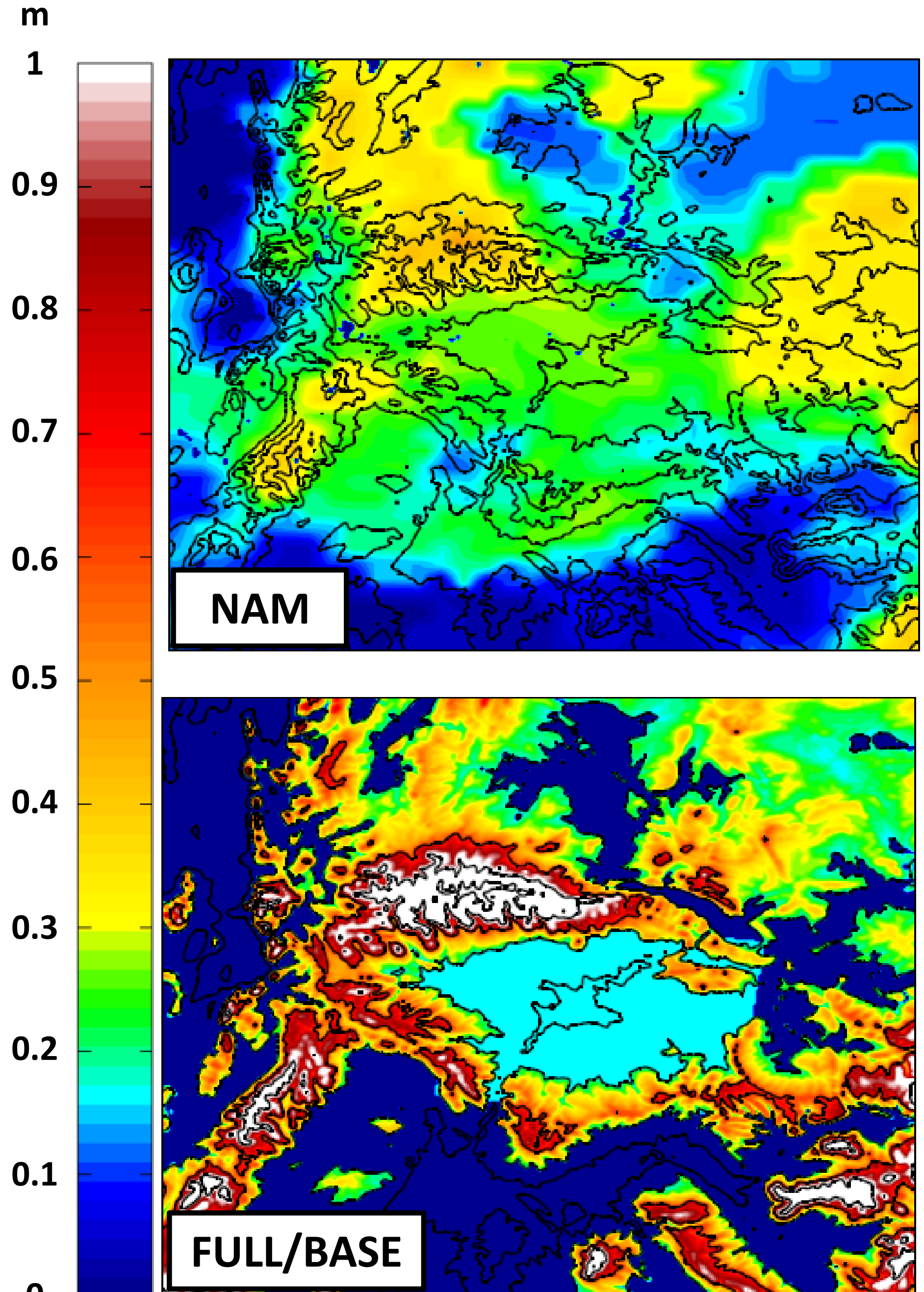
Satellite imagery courtesy NASA SPoRT program

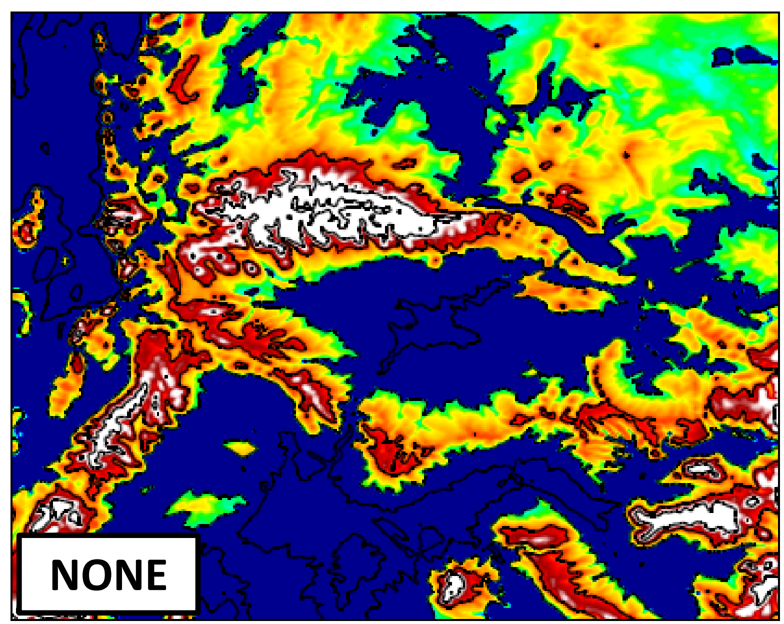
WRF Sensitivity Tests

	Snow Cover in basin	Cloud Ice Sedimentation	Cloud Ice Auto-conversion to Snow	Simulation Name
Microphysics Sensitivity Simulations	Full Snow	ON	ON	**BASE**
	Full Snow	OFF	OFF	**FULL**
Snow Cover Sensitivity Simulations	No Snow below 2100 m in Western 1/4 of basin	OFF	OFF	**NW**
	No Snow below 2000 m	OFF	OFF	**NONE**

NAM and Prescribed Snow Cover

- Snow cover difference in primary model simulations
- Depth/SWE prescribed by elevation
- Based on observations available in Uintah Basin and surrounding mountains

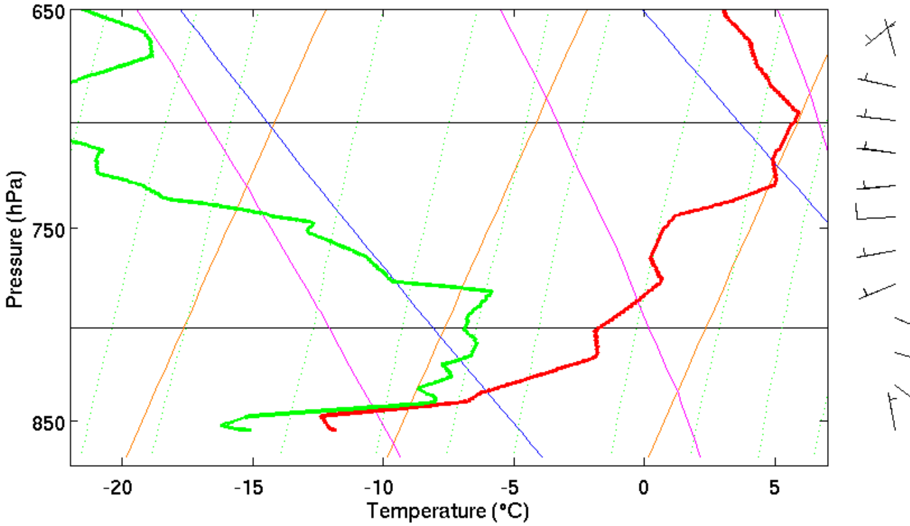




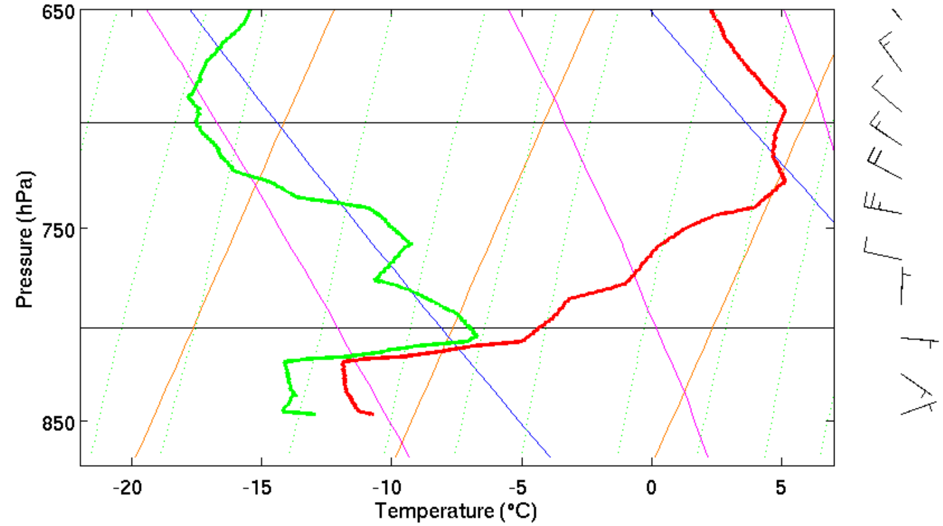
1-6 Feb 2013 CAP Evolution

1800 UTC Roosevelt Soundings

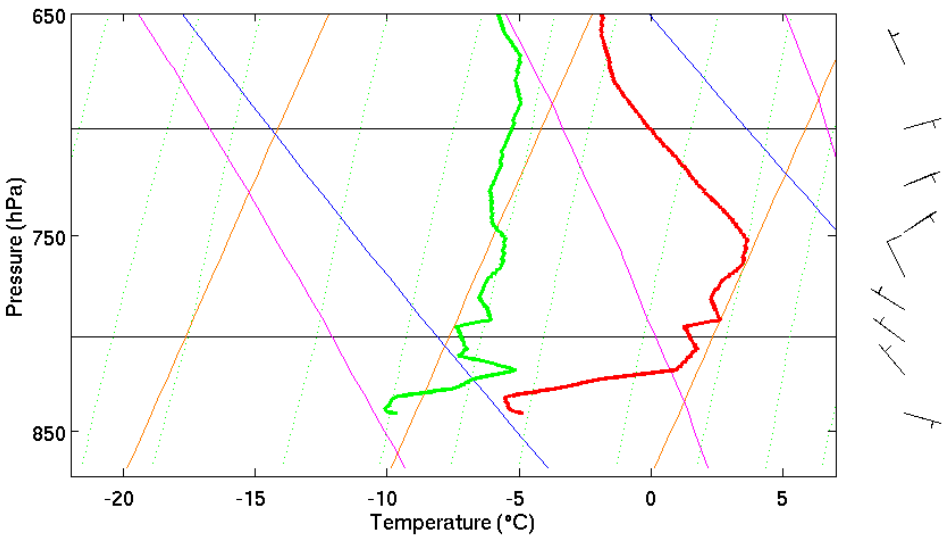
2 Feb 2013



4 Feb 2013



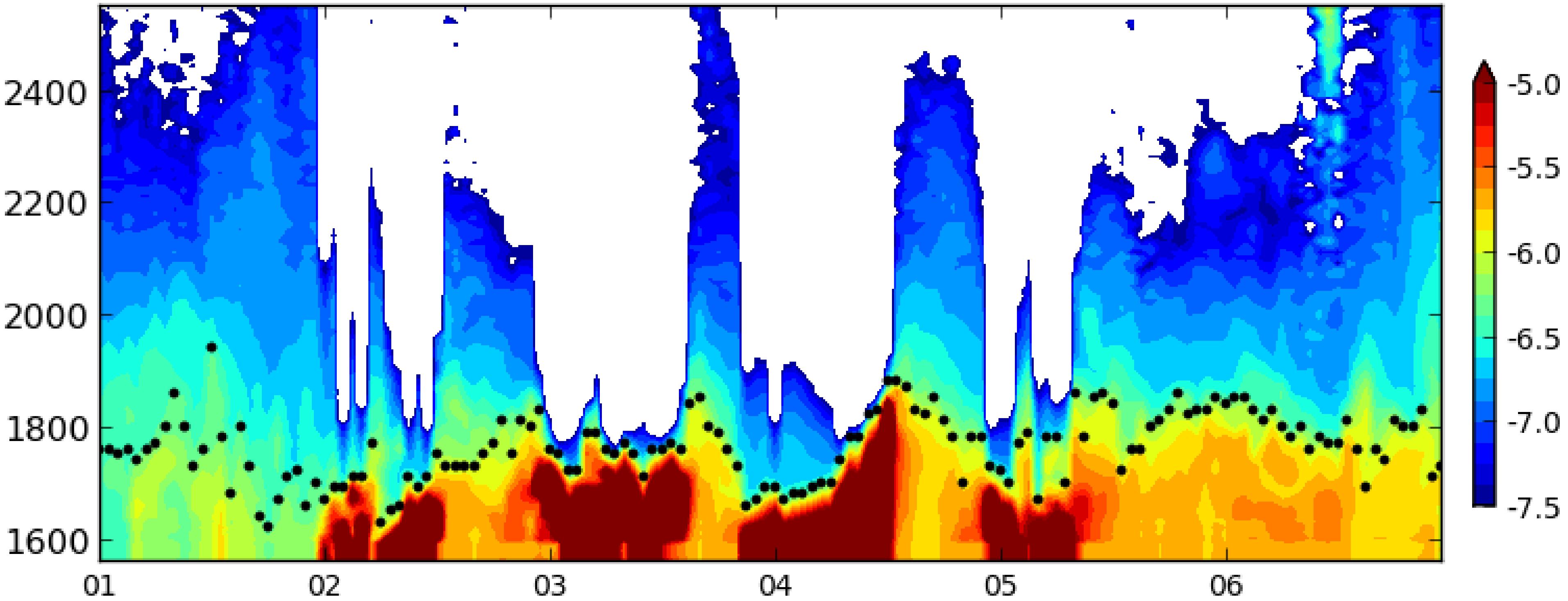
6 Feb 2013



- **High RH in low levels on 2 & 4 Feb**
- **Mixed layer deepens 2-4 Feb, then becomes more shallow by 6 Feb**
- **Inversion near 700 hPa descends to 750 hPa from 4-6 Feb**
- **Light easterly flow in stable layer on 2 & 4 Feb with stronger, westerly flow above**

1-6 Feb 2013 CAP Evolution

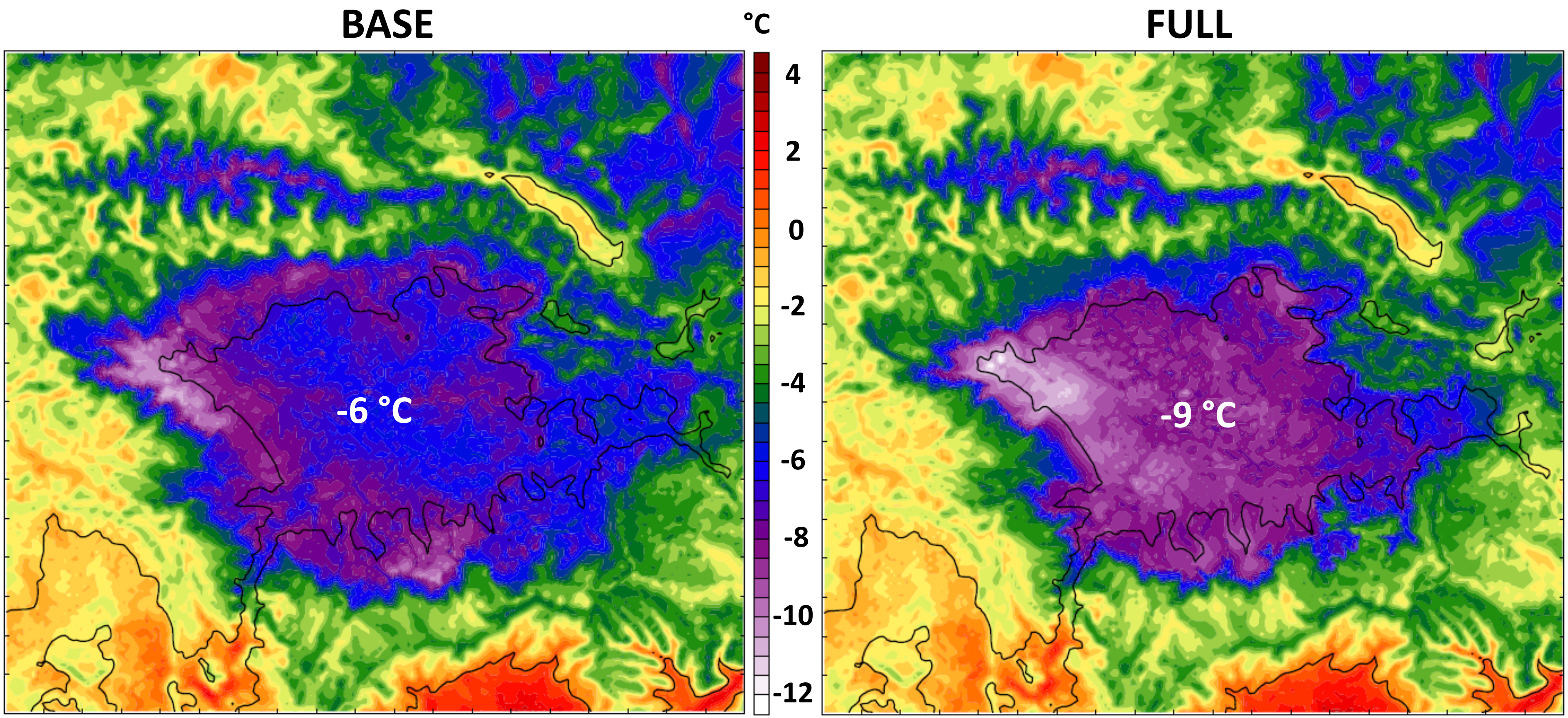
Ceilometer Backscatter and Estimated Aerosol Depth (Roosevelt, UT)



- **Cloud-free in low levels 1 & 6 Feb**
- **Pattern of low shallow clouds/fog overnight before thinning by mid-day from 2-5 Feb**
- **Greatest low clouds and fog on 3-4 Feb**

Microphysics Sensitivity

2-m Temperatures 1800 UTC 2 Feb 2013

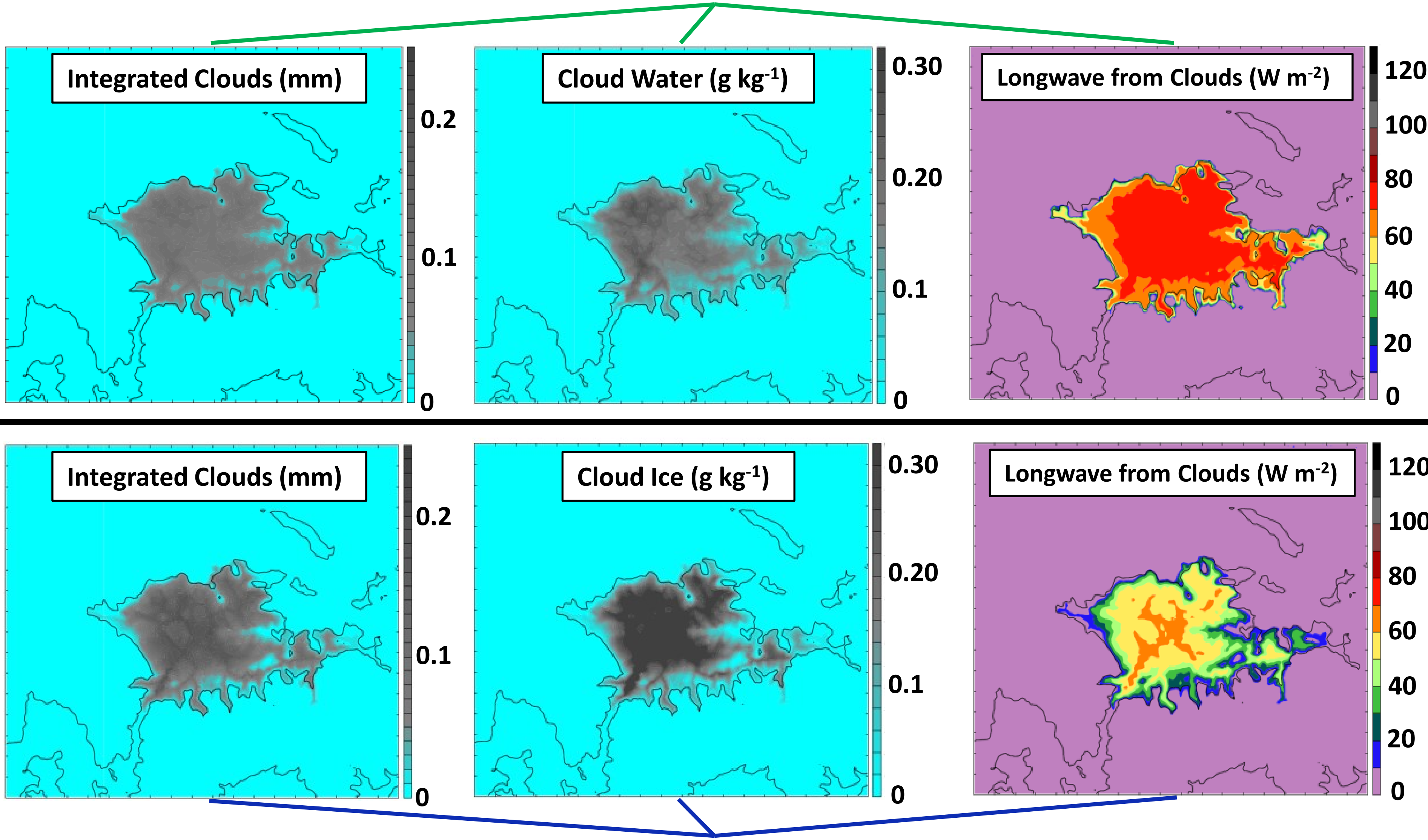


- Unrealistic warm region often present in center of BASE simulation
  - Greatest during overnight and morning hours
- Notable improvement in FULL simulation with lower temperatures

Microphysics Sensitivity

0600 UTC 5 Feb 2013

BASE

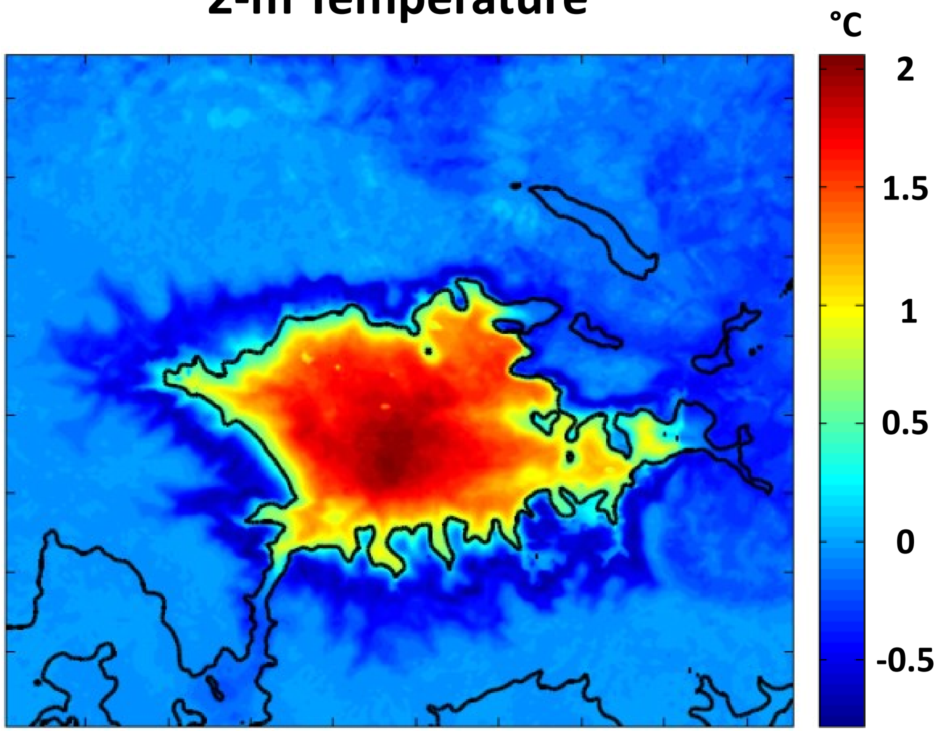


FULL

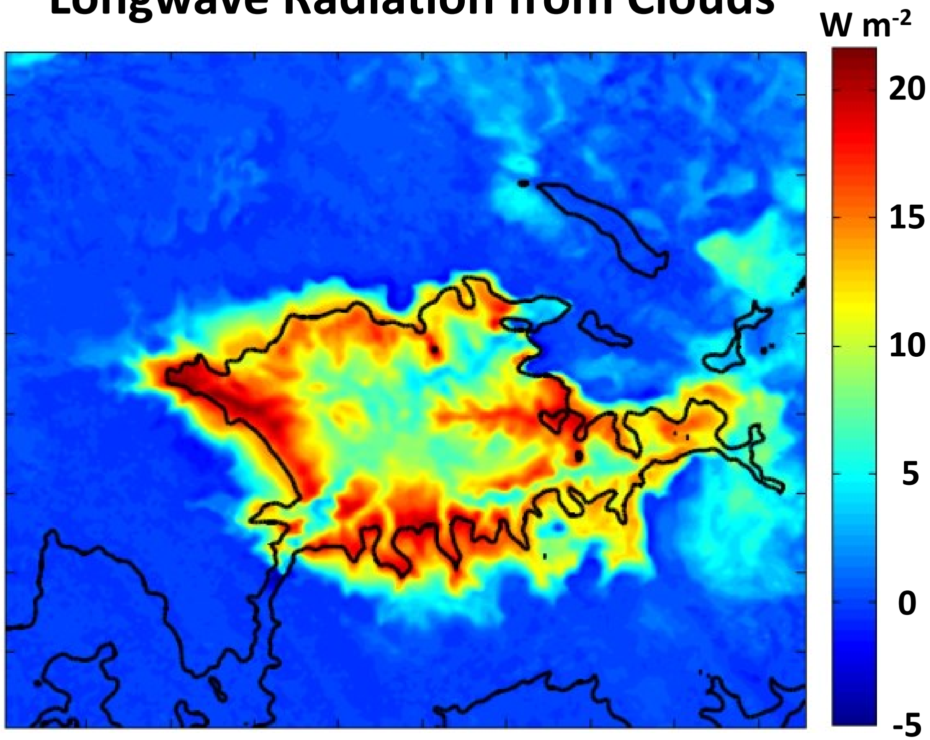
Microphysics Sensitivity

Mean BASE - FULL Difference

2-m Temperature

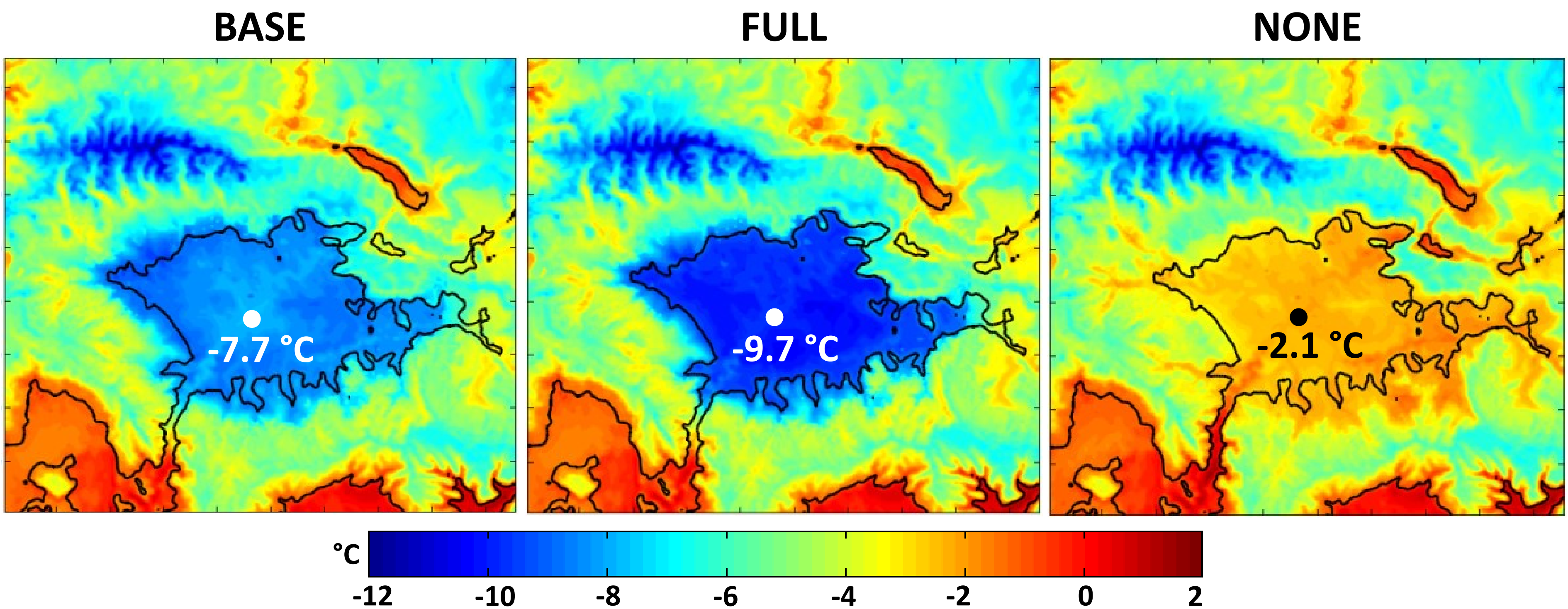


Longwave Radiation from Clouds



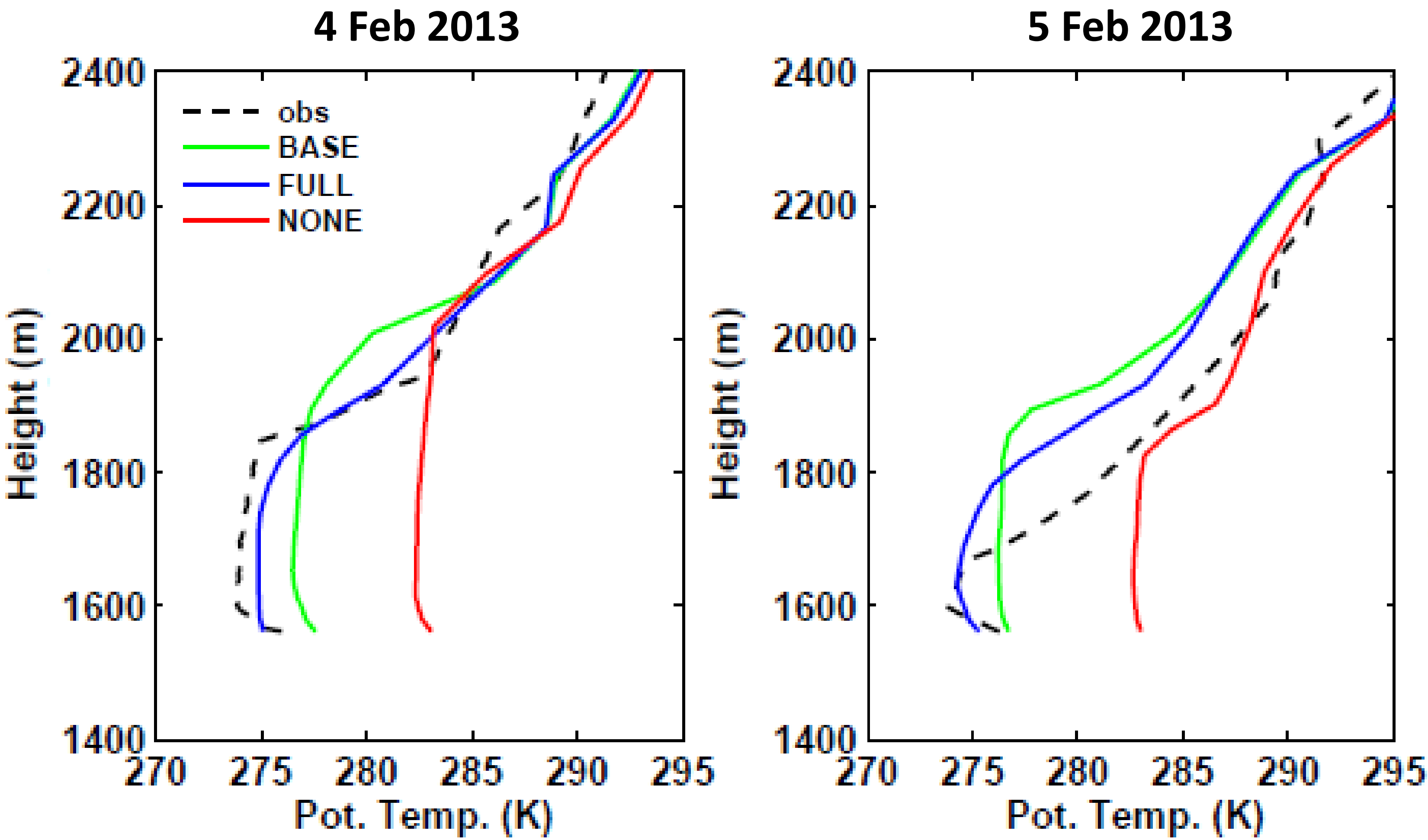
- **Mean temperature in basin ~1.5 °C higher in BASE simulation**
- **Related to additional longwave radiation from clouds of 7-20 W m^{-2}**
- **Greater coverage of stratus in BASE vs. ice fog in FULL leads to large differences where stratus is present but ice fog isn't**

Mean 2-m Temperatures



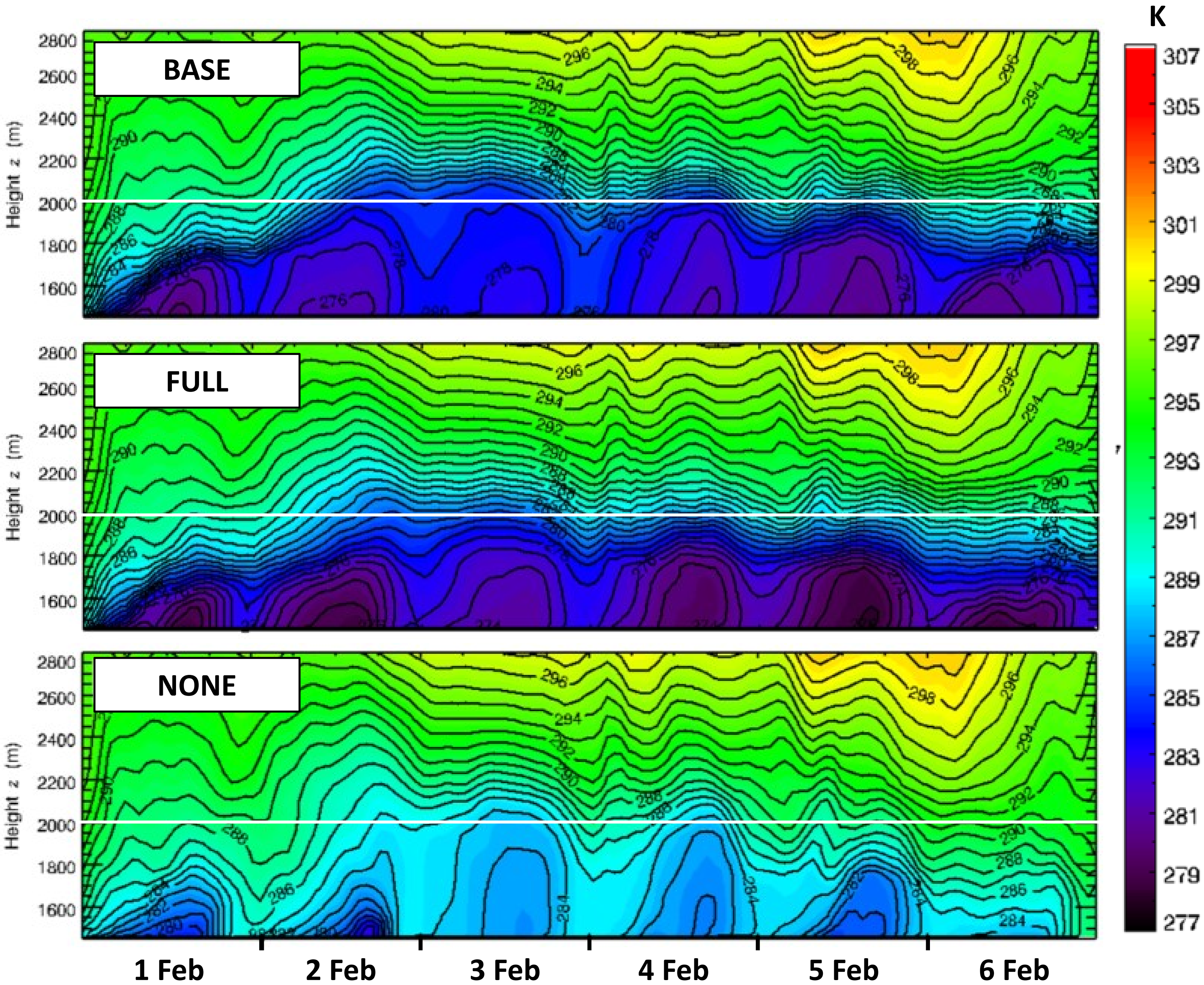
- Warm bias in BASE due to cloud phase sensitivity greatly reduced in FULL
- Removal of snow in NONE leads to mean temperatures 7.6 °C greater than FULL
- All simulations nearly identical outside the Uintah Basin

Vertical Profile Comparisons (Roosevelt)



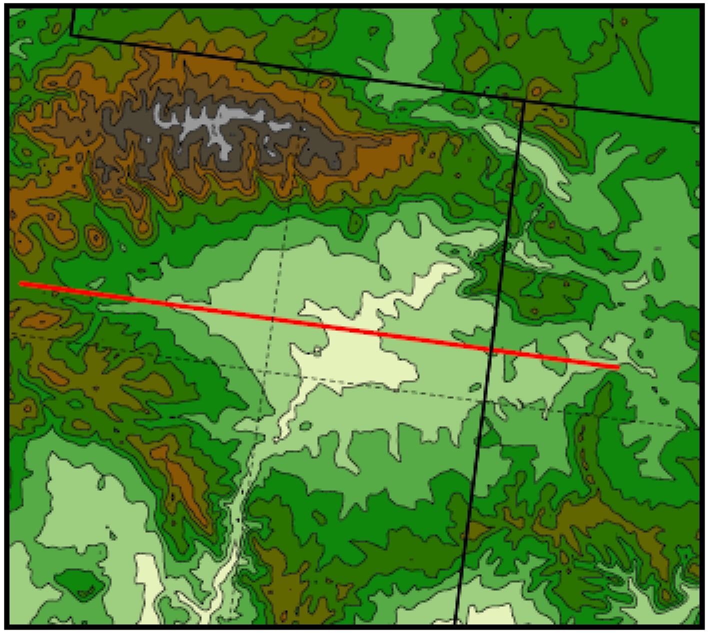
- Mixed layer in BASE generally deeper than observed
- Improved results in FULL simulation for temperature and PBL depth
- NONE simulation much warmer (~7 °C) with deeper mixed layer
- Minimal differences above ~500 m AGL

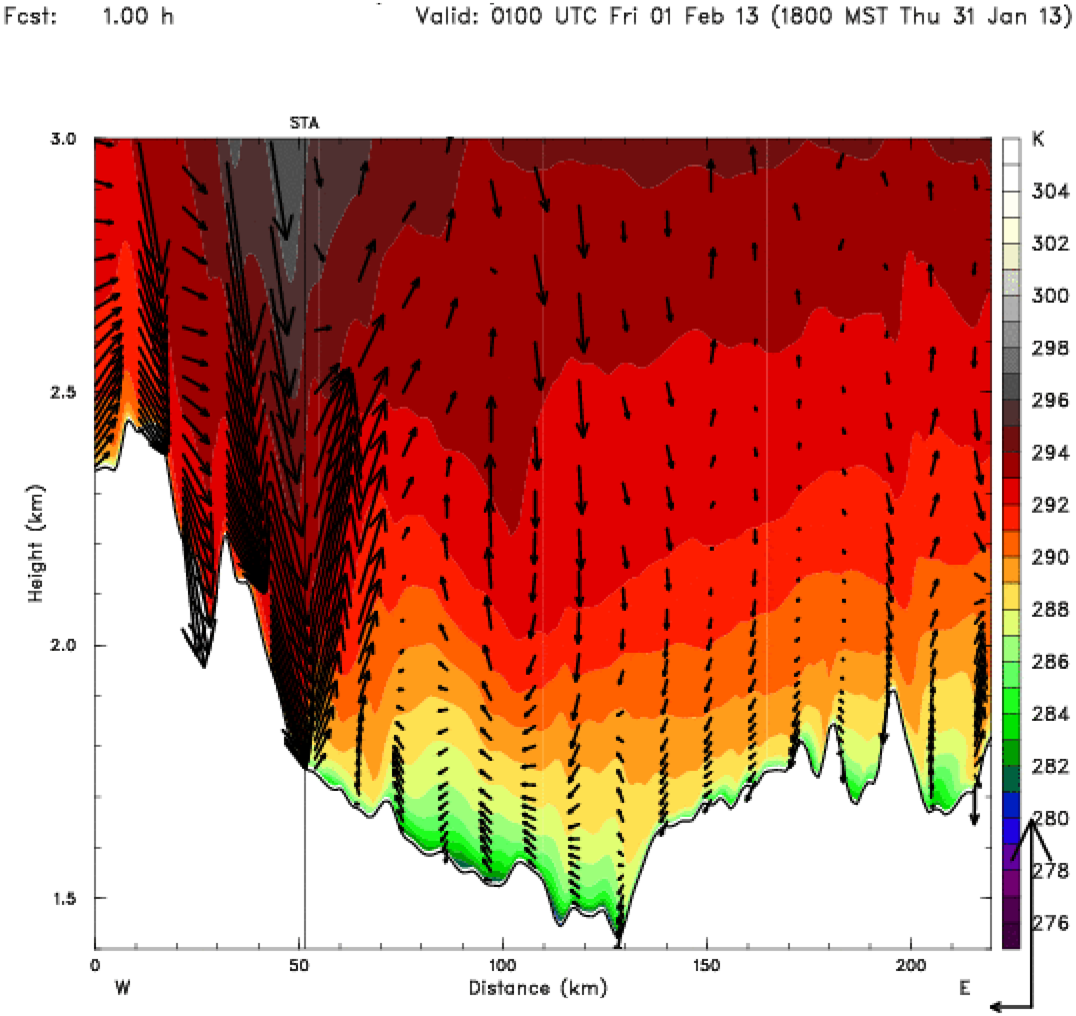
Potential Temperature Time-Heights (Horsepool)



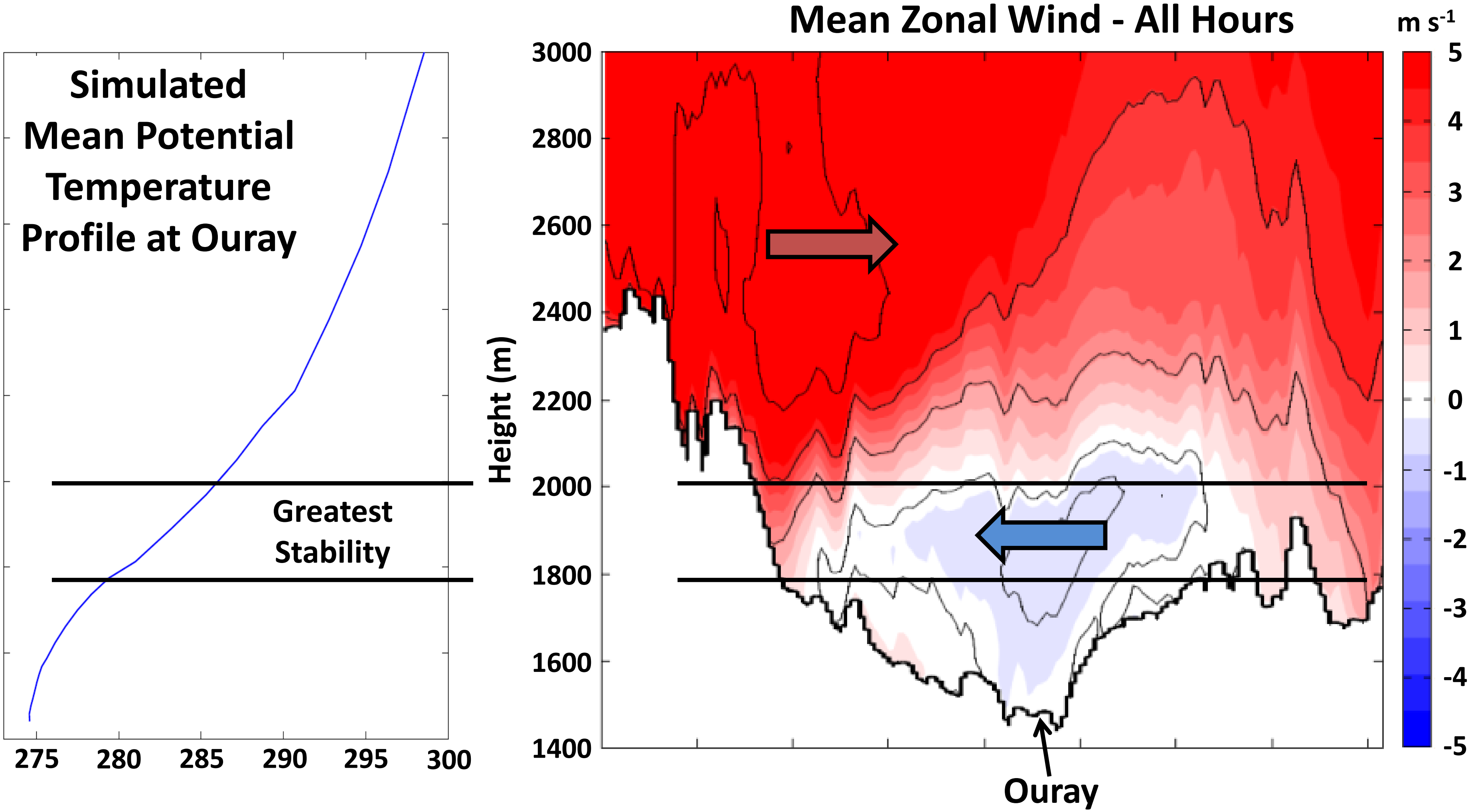
Simulated Cold Pool Evolution

00 UTC 1 Feb to 00 UTC 7 Feb



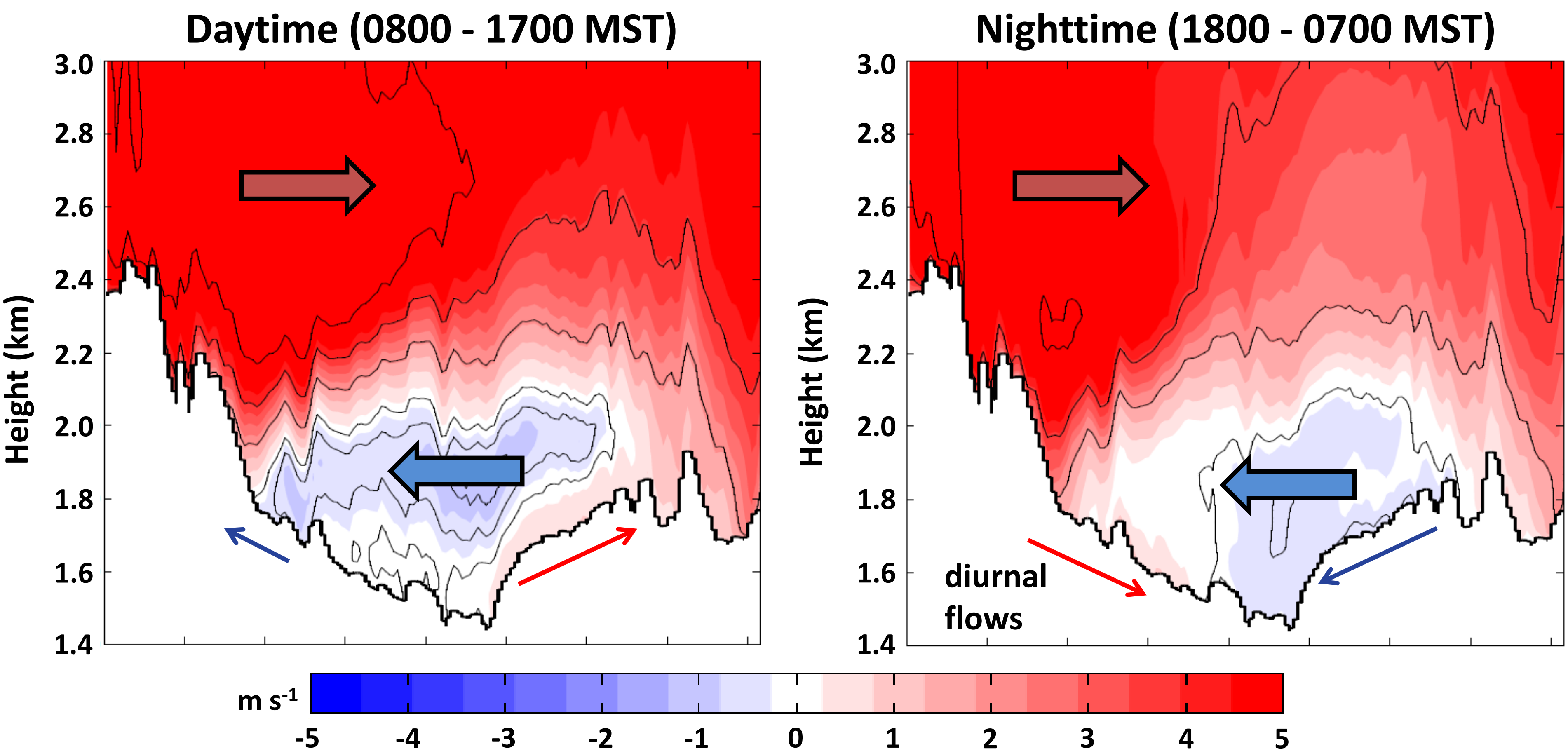


Simulated Uintah Basin Flow Features



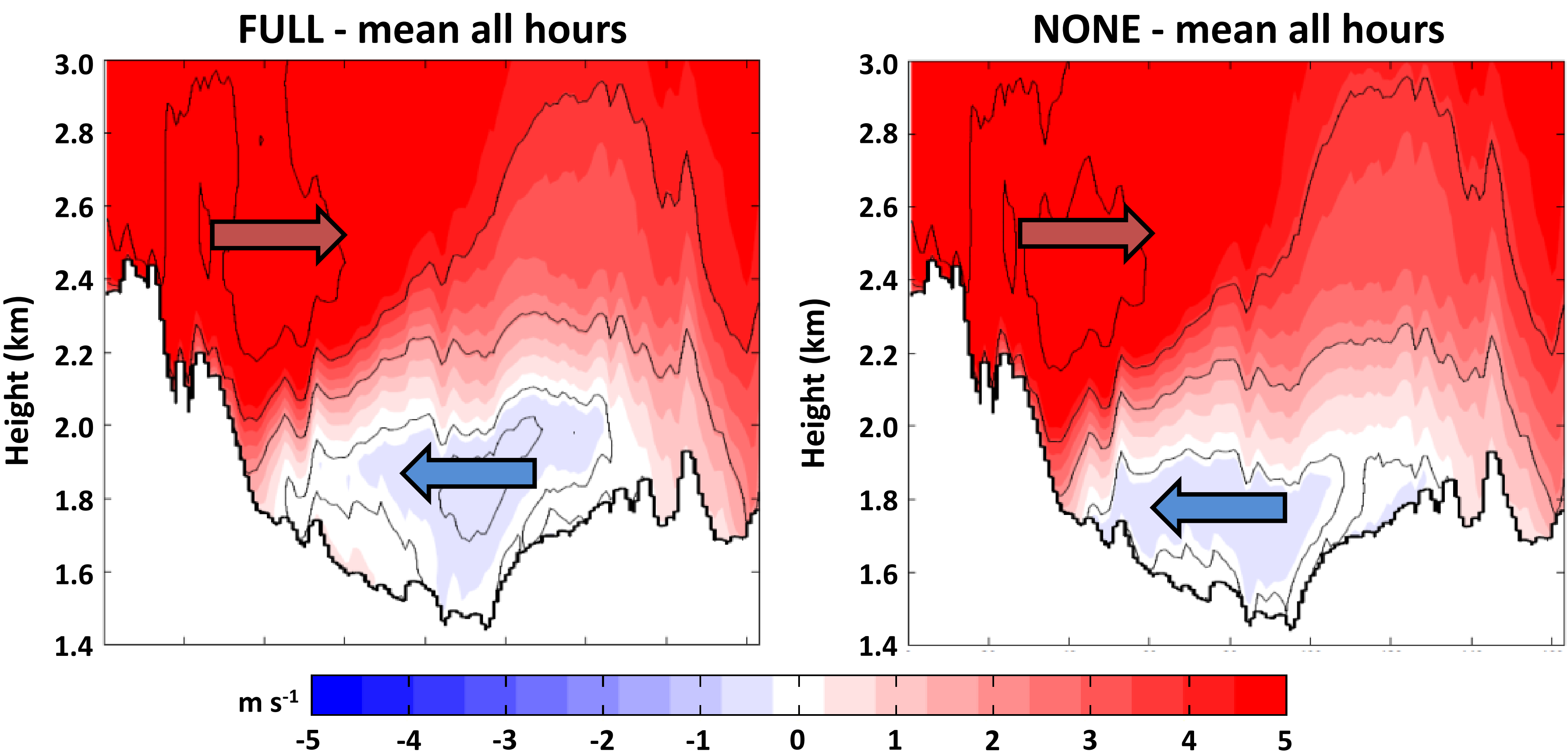
- Inversion/greatest stability typically between 1800 - 2000 m MSL
- Weak easterly flow exists within and below inversion layer
  - Core greater than 0.5 m s^{-1}
  - Likely important role in pollutant transport within the basin

Simulated Uintah Basin Flow Features



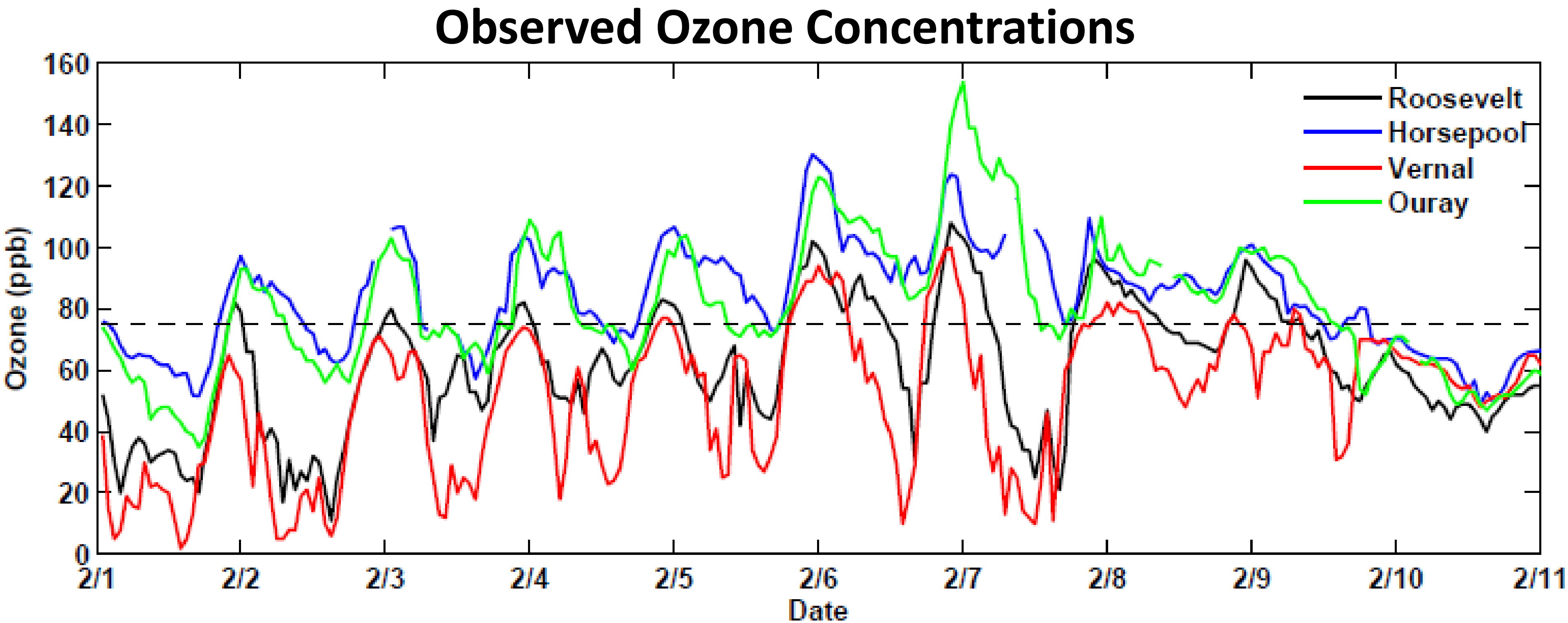
- Easterly flow stronger during the day, weaker at night
  - Indicates thermal gradients likely the main driver
  - Core winds greater than 1 m s^{-1} during the day
- Diurnal flows apparent in day/night plots

Snow Cover Differences



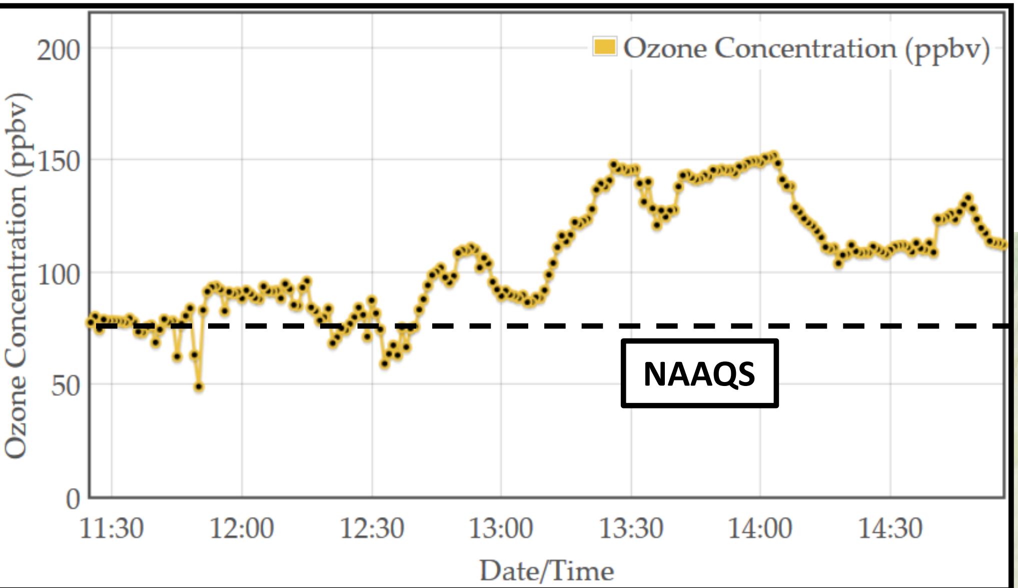
- Core easterly winds weaker and shallower in NONE simulation
- Weaker stability in NONE likely allows synoptic-scale westerlies to extend down closer to the surface
- Snow removal only affects near-surface atmosphere below capping inversion

1-6 Feb 2013 CAP Evolution

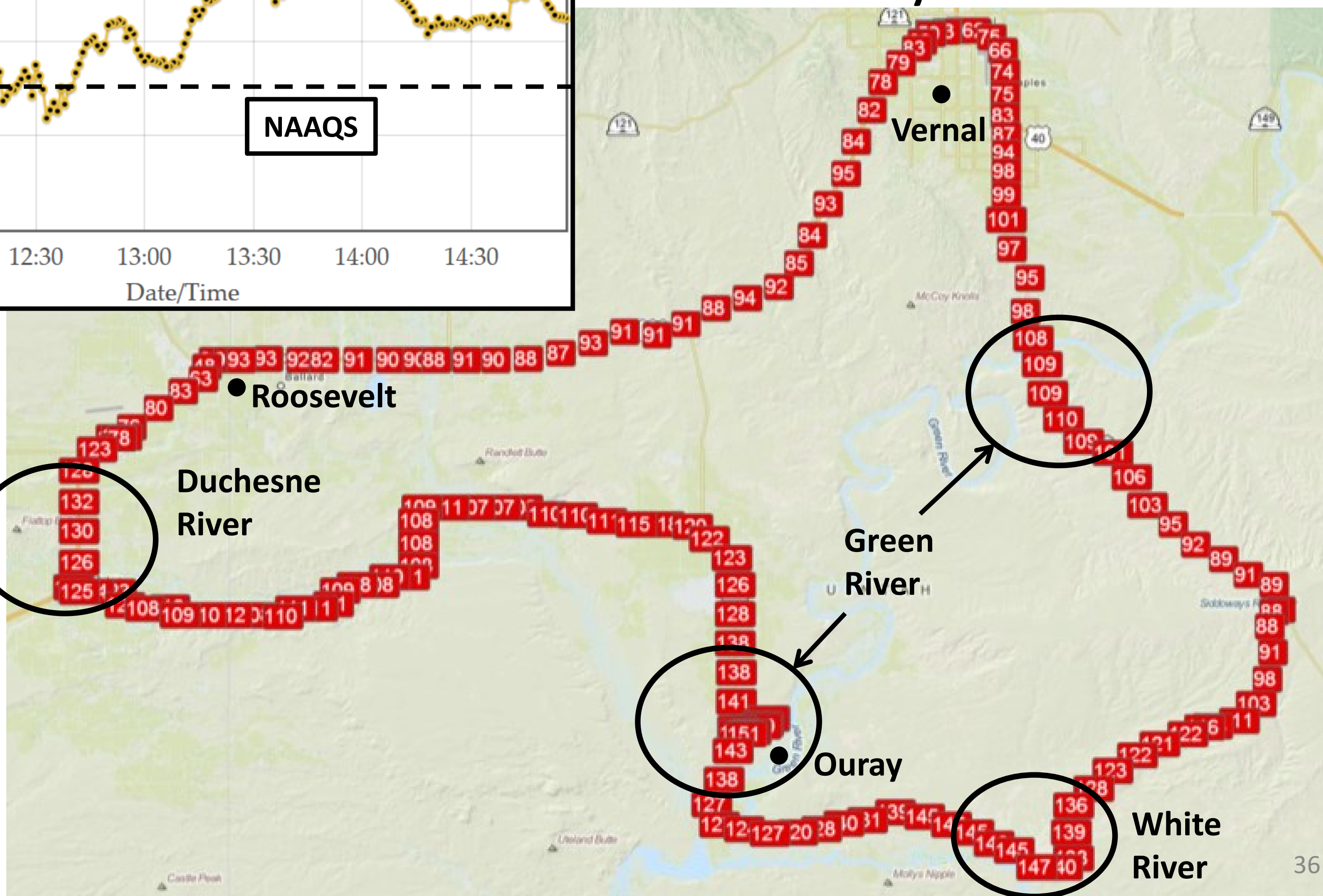


- Gradual buildup of ozone concentrations during multi-day episode
- All Locations exceed NAAQS standard on several days
- Ozone depletion seen overnight at Vernal
- Horsepool and Ouray above NAAQS nearly all hours after 3 Feb
- Strong system cleared basin on 9 Feb

Mobile Ozone Transect - 6 Feb 2013

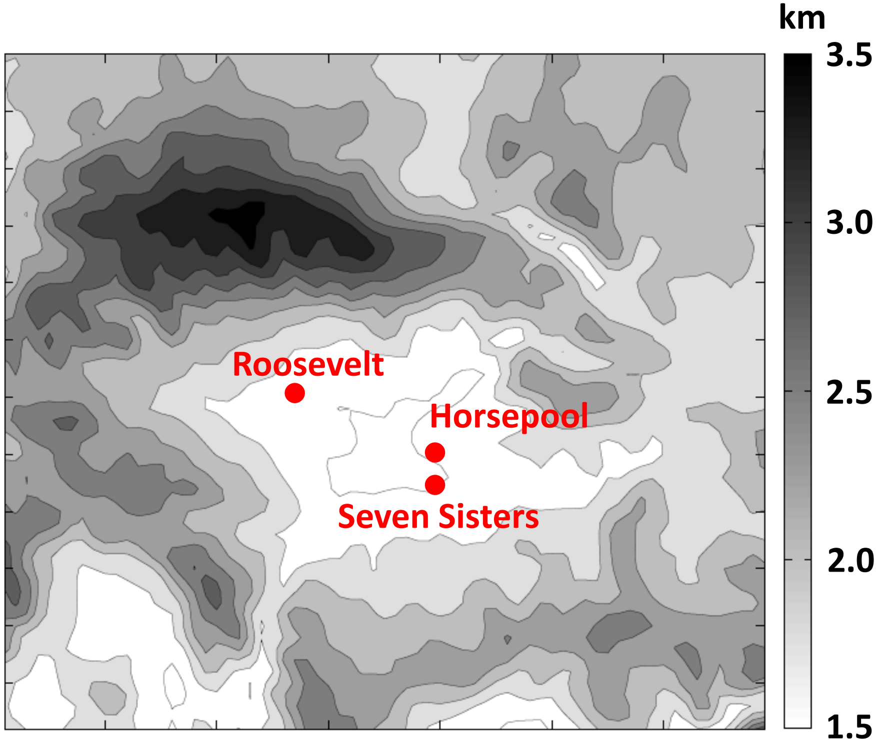


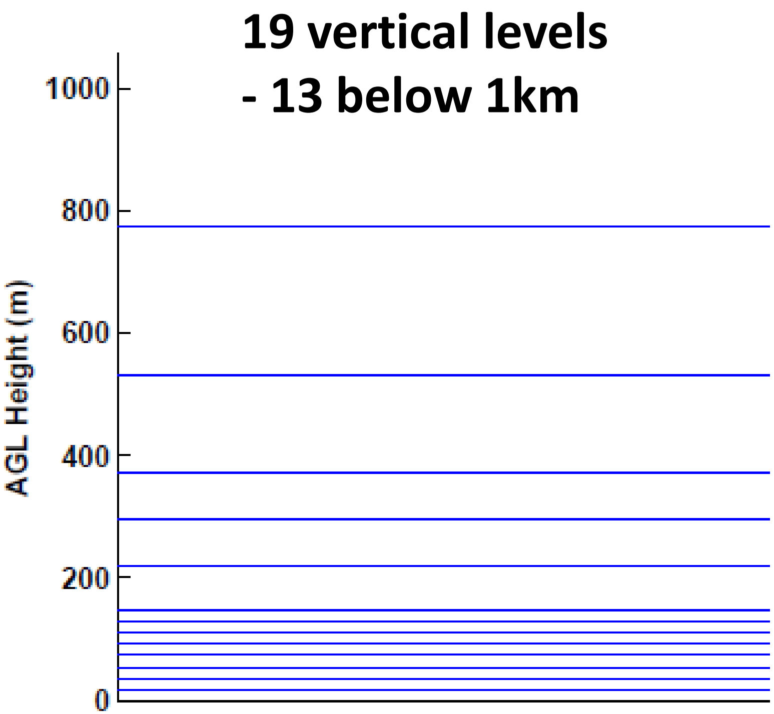
- High concentrations measured through the basin
- Greatest values in lower elevations and river valleys



Air Quality Simulations

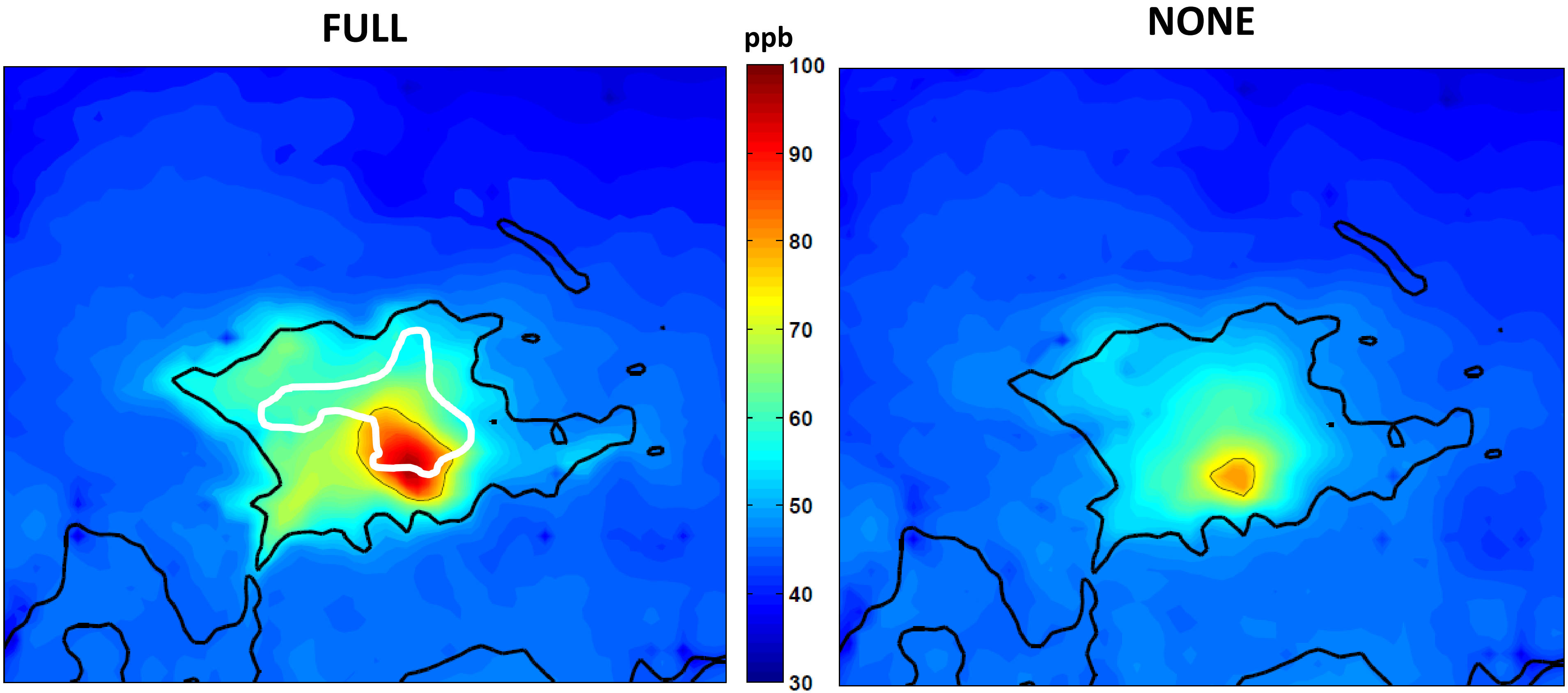
- Utah Division of Air Quality's Community Multi-Scale Air Quality Model (CMAQ)
- Provided courtesy of Lance Avey
- Combines meteorological data, emissions inventory, and chemistry-transport model to simulate pollutant concentrations
- Atmospheric variables forced by 4-km domain WRF output
  - FULL and NONE simulations





CMAQ Mean Afternoon Ozone

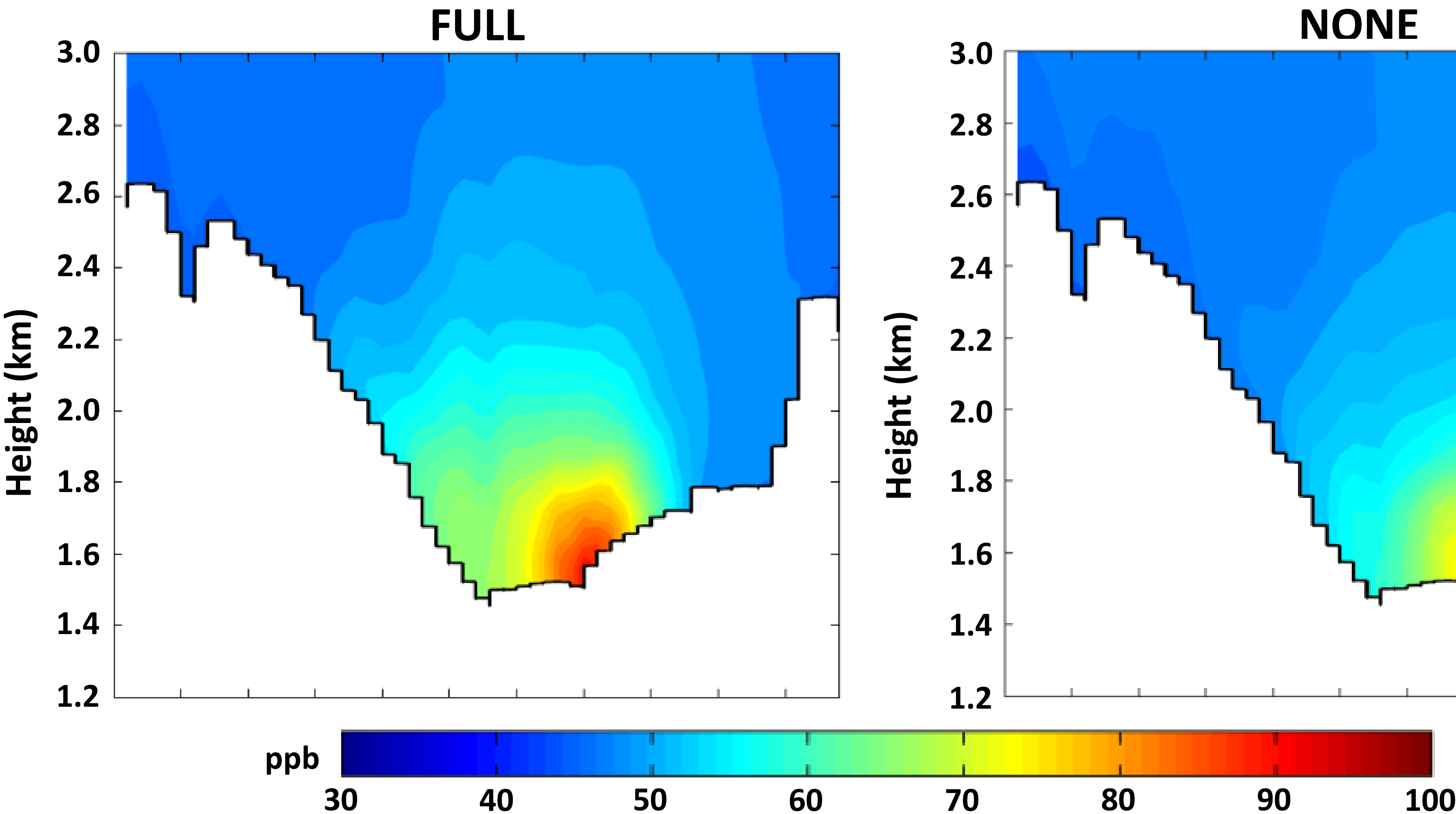
1100 - 1700 L



- Concentrations in FULL simulation 15-30% greater than NONE
- Areal extent of region exceeding NAAQS 6 times larger in FULL
- FULL simulation adequately represents observations in southeast quadrant, underpredicts concentrations elsewhere

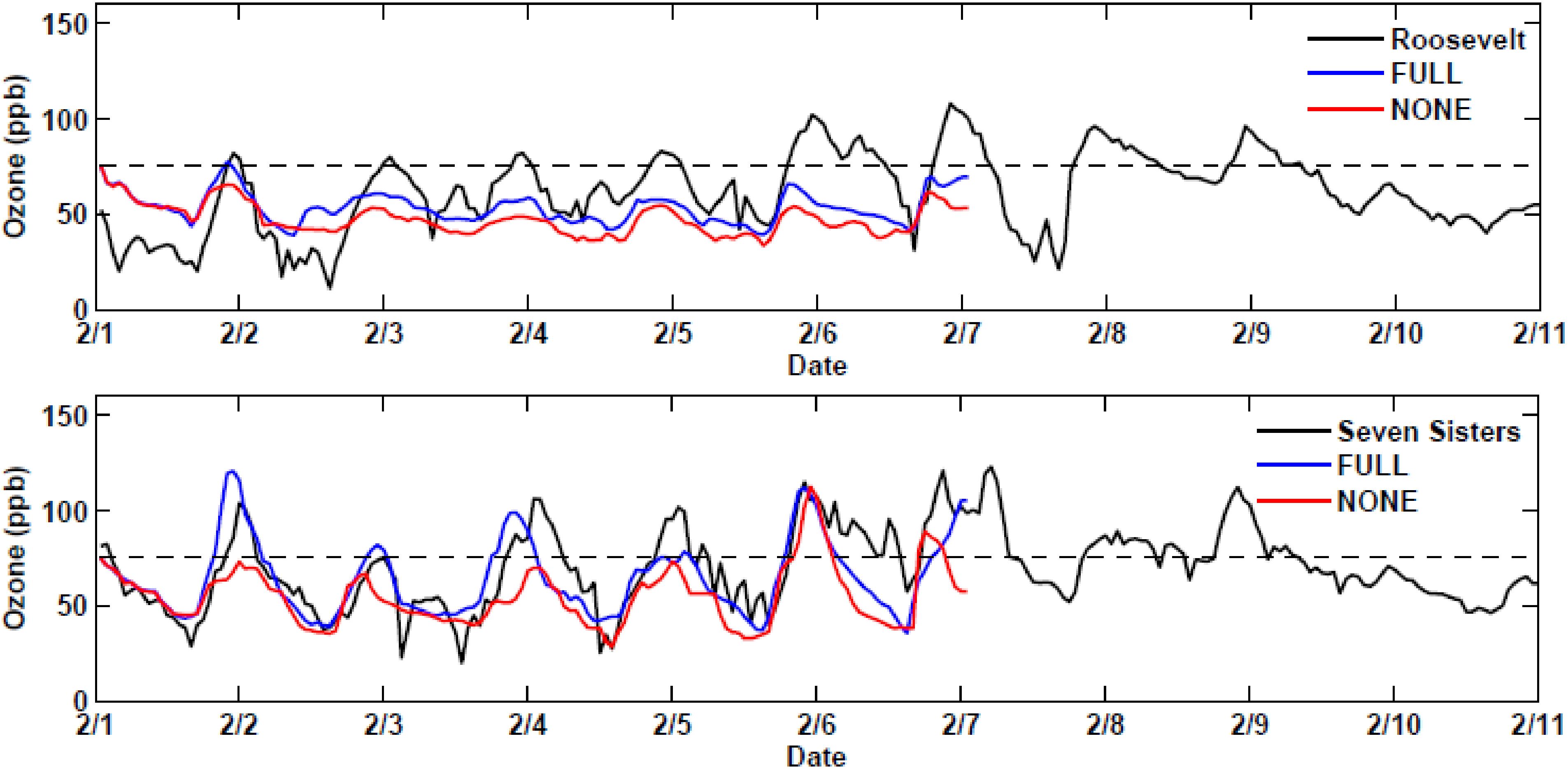
CMAQ Mean Afternoon Ozone

1100 - 1700 L



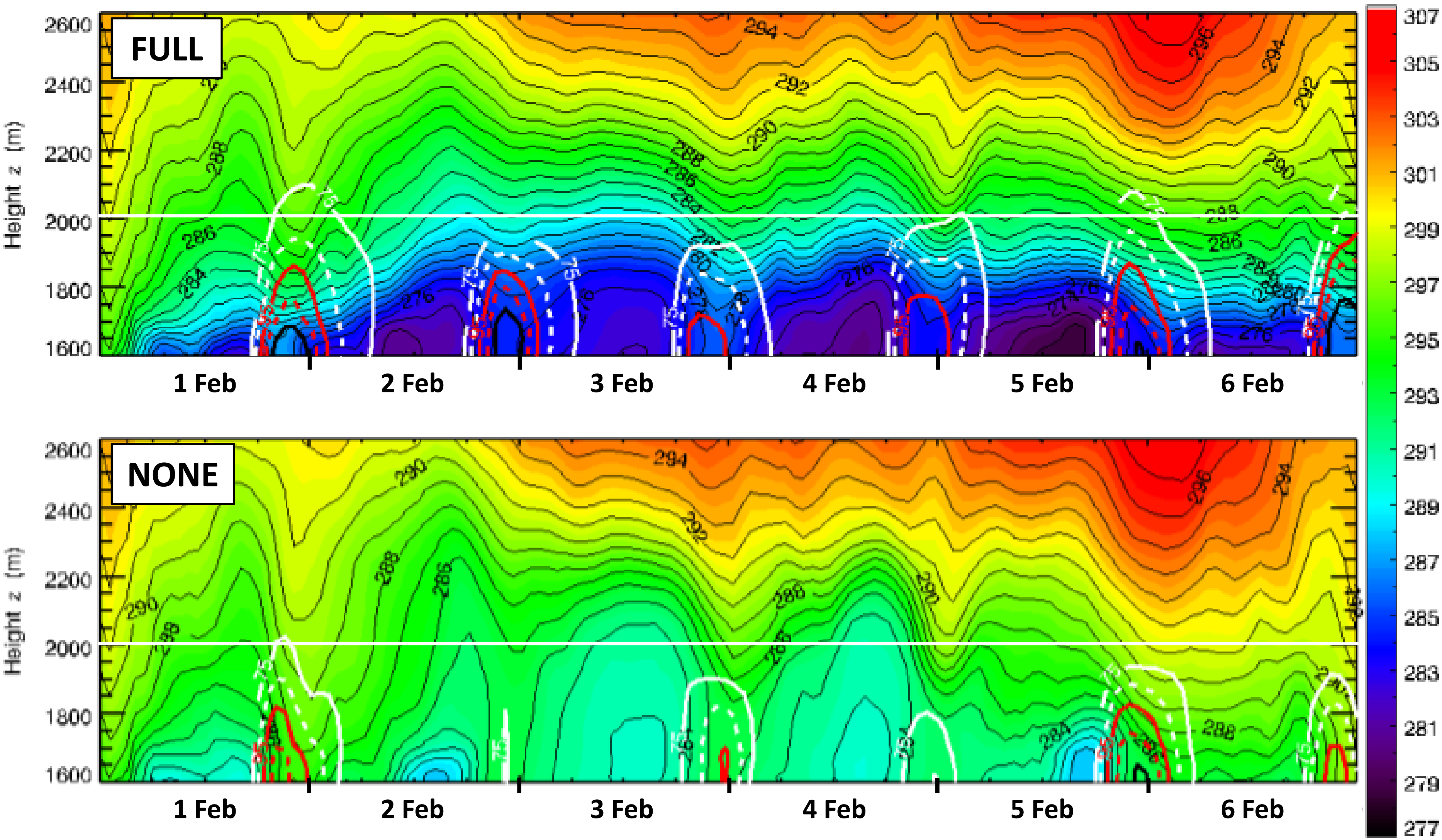
- Ozone concentrations notably higher in FULL simulation
- Drop-off to background level (~60 ppb) occurs near 2000 m in FULL
  - Observed drop-off to ~60 ppb around 1900 m at Horsepool (Karion et al. 2014)

CMAQ Ozone Variations



- Simulated zone concentrations remain under NAAQS at Roosevelt
- Ozone concentrations at Seven Sisters are simulated quite well
- Performance disparity among locations illustrates CMAQ's struggle to represent broad extent of observed high ozone concentrations

CMAQ Ozone Variations (Horsepool)



Conclusions

- ***What is the sensitivity of simulated CAP structure and evolution to cloud microphysics?***
  - **Simulated ice fog leads to reduced 2-m temperature bias and shallower, more realistic mixed layer within CAP vs. liquid stratus**
  - **Improvement attributed to changes in longwave radiation and greater cooling due to cloud phase change**

- ***How do snow cover variations affect CAP simulations and structure?***
  - **Removing snow from basin results in much greater 2-m temperatures and a much deeper boundary layer**
  - **Differences contained in lowest ~1 km AGL due to strong stability above CAP**

Conclusions

- ***What are the important wind flow regimes in the Uintah Basin CAP? Can they be diagnosed by mesoscale modeling and how might they affect air quality in the basin?***
  - **1.3 km simulations resolve flow features fairly well**
  - **Synoptic intrusions of clean air, elevated easterly flow in stable layer, and diurnal thermally driven flows are all important**
  - **Redistribution of pollutants by these flows likely impacts air quality within the basin**

- ***What is the influence of snow cover on simulated air quality in the Uintah Basin?***
  - **Snow cover and high surface albedo critical to high wintertime ozone:**
    - **Strengthens CAP and increases stability**
    - **Increases photolysis rates, leads to rapid ozone production**

Future Work

- **Expand number of CAP cases investigated**
- **More sophisticated application of microphysics modifications, and examine sensitivity with other microphysics schemes**
- **Utilize different PBL parameterizations and improve performance of schemes in stable boundary layers**
- **Improve representation of snow variables in analysis and initialization fields**
  - **Incorporate use of snow physics model**

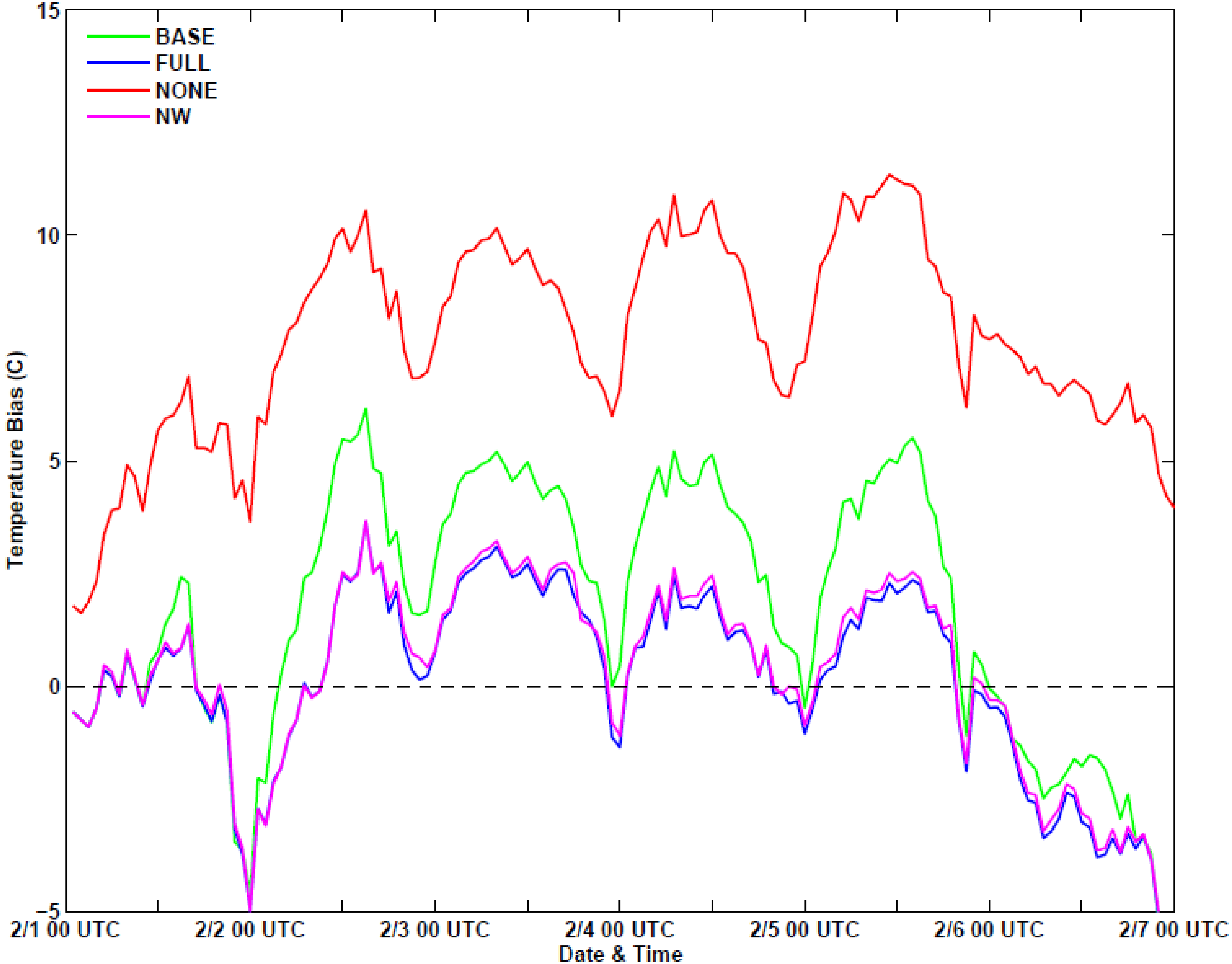
Acknowledgements

- My Committee: John Horel, John Lin, Jim Steenburgh
- Erik Crosman
- The U of U WRF User's Group
- Graduate classmates
- 2013 Uintah Basin Winter Ozone Study participants
    - Utah Division of Air Quality - Lance Avey
    - Alex Jacques, Matt Lammers, John & Maggie Lawson, Nola Lucke
    - Utah State University
- NASA SPoRT program
- Air Force Institute of Technology

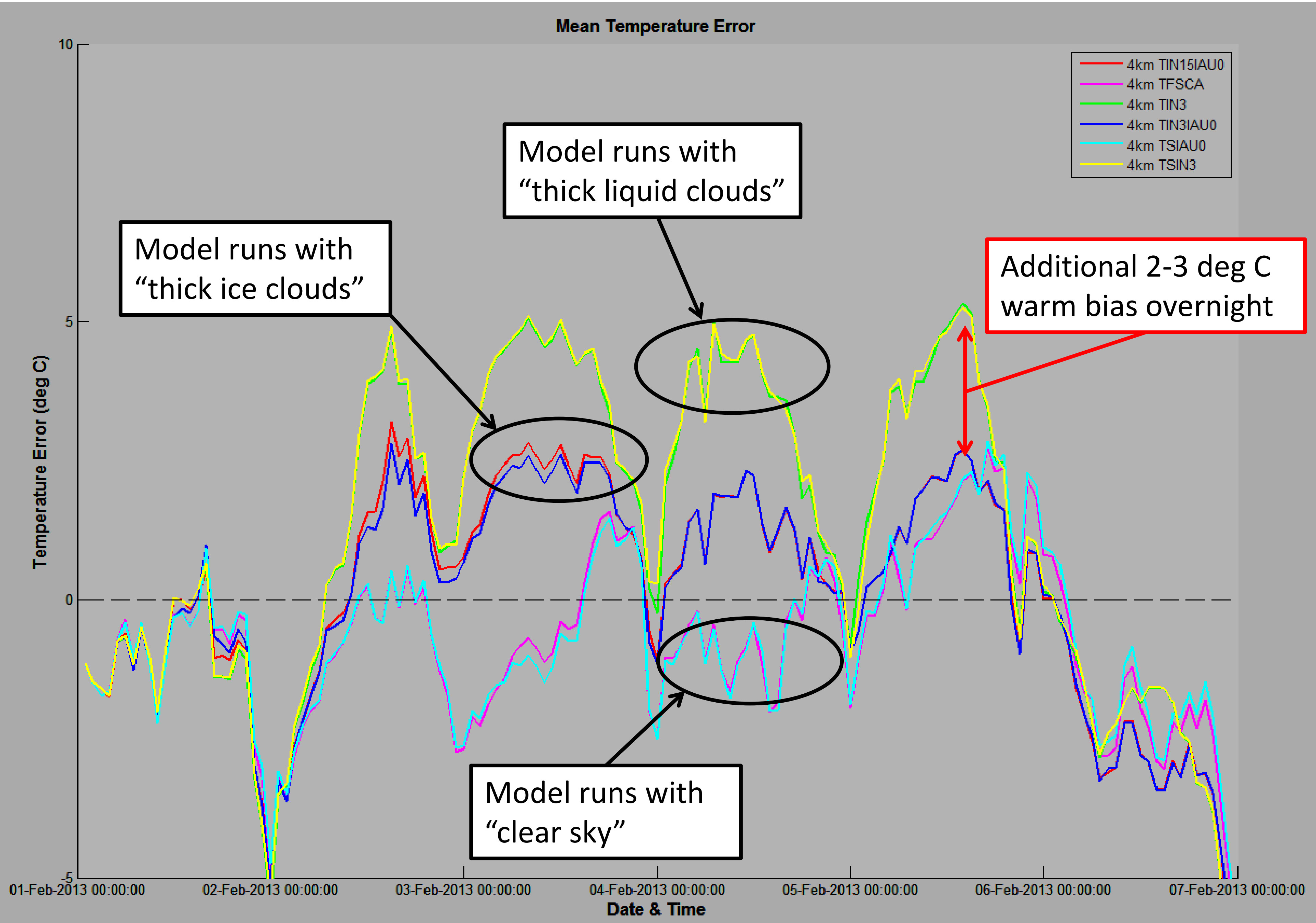
The views expressed in this presentation are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.


Questions?

2-m Temperature Bias



Primary Outcomes from Microphysics Testing



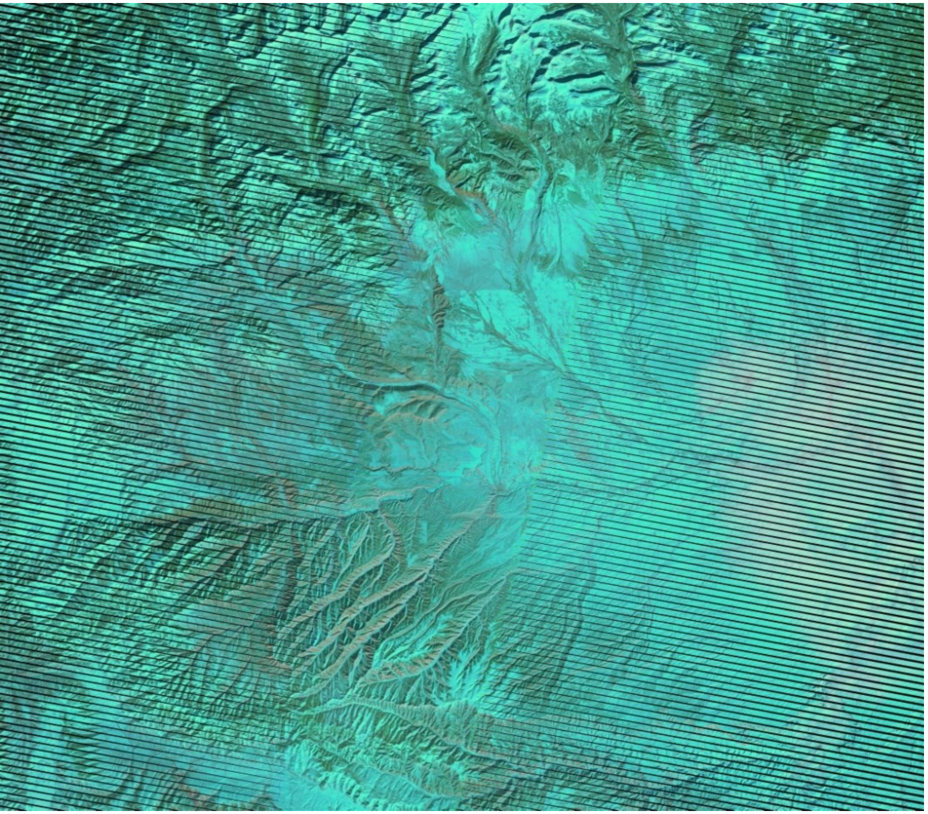
WRF v3.5 Setup

- **See Alcott and Steenburgh 2013 for further details on most aspects of this numerical configuration:**
- **http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-12-00328.1**

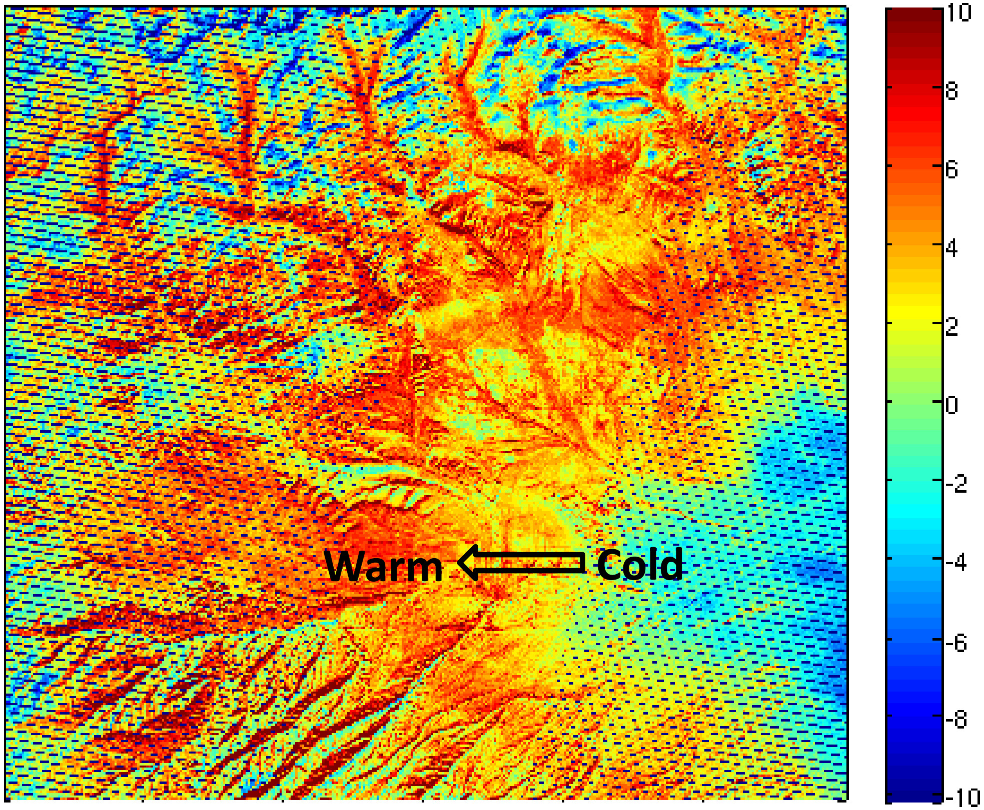
- **Overview summary of WRF Namelist options:**
  - **map_proj= 1: Lambert Conformal**
  - **NAM analyses provide initial cold start, land-surface conditions, & lateral boundary conditions**
  - **Idealized snow cover as function of height input to replace poor NOHRSC snow**
  - **3 Domains with 12, 4, 1.33 km horizontal resolution (see next slide)**
  - **Number of vertical levels = 41**
  - **Time step = 45 seconds (15, 5 s for inner 2 grids)**
  - **Microphysics: Thompson scheme**
  - **Radiation: RRTMG longwave, RRTMG shortwave**
  - **Surface layer: Monin-Obukov**
  - **Land Surface: NOAH**
  - **Planetary Boundary Layer: MYJ**
  - **Kain-Fritsch cumulus scheme in outer coarse 12 km grid**
  - **Slope effects for radiation, topographic shading turned on**
  - **2nd order diffusion on coordinate surfaces**
  - **Horizontal Smagorinsky first-order closure for eddy coefficient**
  - **Landcover/Land use: National Land Cover Database (NLCD) 2006 1 arc-second (30 m)**
  - **Terrain Data: U.S. Geological Survey 3 arc-second (90 m)**

Differential Heating in Uintah Basin

2 February 2013 1836 UTC Landsat 7 ETM+ (60 m resolution)



Visible: Cyan- snow; light grey- cloud

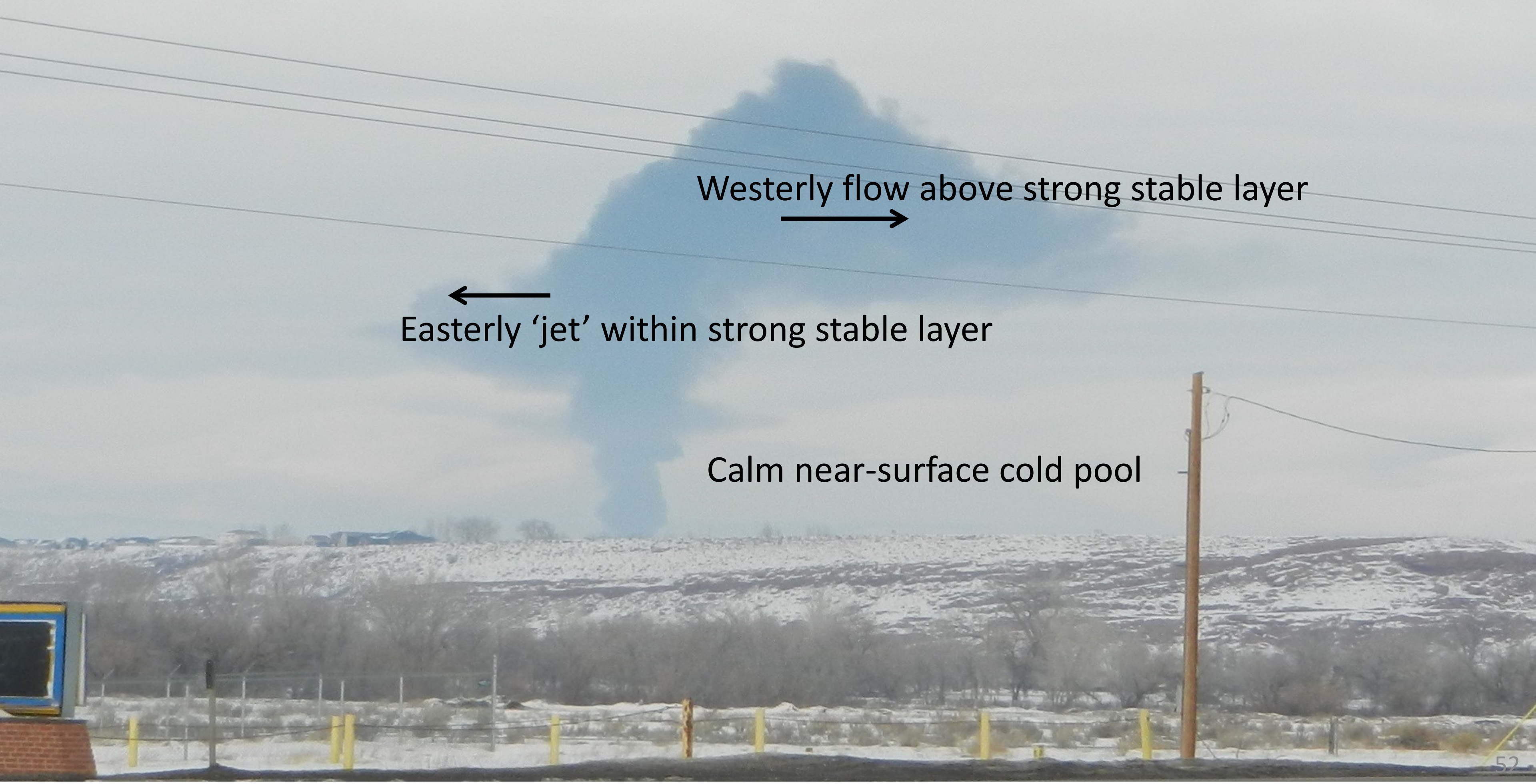


Skin temperature (^oC)

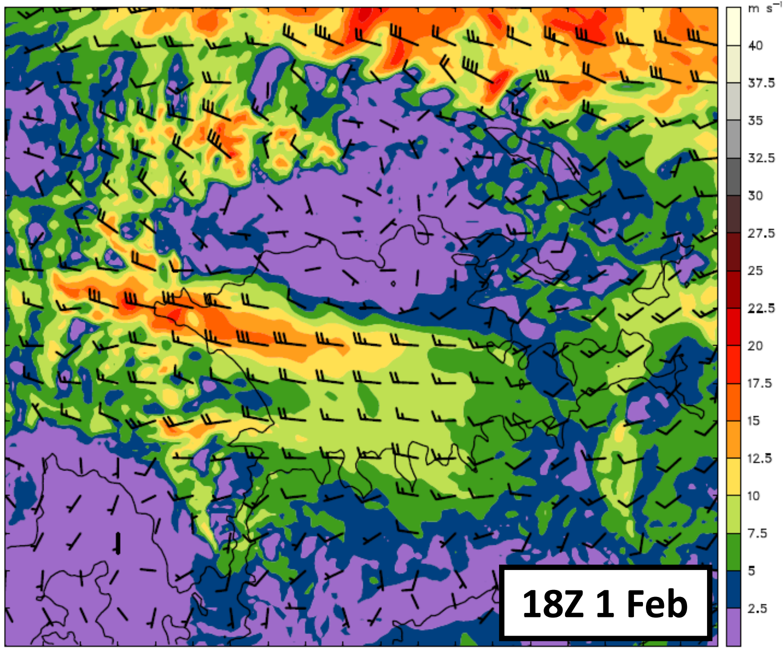
Elevated Easterly Flow on 26 Jan 2013

Semi-permanent easterly ‘jet’ embedded within inversion layer during ***weak*** NW synoptic flow

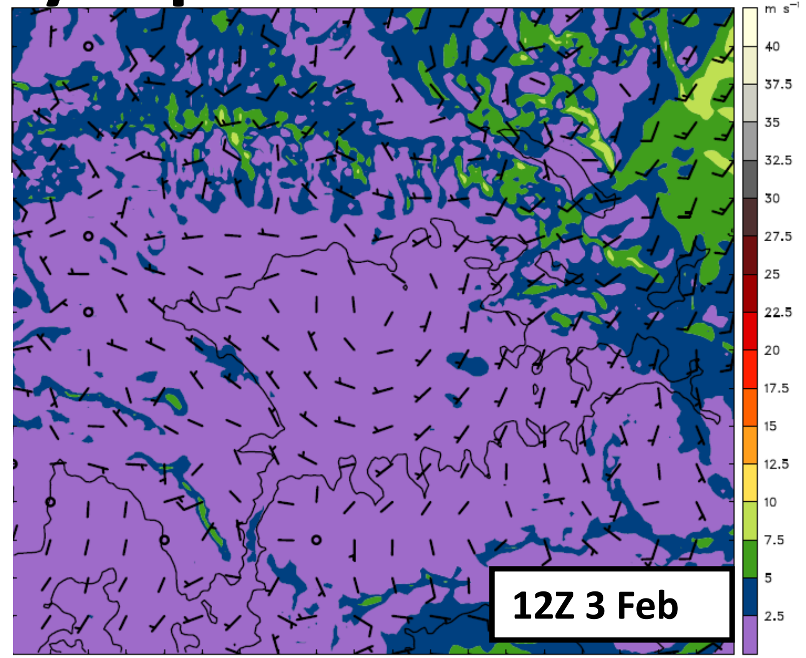
Oil well fire plume, looking north

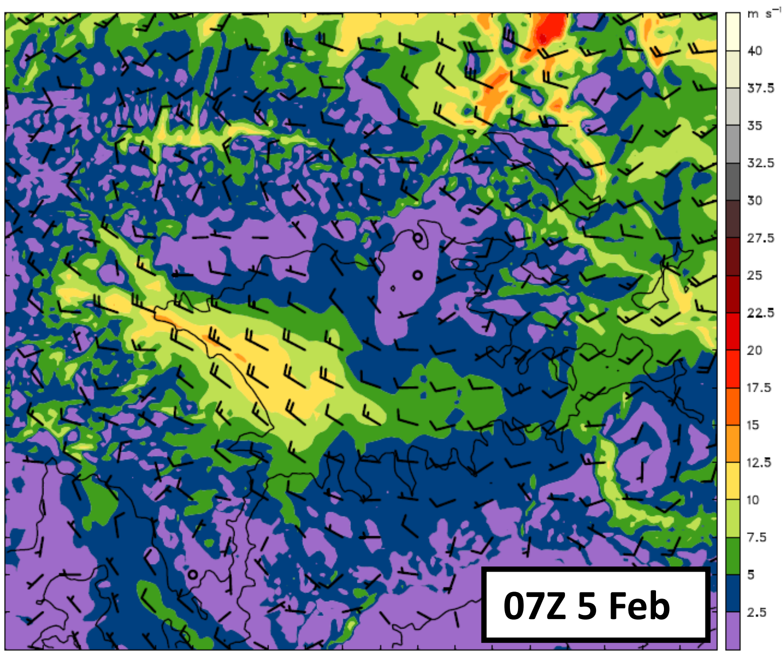


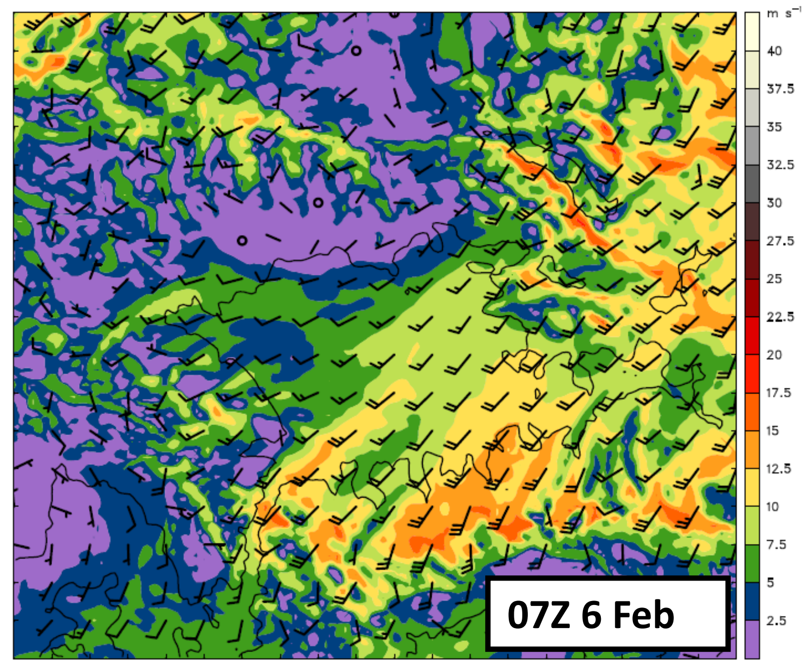
Variations in Westerly Synoptic Flow



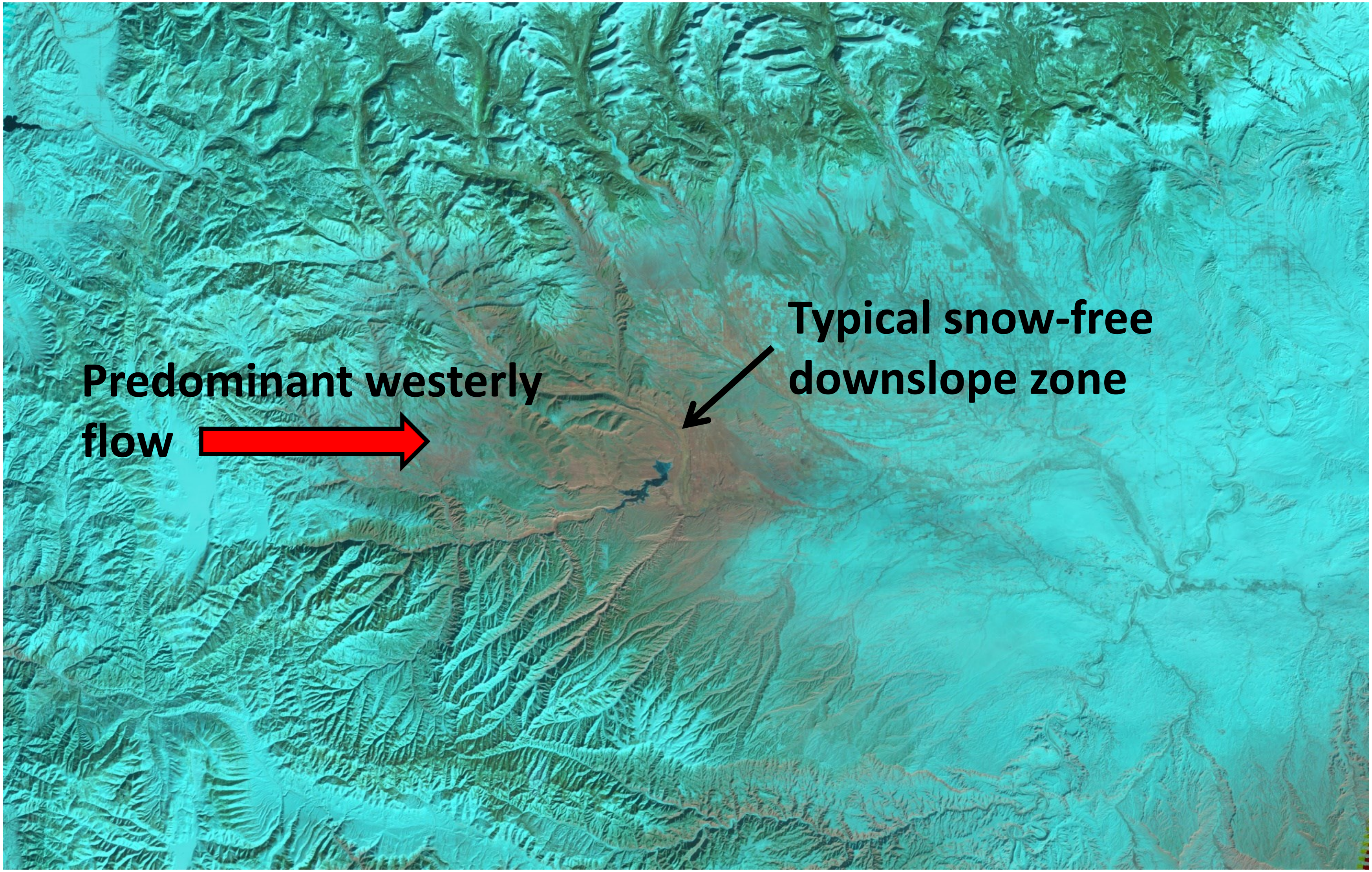
Large variation in 2.3 km MSL winds during the 1-7 Feb period



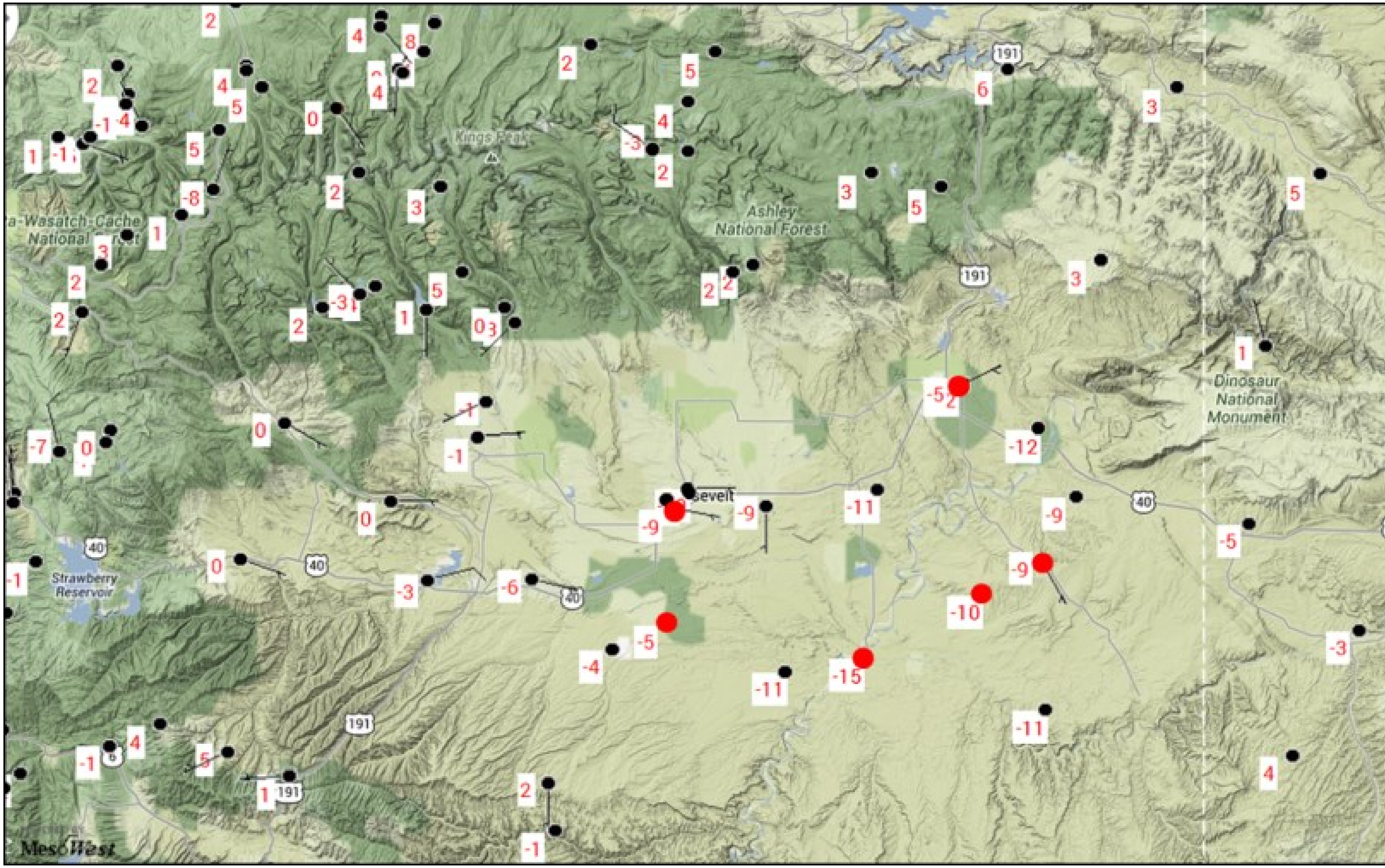




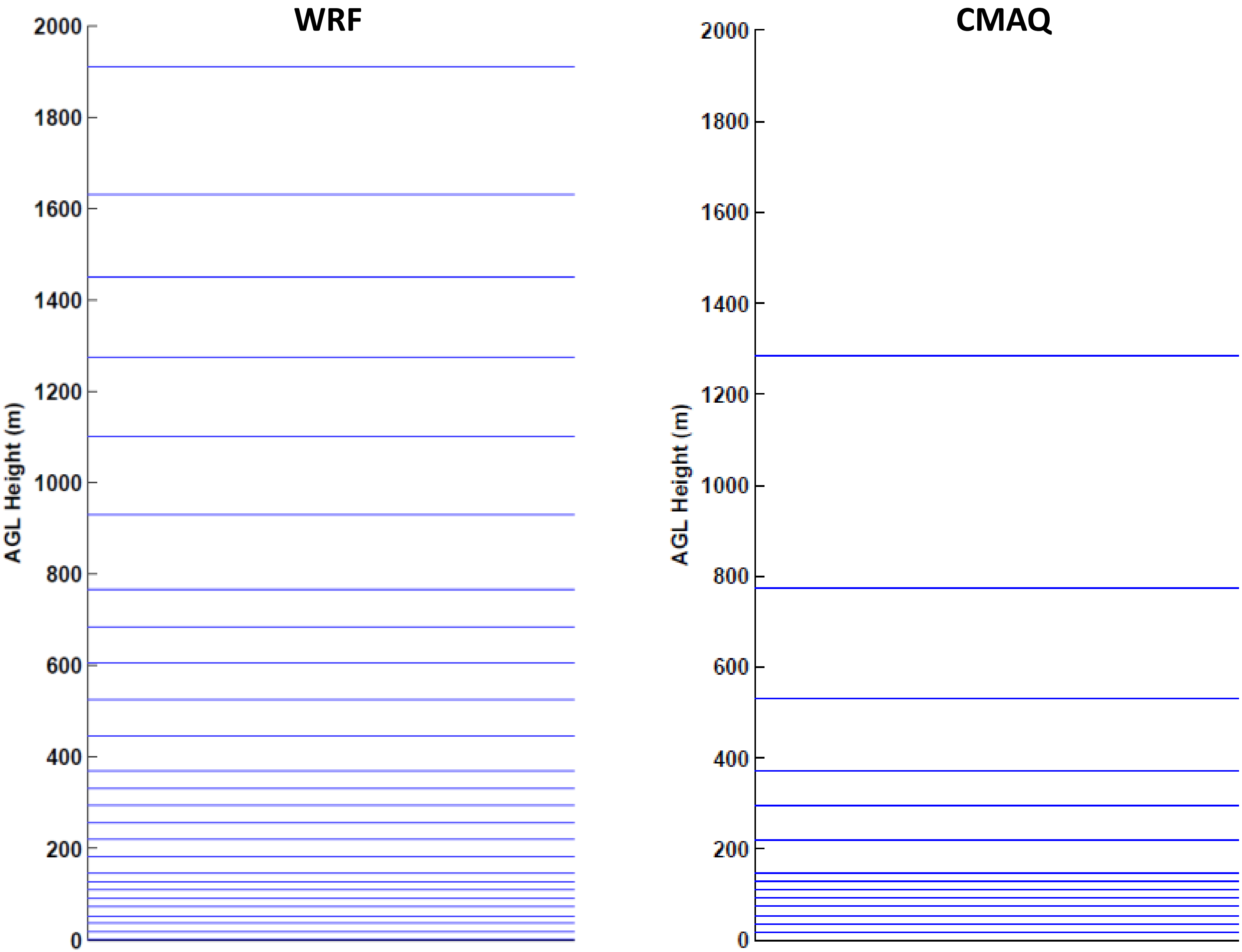
Impact of Downslope on Snow Cover



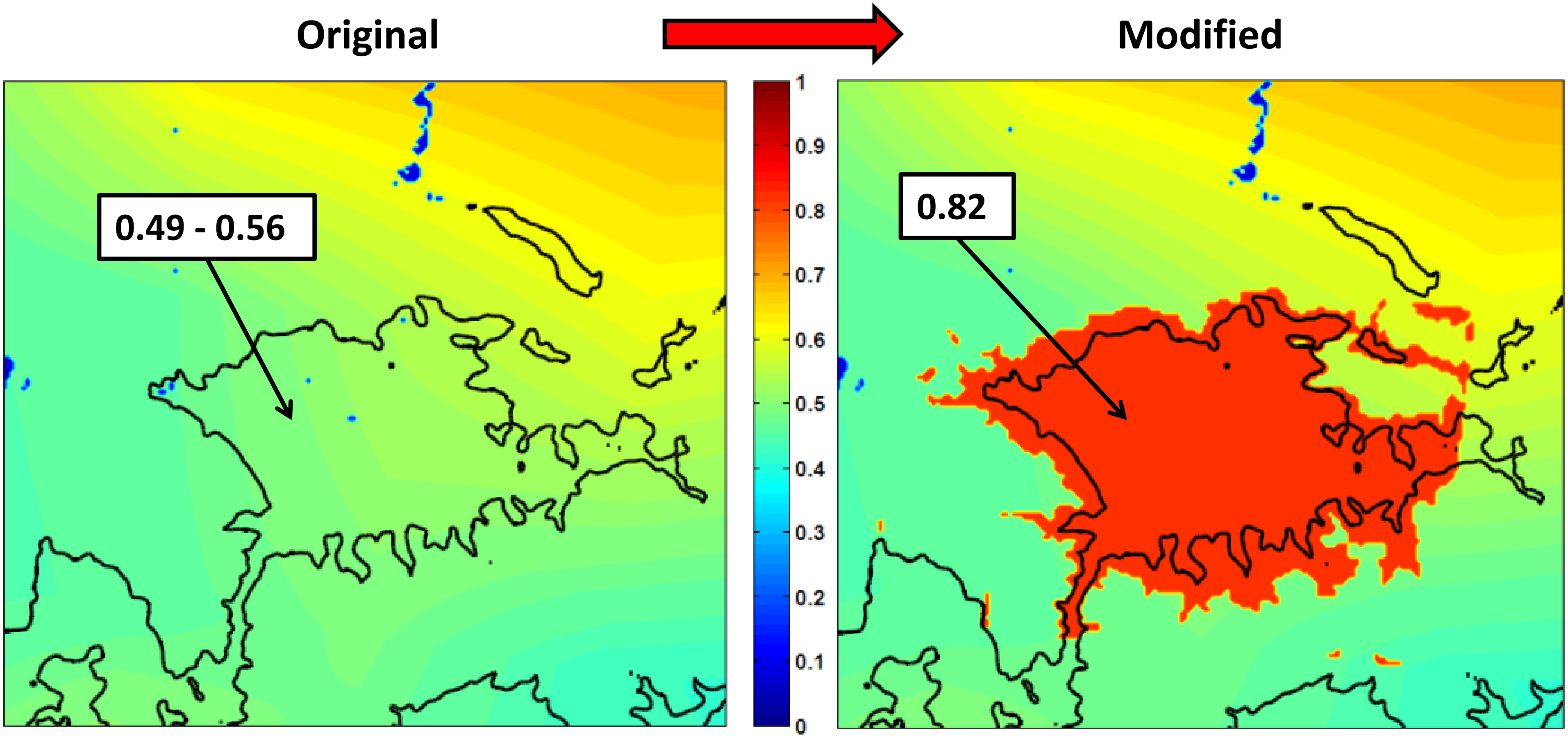
1800 UTC 2 Feb 2013 Observations



WRF vs. CMAQ Vertical Levels

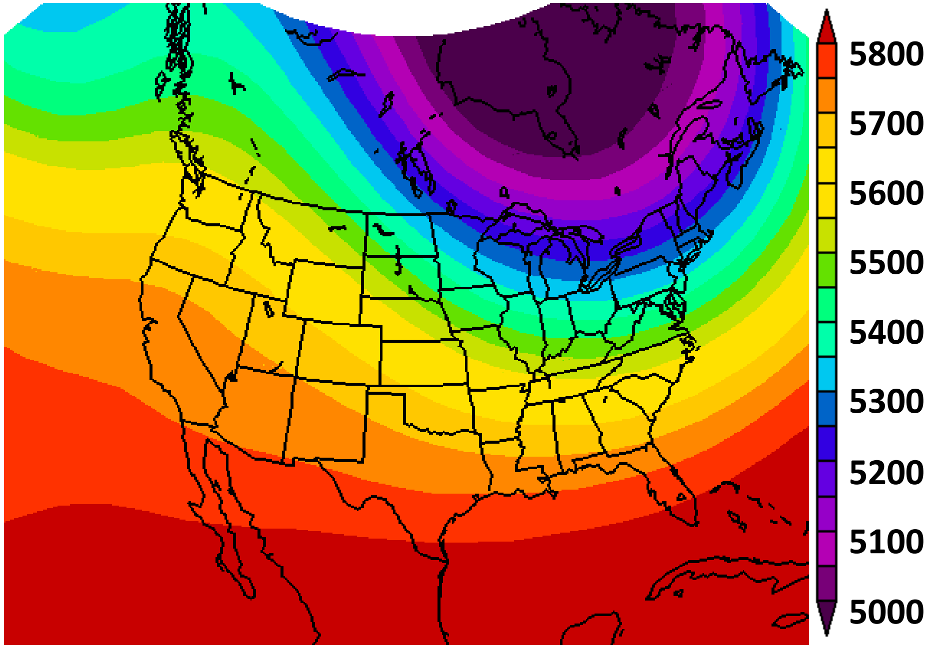


WRF Snow Albedo Variable

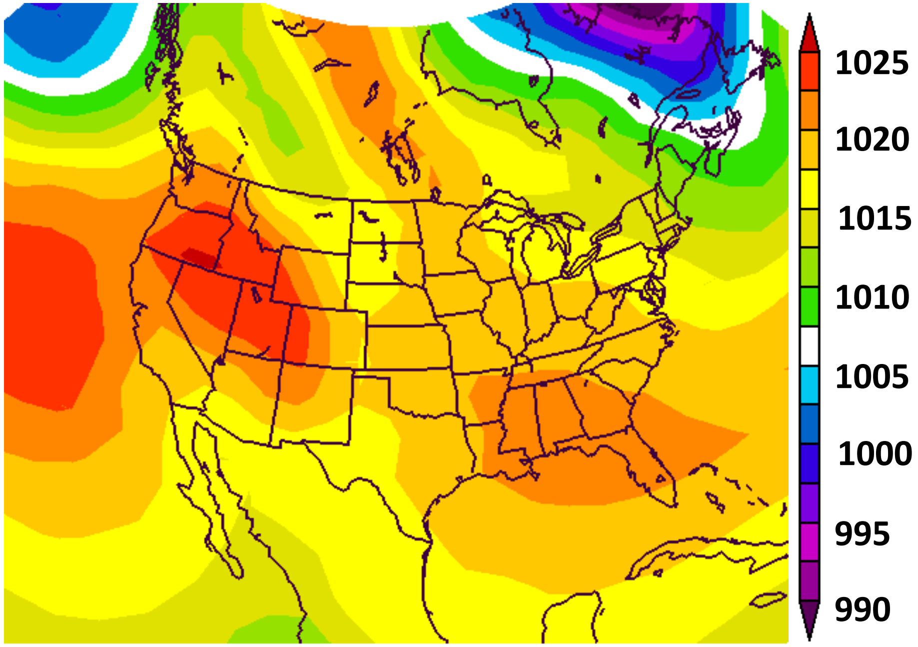


NARR Composites 1-7 Feb 2013

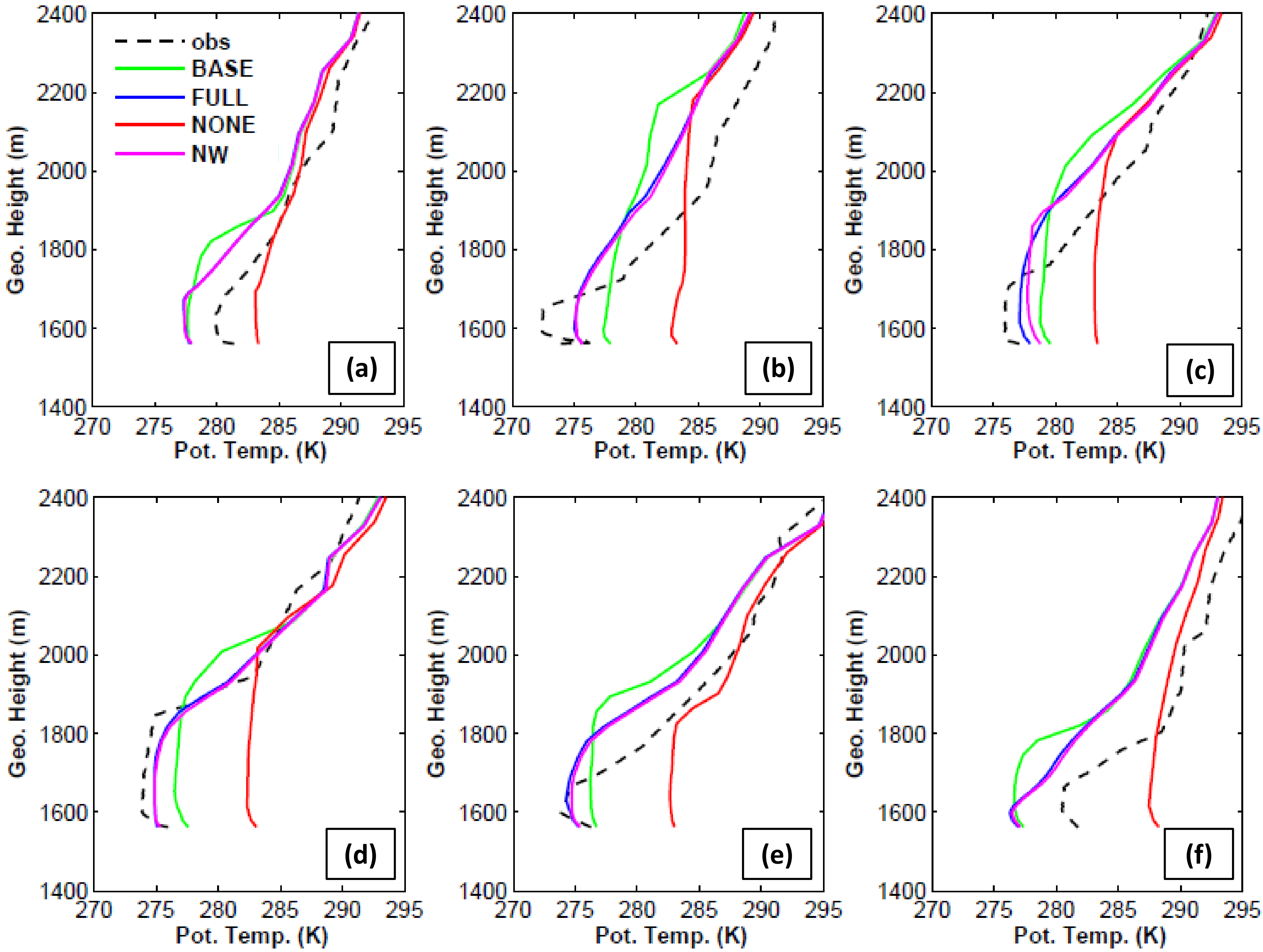
500 hPa



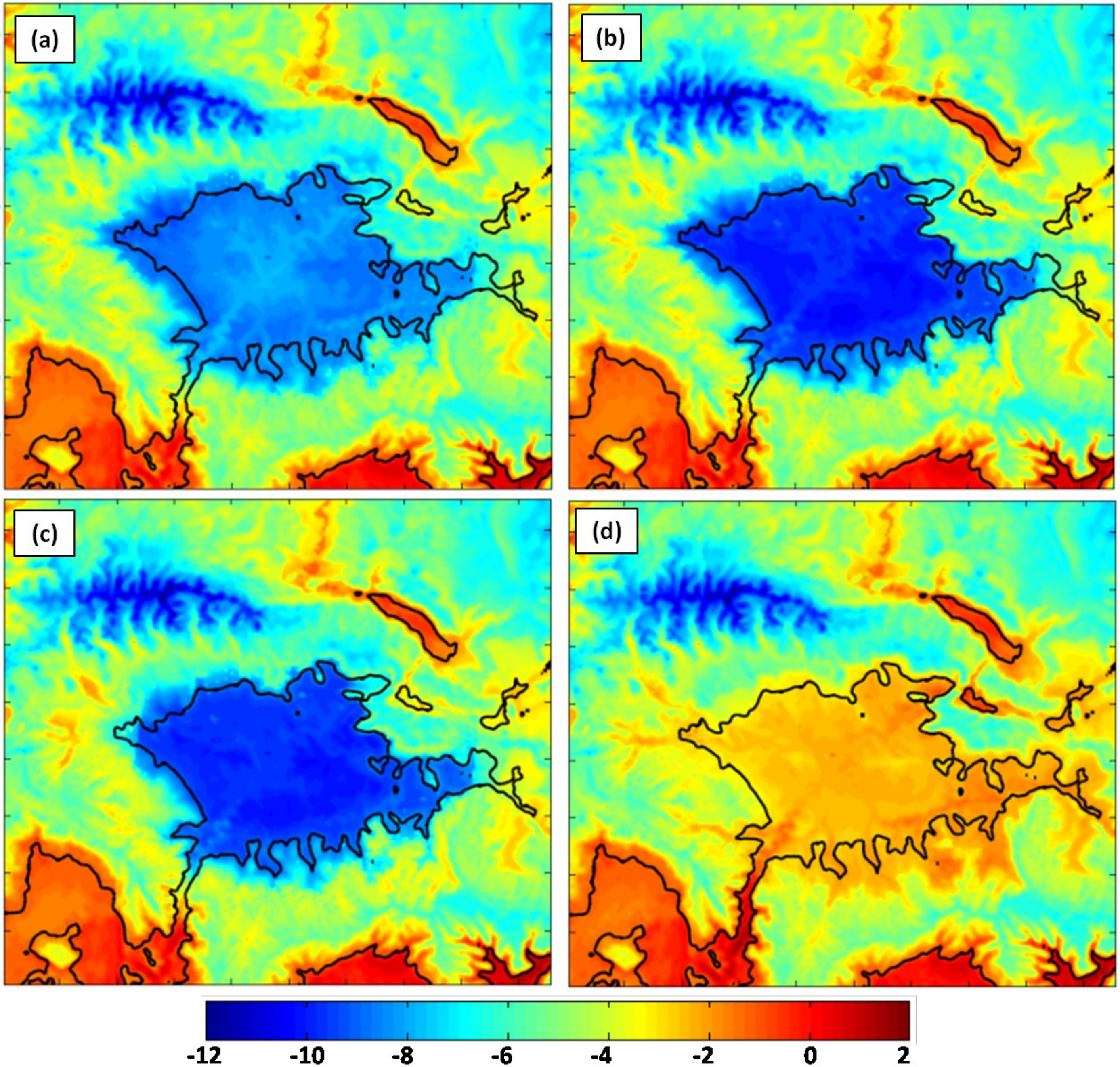
SLP



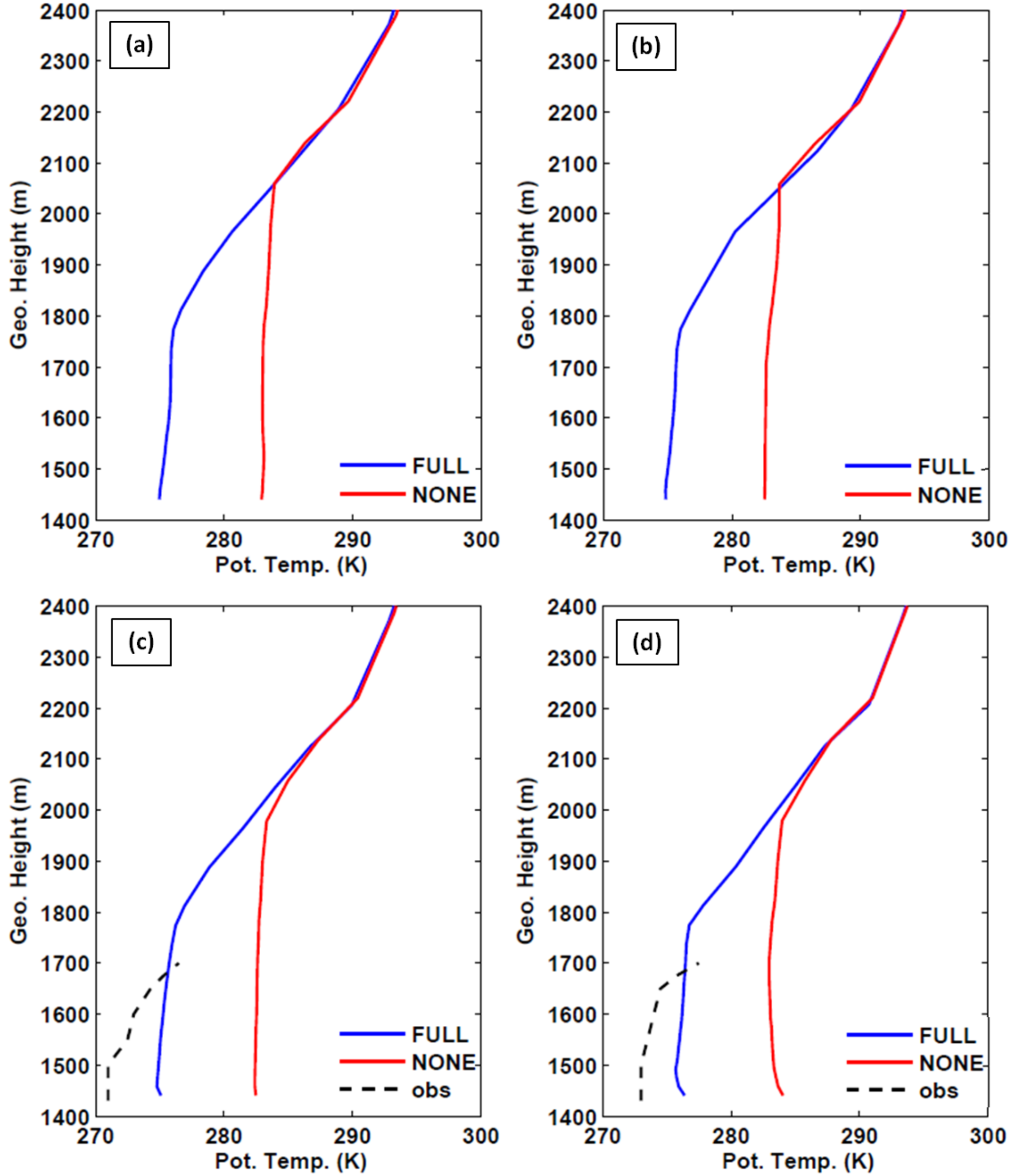
Roosevelt 1800 UTC Profiles



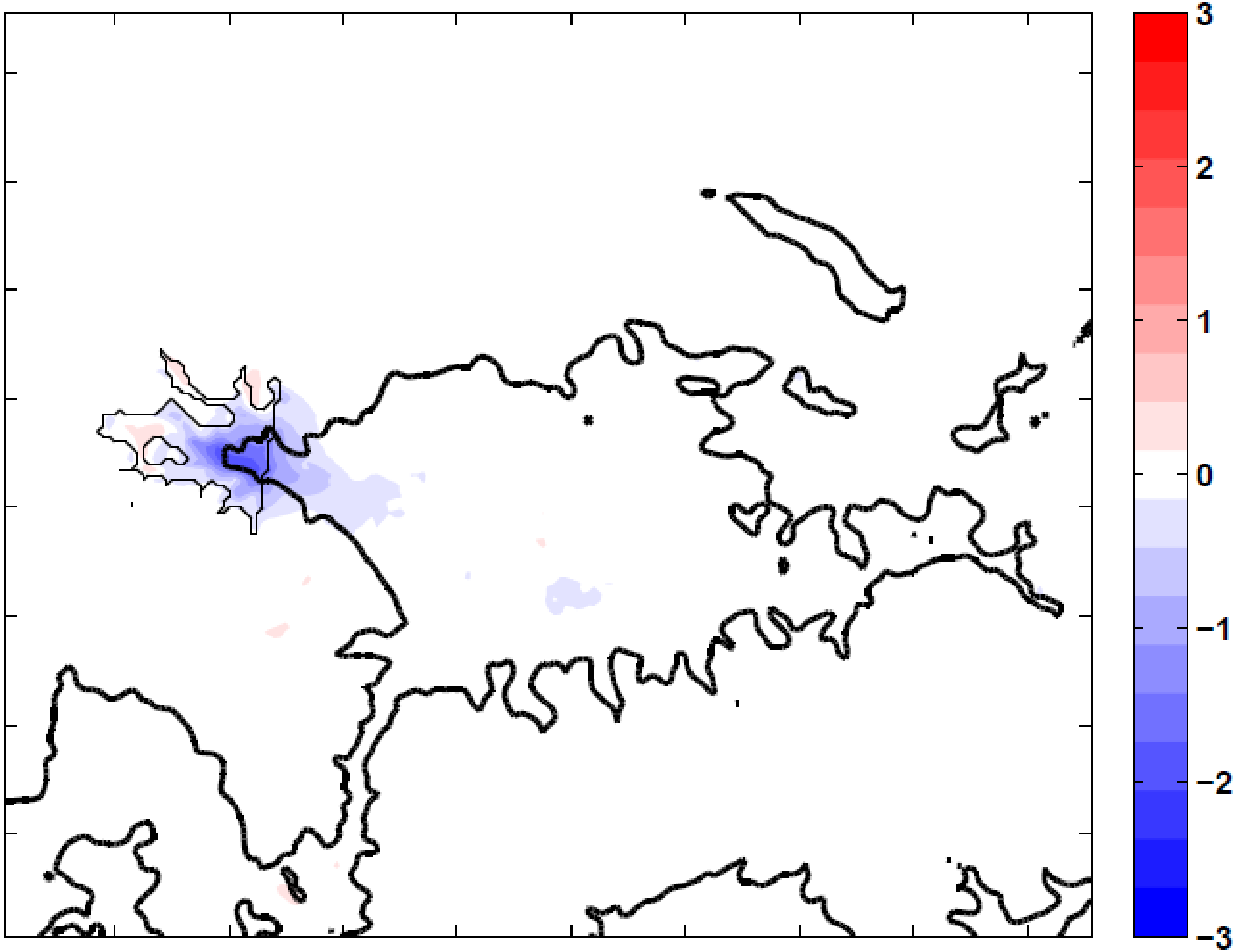
Mean 1-6 Feb 2-m Temperature



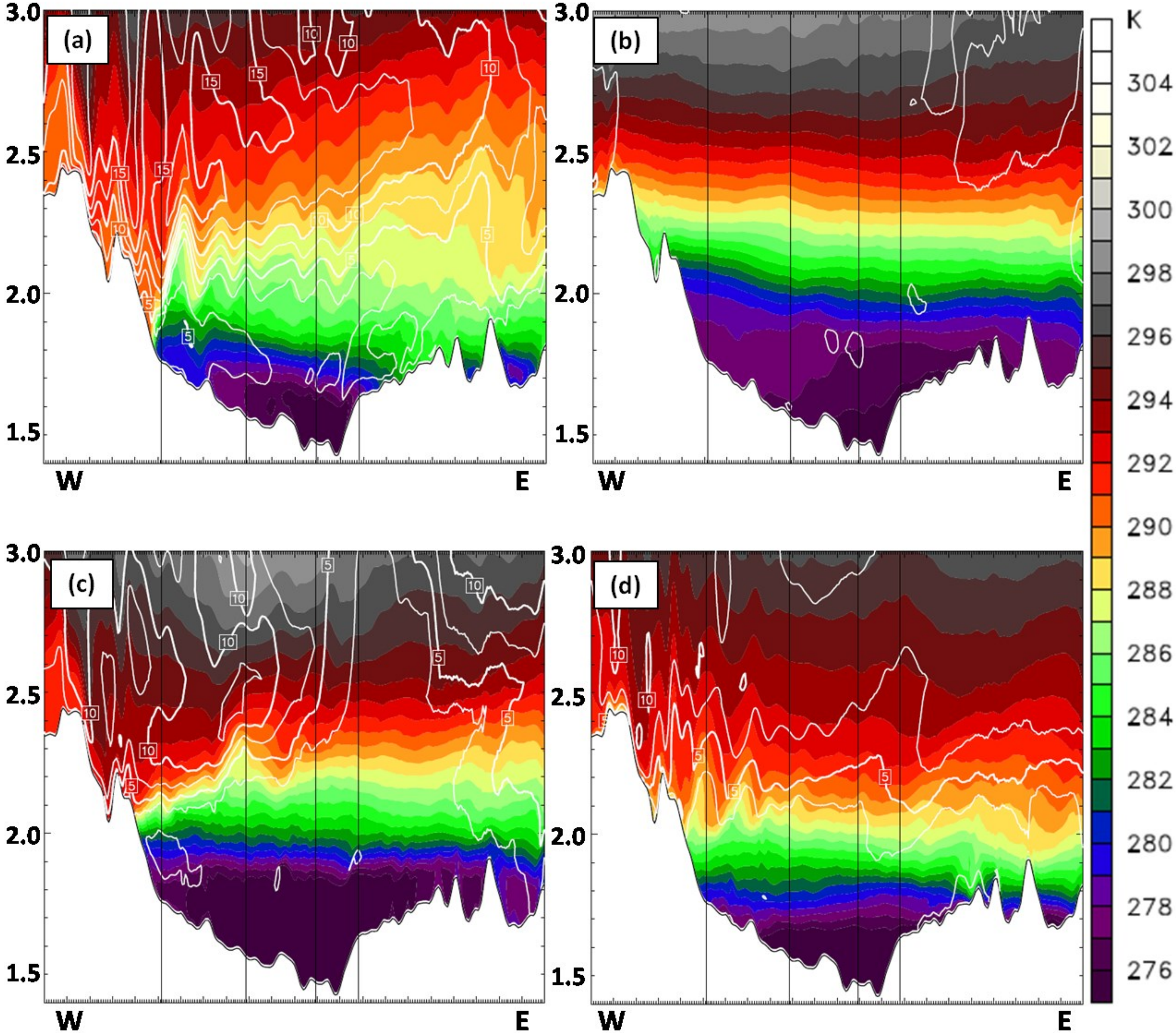
Ouray Profiles 3 Feb 0900 - 1800 UTC



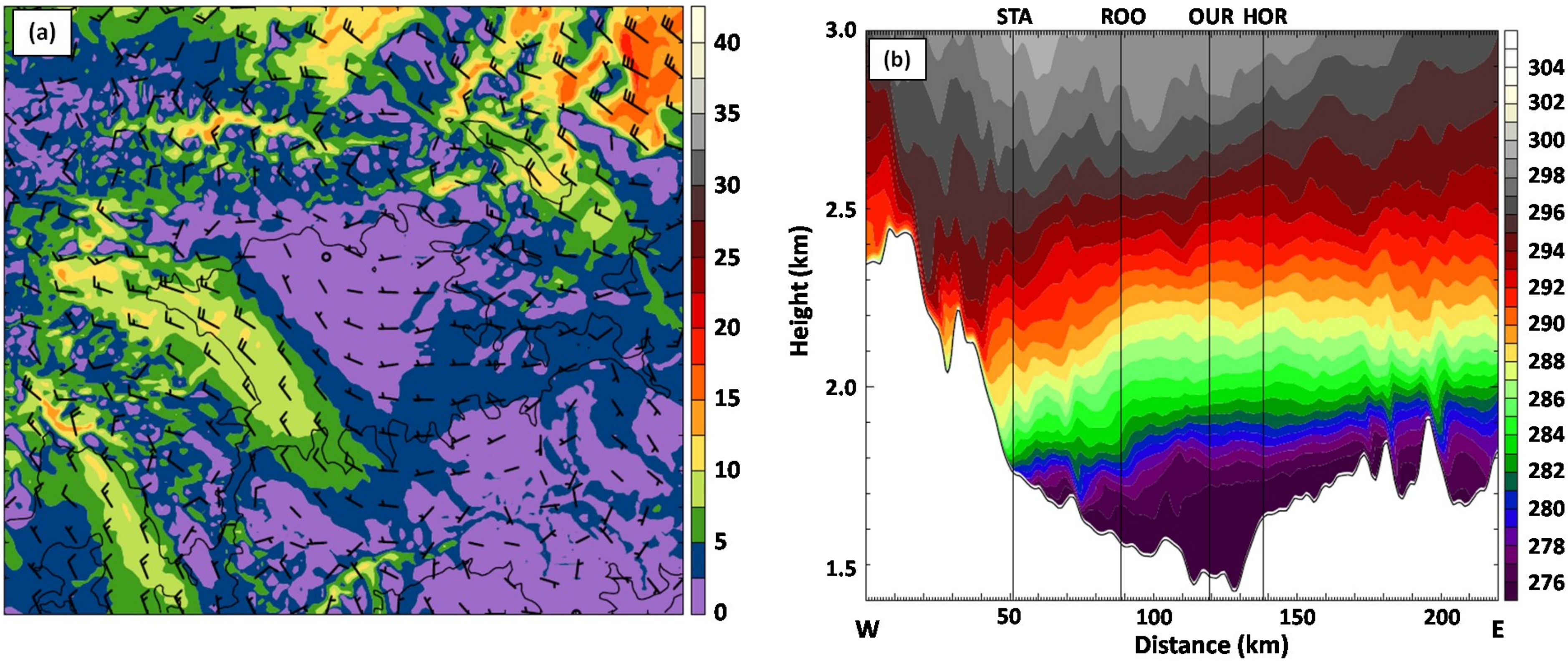
Mean Zonal Wind Difference (NW-FULL)



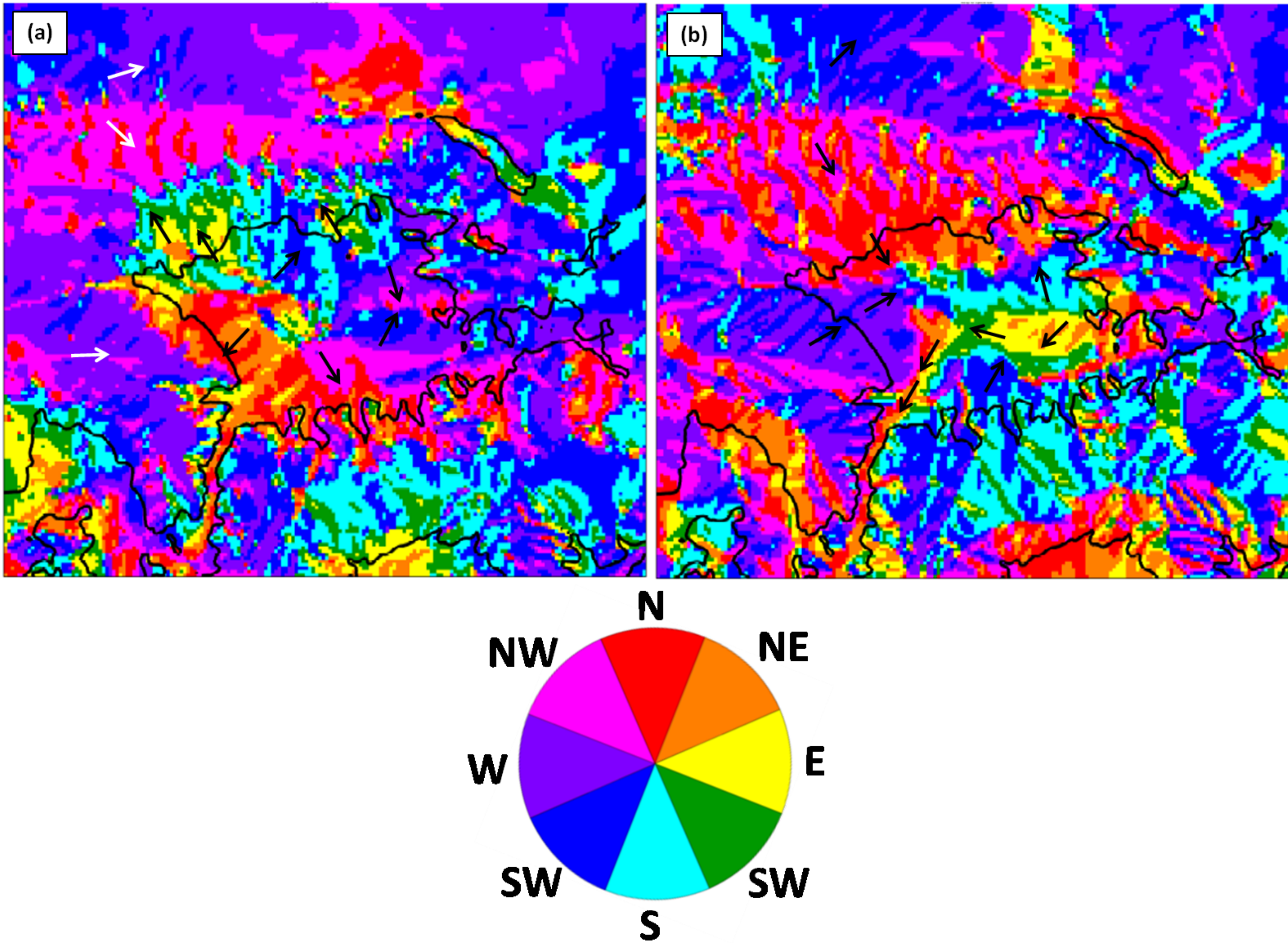
Potential Temperature Cross Sections



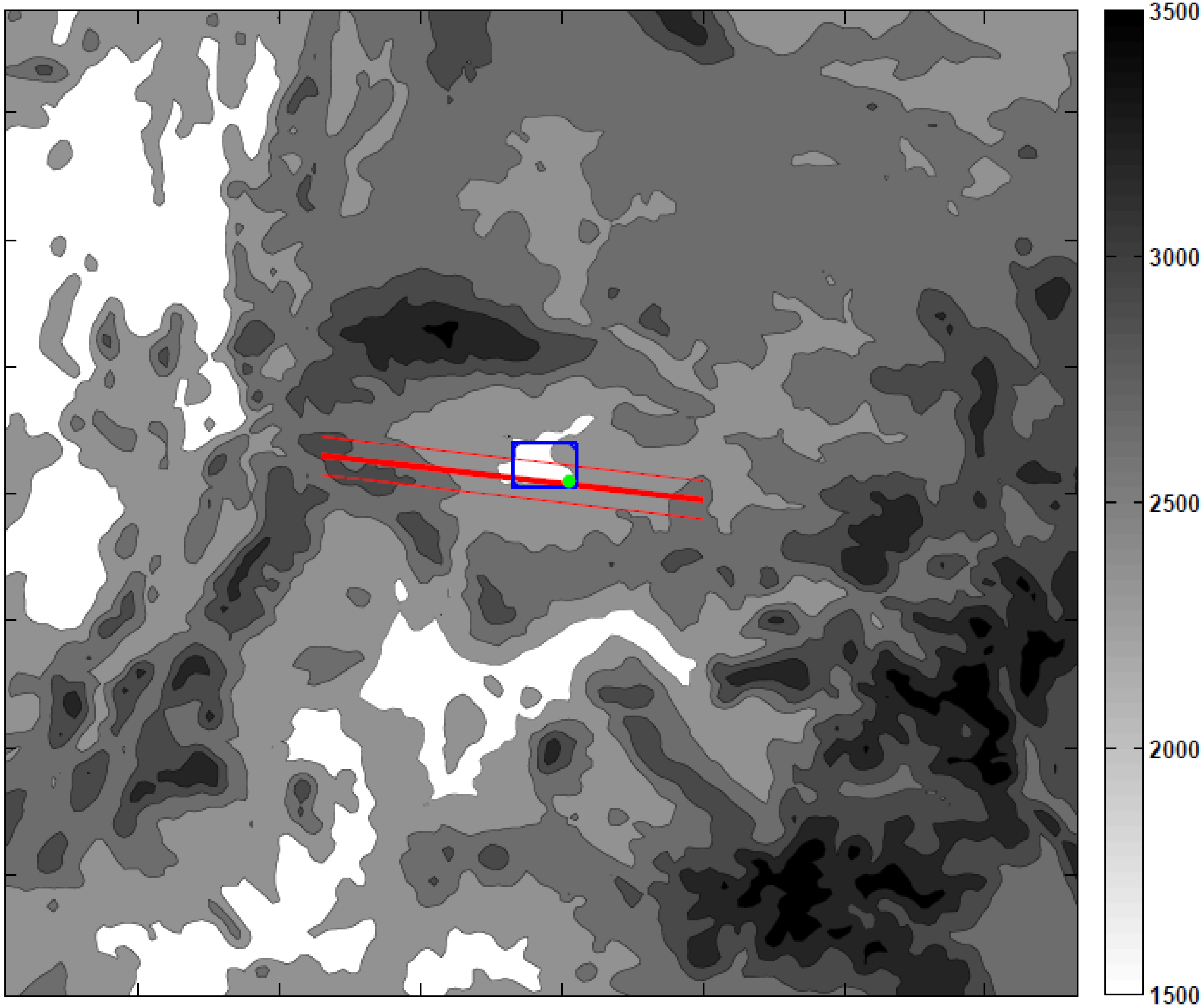
West Basin Mix-Out



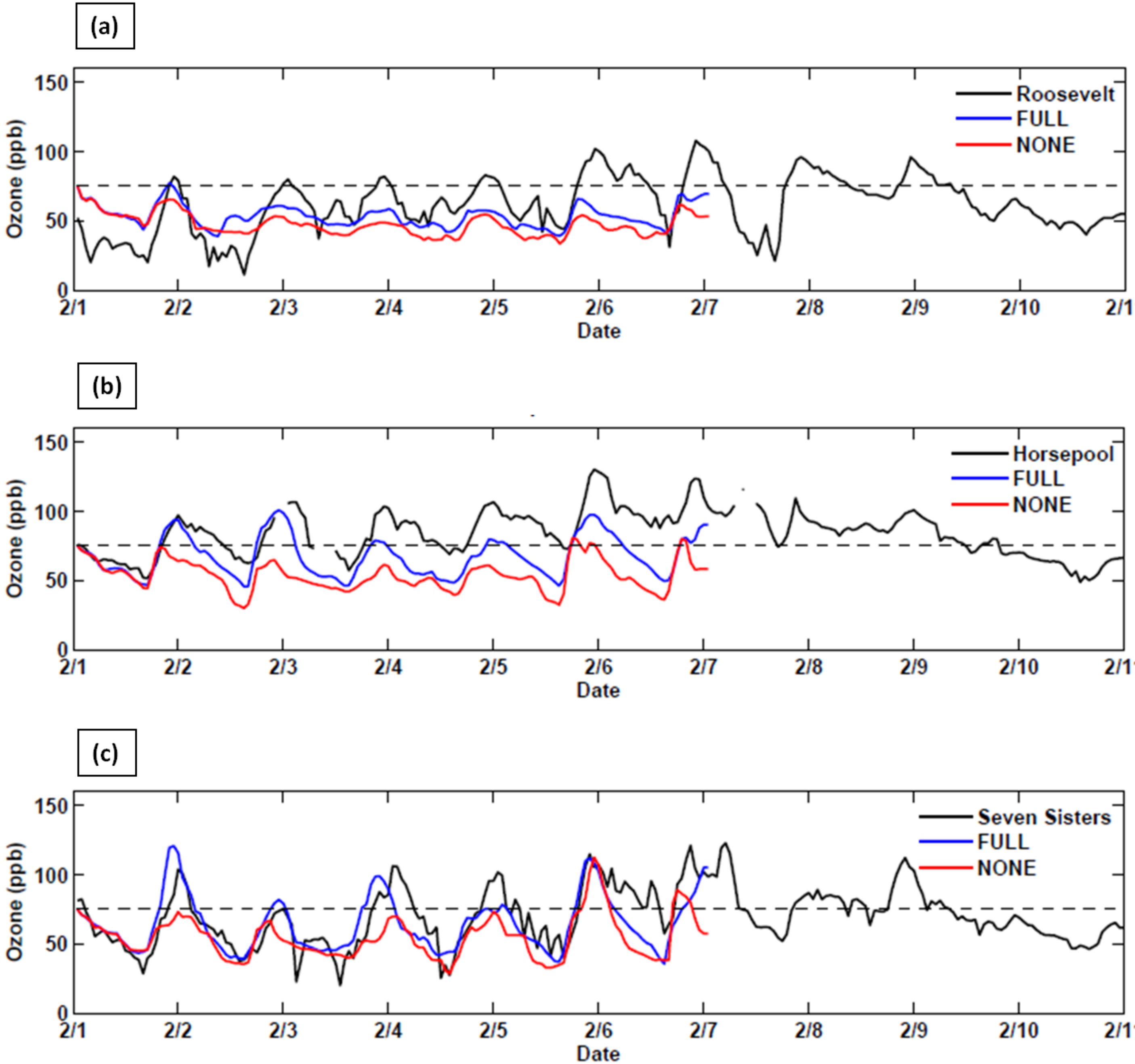
Mean Wind Direction Day/Night



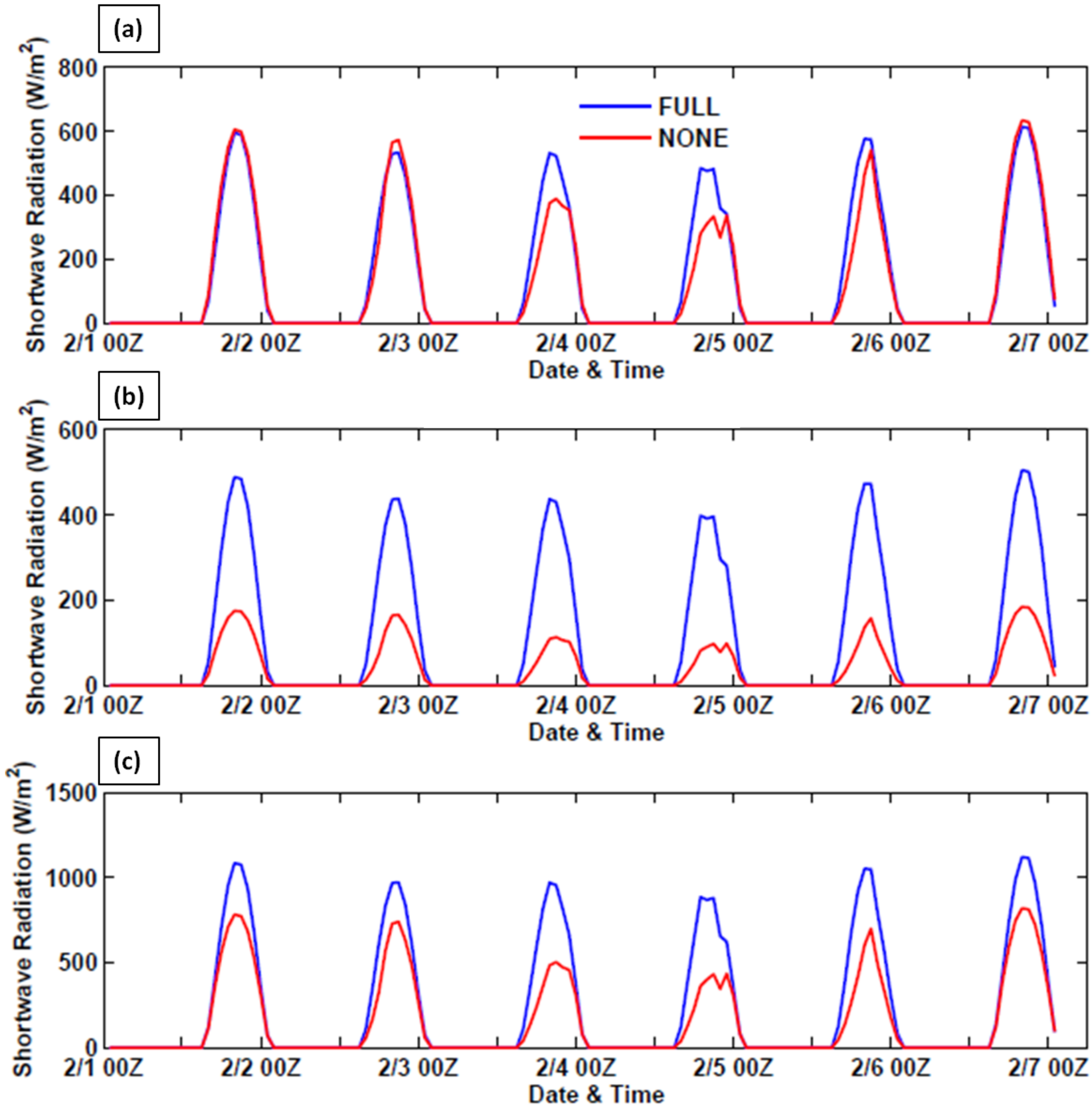
CMAQ Domain



Ozone Timeseries

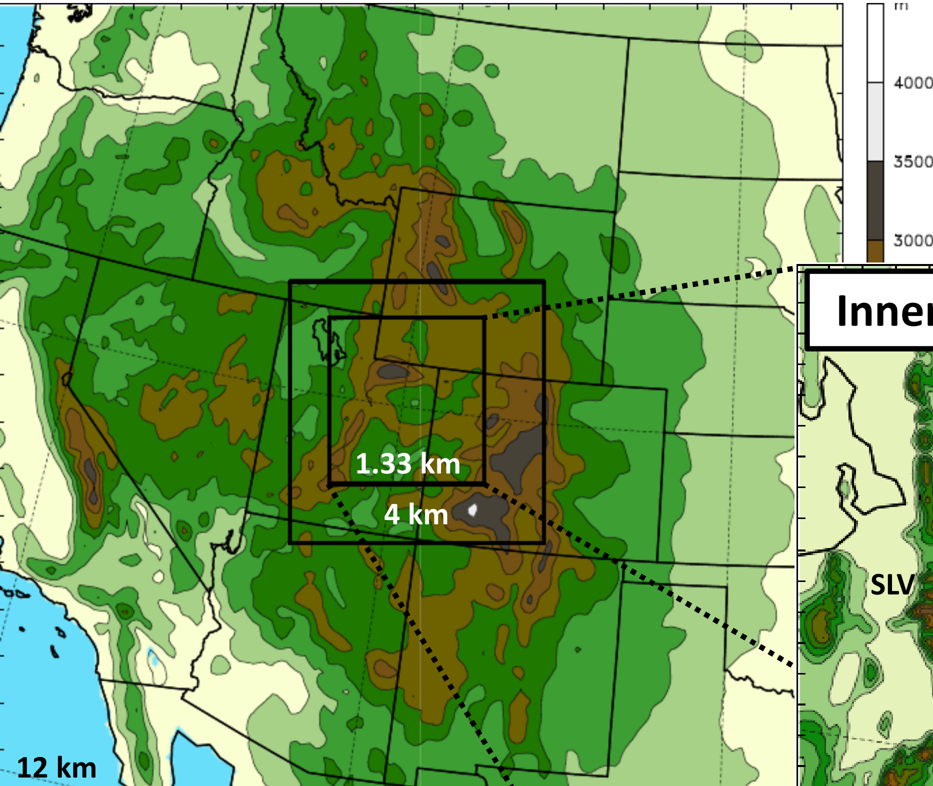


SW Radiation from FULL/NONE



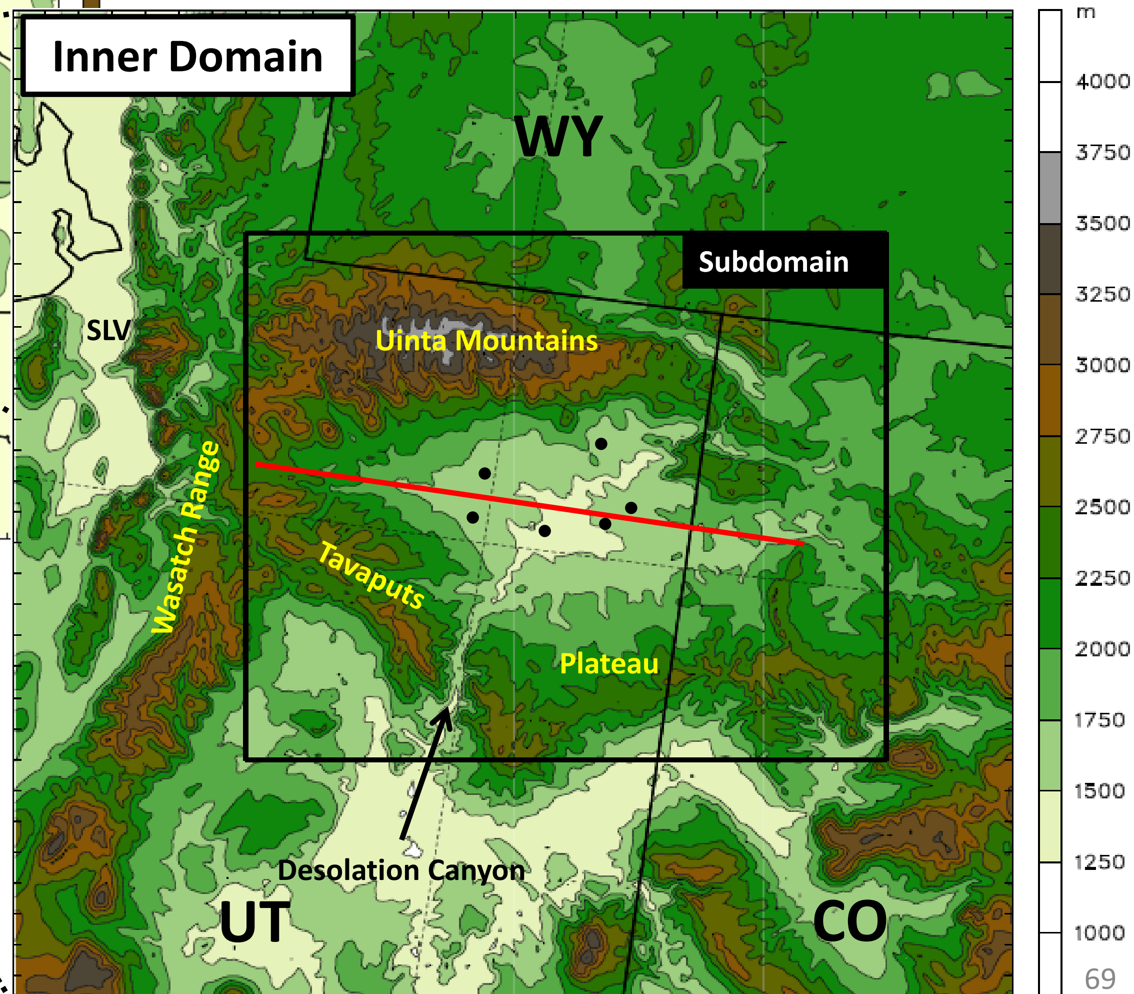
Model Setup & Domains

Outer Domain



WRF-ARW v3.5

- NAM analyses for initial & lateral BC
- 41 vertical levels
- Time step = 45, 15, 5 seconds
- 1 Feb 0000 UTC to 7 Feb 0000 UTC 2013



Parameterizations:

- Microphysics: Thompson
- Radiation: RRTMG LW/SW
- Land Surface: Noah
- Planetary Boundary Layer: MYJ
- Surface layer: Eta Similarity
- Cumulus: Kain-Fritsch (12 km domain)
- Landcover/Land use: NLCD 2006 (30 m)