Project Report

Improving Air Quality Modeling for the Wasatch Front & Cache Valley Winter Air Pollution Episodes
Project Period: 15 July 2014-14 January 2016
Submitted to Patrick Barickman, Manager, Technical Analysis, Utah Division of Air Quality

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1. Summary

The 2014 Utah state legislative session provided funding for pilot projects led by the Utah Division of Air Quality (DAQ) to address air quality concerns facing the state. One such pilot project was the 2015 study on Improving Air Quality Modeling for the Wasatch Front and Cache Valley Winter Air Pollution Episodes (Hereafter referred to as the 2015AQMS).

Significant progress was made during this study to improve the numerical treatment of land use, snow cover, initialization, and vegetation parameters used in simulations of northern Utah valleys. The results of this research are detailed in the thesis of Chris Foster (final Proquest thesis pdf attached). The findings of Chris Foster's thesis work will also be distilled and submitted as a shorter journal article to *Boundary-Layer Meteorology* within the next month. The results of large-eddy simulation tests of cold pool simulations in the Salt Lake Valley are outlined in the draft paper entitled 'Large-eddy simulations of a Salt Lake Valley Cold Pool which will also be submitted within the next few weeks *the Journal of Geoscientific Model Developments*. . A link to the most recent and submitted paper drafts will be continually update at

http://home.chpc.utah.edu/~u0198116/COLD_POOL_METEOROLOGICAL_MODEL_SALT_LAKE_DRAFT_PAPERS/

When the papers have been accepted and are subject to journal copyright laws, online links to the associated papers will be linked in the aforementioned directory so that anyone reading this report will be able to quickly find them.

The core objectives of this project are:

1. **Determine appropriate atmospheric model configurations including treatment of the underlying surface to simulate wintertime cold pool events along the Wasatch Front and in the Cache Valley that lead to high PM2.5 pollution**
2. **Collaborate with Utah DAQ staff to identify and simulate selected cold-air pool episodes to be used in PM2.5 SIP development**

The deliverables initially listed for this project are listed below in **bold**. Further information on the final deliverables provided are in *italics*

1. **Evaluation of possible case studies and periods that are appropriate for future SIP modeling studies**

   A long-lived cold air pool episode January 1-11 2011 was selected as the primary case to study and improve the meteorological models for and for input into the DAQ wood smoke emissions study. Additional time periods may be simulated by DAQ staff in the future for the SIP to include cases in December 2013.

2. **Informal updates with DAQ staff on our results on appropriate model configurations and parameterizations as well as the degree to which improved specification of the underlying surface state improves model performance**

   Several productive meetings and exchanges have occurred between University of Utah researchers and DAQ modeling staff over the past year. The DAQ staff have been fully informed of the improvements made to the model and have been given the best output data of a cold pool episode that we were able to simulate.

3. **Output from all case studies provided in a format convenient for use in photochemical models used by DAQ modelers (e.g., CMAQ)**

   DAQ modelers have used the WRF meteorological output files as input into photochemistry models.

4. **Validating data sets archived in formats convenient for additional model testing and evaluations**

   Extensive validation data sets are available from PCAPS and Mesowest. As part of his MS Thesis, Chris Foster provided the most complete meteorological evaluation of a cold pool simulation ever conducted. The results are available in his full thesis.

5. **All model configuration files and modifications to model codes stored in a repository for use by DAQ staff and other researchers**

   WRF namelist files and output files from the aforementioned case are available to DAQ researchers in the CHPC filesystem.

6. **Final report detailing model set-up and configuration and model performance of modeled meteorological features of cold-pool pollution events (e.g., snow cover, boundary layer structure, wind flows).**

   The MS thesis of Chris Foster will serve as the report for detailing the WRF model set-up as well as improvements obtained through changes in land use, snow cover, and vegetation and albedo parameters. Please refer to the thesis PDF attached herein or located at: proquest link inserted here when becomes available

2. <u>Study Result Abstracts Supported by UDAQ</u>

2a. SIMULATION OF A COLD-AIR POOL IN UTAH'S SALT LAKE VALLEY. M.S. Thesis by Chris Foster supported by funding by the Utah Division of Air Quality.

The Persistent Cold-Air Pool Study (PCAPS), which took place in Utah's Salt Lake Valley during winter 2010-2011, provides a rich dataset of targeted observations at scales appropriate for better understanding the dynamical evolution of persistent cold-air pools.

We examine the influence of the land use and land cover datasets available within the Weather Research and Forecasting (WRF) numerical model on the model's ability to accurately simulate a persistent cold-air pool (CAP). A modified version of the most recently released land use dataset, 2011's National Land Cover Database (NLCD 2011), was used to model a CAP that occurred from 1 January 2011 to 8 January 2011. Modifications to the NLCD 2011 dataset included reducing the areal extent of the Great Salt Lake to reflect the lake state at that time as well as changing the characteristics of a number of land use classifications (e.g., urban and barren land) to more closely match albedo observations obtained during PCAPS. Snow cover obtained from North American Mesoscale (NAM) reanalysis was also modified to better match observations.
The resulting model simulation for the 1-8 January 2011 period was notably improved compared to an 'out-of-the-box' run for the same period relying on the default U.S. Geological Survey (USGS) and unmodified NAM reanalysis snow cover data. The most substantive improvements were observed within the Salt Lake and Cache Valleys, where modifications to the areal extent of the Great Salt Lake and improved snow coveriv allowed for a more realistic simulation. The time of model initialization relative to the onset of the CAP was found to be a less critical factor than the improvements to land use and snow cover.

2b. Large-Eddy Simulations of a Great Salt Lake Valley Cold Air Pool. To be submitted to the Journal of Geoscientific Model Development. Erik Crosman and John Horel.

Persistent cold air pools (CAPs) are often poorly forecast by mesoscale numerical weather prediction models. Two major factors in poor numerical forecasts of CAPs are (1) the inability of planetary boundary layer (PBL) schemes to properly simulate CAP evolution and (2) poor initialization of model surface state. In this study, the importance of accurately simulating top-down turbulent erosion processes and initial land surface state during CAP episode are shown. The Weather Research and Forecasting (WRF) model simulated the lifecycle of the 26-31 January 2011 persistent CAP in Utah's Great Salt Lake Basin more realistically when run as a large-eddy simulation (LES) where a significant portion of the turbulent motions are explicitly simulated, compared to the WRF model run as a mesoscale model with a PBL scheme where turbulence is highly parameterized. The LES showed the most improvement compared to the mesoscale simulation during the second half of the CAP episode when mountaintop synoptic flow increased and wind-induced mixing and turbulence resulting from interactions between the stable boundary-layer and large-scale flow aloft occurred. The LES simulations of the cold air pools were also found to be highly sensitive to variations in the Great Salt Lake temperature and Salt Lake Valley snow cover, illustrating the importance of proper land surface initialization.

3. <u>Attached Supporting Documents</u>

Please refer to the following document which summarizes the findings of this study:

Foster, Christopher 2016: M.S. Thesis entitled a "SIMULATION OF A COLD-AIR POOL IN UTAH'S SALT LAKE VALLEY" (submitted as separate attached document). This will become available on Proquest online in the next 2 months; at that time the link to the proquest document will be listed at http://home.chpc.utah.edu/~u0198116/COLD_POOL_METEOROLOGICAL_MODEL_SALT_LAKE_DRAFT_PAPERS/).

Crosman and Horel, 2016: Large-eddy Simulations of a Great Salt Lake Valley Cold-air Pool. To be submitted to Geoscientific Model Development.

Foster, Horel and Crosman, 2016: The Sensitivity of a Cold-Air Pool in Utah's Salt Lake Valley to Variations in Land Use and Cover Specification.

4) Project Background

The metropolitan Wasatch Front area along the west slopes of the Wasatch Mountains and Cache Valley include 85% of Utah's population. As the state's population doubles to over 5 million residents in the next several decades, virtually all of the population growth will occur in this region, which has experienced poor wintertime air quality in recent years. Cache, Box Elder, Weber, Davis, Tooele, Salt Lake, and Utah counties are classified as not in attainment for $PM_{2.5}$ relative to the current EPA National Ambient Air Quality Standard (NAAQS).

The proposed research builds upon recent observational and modeling studies of winter air pollution episodes in the Salt Lake Valley. The National Science Foundation supported the Persistent Cold-Air Pool Study (PCAPS) from 2010-2014, which was a collaborative research project with Principal Investigators C. D. Whiteman and J. D. Horel from the University of Utah and Sharon Zhong from Michigan State University. A description of the project and key results are found in peer-reviewed papers by Lareau et al. (2013), Whiteman et al. (2014), and Lareau and Horel (2014a,b). The proposed research also leverages observational and modeling studies conducted with funding from the Utah Division of Air Quality (DAQ) for episodes of high winter ozone concentrations in the Uintah Basin (Neemann et al. 2014).

As summarized by Whiteman et al. (2014), atmospheric particulate concentrations in the Salt Lake Valley have decreased over the last 40 years as air quality regulations have taken effect. Exceedances of the 2006 federal 24-h-average NAAQS for fine particulates in winter occur during multi-day episodes associated with high-pressure ridges aloft. The 35 µg m-3 standard is exceeded ~18 days per winter in the Salt Lake Valley. The particulate concentrations in the Salt Lake Valley tend to build up rather uniformly with time during these multi-day periods during which cold polluted air is trapped beneath the ridging aloft (Malek et al. 2006, Gillies et al. 2010, Whiteman et al. 2014). These polluted cold-air pools are affected by atmospheric processes on a range of scales (Lareau et al. 2013). Synoptic-scale processes control the development of the trapping stable layer aloft while terrain-flow interactions affect pollutant concentrations within the boundary layer and near the surface (Lareau and Horel 2014a).

Modeling the complex meteorological features associated with these cold-air pools is difficult and is recognized as one of the greatest challenges facing boundary layer meteorology (Holtslag et al. 2014). DAQ staff have used the Community Multiscale Air Quality (CMAQ) model, driven with meteorology from the Weather Research and Forecasting (WRF) model, to investigate ways to bring $PM_{2.5}$ levels in nonattainment areas of northern Utah in compliance with the NAAQS. DAQ staff have undertaken hundreds of model runs in collaboration with EPA modelers to evaluate configurations of the WRF model and CMAQ to develop the State Implementation Plan (SIP) for PM2.5, recently submitted to the EPA (DAQ 2013). However, from DAQ's experience, their combined WRF/CMAQ runs required unphysical modifications to simulate the buildup of pollutants during wintertime cold-air pool events. Present versions of the WRF model tend to develop mixing heights that are too deep and surface layers that are too warm during wintertime pollution events, a common problem attributable in part to the limitations of the commonly-used parameterization schemes for stable boundary layers (Holtslag et al. 2014).

DAQ staff have identified that the most critical processes requiring WRF model improvements include:

a) vertical temperature profile and stability within the planetary boundary layer that controls the buildup of pollution and its precursors
b) influence of snow cover/depth on surface temperature and stability
c) diurnal wind flows (slope and valley flows) common during high PM2.5 episodes.

Similarly, common themes emerging out of our PCAPS and Uintah modeling experiences are the need to:

a) have accurate large-scale initial and lateral boundary conditions that define the synoptic evolution of the cold-air pools
b) view the Wasatch Front and Cache Valley air pollution environment in a broader context that encompasses the entire Great Salt Lake Basin
c) specify the lower boundary state well, i.e., the underlying land, water, snow and soil surface conditions (Lareau et al. 2013, Lu and Zhong 2014, Neemann et al. 2014)
d) simulate atmospheric flows at higher resolution (≤~1 km) than that (~4 km) used by DAQ modelers previously for SIP applications.

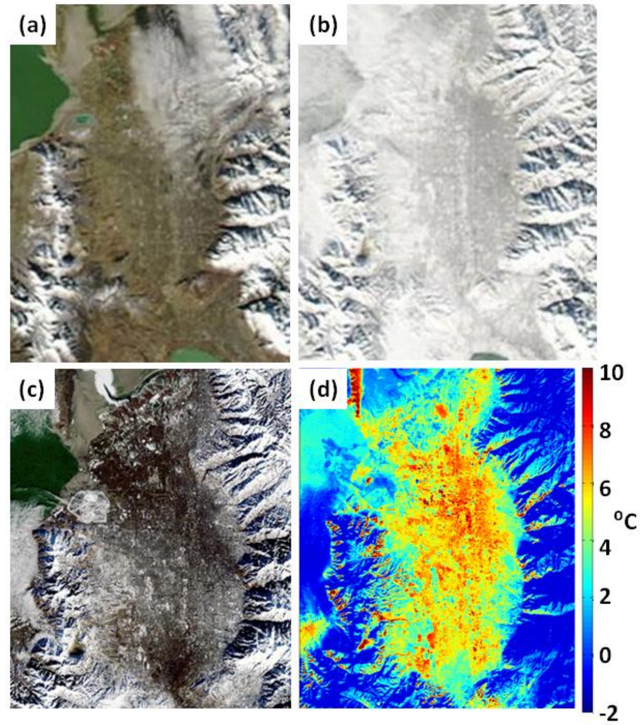

Fig. 1 a) Snow free period in the Salt Lake Valley (MODIS true color image 2040 UTC 12 Dec 2010), **b)** Snow-covered period (MODIS on 1900 UTC 6 January 2011), **c)** Partially snow covered over higher elevations in the Valley (Landsat 5 TM True color 1758 UTC 27 Jan 2011 from bands 1-4 at ~30 m resolution), **d)** Skin temperature for the same time as (c) **(**Landsat 5 TM skin temperature (^{0}C) derived from band 6 (10.4-12.5 µm) at ~120 m resolution).

For example, Figure 1 illustrates with MODIS and Landsat imagery the variations in surface state that are common along the Wasatch Front during winter—i.e., snow free (Fig. 1a), snow covered (Fig. 1b), or partial snow cover (Fig. 1c). In addition, the time-height sections of potential temperature at a location near the center of the Salt Lake Valley from a Large-Eddy Simulation (200 m horizontal resolution with 72 vertical levels) are compared in Fig. 2 to the observed potential temperature profiles during the period of diminishing snow cover (Fig. 1c). While the simulation misses some details related to the depth of the cold-air pool beneath the stable layer, our experience and that of other researchers suggests simulations at 1 km or less are necessary to simulate more accurately these episodes of winter poor air quality.

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