Advancing Analysis, Forecast and Warning Decision Support Capabilities for High Impact Weather Events

Project Areas Being Addressed:

(1) Warn on Forecast for High Impact Events
(2) Integrated Observing and Analysis System

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<u>Introduction</u>

This is the final project report for NOAA Award NA13NWS4680003. Specific goals for this project were: (1) to advance short-to-medium range precipitation forecasts over the western U.S. with an emphasis on high-impact events associated with the inland penetration of atmospheric rivers (ARs) and (2) to improve integrated observing and analysis systems nationwide by evaluating the sensitivity to boundary layer data assets during high-impact weather events. We have made significant progress in these areas and others, have summarized below.

1. Advance western US precipitation forecasts with emphais on inland-penetrating ARs

Atmospheric rivers (ARs) are frequent contributors to hazardous weather over the western United States. We completed a series of studies that quantify the climatological characteristics of ARs and their influence on precipitation, including the largest (i.e., top decile) precipitation events from the Pacific coast to the western interior (Rutz and Steenburgh 2012; Rutz et al. 2014, 2015). Results have been diseminated broadely across the National Weather Service (NWS) through webinars, seminars, and e-mail correspondence with the Weather Prediction Center (WPC), Western Region SOOs, and the Salt Lake City NWS Forecast Office (NWSFO).

Amongst the key findings are the imporatance of using integrated vapor transport (IVT) rather than integrated water vapor (IWV) for tracing ARs inland, the identification of important pathways for AR penetration into the interior, and advances in our understanding of AR maintenance and decay processes over mountainous terrain. The importance of this work is highlighted by the 88 citations that Rutz et al. (2014) has received in only 3 years, including many additional studies that utilize the techniques we developed to improve AR identification. Jon Rutz, who led this work as a graduate student at the University of Utah, is now a meteorologist with the NWS Western Region Science and Technology Infusion Division (WR-STID), and has spearheaded efforts to improve the diagnosis and prediction of major AR events over the western U.S.

For example, working with Jon and Trevor Alcott (now at the NOAA Earth Systems Research Laboratory), we integrated IVT diagnostics into the Western Region Ensemble Situational Awareness Table (http://ssd.wrh.noaa.gov/satable/) and NAEFS Ensemble Graphics (http://ssd.wrh.noaa.gov/naefs/) web pages (access may be limited to NWS sites) that are widely used by NWS forecasters for identifying potential AR impacts on the western U.S. Such products were used, for example, to anticipate and evaluate forecast confidence during two major AR events in Utah and Colorado in late January and early February 2014. The first event produced 3-4 feet of snow in the central Colorado Rockies, whereas the second event produced more than 6-inches of water-loaded snow in northern Utah mountains resulting in extreme avalanche hazard that forced an extended closure of Utah SR-89 (Logan Canyon) and Utah SR-92 (American Fork Canyon).

During the project periods, it was clear that there was a pressing need for improved knowledge of the capabilities and limitations of quantitative precipitation forecasts produced by numerical forecast systems over the western U.S., including ensembles and post-processed guidance. Model validation is particularly difficult over the western U.S. due to the low density of operational precipitation observations and the large spatial variability in precipitation.

To address this issue, we have developed techniques to use observations from upper-elevation SNOTEL stations maintained by the Natural Resources Conservation Service to validate forecasts produced by National Centers for Environmental Prediction (NCEP) and other modeling systems. This was a collaboration with WR-STID meteorologists Jon Rutz and Trevor Alcott involving University of Utah graduate students Wyndam Lews and Tom Gowan.

We began with an evaluation of the fidelity of cool-season Global Ensemble Forecast System (GEFS) precipitaton forecasts over a three year period using both reforecasts and forecasts of the current operational version of the GEFS to ensure forecast rlevance. We also examined the fidelity of statistically downscaled GEFS forecasts derived using the high-resolution (800-m) PRISM precipitation climatology and methods similar to those employed in operations by the WPC and many NWSFOs. This work shoed that the GEFS exhbits a widespread dry bias with a large underprediction of events > 22.9 mm in the Pacific Ranges (i.e., the Cascade Mountains, Sierra Nevada, and Coastal Ranges) and > 10.2 mm over ranges in the western interior. Performance metrics like the hit rate and equitable threat score degrade from the coast to the interior. Ensemble validation shows that the GEFS is strongly underdispersive (i.e., overconfident), especially at shorter forecast lead times, and by Day 5 the ensemble spread captures only 30% of upper-quartile precipitation events. Downscaling significantly improves model biases, equitatable threat scores, and hit rates, with a modest increase in false alarms. Results based on this work, summarized in Lewis et al. (2017) were presented to NWSFO-Salt Lake City SOO Darren Van Cleave in February 2016, to NCEP and WPC by webinar in April 2016, and to western region SOOs by webinar in November 2016.

During the past year, we have been conducting an extensive validation of cool-season quantitative precipitation forecasts produced by several NCEP operational modeling systems, including the HRRR, 3-km NAM, GFS and SREF, as well as a cloud-permitting ensemble run by the National Center for Atmospheric Research (hereafter the NCAR ensemble). This is likely the most compreshensive evaluation ever conducted of precipitation forecasts produced by operational ensembles and cloud-permitting modeling systems over the western U.S. Work began with the support of NOAA Award NA13NWS4680003 and continues under NA17NWS4680001. This research clearly shows that higher-resolution models, such as the HRRR, 3-km NAM, and NCAR ensemble members, are more skillful than coarser models, especially over the interior ranges of the western U.S. Comparisons between the SREF and NCAR ensemble highlight some of the issues with both ensemble systems, the former presenting challenges for interpretation due to the unequal likelihood of forecasts produced by the members of each dynamical core, and the latter from insufficient spread, and the advantages of a cloud-permitting ensemble over the complex terrain of the western U.S. Preliminary results were shared with WR SOOs and NCEP last winter (during the WPC Winter Weather Experiment) and a paper based on this work will be submitted to *Weather and Forecasting* in the near future (Gowan et al. 2017).

2. Improve integrated observing and analysis systems

We have continued to work with NWS field offices and MADIS staff to improve access to mesonet observations around the nation. This work has also been supported by the NWS National Mesonet Program. We answer questions, identify new data resources, and improve software to minimize the latency between when observations are taken and when they are available to field offices.

A discussion started during December 2014 with NWS Western Region staff about new database procedures that we have implemented to streamline the storage and access to observations received continuously as well as those in the ~20 year MesoWest archive. The continued development of those application programming interface (api) services (synopticlabs.org) for data delivery are now used extensively by the NWS Western Region and other NWS entities (see Table 1). The usage of the api services within the NWS has continued to grow during the past 6 months as developers at the national, regional, and WFO levels become aware of the ease to obtain environmental observations from over 40,000 locations nationwide. Overall, NOAA applications have made 23 million requests for 117 billion data values during a recent one-month period.

Table 1. Usage of the MesoWest api (synopticlabs.org) by NOAA from 17 August – 16 September 2017

Organization	Requests	Data values
Total NOAA Usage	23.2 million	117.5 billion
NWS Western Region	13.9 million	90.3 billion

NWS Enhanced Data Display software	4.2 million	25 billion
NWS Central and Southern Region	1.5 million	31 million

Extensive work has been underway to implement quality control procedures providing access to MADIS QC flags as well as ones we have developed. A sidebar meeting with MADIS staff was held at the 2017 AMS Annual meeting with a follow up meeting in Boulder in May to discuss metadata, quality control, and other related issues. We are implementing the UU2DVAR system (Tyndall and Horel 2013) primarily as a quality control tool for publicly-accessible surface observations. The analysis system uses the 2.5 km resolution background fields used by the RTMA and ~15000 observations available each hour from many different mesonets are then used to modify the background grids and obtain hourly analyses.

Increasing attention is being placed on improving access to observations from surface-based remote sensors (sodars, ceilometers, radiometers, profilers, etc.). Observations have been sent to MADIS for use in data assimilation and other applications. Access to graphics is available online at http://asn.synopticdata.com. Leclair-Marzolf et al. (2018) describe procedures in place to use ceilometers to monitor boundary layer heights.

A necessary step to integrate existing and future networks into a national network of networks is to assess the impact of existing mesonets. The adjoint of the two-dimensional variational analysis system developed at the University of Utah of surface weather parameters has been used to assess objectively the sensitivity of the resulting CONUS-scale analyses to the source of the observations used in the analyses. The sensitivity of the differences in weather parameters between the resulting analyses and the background fields are examined as a function of the various data assets: NWS; RAWS; Air quality; Agriculture and hydro; Transportation; Local, state and regional networks (e.g., West Texas Mesonet or Oklahoma Mesonet); Buoys and coastal observations; Public (typically weather hobbyists); and other federal and commercial networks. Statistics for individual stations as well as for entire networks are obtained that help to identify network characteristics that strongly influence analyses.

As an illustration of the utility of MesoWest activities to the National Weather Service, severe thunderstorm reports were facilitated by the dense observing network in northern Utah that we have fostered on 22 September, 2016. Nearly all of the reports cited in the Storm Reports for that day involved University of Utah sensors or ones we send to MADIS.

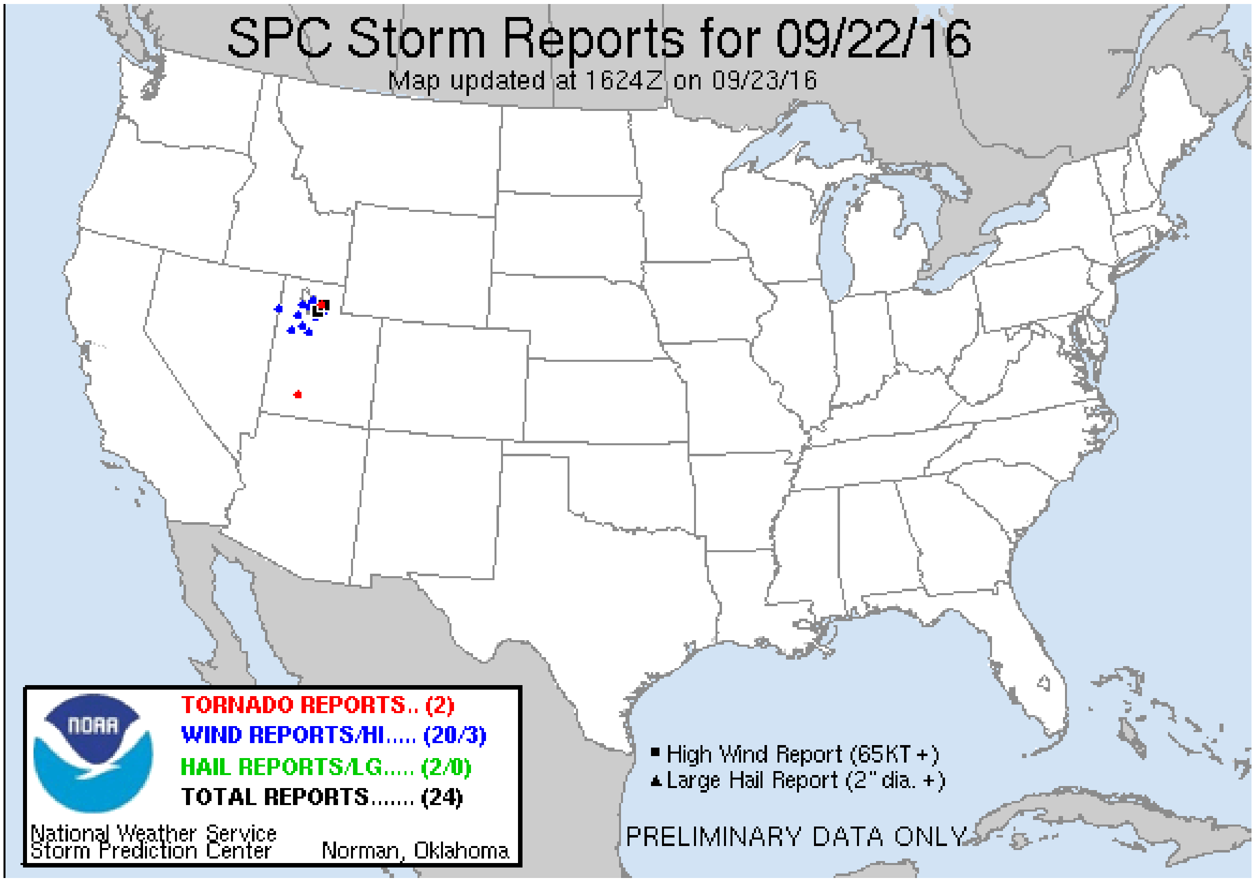
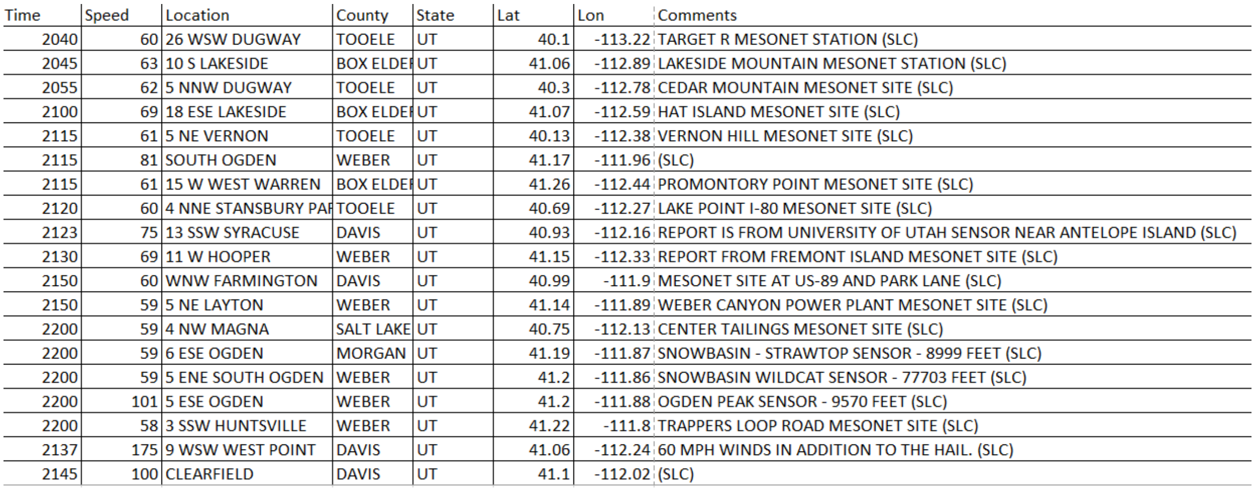

SPC Storm Reports for 09/22/16
Map updated at 1624Z on 09/23/16
TORNADO REPORTS.. (2)
WIND REPORTS/HI..... (20/3)
HAIL REPORTS/LG..... (2/0)
TOTAL REPORTS....... (24)
NOAA
National Weather Service
Storm Prediction Center
Norman, Oklahoma
■ High Wind Report (65KT +)
▲ Large Hail Report (2" dia. +)
PRELIMINARY DATA ONLY

Figure 4. Severe thunderstorm warnings on 22 September 2016 were facilitated by utomated high wind reports available via MesoWest.



Time	Speed	Location	County	State	Lat	Lon	Comments
2040	60	26 WSW DUGWAY	TOOELE	UT	40.1	-113.22	TARGET R MESONET STATION (SLC)
2045	63	10 S LAKESIDE	BOX ELDEI	UT	41.06	-112.89	LAKESIDE MOUNTAIN MESONET STATION (SLC)
2055	62	5 NNW DUGWAY	TOOELE	UT	40.3	-112.78	CEDAR MOUNTAIN MESONET SITE (SLC)
2100	69	18 ESE LAKESIDE	BOX ELDEI	UT	41.07	-112.59	HAT ISLAND MESONET SITE (SLC)
2115	61	5 NE VERNON	TOOELE	UT	40.13	-112.38	VERNON HILL MESONET SITE (SLC)
2115	81	SOUTH OGDEN	WEBER	UT	41.17	-111.96	(SLC)
2115	61	15 W WEST WARREN	BOX ELDEI	UT	41.26	-112.44	PROMONTORY POINT MESONET SITE (SLC)
2120	60	4 NNE STANSBURY PAI	TOOELE	UT	40.69	-112.27	LAKE POINT I-80 MESONET SITE (SLC)
2123	75	13 SSW SYRACUSE	DAVIS	UT	40.93	-112.16	REPORT IS FROM UNIVERSITY OF UTAH SENSOR NEAR ANTELOPE ISLAND (SLC)
2130	69	11 W HOOPER	WEBER	UT	41.15	-112.33	REPORT FROM FREMONT ISLAND MESONET SITE (SLC)
2150	60	WNW FARMINGTON	DAVIS	UT	40.99	-111.9	MESONET SITE AT US-89 AND PARK LANE (SLC)
2150	59	5 NE LAYTON	WEBER	UT	41.14	-111.89	WEBER CANYON POWER PLANT MESONET SITE (SLC)
2200	59	4 NW MAGNA	SALT LAKE	UT	40.75	-112.13	CENTER TAILINGS MESONET SITE (SLC)
2200	59	6 ESE OGDEN	MORGAN	UT	41.19	-111.87	SNOWBASIN - STRAWTOP SENSOR - 8999 FEET (SLC)
2200	59	5 ENE SOUTH OGDEN	WEBER	UT	41.2	-111.86	SNOWBASIN WILDCAT SENSOR - 77703 FEET (SLC)
2200	101	5 ESE OGDEN	WEBER	UT	41.2	-111.88	OGDEN PEAK SENSOR - 9570 FEET (SLC)
2200	58	3 SSW HUNTSVILLE	WEBER	UT	41.22	-111.8	TRAPPERS LOOP ROAD MESONET SITE (SLC)
2137	175	9 WSW WEST POINT	DAVIS	UT	41.06	-112.24	60 MPH WINDS IN ADDITION TO THE HAIL. (SLC)
2145	100	CLEARFIELD	DAVIS	UT	41.1	-112.02	(SLC)

3. Additional activities

With support from the National Science Foundation, we conducted an extensive observational and numerical modeling study of lake-effect storms east of Lake Ontario, including enhancement over Tug Hill Plateau (Veals and Steenburgh 2015; Minder et al. 2015; Campbell et al. 2016; Welsh et al. 2016; Kristovich et al. 2017; Campbel and Steenburgh 2017; Steenburgh and Campbel 2017). In particular, we show that previous conceptual models emphasizing the lifting of the caping inversion and invigoration of convection as the causes of enhancement over

Tug Hill are innacurate. Instead, a convective-to-stratiform transition occurs, with radar echoes shallowing, but precipitation becoming more persistent We also idenify a strong dependence of enhancement over the Tug Hill Plateau on lake-effect mode, with enhancement strongest during non-banded lake-effect periods and smallest during banded periods. Finally, we show that the shoreline of Lake Ontario, especially bulges in the south and north shoreline, play a major role in the initiation of lake-effect, as well as enhancement over the Tug Hill Plateau. Much of this work has strong operational forecasting implications. We have shared results on several occaisions with the Buffalo NWSFO.

We have also validated simulations of Great Salt Lake-effect snowstorms and have shown that there is great sensitivity to the microphysics parameterization, with the relative generation of snow vs. graupel strongly influencing the amount and distribution of precipitation (McMillen and Steenburgh 2015a). We have also analyzed reforecasts of 11 banded and 8 non-banded Great Salt Lake-effect precipitation events and have shown that (1) the Weather Research and Forecast model (WRF) typically generates banded precipitation features even when non-banded features are often observed, (2) WRF lake-effect precipitation is typically displaced to the right (relative to the flow) and downstream compared to observed, and (3) WRF forecast accuracy for lake-effect precipitation is comparable to that of warm-season convection (McMillen and Steenburgh 2015b). These results paint a somewhat sobering perspenctive on our ability to forecast the Great Salt Lake effect and results have been shared with the Salt Lake City NWSFO.

Two papers evaluating the 1 December 2011 downslope windstorm along the Wasatch Front have been published (Lawson and Horel 2015a,b). This event was well forecast by the SLC

NWSFO and one aspect of this study was to examine why the predictability horizon for this mesoscale event was much longer than usual.

Support from the Joint Fire Science Program allowed for the development of verification of spot forecasts for prescribed and wild fires. Lammers and Horel (2014) describe this system available online at http://meso1.chpc.utah.edu/jfsp/. Matt Lammers presented a Western Region SOO/DOH webinar on this project. Staff from the NWS Performance Branch visited the University of Utah in June 2015 to discuss how to transition this research and software to operations. Nauslar et al. (2016) extended this work to examine the accuracy of spot forecasts of boundary layer height and other above-the-surface parameters critical for fire weather professionals.

Graduate student Alex Jacques studied mesoscale pressure perturbations originating from a variety of atmospheric processes (e.g., convective systems, gravity waves, frontal passages, etc.) with collaborative support from the NSF (Jacques et al. 2015, 2016, 2017). He used the UU2DVAR variational approach to combine numerical grids of surface pressure (at high spatial resolution) with observations (at high temporal resolution) to produce analysis grids that can be temporally filtered to isolate mesoscale perturbation features in space and time. The surface pressure observations utilized arise from a unique field campaign focused on seismic research. Background grids are generated from the first guess and analysis surface pressure grids of the hourly Real Time Mesoscale Analysis (RTMA) to produce analysis grids at five-minute intervals. Analysis grids are filtered to identify prominent perturbation features over the central U.S. region.

The experimental High-Resolution Rapid Refresh – Alaska (HRRR-AK) modeling system developed to provide high spatial (3 km horizontal) and temporal (hourly out to 36 h) forecast guidance for weather conditions over Alaska has been evaluated (McCorkle 2017, McCorkle et al. 2018). The model's ability to forecast the evolution, intensity and timing of weather systems was assessed on the basis of surface pressure observations assimilated during its production cycle (e.g., from NWS stations) and those not assimilated (from USArray Transportable Array, TA, stations). Observations from both the NWS and TA networks were used to evaluate 265 complete 0-36 h forecasts of altimeter setting initialized at 00 or 12 UTC. Throughout the seven-month study period (December 2016-June 2017), systematic differences in altimeter setting between the HRRR-AK analyses and the assimilated NWS (unassimilated TA) observations were small (large). Upon removal of these initial biases from each of the subsequent 1-36 h altimeter setting forecasts at the observation locations, model errors at the NWS and TA locations were comparable, which suggests limited sensitivity locally to the assimilation of the pressure data. When aggregated over the entire state, forecast errors were highest during the 12-15 February period associated with a complex synoptic environment that led to downslope windstorms in the lee of the Alaska Range.

Co-PI Horel co-chaired the AMS Forum on Observing the Environment from the Ground Up held March 8-9 in Washington D.C.. The Forum with over 100 attendees from the government, commercial, and academic sectors of the atmospheric science community built on efforts over the past decade to develop an integrated, multi-purpose observing system focused on the conditions from the surface through the atmospheric boundary layer. The objective of the Forum was to discuss innovative observing efforts underway nationwide, prospects for taking advantage of new technologies, improving coordination among the diverse efforts throughout the environmental observing enterprise, and meeting the multiple and ever growing needs of the users of environmental information. Participants evaluated the Forum as being very useful. Follow on presentations about the Forum were made at the 2017 AMS Annual Meeting by Curtis Marshall in the Observation Symposium and by a panel including J. Horel as part of the Fifth Symposium on the Weather, Water, and Climate Enterprise

4. Publications, Presentations, NWS-related training activities, or Publications Relying Extensively on MesoWest Resources

Abernathy, A., C. Galli, A. Dugan, R. Vowles, and J. Horel, 2017: Monitoring the Health of Surface-Based Observational Networks. 33rd Conference on Environmental Information Processing Technologies. Seattle Wa. Poster Presentation.

Alcott, T. I., 2014: Evaluating mountain precipitaiton forecasts from operational models. Poster presentation, 16th Conference on Mountain Meteorology, American Meteorological Society, San Diego, CA.

Bergmaier, P. T., B. Geerts, L. S. Campbell, and W. J. Steenburgh, 2017: The OWLeS IOP2b lake-effect snowstorm: Dynamics of the secondary circulation. *Mon. Wea. Rev.*, **145**, 2437–2459.

Bergmaier, P. T., B. Geerts, W. J. Steenburgh, and L. Campbell, 2017: Understanding heavy lake-effect snow: On secondary circulations within LLAP bands over Lake Ontario. Oral presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

Blaylock, B., J. Horel, E. Crosman, 2016: Impact of Lake Breezes on Summer Ozone Concentrations in the Salt Lake Valley. *J. Appl. Meteor. Clim.*, **56**, 353–370.

Campbell, L. S., and W. J. Steenburgh, 2017: The OWLeS IOP2b lake-effect snowstorm: Mechanisms contributing to the Tug Hill Precipitation Maximum. *Mon. Wea. Rev*. **145**, 2461–2478.

Campbell, L. S., W. J. Steenburgh, P. G. Veals, T. W. Letcher, and J. R. Minder, 2016: Lake-effect mode and precipitation enhancement over the Tug Hill Plateau during OWLeS IOP2b. *Mon. Wea. Rev.*, **144**, 1729-1748.

Campbell, L., W. J. Steenburgh, P. G. Veals, T. W. Letcher, and J. R. Minder, 2017: Lake-effect mode and precipitation enhancement over the Tug Hill Plateau during OWLeS IOP2b. Poster presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

Crosman, E., and J. Horel 2016: Winter lake breezes near the Great Salt Lake. *Boundary Layer Meteorology.* 1-26. doi:10.1007/s10546-015-0117-6

Crosman, E., A. Jacques, J. Horel, 2017: A Novel Approach for Monitoring Vertical Profiles of Boundary-Layer Pollutants: Utilizing Routine News Helicopter Flights. *Atmospheric Pollution Research.* http://dx.doi.org/10.1016/j.apr.2017.01.013

Foster, C., E. Crosman, J. Horel, 2016: Simulations of a cold-air pool in Utah's Salt Lake Valley: Sensitivity to land use and snow cover. *Boundary-Layer Meteorol.*, doi:10.1007/s10546-017-0240-7.

Gowan, T, 2016: Validation of QPF from the NCAR Ensemble (3-km) and high-resolution NWP over the western U.S. *Webinar for NWS Western Region SOOs*, 16 Nov 2016.

Gowan, T., 2017: Performance of precipitation forecasts from a convection-permitting ensemble relative to operational guidance over the western United States. Seminar and NWS Webinar, National Centers for Environmental Prediction, 8 Feb 2016.

Gowan, T. M., and W. J. Steenburgh, 2016: Validation and intercomparison of quantititative precipitation forecasts from the NCAR high-resolution (3-km) ensemble and NCEP operational models over the western US. *17th Conference on Mountain Meteorology*. Burlington, VT.

Gowan, T. M., and W. J. Steenburgh, 2017: Overview of the NCAR high-resolution (3-km) ensemble and validation of its quantitative precipitation forecasts over complex terrain in the western U.S. Poster presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

Gowan, T. M., and W. J. Steenburgh 2017: Validation and intercomparison of quantitative precipitation forecasts from the NCAR high-resolution (3-km) ensemble and NCEP and ESRL operational models over the western U.S. Poster presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

Gowan, T. M., W. J. Steenburgh, and C. S. Schwartz, 2017: Validation of mountain precipitation forecasts from the NCAR convection-permitting ensemble and operational forecast systems over the western United States. In preparation for submittal to *Wea. Forecasting*.

Horel, J., "Terrain-Flow Interactions that Affect Winter Air Pollution in Urban and Rural Basins" AMS Mountain Meteorology webinar. Jan 15 2014 (>15 NWS forecasters on the call).

Horel, J., R. Ziel, C. Galli, J. Pechmann, X. Dong, 2014: An evaluation of fire danger and behavior indices in the Great Lakes region calculated from station and gridded weather information. *International Journal of Wildland Fire*. 23, 202–214. http://10.1071/WF12186

Horel, J., E. Crosman, A. Jacques, B. Blaylock, S. Arens, A. Long, J. Sohl, R. Martin, 2016: Influence of the Great Salt Lake on summer air quality over nearby urban areas. *Atmospheric Science Letters*. 17, 480-486. doi: 10.1002/asl.680

Horel, J., 2017: Surface Observations: How Do We Best Utilize the Flood of Observations From Fixed, Mobile, and Internet of Thing Platforms? 2017 AMS Observation Symposium. Seattle Wa. (Invited Presentation)

Jacques, A., J. Horel, 2014: Pressure Signatures of Extreme Weather Events Deduced from Earthscope's USArray. *26th Conference on Weather Analysis and Forecasting / 22nd Conference on Numerical Weather Prediction*. Atlanta GA.

Jacques, A., J. Horel, 2014: Utilizing Earthscope's USArray Network to Examine Pressure Variations near the Appalachian Mountains. *16th Conference on Mountain Meteorology, American Meteorological Society,* San Diego, CA.

Jacques, A., J. Horel, E. Crosman, F. Vernon, 2015: Central and Eastern United States surface pressure variations derived from the USArray network. *Mon. Wea. Rev.* 143, 1472-1493. doi:http://dx.doi.org/10.1175/MWR-D-14-00274.1

Jacques, A., J. Horel and E. Crosman, 2015: Spatial Assessments of Mesoscale Pressure Perturbations using Gridded Analyses and Observations from Earthscope's USArray Network. *16th Conference on Mesoscale Processes*. Boston, MA.

Jacques, A., J. Horel, E. Crosman, F. Vernon, J. Tytell, 2016: The Earthscope US Transportable Array 1 Hz Surface Pressure Dataset. *Geoscience Data Journal*, 3: 29–36. doi: 10.1002/gdj3.37

Jacques, A., J. D. Horel and E. T. Crosman, 2017: Detection of Mesoscale Pressure Perturbations with Five Minute Gridded Analyses. *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Seattle WA. 3rd Place Student Oral Presentation.

Jacques, A., J. D. Horel, E. T. Crosman, F. L. Vernon, 2017: Tracking Mesoscale Pressure Perturbations Using the USArray Transportable Array. *Mon. Wea. Rev.,* **145**, 3119-3142. http://journals.ametsoc.org/doi/pdf/10.1175/MWR-D-16-0450.1

Kristovich, D. A. R., R. D. Clark, J. Frame, B. Geerts, K. R. Knupp, K. A. Kosiba, N. F. Laird, N. D. Metz, J. Minder, T. D. Sikora, W. J. Steenburgh, S. M. Steiger, J. Wurman, and G. S. Young, 2016: The Ontario Winter Lake-effect Systems (OWLeS) Field Campaign: Scientific and educational adventures to further our knowledge and prediction of lake-effect storms. *Bull. Amer. Meteor. Soc*., **98**, 315–332.

Lammers, M., and J. Horel, 2014: Verification of National Weather Service spot forecasts using surface observations. *J. Operational Meteor,* **2**, 246–264.

Lawson, J. and J. Horel, 2014: Analysis and Predictability of the Wasatch Windstorm of 1 December 201. *26th Conference on Weather Analysis and Forecasting / 22nd Conference on Numerical Weather Prediction*. Atlanta GA.

Lawson, J., and J. Horel, 2014: Predictability and error growth in medium-range forecasts of the 1 December 2011 Wasatch Windstorm. *16th Conference on Mountain Meteorology, American Meteorological Society, San Diego, CA.*

Lawson, J., and J. Horel 2015: Analysis of the 1 December 2011 Wasatch downslope windstorm. *Wea. Forecasting,* **30**, 115-135. doi: http://dx.doi.org/10.1175/WAF-D-13-00120.1

Lawson, J., and J. Horel 2015: Ensemble forecast uncertainty of the 1 December 2011 Wasatch downslope windstorm. Wea. Forecasting, 30, 1749-1761. doi: http://dx.doi.org/10.1175/WAF-D-15-0034.1

Lazarus, S., M. Splitt, J. Horel, X. Dong, 2014: Impact of the Local Roughness on 2DVAR Wind Analyses During Hurricane Sandy. *18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS).* Atlanta GA.

Leclair-Marzolf, L., J. S. Young and J. Horel, 2017: Urban and Rural Boundary Layer Characteristics Assessed From Ceilometer Observations. *13th Symposium of the Urban Environment.* Seattle WA. Poster presentation.

Leclair-Marzolf, L., J. D. Horel, J. S. Young, 2018: Retrospective and ongoing analyses of aerosol layers using laser ceilometers. Submitted to *Journal of Atmospheric and Oceanic Technology*.

Lewis, W. R. and W. J. Steenburgh, 2016: Verification of GEFS precipitation forecasts and the implications of statistical downscaling over the western United States. *17th Conference on Mountain Meteorology*. Burlington, VT.

Lewis, W. R., W. J. Steenburgh, T. I. Alcott, and J. J. Rutz, 2017: GEFS precipitation forecasts and the implications of statistical downscaling over the western United States. *Wea. Forecasting*, **32**, 1007–1028.

Lewis, W. R., and W. J. Steenburgh, 2017: GEFS precipitation forecasts and the implications of statistical downscaling over the western United States. Oral presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

McCorkle, T., 2017: *An Evaluation of the Experimental High Resolution Rapid-Refresh Modeling System.* M.S. thesis. University of Utah. 75 pp.

McCorkle, T., J. Horel, A. Jacques, T. Alcott, 2018: An evaluation of the experimental High Resolution Rapid-Refresh Modeling System. Submitted to *Wea. Forecasting*.

Minder, J. R., T. Letcher, J. Steenburgh, P. G. Veals, and L. Campbell, 2014: Modification of long-axis lake-effect snow bands associated with landfall and orographic uplift: Results from a profiling radar network deployed during OWLeS. *16th Conference on Mountain Meteorology*. San Diego, CA.

Minder, J. R., T. Letcher, L. S. Campbell, P. G. Veals, and W. J. Steenburgh, 2015: The evolution of lake-effect convection during landfall and orogrpahic uplift as observed by profiling radars. *Mon. Wea. Rev*., **143**, 4422-4442.

McMillen, J. D., and W. J. Steenburgh, 2015a: Impact of microphysics parameterization on simulations of the 27 October 2010 Great Salt Lake Effect snowstorm. *Wea. Forecasting*, **30**, 136–152.

McMillen, J. D., and W. J. Steenburgh, 2015b: Capabilities and limitations of convection-permitting WRF simulations of lake-effect systems over the Great Salt Lake. *Wea. Forecasting*, in review.

Nauslar, N. J., T. J. Brown, and J. D. Horel, 2016: Verification of National Weather Service spot forecasts using atmospheric sounding observations. J. Operational Meteor., 4 (4), 46-57, doi: http://dx.doi.org/10.15191/nwajom.2016.0404.

Neemann, E., E. Crosman, J. Horel, L. Avey, 2015: Simulations of a cold-air pool associated with elevated wintertime ozone in the Uintah Basin, Utah. *Atmos. Chem. Phys*., 15, 135-151, 2015. doi:10.5194/acp-15-135-2015 154, 2, 291-316.

Rutz, J. J., 2013: Atmospheric rivers over the western United States: Climatological characteristics and factors influencing inland penetration. Webinar for NWS CSTAR Focal Points, 20 Nov 2013.

Rutz, J. J., 2013: NWS-WR science update: Part 1 – Update on atmospheric river research. Webinar for NWS-WR SOOs, 26 Nov 2013.

Rutz, J. J., 2014: The climatological characteristics and inland penetration of atmospheric rivers over the western united States. Ph. D. Dissertation, University of Utah, 107 pp.

Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western U.S. *Mon. Wea. Rev.*, **142**, 905–921.

Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2014: A Lagrangian analysis of the inland penetration of atmospheric rivers over western North America. Oral presentation, 16th Conference on Mountain Meteorology, American Meteorological Society, San Diego, CA.

Rutz, J. J., and T. I. Alcott, 2014: Quantifying the skill of the Global Ensemble Forecasting System in predicting observed precipitation based on 20 years of reforecast data. Poster presentation, 16th Conference on Mountain Meteorology, American Meteorological Society, San Diego, CA.

Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2015: The inland penetration of atmospheric rivers over western North America: A Lagrangian Analysis. *Mon. Wea. Rev*., **143**, 1924–1944.

Splitt, M. S. Lazarus, J. Horel, X. Dong, 2014: Surface Roughness and 2DVAR Wind Field Innovations in High Wind Events. *18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS).* Atlanta GA.

Steenburgh, W. J., 2014: The OWLeS Orographic (O2) Field Campaign: Adventures in intense snowstorms on the Tug Hill Plateau. *16th Conference on Mountain Meteorology*. San Diego, CA.

Steenburgh, W. J., 2017: Lance Bosart, Mountain Meteorologist: Contributions to our understanding of the influence of complex terrain on weather and climate. Oral presentation, *Lance Bosart Symposium*, Amer. Meteor. Soc., Seattle, WA.

Steenburgh, J., W. Lewis, T. Alcott, and J. Rutz, 2016: GEFS Precipitation Forecasts and the Implications of Statistical Downscaling. *Webinar for NWS Western Region SOOs*, 16 Nov 2016.

Steenburgh, W. J., and L. S. Campbell, 2017: The OWLeS IOP2b lake-effect snowstorm: Shoreline geometry, airmass boundaries, and the mesoscale forcing of precipitation. *Mon. Wea. Rev*., **145**, 2421–2436.

Steenburgh, W. J., and L. Campbell, 2017: Mesoscale forcing of lake-effect precipitation over Lake Ontario during OWLeS IOP2b. Poster presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

Steenburgh, W. J., and J. McMillen, 2015: Capabilities and limitations of convection-permitting WRF simulations of lake-effect systems over the Great Salt Lake. Poster presentation, *16th Conference on Mesoscale Processes*, American Meteorological Society, Boston, MA.

Steenburgh, W. J., and J. J. Rutz, 2015: Climatological characteristics and inland penetration of atmospheric rivers over the western United States. Poster presentation, *16th Conference on Mesoscale Processes*, American Meteorological Society, Boston, MA.

Steenburgh, W. J., and J. Rutz, 2015: Climatological characteristics and inland penetration of atmospheric rivers over the western United States. Poster presenation, *33rd International Conference on Alpine Meteorology*, Innsbruck, Austria.

Steenburgh, W. J., L. Campbell, P. G. Veals, T. Letcher, and J. R. Minder, 2016: Lake-effect mode and precipitation enhancement over the Tug Hill Plateau during OWLeS IOP2b. *17th Conference on Mountain Meteorology*. Burlington, VT.

Steenburgh, W. J., L. Campbell, J. R. Minder, T. Letcher, P. G. Veals, D. Welsh, B. Geerts, P. T. Bergmaier, and X. Jing, 2016: The enhancement of lake-effect precipitation over the Tug Hill Plateau during the Ontario Winter Lake-effect Systems (OWLeS) Field Program. *17th Conference on Mountain Meteorology*. Burlington, VT.

Steenburgh, W. J., L. Campbell, P. G. Veals, J. R. Minder, T. W. Letcher, B. Geerts, D. Welsh, and P. T. Bergmaier, 2017: The enhancement of lake-effect precipitation over the Tug Hill Plateau during the Ontario Winter Lake-effect Systems (OWLeS) Field Program. Oral presentation by L. Campbell, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*, Amer. Meteor. Soc., Seattle, WA.

Veals, P. G., and W. J. Steenburgh, 2014: Climatological characteristics of lake-effect storms over eastern Lake Ontario and orographic enhancement by the Tug Hill Plateau. Oral presentation, 16th Conference on Mountain Meteorology, American Meteorological Society, San Diego, CA.

Veals, P. G., and W. J. Steenburgh, 2015: Climatological characteristics and orographic enhancement of lake-effect precipitation east of Lake Ontario and over the Tug Hill Plateau. *Mon. Wea. Rev.*, **143**, 3591–3609.

Veals, P. G., W. J. Steenburgh, and L. Campbell, 2016: Environmental control of the inland and orographic enhancement of lake-effect precipitation over the Tug Hill Plateau. *17th Conference on Mountain Meteorology*. Burlington, VT.

Veals, P. G., W. J. Steenburgh, and L. Campbell, 2017: Precipitation enhancement during lake-effect storms over the Tug Hill Plateau: Climatological and field program perspectives. Oral presentation, *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction*. Amer. Meteor. Soc., Seattle, WA.

Welsh, D., B. Geerts, X. Jing, P. T. Bergmaier, J. R. Minder, W. J. Steenburgh, and L. S. Campbell, 2016: Understanding heavy lake-effect snowfall: The vertical structure of radar reflectivity in a deep snowband over and downwind of Lake Ontario. *Mon. Wea.Rev.,* **144**, 4221–4244.