PROJECT DESCRIPTION

1. RESULTS FROM PRIOR NSF SUPPORT

1.1 Previous award

Award # AGS-0837870, $616,846, 1 Jan 2009 - 31 Dec 2011, “Collaborative research: The diurnal evolution of stable boundary layers in an enclosed basin”. This award followed NSF award ATM-0444205 that funded the field program at Meteor Crater in 2006 and subsequent initial analyses and publications.

1.2 Summary of results from previous award

Peer-reviewed publications: Scientific accomplishments include 1) discovery of near-continuous shallow cold air intrusions over the crater's rim (Whiteman et al. 2010). These intrusions produce unusual temperature profile evolution, including the development and nighttime maintenance of a near-isothermal temperature structure in the upper 75% of the crater atmosphere, 2) development of a mass-flux model that successfully explains the unusual temperature structure (Haiden et al. 2011). Co-PI Dr. Sharon Zhong at Michigan State University has extended this work by making numerical simulations with the ARPS model (Kiefer and Zhong 2011), 3) discovery of downslope-windstorm-type flow (DWF) events that affect the upwind inner sidewall of the crater and produce warm air intrusions into the crater atmosphere (Adler et al. 2011), 4) determination (with ARO funding) of the role of longwave radiative flux divergence in nighttime atmosphere cooling in basins and valleys of different size, with a real-case simulation of Meteor Crater (Hoch et al. 2011), 5) determination of the physical processes leading to the evening transition between upslope and downslope flows on a Meteor Crater sidewall (Martinez et al. 2011), 6) assessment of the role of the Topographic Amplification Factor in basin cooling (Hahnenberger 2008; Hahnenberger et al. 2011), 7) study of the relationship between turbulence levels inside and outside the crater (Fu et al. 2010), 8) determination of the topographic effects on the surface radiation balance inside the crater (Hoch and Whiteman 2010), 9) assessment of regional scale drainage flows over the adjacent plain (Savage et al. 2008), and 10) determination of the causes and characteristics of thermally driven cross-basin flows (Lehner et al. 2011; Lehner and Whiteman 2011). Additionally, with a German colleague, we modified a Monte Carlo radiative transfer model to improve performance in simulating radiative transfer in mountainous terrain (Mayer et al. 2010). We produced an overview of Meteor Crater meteorology for a general audience (Whiteman et al. 2008b) and have written a research article with Austrian scientists on meteorological events that affect basin temperature structure (Dorninger et al. 2011). We co-wrote a book chapter on thermally driven flows that will be published soon (Zardi and Whiteman 2011).

Broader Impacts: We developed and maintained a METCRAX website for a general audience (www.inscc.utah.edu/~whiteman/METCRAX/), produced a poster displayed at the Meteor Crater Visitors Center during the METCRAX 2006 experiment explaining the scientific goals of METCRAX and activities inside the crater, and we have prepared approximately 33 conference and seminar presentations. Through collaboration with a planetary geologist, we contributed a conference paper suggesting meteorological mechanisms that may be important for geological processes in Martian craters (Whiteman et al. 2008a). The field experiment itself and the resulting laboratory research activities have trained approximately 15 students in field and laboratory research. Several students have used the METCRAX datasets in class projects. One master's degree was completed using Meteor Crater datasets (Hahnenberger 2008) and 2 others are underway. We advised one post-doc, one Ph.D. candidate, several M.S. candidates...
and 3 visiting research scientists using the METCRAX datasets. We collaborated extensively with foreign scientists, and have hosted several scientists for extended stays at UU (Drs. Meinolf Kossmann, Thomas Haiden, Bernhard Mayer, Norbert Kalthoff, and Matthias Hornsteiner, as well as Mr. Dani Martinez, Ms. Bianca Adler, and Ms. Meike Zwanzger). We have also worked with foreign scientists hosted by co-PI Dr. Sharon Zhong, including Drs. Wenquing Yao and P. Fu. New meteorological research equipment purchased in connection with METCRAX, including a mini-SoDAR, is now being used by other research projects at UU. The MYSTIC Monte Carlo radiative transfer model, with our modifications for complex terrain simulations, is available as part of the libRadtran software package described by Mayer and Kylling (2005). Prof. Whiteman has made occasional presentations to NCAR COMET training courses, has produced a COMET Computer Based Learning Module, and has taught short courses featuring METCRAX results at the University of Vienna, the University of Trento and the University of Zagreb.

1.3 Publications resulting from the NSF award.

Publications resulting from the two previous Meteor Crater awards are identified in the list of references by an asterisk.

1.4 Evidence of research products and their availability

METCRAX research findings are publicly available through journal publications and the project website. METCRAX data are available through the following NCAR and UU websites or by personal requests:
http://www.eol.ucar.edu/deployment/field-deployments/field-projects/metcrax
http://www.eol.ucar.edu/isf/projects/metcrax/iss/
http://www.inscc.uta.edu/~whiteman/METCRAX/

2. INTRODUCTION

A 4-yr research program is proposed to follow-up on a serendipitous discovery that we made recently in our ongoing NSF-funded research project, which will end on 31 December 2011. We seek additional funding to extend the research in a promising new direction. Our existing project is investigating the stable nighttime boundary layer that forms inside Arizona's Barringer Meteorite Crater (AKA Meteor Crater), a nearly ideal axisymmetric basin formed by the impact of a meteorite 49,000 years ago (Kring 2007). The bowl-shaped crater, 175 m deep and 1.2 km in diameter, is located on a plain that is tilted up slightly (1° angle) to the southwest toward Arizona's Mogollon Rim. The crater rim, unbroken by any major passes or saddles, extends 30-50 m above the surrounding plain (Fig. 1).

Figure 1. Meteor Crater, looking southwest.

During an Intensive Observing Period (IOP) conducted in the crater on a synoptically undisturbed night in October 2006, we experienced an unusual meteorological event on the
west sidewall of the crater. A short-lived high wind and turbulence event occurred there, while other sites within the crater were completely unaffected. The tethered balloon was subsequently moved somewhat downhill where these episodic events were no longer experienced. Our recent analyses have focused on determining the nature of these events using a full month of data. We have concluded that they are downslope-windstorm-type flows (DWFs) driven by large-scale katabatic winds. The design of the original field experiment did not anticipate these events and the meteorological instrumentation was not located ideally for observing them. The lightning-caused failure of an NCAR-supplied SoDAR that was located upstream of the crater exacerbated this situation. Nonetheless, we have been able, with available data, to identify these events as DWFs confined to the immediate lee of the upwind rim of the crater. Many such events occurred during the one-month observational period, suggesting that the crater is an ideal natural laboratory for studying this phenomenon, as the temporary and often short-lived instability leading to these discrete events is produced repeatedly on clear, synoptically undisturbed nights when a thermally driven, regional-scale, southwesterly drainage flow from the terrain southwest of the crater (Fig. 2) impinges on the crater rim. This drainage flow has a jet maximum and an inversion height that correspond roughly to the height of the crater rim above the adjacent plain, so that minor changes in the approaching flow’s structure produce these discrete events. This site thus provides an unusual opportunity to investigate the sensitivity of DWFs in a stably stratified atmosphere to temporal changes in the ambient approach flow structure. We have used this fortuitous topographic/meteorological situation to design a field experiment and modeling program to systematically study this phenomenon in a natural setting. This has not been possible before and has the potential to greatly improve understanding of analogous atmospheric flows such as those that occur in Bora and Foehn events, and in cascades of air over passes and through gaps and channels.

Figure 2. Topography of the Meteor Crater region. Southwest of the crater is the Mogollon Rim, a high altitude ridge of mesas. A mesoscale drainage flow forms on the slope between the Mogollon Rim and the Meteor Crater, with an inversion depth of about 30-50 m and a drainage flow extending to 100-250 m AGL with a jet maximum height of 20-35 m.

3. EVIDENCE FOR DWFs AT METEOR CRATER

A journal paper detailing the observational evidence for DWFs at Meteor Crater has just been submitted (Adler et al. 2011) and is available at http://www.inscc.utah.edu/~whiteman. Our
conceptual model of the phenomenon at Meteor Crater is shown in Fig. 3. Here, we summarize the key findings.

During clear undisturbed nights, a very stable surface-based inversion forms on the plain outside Meteor Crater. A near-isothermal layer (hereafter called a ‘residual layer’) is found above this surface layer. A mesoscale drainage flow develops in connection with the inclined surface-based stable layer over the plain that extends through the stable layer and into the residual layer aloft. The mesoscale flow builds up cold air upwind of the crater. The cold air splits around the crater, but with a shallow layer of cold air spilling near-continuously over the crater rim and into the crater. This ‘cold air intrusion’ plays an important role in maintaining a near-

![Conceptual model for warm air intrusions in Arizona’s Meteor Crater (Adler et al. 2011). Isentropes (gray) and streamlines (black) are shown.](image)

isothermal layer in the upper 75% of the crater’s atmosphere during the night (Whiteman et al. 2010; Haiden et al. 2011). At intervals, however, increases in the stable layer depth and the strength of the approach flow over the plain, causing a deeper cold air layer to flow over the crater rim and accelerate down the upwind inner sidewall. These episodic events bring an elevated layer of warmer air into the west side of the crater. The flow conditions near the sidewall during these warm air intrusion events differ from the continuous cold air intrusions noted in our earlier work. The cold air accelerating down the sidewall becomes supercritical and produces a hydraulic-jump-like feature near the foot of the crater’s west sidewall. The approximately 30-m-deep crater floor inversion keeps the flow from penetrating all the way to the crater floor. The isentropes of potential temperature ascend rapidly as a hydraulic jump returns the flow to ambient conditions. We hypothesize that the changing characteristics of the approach flow, which are episodic in character, are caused by occasional cold air avalanches off the mesa terrain of the Mogollon Rim approximately 30 km southwest of the crater (Fig. 2).

This conceptual model is based on extensive observations made inside the crater during the month of October 2006 (Whiteman et al. 2008b). There, three tethersondes were flown on an east-west line from the crater floor and from the east and west sidewalls. 23% of tethersonde flights from the west sidewall encountered the warm air intrusions that indicate the presence of the DWFs, while none were present in synchronous tethered balloon soundings over the basin center or east sidewall. An example of data from one such event is shown in Fig. 4. Because tethered balloons were flown only intermittently on selected IOP nights, we looked for proxy indicators of the DWFs events using continuous observations made inside the crater. Increases in wind speed at a flux tower on the west sidewall and decreases in pressure below the warm air intrusions were found to be good proxies for these features (Adler et al. 2011). Using these proxy indicators we found that the DWFs occurred episodically on more than 50% of the nights. 138 events occurred during the month, with events having a mean duration of 14 minutes. The episodic events occurred only on clear, synoptically undisturbed nights when the mesoscale
drainage flows were present on the outside plain. The necessary pre-conditions appear to include 1) a mesoscale drainage flow on the adjacent plain having a surface-based inversion top at about the level of the crater rim and with a jet-like wind profile with the maximum speed at about the rim level and a negative shear above, and b) a sudden increase in the cold air depth over the plain and a coincident increase in the speed of cold air intrusions coming over the crater rim. The DWFs events were confined to the immediate lee of the upwind rim of the crater and did not extend to the base of the west slope or horizontally into the crater atmosphere beyond the base of the west slope. There was no major disturbance to the rest of the crater atmosphere during these events, as isentropes remained horizontal between the valley center and east slope tethersondes. The warm air intrusion was found to be isolated above the west slope, with colder air below it on the slope. The cold air on the slope was colder than the air at the same time and height on the opposite sidewall of the crater. Thus a shallow, strong temperature inversion occurred over the west slope while the warm air intrusion occurred above the slope, characterized by strong winds, enhanced turbulence, and with potential temperatures and wind directions and speeds about the same as those in the residual layer over the plain. The warm air intrusion had a very steep trailing edge (i.e., hydraulic jump) that was confined over the west slope between two west slope flux tower sites that were less than 150 m apart. Unfortunately, while our analyses provided useful knowledge on the DWFs inside the crater, there were few instruments on and above the southwest sidewall of the crater and little information on the flow conditions outside the crater that led to such flow. This proposal is thus focused on gaining knowledge on the DWFs and the approach flow conditions leading to them, with an emphasis on generalizing the resulting knowledge to better understand the phenomenon. The data collection, analysis and modeling plans are directed at answering a set of scientific questions regarding the phenomenon, as listed in section 5.

Figure 4. West-east cross-section through Arizona’s Meteor Crater at 2100 MST 28 October 2006 showing a warm air intrusion over the west sidewall. a) four synchronous atmospheric temperature soundings from the west (TS-W), center (TS-C) and east (TS-E) tethersondes inside the crater and from a radiosonde (RS-NW) launched from the adjacent plain. Warm air has descended 120 m into the crater over the west sidewall, while colder air remains over the crater center and east sidewall. b) wind vectors and temperatures (colors) on a west-east cross-section of the crater. The RS-NW radiosonde soundings, while plotted as though it were upwind of the crater, was actually launched northwest of (downwind of) the crater.
4. PRESENT STATE OF KNOWLEDGE ON DWFs

The conceptual flow described in Fig. 3 bears a strong resemblance to that associated with intense downslope windstorms (Durran 2003). Such windstorms occur frequently in mountain areas and are known to produce substantial damage to life and property (Whiteman and Whiteman 1973; Bergen and Murphy 1978; Gohm et al. 2008). In contrast with the larger-scale drainage flow driven by diabatic cooling over the gentle slope (Fig. 2), the downslope windstorm is an adiabatic adjustment of stratified flow passing over steep topography (illustrated in Fig. 3), i.e., it is a feature of a large-amplitude topographically generated internal gravity wave. According to Durran (2003) intense downslope winds can occur in three broad categories:

“(1) when a standing mountain wave in a deep cross-mountain flow achieves sufficient amplitude to overturn and breakdown at some level in the troposphere, (2) when standing mountain waves break and dissipate at a critical level in a shallow cross-mountain flow, and (3) when there is sufficient static stability near mountain-top level in the cross-mountain flow to create high downslope winds even without wave breaking.”

From the evidence presented in the previous section it appears that the observed flow is a type of large-amplitude topographic wave occurring with both a critical level and strong low-level stability (Fig. 3).

The evolution of thinking on severe downslope-windstorm flow has followed a long and, in retrospect, circuitous path to the present understanding. In the earliest formal studies (Long 1954), the analogy between severe downslope winds and water flowing past an obstacle (hydraulic theory) seemed obvious given the strong visual similarity (clouds in the atmosphere, tracers in water stream flows). Strong downslope flow in hydraulic flow was observed for the condition of transcritical flow [Froude number \( U/(gh)^{1/2} \) increasing from less than to greater than unity on the lee side of the obstacle, where \( U \) is the flow speed, \( g \) is the acceleration due to gravity and \( h \) is the height of the free surface]. Extension of hydraulic theory to its stratified version was also considered straightforward as laboratory experiments (Long 1955) in vertically confined channels gave results analogous to their single-layer counterparts. The fundamental similarity seemed so obvious that the atmospheric relevance of detailed calculation of hydraulic theory using the shallow water equations (e.g. Houghton and Kasahara 1968) was never seriously doubted. The theory has two nondimensional numbers \( U/(gh)^{1/2} \) and \( h_m/h \) where \( h_m \) is the height of the obstacle; for certain combinations of these parameters strong downslope winds occur.

In a related line of atmospheric research, waves produced by density-stratified airflow over mountains were discovered in the 1930s and were the subject of theoretical investigation by Lyra, Queney, Scorer and others (Smith 1979). A critical difference between these studies of mountain waves and those of the stratified-flow experiments of Long (1955) is the vertically unconfined nature of atmospheric flows. In the latter case, linear wave theory, subject to the condition that energy propagation is directed away from the obstacle at great vertical distance, produces a fundamentally different response from that of its vertically confined counterpart. Recognizing the importance of vertically confining wave energy in the production of downslope winds, Klemp and Lilly (1975) explored, using linear theory, how downward reflection of upward, mountain-generated, wave energy from sharp variations with height \( z \) in the ambient wind speed \( U=U(z) \) and stability \( N^2=N^2(z) \) might produce significant downstream enhancement of downslope winds. They called the relevance of hydraulic theory into question.
In a series of numerical simulations with vertically constant ambient wind and stability \((U, N^2)\), Clark and Peltier (1977) and Peltier and Clark (1979) found that increasing the mountain height \(h_m\) led to increasingly nonlinear wave solutions, and at a threshold in nondimensional mountain height, \(Nh_m/U\), wave overturning (a region of static instability) develops at some level above the mountain in association with the development of strong winds on the lee slope. They developed a theoretical model in which the over-turn layer would act to reflect energy back down towards the obstacle and, if that layer were positioned at the correct height, it would lead to a resonant amplification of trapped wave energy. Considering the importance of the nonlinear wave overturning, they called the relevance of linear theory into question.

The results of the Clark-Peltier nonlinear calculations motivated Smith (1985) to develop a hybrid model involving the flow of a single, stratified layer over an obstacle. Reasoning that the essential element of the Clark-Peltier simulations was the existence of a streamline above which the mountain has only slight effect on the atmosphere, Smith (1985) used the nonlinear Long’s equation to calculate the flow of a finite-depth stratified layer over an obstacle. Pressure was calculated on the uppermost streamline of the flowing layer by assuming a stagnant well-mixed layer (as result of overturning) downstream between it and its height upstream \(h_0\) where the flowing layer is assumed to have constant \(N\) and \(U\). Under the hydrostatic assumption, Smith’s (1985) theory has just two external nondimensional numbers, \(Nh_m/U\) and \(h_m/h_0\) in analogue to the original hydraulic theory (see above).

Durran (1986) and Durran and Klemp (1987), motivated by the Clark-Peltier simulations and Smith’s (1985) theory, undertook a number of sensitivity experiments to separate the essential from the incidental ingredients involved in producing severe downslope wind storms. Since wave-overturning and the development of a critical layer [a height at which \(U(z_c)=0\)] occur together in the Clark-Peltier simulations, they imposed a flow with a critical layer in the ambient conditions and then studied the flow response varying \(z_c\) and \(h_m\). They concluded that Smith’s (1985) theory basically describes the flow response and that, given a means to trap wave energy, hydraulic theory was in fact a good description of downslope wind flows. Interestingly they found that cases without critical levels, but with strong low-level stability and weak stability aloft could also provide the trapping effect necessary for producing hydraulic-type flow.

There is a strong similarity of the flows observed in the Meteor Crater to those under discussion for the past half century regarding severe downslope storms. The smaller scale and repeatability of the Meteor Crater flow presents an excellent opportunity to sample these flows under a variety of conditions and thus to test the meteorological relevance of the various theories and ultimately add to the knowledge base on this fundamental archetype of orographic flow.

Although there are many similarities with the strong downslope wind events as described by Durran (2003), there are potentially important differences. For example the conditions at Meteor Crater differ from most previous studies of strong lee winds because of the stable atmosphere in the lee of the crater rim. Foehn windstorms, another case of strong lee winds, usually do not penetrate into the stable atmosphere of valleys (Mayr and Armi 2008) or do not develop with stable downstream conditions (Mayr and Armi 2010). A destabilization of the valley atmosphere, e.g., through diurnal heating, is necessary for the air to descend to the valley floor. At Meteor Crater the continuous cold air intrusion provides a destabilization mechanism for the air inside the crater (Whiteman et al. 2010; Haiden et al. 2011) producing a near-isothermal atmosphere that is much easier to penetrate than a strong inversion. The strong stable layer in the lowest 30 m of the crater, however, cannot be penetrated by these intrusions.
5. SCIENTIFIC QUESTIONS - HYPOTHESES TO BE TESTED

The research is designed to answer extant scientific questions about atmospheric downslope-wind-type flows that form in stratified airflow over topographic ridges. Scientific questions include:

- What is the three-dimensional structure of downslope-windstorm-type flow that develops behind the circular ridge of Meteor Crater? How do these three-dimensional flows evolve? What intermediate changes in flow structure occur as the approach flow changes? What are their characteristics and climatology? How does the crater atmosphere respond to the warm air intrusion associated with the DWF? What role does the downstream stability inside the crater play in determining the depth of penetration of this flow?

- What are the controlling upstream parameters (e.g., inversion depth and stability, wind speed and vertical shear) that cause the DWF to develop? How does a blocked flow layer upwind of the circular rim of the crater modify the inflow? How much fluid is drawn from the upwind blocked layer as the flow goes over the ridge? What meteorological mechanism produces pulses in the approach flow that tip the fluid structure into a full-fledged downslope-wind-type flow?

- Which of the existing theories on DWFs is responsible for DWFs at Meteor Crater?

- Can existing mesoscale models produce accurate simulations of the evolution of the DWFs at Meteor Crater and for other idealized basins and ridges of different size and shape? Will parametric studies with the models be successful in defining the parameter space in which such flows can be expected and assist in leading to improved understanding that will provide practical benefits for forecasting of downslope windstorm events?

6. RESEARCH PLAN

6.1 Task 1: Meteor Crater field experiment

We propose a one-month field experiment from 15 September-15 October 2013 at Meteor Crater with field support from the National Center for Atmospheric Research’s (NCAR) ISS and ISFS groups. The goal of the experiment is to answer the scientific questions posed above by designing a laboratory-like experiment where the approach flow is carefully monitored along with the atmospheric response inside the crater. The data will be used to support detailed meteorological analyses to fully characterize these events and to develop and test conceptual and atmospheric numerical models regarding their causes and the role of changes in the approach flow that affect their evolution.

Meteor Crater and the property immediately around it is owned by the Barringer Crater Company. Meteor Crater Enterprises, Inc. leases the property from the Crater Company for use as a tourist attraction and for their visitor center/museum on the north rim of the crater. The Crater Company has strict procedures in place to ensure that any research in the crater preserves the historical and geological features of the crater for future research and education. Those wishing to use the crater for scientific research must submit a proposal to the Crater Company that is passed on to their scientific review board for approval. Approval is subject to
strict requirements regarding times of access, crater preservation, etc. The attached letter from the Barringer Crater Company provides a preliminary approval for the proposed research use of the crater, which will be subject to certain restrictions yet to be determined. The PI arranged such approvals for prior experiments at Meteor Crater and is looking forward to reestablishing working relations with all parties. Other property owners and land management agencies own the land farther southwest of Meteor Crater. Access agreements will be necessary for all properties on which equipment is placed.

The meteorological measurements required to meet the experimental goals include measurements from 5 sites, as indicated in Fig. 5. For reference, the nighttime mesoscale drainage flow approaches the crater from the southwest.

![Figure 5. Maps of Meteor Crater and vicinity, showing measurement sites A-E. a) Meteor Crater's location in Arizona, b) Meteor Crater environs, and c) Meteor Crater. Dashed lines indicate the approximate horizontal angular range of the scanning lidars at sites B, D, and E.](image)

The five sites are described and instrumented as follows:

**Site A: Distant upwind.** This site will determine if cold air pulses are transported to the Meteor Crater from Mogollon Rim mesa areas southwest of Meteor Crater. It will be instrumented with a SoDAR and an ISFS flux-PAM. Both will be operated continuously during the one-month general experimental period (GEP) from solar panels and batteries. An access agreement will be necessary with the land management agency (probably BLM) and a barbed wire fence will be built around the equipment to protect it from grazing animals.
Site B. Immediate upwind area and approach ramp. This site will measure approach flow parameters immediately upwind of the crater rim. It will be located about 2 crater diameters upwind of the crater and will be able to observe the blocked flow zone, where air may split around the crater. A SoDAR, a Radio Acoustic Sounding System (RASS), and a laser ceilometer will continuously monitor the vertical wind profile, the temperature profile, the aerosol backscatter profile and the sky condition (clouds) above this site. A scanning pulsed Doppler LiDAR at this site will monitor the change in airflow as it approaches the crater, overtops the rim and/or splits around the crater, using a sequence of RHI scans at different azimuth angles. An instrumented tower will continuously monitor wind and temperature profiles to heights of 50 m as well as the full energy and radiation balance on the plain. Our earlier experiments show that a 50 m tower will be sufficient to measure the desired profiles. Data from the SoDAR and RASS will supplement this tower information, extend the measurements to greater heights, and provide redundancy for these critical measurements (note: two earlier NSF experiments in which we were involved suffered from failures of the NCAR-supplied SoDAR). A line of temperature data loggers will extend from this site over the rim and down into the crater to measure the temperature profile of the blocked flow layer and the temperature of the air flowing over the rim. A diesel generator will be operated continuously at this site and a fence will be constructed around the equipment. Access permission will be obtained from the landowner, Bar-T-Bar Ranch. We have used this site in previous Meteor Crater experiments.

C. Crater Rim: Instrumentation at this site on the southwest rim will document the changing stability and flows over the crater’s rim. A 40-m-tall tower with multiple levels of wind and temperature measurements will be placed here. Five 3-m automatic weather stations (AWSes) will be spaced along the rim from the west to the south-southeast to measure the temperature, humidity, pressure, wind speed and wind direction of flows coming over the rim and determine whether the inflows converge as they pass over the circular rim. Winds above the rim will also be measured using scanning Doppler LiDARs from points B, D and E. A mobile tethered balloon sounding system will be used to make occasional measurements of stability and inversion depth at different points along the rim and in the blocked flow region between the rim and site B. The ground station and computer necessary to receive data from the tethersonde will be operated from a single point on the rim, with power supplied by a small gasoline generator.

D. In crater: A Halo Photonics scanning Doppler LiDAR owned by the University of Utah (UU) will be placed on the crater floor to scan for wind disturbances that form in the lee of the upwind rim. The view from this site will detect the descending and ascending branches of the DWF and their detailed time evolution. Two tethered-balloon sounding systems will be used occasionally at the floor of the crater to measure temperature profiles within and outside the warm air intrusions. An ISFS Flux-PAM will be located at the LiDAR site to make routine surface energy budget and meteorological measurements, including pressure at a location under the warm air intrusion associated with the DWF. A second pressure sensor with its own datalogger will be placed on the northeast sidewall, at a site unaffected by the warm air intrusions. Pressure differences between the two pressure measurement sites will provide a continuous proxy indicator of DWFs (Adler et al. 2011). Lines of temperature data loggers will run up the inner sidewalls of the crater to the northeast (where the air is undisturbed by the DWFs), the west, southwest and south, running out onto the adjacent plain. Heavy equipment (including helium cylinders) and supplies will be transported into the crater at the beginning of the GEP by helicopter. The LiDAR, tethersonde winches, and lighting require portable generators and fuel and will be operated during designated IOPs by a two-person team that will hike into the crater for an overnight stay.
E. **Visitor center:** A scanning Doppler LiDAR will be placed inside the crater just below the rim on a metal catwalk accessed from the visitor center. Line power is available at this location, which is ideal for scanning flows coming over the rim on the far side of the crater. An infrared time-lapse camera will also be used to visualize the effects of cold and warm air intrusions on surface radiating temperature patterns on the opposite sidewall of the crater, following a technique developed recently by Prof. Roland Vogt (University of Basel; pers. comm., 2010). This LiDAR will be run continuously during the one-month experiment.

We have run two previous field experiments successfully at Meteor Crater and are confident that we can organize and execute the planned experiments. Both previous experiments were run in October, which is after the end (~15 September) of the Southwest Monsoon, when monsoonal weather systems have ended and synoptic conditions are suitable for the proposed experiments.

Separate proposals are being prepared to secure NCAR EOL field support and to develop operating protocols that will meet the requirements of the Barringer Crater Company. The University of Utah has recently purchased a Halo Photonics StreamLine scanning Doppler wind LiDAR (~$230K) that has now been tested and is available for this project, greatly decreasing the costs of this research proposal. A second, identical LiDAR will be provided by co-PI Prof. Ron Calhoun at Arizona State University; this LiDAR will be rented from the manufacturer. Prof. Calhoun will submit a separate proposal to support his field and analysis costs. A third LiDAR will be rented from a manufacturer and supplied and operated by NCAR’s Earth Observing Laboratory. This LiDAR will be rented with an option to buy. Preliminary inquiries with EOL personnel and management have given sufficient notice that this request can be programmed into their upcoming budgets. If NCAR funding is available to purchase the LiDAR, it would then become available to other NSF-funded investigators in subsequent field programs. Other field equipment (tethersondes, a mini-SoDAR, temperature data loggers, 5 automatic weather stations) will be supplied by UU. Dr. Eric Pardyjak at UU will loan us a Vaisala tethersonde system. Prof. Joe Fernando at Univ. of Notre Dame will loan us a high-resolution infrared time-lapse camera.

6.2 Task 2: Simulating DWFs

The numerical simulations will be performed with the Advanced Research WRF (ARW) model. WRF is a fully compressible, non-hydrostatic numerical model (Skamarock et al. 2008). The vertical coordinate is a terrain-following pressure coordinate. WRF can be run for idealized setups or for real-data, case-study setups; in the latter case the model fields are nudged towards a large-scale model forecast or reanalysis. Several model grids can be nested to span a wide range of resolutions within one model run, using either one-way or two-way nesting. Multiple different physics packages are available and can be chosen depending on the application. The WRF model code is written for parallel-computing platforms. Three large compute clusters with 900 to 2800 processors are available for this research at UU’s Center for High Performance Computing.

WRF can be run as an LES model without a planetary-boundary layer (PBL) parameterization if the large-scale turbulent motions are directly resolved. Subgrid-scale turbulent motions are represented either by a three-dimensional Smagorinsky (1963) closure or a 1.5 order turbulent kinetic energy (TKE) closure. Previous WRF LES simulations have been used to investigate two-way nesting for LES (Moeng et al. 2007), to study sea breezes (Antonelli and Rotunno 2007), and to compare the existing WRF subgrid-scale turbulence models with a new implementation (Mirocha et al. 2010). Recently, first studies have successfully applied the LES
capabilities of WRF to complex terrain in studies of slope flows (Catalano and Cenedese 2010) and daytime boundary-layer development in a valley (Catalano and Moeng 2010).

We are currently running WRF as an LES model for the Meteor Crater in a study of the daytime wind circulation inside the crater, with a horizontal grid point distance of 50 m and a vertical grid point distance of ≈10 m near the surface. Initial simulations of the nocturnal drainage flow over the crater rim show that WRF can produce a flow pattern reminiscent of DWFs in the lee of the crater rim under certain upstream flow conditions. An example is shown in Fig. 6. It is taken from a two-dimensional (non-LES) simulation, which was initialized with idealized upstream (outside the crater) and downstream (inside the crater) soundings typical of quiescent nights at Meteor Crater. The simulation was run with increased resolution (horizontal grid point distance = 40 m, vertical grid point distance ≈ 7 m near the surface) and a free-slip lower boundary. The isentropes rise in a hydraulic-jump-like feature behind the upstream crater rim similar to the conceptual model of Fig. 3.

Idealized two-dimensional (2-D) and three-dimensional (3-D) simulations will be performed for the Meteor Crater. The idealized setup will allow us to control the upstream and in-crater conditions (i.e. stability and winds) and, thus, to determine the conditions necessary for the formation of DWFs in the lee of the crater rim. We will focus on the controlling parameters individually, changing one parameter at a time, and determine the respective change in the flow regime.

Figure 6. Initial simulation of the formation of a DWF in the Meteor Crater.

With the comparison of 2-D and 3-D simulations we will examine whether the DWFs can be described adequately by simple 2-D flow over a ridge. The circular crater topography most likely produces 3-D phenomena, such as flow splitting around the crater in contrast to a blocking of the flow by the crater rim, which may affect or determine the resultant flow regime.

We will investigate the upstream and in-crater atmospheric conditions systematically in a parametric study. Our simulations will be guided by the field observations and thus will be focused on those parameters that can be identified in the observations as controlling the formation of hydraulic jumps. Based on the data from the previous field campaign at Meteor Crater, upstream temperature conditions are likely to include (i) the depth of the surface inversion that forms on the sloping plain outside the crater, (ii) the inversion strength, (iii) the absolute temperature difference between the air that comes over the rim and the air inside the crater, and (iv) the temperature profile of the stagnant air that pools up ahead of the crater rim in contrast to the temperature profile further upstream. Upstream wind parameters may include (v) the height of the jet in the drainage flow with respect to the rim height, (vi) the jet depth with respect to the rim height, (vii) jet strength, (viii) wind shear at the height of the rim, and (ix) the possible deformation or lifting of the drainage flow by the cold-air pool upstream of the crater rim. In-crater conditions may include (x) the stability of the crater atmosphere, and (xi) capping inversions on top of the crater atmosphere.
Model simulations will be used to evaluate the effect of the unique crater topography and to generalize the findings from Meteor Crater. The spatial scale of Meteor Crater is small compared to most locations where severe downslope windstorms and atmospheric hydraulic jumps have been observed. Furthermore, the crater is strongly asymmetric, with a height of 30-50 m above the surrounding plain and a depth of 175 m above the crater floor. Thus, an important question to be answered is how the results from Meteor Crater can be scaled to larger topography and applied to ridges with different ratios of upstream ridge height to downstream ridge height.

7. PERSONNEL AND SCHEDULE

Dr. C. David Whiteman, Research Professor at the University of Utah, will be the Principal Investigator. Dr. Rich Rotunno, an unfunded co-investigator at the National Center for Atmospheric Research will be supervising the modeling aspects of the research. A support letter from Dr. Rotunno is attached to this proposal. Dr. Ron Calhoun of Arizona State University, as co-investigator, will assist with LiDAR planning and operation. Dr. Calhoun has expertise in field deployment of 3D scanning Doppler lidars over the last 8 years (including deployments in Africa, Australia, and Germany) and in Doppler lidar algorithm development (see Krishnamurthy et al. 2011, Choukulak et al. 2011, Krishnamurthy et al. 2010, Kongara et al. 2011, Retallack et al. 2009, Hill et al. 2009, Drechsel et al. 2009, Xia et al. 2008, Lin et al. 2008, Newsom et al. 2008, Calhoun et al. 2006, and Wang et al. 2007). Dr. Calhoun has experience both with previous generations of Doppler lidar and with the new compact versions available through Halo Photonics (Swiss lidar experiment – summer 2011). Dr. Sebastian Hoch, Research Assistant Professor at UU and co-investigator, will have primary responsibility for the field program and participate in data analysis and reporting. Drs. Whiteman and Hoch ran field operations during METCRAX 2006 and a smaller program at Meteor Crater in 2009 and have intimate knowledge of Meteor Crater, experience with working with NCAR EOL and crater personnel, and facility in dealing with existing data sets. Ms. Manuela Lehner at UU will have primary responsibility for numerical modeling, with guidance from Dr. Rotunno. She has extensive experience with WRF and has produced initial simulations of DWF flows in the crater. She will receive her Ph.D. in 2012 and will thereafter work on this research project as a full-time postdoc. A second part-time postdoc at UU will assist with field operations and data analysis and reporting during the field year. A UU M.S. student will be funded by this project and will be actively involved in all aspects of the proposed research.

The project will begin on 1 January 2013, allowing sufficient time to organize the 15 September-15 October 2013 field program, to make contractual arrangements for access to field sites, and to perform initial model simulations to assist with locating field equipment. The second year of the research will focus on data quality control, data archiving, initial data analyses, and refinement of the model approach and simulations. Our previous experience is that quality-controlled NCAR data will be delivered approximately 9-12 months after the field experiment. The latter half of the second year and the third year of the project will focus on detailed analysis of DWF events to answer research questions in section 5 and parametric simulations to answer research questions in section 6.2. The final or fourth year of the project will be heavily focused on reporting of research results.
8. INTELLECTUAL MERITS AND BROADER IMPACTS OF PROPOSED RESEARCH

8.1 Intellectual merits

The proposed research will advance knowledge and understanding of physical processes that control the development of DWFs in complex terrain settings. It will likely engender broad scientific interest in other disciplines including hydrology and engineering fluid mechanics. The proposed work recognizes the large body of published literature in this area, yet will explore innovative approaches and concepts. The extensive use of a new generation of portable LiDARs using communication technologies is a novel feature of the proposal that provides an effective way to document and explore mesoscale atmospheric wind structures on the scale of the crater. Our research is expected to lead to improvements in understanding and modeling of DWFs and their role in SBL development, and the roles of surface energy budgets and diurnal complex terrain flows in producing DWFs. The integration of analyses of field data with state-of-the-art analytical and numerical modeling experiments will stimulate realistic research questions that can be tested. University of Utah, NCAR, and Arizona State University resources are more than adequate for this study.

8.2 Broader impacts

**Potential benefits of proposed activity for society at large:** Potential benefits of the proposed activity for society at large include improved understanding, analysis, and prediction of atmospheric flows leading to downslope windstorm-type events.

**Integration of research and teaching:** Research results will be incorporated into our curricula as traditional classroom lectures (Mountain Meteorology, Synoptic Lab, and introductory Meteorology courses). Learning modules will be built by the PIs and used for classroom instruction. In the past, we have developed teaching modules for use at other universities, at the NCAR COMET program, the Summer School on Mountain Meteorology (Trento, Italy), National Weather Service offices, the National Interagency Fire Center and American Meteorology Society short courses. Similar integration of research findings into education and training efforts of this type will continue in this project.

**Undergraduate student participation:** Opportunities will be available for undergraduates to participate in the field experiments and to use data for class projects and capstone projects.

**Support for graduate student and post-doctoral mentoring:** The project involves the support and mentoring of two postdocs at UU and one graduate student. Other graduate students will have an opportunity to participate in the October 2013 field experiments.

**Dissemination of project results:** Based on past experience, we anticipate publishing one to two peer-reviewed manuscripts per year in American Meteorological Society (AMS) and AGU journals. Project results will be presented at AMS specialty conferences or American Geophysical Society conferences and be made available to the public through a website similar to that of our ongoing project at www.inscc.utah.edu/~whiteman/METCRAX/.

**Promotion of diversity:** Gender and geographic diversity are features of the proposal. Co-I Hoch is a German citizen. Co-I Calhoun is from Arizona. Co-I Rotunno is from Colorado. The gender of postdoc Manuela Lehner is underrepresented in meteorology, and she is an Austrian citizen. Graduate students, while not yet employed, will likely expand the geographical diversity. Efforts will be made to attract students to the research from underrepresented groups.
9. COLLABORATIONS AND NCAR FIELD SUPPORT

NCAR’s Earth Observing Laboratory will provide field support for this project. Equipment to be provided by NCAR includes a scanning wind LiDAR, two instrumented towers, two Flux-PAM energy budget stations, a laser ceilometer, and a Doppler SoDAR with RASS. NCAR will arrange for helicopter transport of equipment into and out of Meteor Crater, helium purchase, and operation of portable power generators, as they did for METCRAX 2006. NCAR does not presently have a scanning Doppler LiDAR in its EOL deployment pool. A scanning LiDAR will be rented by EOL, with the possibility of purchasing it to add to their future deployment pool.

Prof. Norbert Kalthoff at the Karlsruhe Institute of Technology and Prof. Roland Vogt at the University of Basel have expressed interest in participating in the field experiments at no cost to this project. While these discussions are still at a preliminary stage, both have expressed interest in supplementing the experiments with specialized research tools that they have on hand (WindCube LiDAR and IR time-lapse camera, respectively). We anticipate and welcome research collaborations with other scientists who wish to use the unique data set that will come from the proposed experiments.

10. SUMMARY

We will investigate basic mechanisms that lead to the evolution of downslope windstorm-type flows (DWFs), a topic of important theoretical and practical value, using both a field study and numerical modeling. Our project takes advantage of an idealized topographic situation at Arizona’s Barringer Meteorite Crater in which windstorm events occur regularly on a scale that can be cost-effectively instrumented without the use of research aircraft. The experimental design has parallels to a laboratory study in which approaching flows outside the crater are monitored continuously at the same time that the DWF response is monitored inside the crater. Key scientific questions about DWFs in this environmental setting have been formulated to design the field experiment and model simulations. The field experiment has been designed using a combination of routine and innovative new field research equipment, including small, portable, scanning Doppler wind LiDARs and a high-resolution infrared time-lapse camera. Costs have been reduced by prior purchase of one of the LiDARs and a Doppler mini-SODAR. Other needed equipment is cost-effectively utilized by drawing on equipment available from NCAR’s field deployment pool. Operational knowledge, existing personal relationships with landowners, and data and experience gained from prior research at Meteor Crater will facilitate the proposed research.

A mesoscale numerical model has been tested at the scales involved, and initial simulations appear promising. A comprehensive plan has been developed to simulate the Meteor Crater and to make parametric simulations to extend the findings to different topographies and approach flows. The project team is strong, including experts in field program planning and data collection, LiDAR technology, and numerical modeling. The collaborative project is expected to be productive, and the project includes an educational component that will train postdocs, as well as graduate and undergraduate students. The 4-yr proposal term is chosen to allow sufficient time to get firm access permissions, run the experiments, quality control and process the data, analyze the data, and report the results. We anticipate and welcome research collaborations with other scientists who wish to use these data.