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Field Studies Delve Into the Intricacies of Mountain Weather

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Mountain meteorology, in particular weather prediction in complex (rugged) terrain, is emerging as an important topic for science and society. Large urban settlements such as Los Angeles, Hong Kong, and Rio de Janeiro have grown within or in the shadow of complex terrain, and managing the air quality of such cities requires a good understanding of the air flow patterns that spill off of mountains. On a daily time scale, the interconnected engineered and natural systems that sustain urban metabolism and quality of life are affected by weather [*Fernando,* 2010]. Further, recent military engagements in remote mountainous areas have heightened the need for better weather predictions—alpine warfare is considered to be one of the most dangerous types of combat.

Improving mountain weather forecasts is the goal of the interdisciplinary cadre of researchers who participate in the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) program. MATERHORN has four principal thrusts—modeling, experiments, technology, and parameterizations—that are symbiotically directed toward identifying model deficiencies and knowledge gaps, conducting process studies, and developing knowledge and tools for model improvements. Following the new paradigm proposed by *Jakob* [2010], model improvements in MATERHORN are conducted through a feedback loop of interdependent scientific tasks, enabled by supporting tools.

MATERHORN is funded through a Multidisciplinary University Research Initiative (MURI) grant from the Office of Naval Research, with grantees at the University of Notre Dame (lead institution); the University of California, Berkeley; the Naval Postgraduate School (NPS); the University of Utah; and the University of Virginia. A number of additional U.S. and foreign institutions have joined MATERHORN, leveraging alternative funding sources, such as the Army Research Office and the Air Force Weather Agency (http://www.nd.edu/~dynamics/materhorn). The collocation of funding sources, academic expertise, operational knowledge, and community support allowed researchers to design and implement two field campaigns that address critical knowledge gaps and weaknesses of predictive models of mountain meteorology.

MATERHORN Field Campaigns

Research for MATERHORN centers around two field campaigns, the data from which scientists hope to use to extract basic fluid dynamics that govern mountain weather. The knowledge gained will be used to develop conceptual, phenomenological, theoretical, and numerical models dealing with multiple space-time scales of mountain weather.

For both campaigns, investigators capitalized on their access to the Granite Mountain Atmospheric Sciences Test Bed (GMAST) located in the U.S. Army's Dugway Proving Ground (DPG), approximately 85 miles (137 kilometers) southwest of Salt Lake City, Utah. Located in the Great Salt Lake Desert, covering about 1250 square miles (3237 square kilometers), DPG is an isolated, arid area with terrain varying from salt flats to sand dunes and from isolated hills to rugged interconnected mountains, with sparse vegetation and little human influence. A special Cooperative Research and Development Agreement between participating universities and DPG allowed GMAST, a secured facility, to be used for MATERHORN.

Prior to the campaigns, researchers and DPG staff equipped the site with a network of high-end sensors over a broad area. This equipment, sited over spatial extents of tens of kilometers and with measurement resolutions down to millimeters, maximized the reachable range of spatial scales within which researchers could study temporally evolving weather patterns. The sensors collected data at rates ranging from a fraction of a second to hours. Mountain weather evolves dramatically over these spatial and temporal time scales, and capturing these varying conditions simultaneously has long been a challenge.

The first campaign, a series of intensive observational periods (IOPs) conducted from 25 September to 31 October 2012, examined quiescent fair weather (wind speeds less than 4 meters per second), in which the main drivers of weather patterns were the heating of ground during the day and cooling at night. The second campaign, from 1 to 31 May 2013, dealt with synoptic influence (phenomena driven by regional-scale pressure gradients), moist surface conditions, and wind speed in moderate (5–10 meters per second) and strong (greater than 10 meters per second) categories.

A series of Weather Research and Forecasting (WRF) model runs conducted before the campaigns began provided guidance for designing the experiments, especially for determining optimal locations of sensors. Background meteorology was characterized using radiosonde launches at seven locations, accomplished by ascending balloons with instruments for vertical meteorological profiles up to tens of kilometers. In addition, six ceilometers (to measure the elevation of cloud layers and their horizontal coverage), three sodars (sonic detection and ranging equipment for measuring wind vectors at various altitudes up to 2 kilometers), a radio acoustic sounding system (RASS) attached to a sodar to measure vertical temperature profiles, three ultrahigh-frequency Doppler wind radars (for wind speed and direction with a lesser resolution), two microwave radiometers (for continuous vertical temperature, humidity, and liquid water profiles up to 10 kilometers), a frequency modulated/continuous wave (FM/CW) S band radar (for boundary layer structure, using refractive index variations), and a C band weather surveillance Doppler radar (for measuring precipitation) were deployed in the field area. Three ground-based Doppler lidars scanned dynamic regions that were identified in GMAST during preliminary WRF runs, each lidar covering a hemisphere of about 1 kilometer. At times, these lidars were coordinated to image subtle changes in wind velocities at different heights along a specific air column, forming virtual towers of data.

An array of 51 portable weather instrumentation data systems (PWIDS), 31 surface atmospheric measurement systems (SAMS), and 51 miniaturized SAMS recorded the wind patterns in GMAST at kilometer and

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subkilometer scales. Two tethered balloon systems measured vertical profiles of temperature, humidity, and winds up to heights of several kilometers at meter-scale resolution. Near-surface moisture was probed using two in-house-developed radio-frequency crosshairs (for surface moisture at kilometer scale), microwave radiometers (for vertical profiles of moisture and temperature at decimeter scales), and infrared gas analyzers (for moisture flux) deployed at various locations of scientific interest.

Swaths along specific slopes, valleys, and canyons were set up with 20 flux towers (10 to 32 meters tall), carrying sonic anemometers (to measure turbulence parameters and heat and momentum fluxes) and thermocouples at multiple heights as well as radiometers (for incoming and outgoing radiation) at a single height, a series of 17 HOBO® weather stations, and 17 local energy balance measurement stations (LEMS) located on the ground. A fiber-optic distributed temperature system (DTS), consisting of a cable stretched over a 2-kilometer track and hung on 1-meter stakes, was deployed on the most highly instrumented slope, providing near-surface measurements on meter and second scales. Five surface energy budget stations were deployed on the ground surface to help evaluate land surface schemes of mesoscale models. The smallest scales of turbulence (which dissipates most of the energy) are millimeter sized and were captured by two novel hotwire stations designed and fabricated in house, which were deployed on shorter masts. High-speed infrared imagery collected by a sensitive infrared camera characterized mountain-induced shadow fronts and their correlations with surface temperatures and turbulent fluxes.

NPS Twin Otter flights, equipped with Doppler wind lidars to measure wind velocities and fluxes, along with unmanned aerial vehicles carrying probes for meteorological and turbulence measurements crisscrossed GMAST vertically and horizontally. Multiple smoke releases helped visualize the pathways (streaklines) of atmospheric air parcels released from various locations.

Each campaign included ten 24-hour IOPs, where all instruments and platforms operated in coordination. The fall study included six quiescent IOPs, with the rest having moderate and strong winds. Nine IOPs of the spring experiment had either moderate or strong winds with higher moisture levels. A repertoire of forecasting products, consisting of WRF ensembles and outputs of North American Meteorological (NAM) and Global Forecast System (GFS) models, along with satellite products, helped researchers determine which days would be good candidates for IOPs.

Preliminary Observations

A quick glance at the data suggests the prevalence of moderately small-scale phenomena, those with length scales less than a kilometer and time scales up to an hour, triggered by interactions of flows of disparate scales. Although the flow surrounding Granite Peak was considered nominally simple, the typical slope/valley flows anticipated existed only for short times and were often overshadowed by those arriving from nearby mountains, basins, canyons, ravines, and gullies. Collision of different flows produced periods of intense turbulence. Cold pools, overflowing from one basin to another through gaps between mountains, produced expanding "thermal rivers" and eddying motions.

Mesoscale models cannot capture the essentials of these submesoscale interactions, as they occur in relatively thin regions, such as fronts, collision bands, interfaces, and instabilities. Finely scaled model simulations, however, exhibited intricate flow topologies and interactions (Figure 1), although detailed comparisons of these with observations may show marked differences.

Other insights may come from analysis of katabatic flows, the winds that sweep down slopes due to ground cooling. Collisions of disparate katabatic flows appeared to produce enhanced shear and sporadic turbulence. At times, these flows were lifted above denser currents undercutting from below, and ensuing spasmodic turbulence produced intense fluxes that lasted tens of minutes. Also contributing to intermittent turbulence were extremely strong, thermally forced, near-surface mesoscale jets, which developed over the surrounding flat terrain at night. Existing flux parameterizations in mesoscale models ignore such ephemeral yet energetic episodes.

Model guidance provides the fabric for interpreting data, which, in turn, provides feedback for model improvements. Preliminary observations show that the flow in GMAST is rich in patterns of high- and low-velocity gradients and regions of stagnation, which are amenable to topological fluid mechanics studies. These dynamically active critical regions may contribute to rapidly changing local weather, and understanding them is an important step toward improving models.

Toward Improving Predictions of Mountain Weather

As the data processing continues, many new patterns and parameterizations are expected to emerge. There is little doubt that the rich variety of physical processes, which have been observed, carefully measured, and linked to the conditions for their occurrences during the two MATERHORN campaigns, will help scientists develop better models for predicting short-term variability in mountain weather.

It is clear that not even the simplest, isolated mountains in nature can act alone. Cross talk among mountain flows produces some intriguing effects that have eluded mesoscale predictive models hitherto. The MATERHORN field campaigns, the most extensive mountain terrain meteorological observational program that has been conducted so far, offer hope that these interactions can finally be understood and quantified.

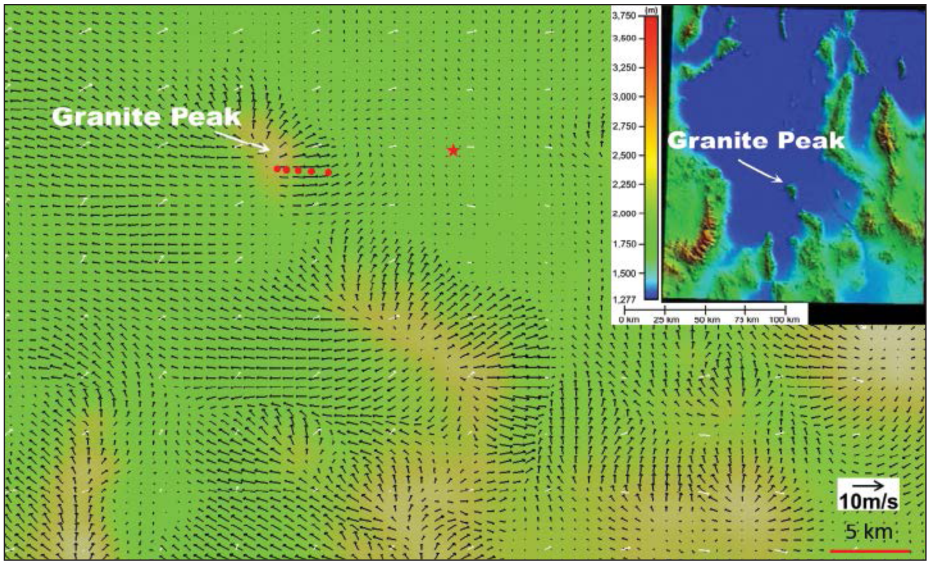

Fig. 1. Wind vectors at 10 meters (black) and 500 meters (white) from numerical simulations with the Weather Research and Forecasting (WRF; version 3.4.1) model for 29 September 2012, 2:30 A.M. local time for a quiescent intensive observational period (IOP). Red circles are the locations of flux towers; the red star is a tethered balloon. The color represents topographic height, from 1000 meters (green) to 2200 meters (brown at the Granite Peak summit) above sea level. The inset shows the actual topography around the Granite Mountain Atmospheric Sciences Test Bed.

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