Report on the ONR – ARO Workshop on

Weather in Mountainous Terrain

(Overcoming Scientific Barriers to Weather Support)

Fiesta Resort & Conference Center

Tempe, AZ

February 1-2, 2010

Abstract

A major part of the Earth's land surface is covered by complex topography, which affects the weather as well as related 'quality of life' indicators such as air pollution, energy production, transportation and security. As a result, extensive work has been done on meteorology and air quality in urban basins located in complex topography. Nevertheless, flow in the proximity of mountains themselves or in very rugged terrain with little human habitation has received only little consideration. High gradients and large heights of terrain lead a host of important phenomena, for example, gravity waves, wind gusts, canyon flows, Venturi effects, stagnation, rotors, cold air pooling, up/down drafts, slope and cross flows, fog, snow/ice, convective clouds and lightning, which are highly variable and defy reliable forecasting. Recent U.S. military engagements in mountainous terrain have brought increased attention to mountain meteorology, and to this end a workshop was convened to bring together practitioners and scientists to discuss the state of the art of research and identify scientific and technological barriers to the prediction of mountain weather. The participants also provided recommendations for future research directions. The workshop was held in Tempe, Arizona, during February 1-2, 2010, and there were twenty six attendees representing the Departments of Army, Navy and Air Force, U.S. Marine Corps and academia.

Introduction

The weather is inexorably intertwined with indicators of human ‘quality of life’ such as air pollution, health, comfort and security. While leaps of advancement have been made in weather prediction on large spatial scales, knowledge gaps continue to challenge the fidelity of local (small space-time) predictions, particularly in the areas of complex terrain where spatial and temporal gradients of meteorological variables are steep and flow and thermodynamics processes are intricate. About 70% of the Earth surface, and more so the urban areas, is covered by complex terrain, and thus basin-scale processes characteristic of urban airsheds have been studied extensively in the context of air quality (Blumen 1991; Whiteman 2000; Fernando 2010). Yet the weather in the thick of mountainous terrain has received less attention, perhaps because of sparse population therein. The more recent U.S. military engagements in mountainous areas, however, have called for a renewed interest on weather in complex topography, and to this end, at the request of the Office of Naval Research and the Army Research Office, a workshop was convened in Tempe, Arizona, during February 1-2, to delve into the overarching science and technological issues that beleaguer reliable weather predictions in mountainous areas.

War fighting in rugged terrain is historically referred to as ‘mountain (or Alpine) warfare’, which is one of the most dangerous types of combat (Winters 2001). A principle element of mountain warfare is meteorological support, given the extreme weather (e.g., lightning, wind gusts, Venturi wind effects between ridges, stagnation, cold air pooling, travelling and stationary waves, up/down drafts, snow/ice, convective clouds and lightning), steep terrain, incomplete environmental information, intricate logistics, greater uncertainties and high risks that the combatants have to endure. The prediction of flow, turbulence and dispersion of contaminants and obscurants in complex terrain is extremely difficult because of the wide range of physicochemical processes involved covering a broad spectrum of space-time scales. Moreover, many of these processes are of small-scale, less than a few km and on the order of an hour or less; to name a few, eddy shedding, aerosols and secondary aerosol formation, mountain waves and phase changes. Thus, in the context of mesoscale modeling of mountainous terrain, the applicability of conventional sub-grid parameterizations is in question whilst the role of sub-grid processes is more crucial than elsewhere. These complexities, confounded by the lack of high resolution meteorological data, have been the bane of predicting mountain weather.

The workshop was designed to bring together a cadre of practitioners and scientists to identify scientific, technological and theater needs and challenges as well as to advise DOD Program managers of potential research directions that will best serve battlefield planners. The DOD presenters identified illumination, visibility, wind speeds and moisture as the most important issues, while deemphasizing wind shear, icing and lightning. Illumination is reduced by shadowing effects, clouds and walls of dust that appear during high wind events. The recent drought in Afghanistan has created islands of low visibility under high winds, and enhanced erosion of soil has impacted on low level helicopter operations; there is a drastic reduction of visibility when the helicopters descend to altitudes of 20-30 feet above ground level. Moisture deleteriously interferes with UAV hardware, making them viable only when the relative humidity is < 30% (Figs. 1 and 2).

Fig.1: Visibility issue in theater

Fig 2: Humidity and winds are critical for UAVs

In the past, the weather forecasting for Mission Essential Meteorological and Oceanographic Center (MetOc) has been made by synthesizing information from stations and weather observers, but at present the forecasts are more reliant on models and routine data. Therefore, the emphasis of the workshop was on improved modeling and predictions. The discussions were along four main topics: Model core issues; Boundary Conditions; Model Initialization and Data; and Small-scale Parameterizations. Each topic was discussed by two breakaway groups in dedicated 2-hour sessions. The agenda of the workshop is in Appendix 1, and the participant list is in Appendix 2. The following are the research issues identified by the twenty six participants of the workshop.

A. Model Core Issues

1. There is a need for better understanding of extrinsic (skill/verification) and intrinsic (foundations and viability for resource allocation) predictabilities.
2. Quantify the multi-scale predictability in mountainous terrain and understand how the large- and small-scales impact it.
3. Is it possible to learn from spectral analyses of topography? It will be useful to consider dominant topographic scales vis-à-vis processes intrinsic to such scales (as in the case of oceanic benthic boundary layer).
4. In addition, in capturing various phenomena (physical processes and their time variability), the space-time resolution is critical for assessing computational resources and methods. Unresolved scales lead to numerous problems.
5. The issues of variable resolution, optimal coordinate systems and nesting need to be studied, paying attention to spurious modes. What vertical coordinate system

[terrain following (pressure), Cartesian (z) or other] works best for mountainous terrain? Other variants are immersed coordinates, shaved cells, distorted grids and step coordinates. The nature of terrain (steep versus gradual) and processes (e.g., waves, cold pools, canyon releases and updrafts) are important in such a selection. It will be better to seek a modeling system that can handle all terrain types, including flat terrain.

6. What types of meshes and mesh sizes are to be adopted (e.g., adaptive mash refinement; AMR in the boundary layer)? What should the scale cut off be and where should we densify the grid?

7. The convergence of numerical models is a frequent issue that needs to be addressed, including criteria of convergence and improved numerical techniques. Issues related to parallelization and scaling need to be revisited for computational efficiency and for adaptation of new techniques (e.g., Discontinuous Galerkin/Spectral Element) must be considered.

8. One-way nesting (down scaling) is common, but the preponderance of energy production in small scales in mountainous terrain may lead to upscale transfer of properties, requiring two-way nesting (up-scaling). Conditions under which the latter is useful ought to be identified. Vertical nesting, in addition to horizontal nesting, must to be considered.

9. There is ample room for improvements of dynamical and statistical downscaling methods. For the former, tradeoffs between large-scale ensembles and smaller scale deterministic methods should be considered. Can a composite of the two be used?

10. Model evaluation and verification are indispensable. In the former, the model is verified against data sets (detailed statistics and ensemble issues) and the latter involves testing against known solutions and for convergence and resolution. Are the current numerical methods sufficient or are higher-order-accuracy numerical schemes necessary? Recent work has demonstrated the benefits of higher order schemes, but it is necessary to ensure that the computational cost is justified in terms of improved predictability.

11. A shift of modeling paradigms may be required, where more emphasis is placed on stochastic rather than deterministic models. Ensembles can be better utilized on smaller scales. As pointed out by Lorenz years ago, the predictability time scales are likely to be too short for circulations on spatial scales of 10 km or less to allow meaningful deterministic forecasts at a reasonable lead time. Working with stakeholders will allow determining how to optimize the operational use of ensembles.

12. Idealized predictability studies and convergence tests can be conducted to learn when/where accurate large-scale flow can "inform" probabilities of events or lead to deterministic skill in mountain-induced processes (e.g., occurrence of clear air turbulence). Conversely, these studies, which probably need to focus on individual phenomenon, inform when/where/at what scales lack predictability in the Lorenz sense.

13. Consistent with focus on ensembles, it is advisable to conduct systematic research on the predictability of mesoscale phenomena. This involves investigations on the error growth rates (the sensitivity to initial conditions at various lead times) and

developing meaningful measures of skill relative to appropriate conditional climatologies (i.e., the skill of capturing a set of specific phenomena of relevance when they suppose to appear; e.g., appearance of lee waves when a Froude number criterion is satisfied).

14. Models should be evaluated under diverse weather conditions to ensure their portability. Most of the models are calibrated and evaluated for mid latitudes, and it is important to know whether they perform well for temperate and high latitudes. Model predictions over km-scale grids are usually validated using single point observations, the latter being influenced by local scales; better methods are needed to address this issue.

B. Surface, Lateral and Upper Boundary Conditions

Surface BC

1. Very good digital elevation data are available covering the Earth's surface (at least ~ 100 m resolution), but improved information on land use/cover and material and surface properties (e.g., albedo, emissivity, hydraulic and thermal conductivity, roughness length, snow cover, soil moisture) are needed. The scale compatibility of data and model is an issue, as properties need to be averaged up to the model resolution. Often the model assigns a land use type based on the most covered land-use type within the grid, neglecting the heterogeneities within.

2. The shadowing creates space-time heterogeneities, which impacts flux and radiation calculations. Some models account for this (e.g., Dudhia shadowing in WRF), but the

absence of small-scale heterogeneities in the models may pose errors in determining local conditions. Can flux scaling laws be derived for the cases of land-use and shadow heterogeneities, say by using some modified roughness and thermal length scales?

3. The vertical variability of surface elements (trees, isolated topography) creates serious issues, much the same way as buildings in urban canopies. Methods are required to account for such variability. In most cases, these elements protrude beyond the first or first few grid layers, whence the usual similarity theories (e.g., Monin-Obukhov) are invalid.

4. Initialization of land-surface models (LSM) is predicated by the lack of information on moisture, wherefore the models tend to drift. Similar issues arise when dealing with arid regions and areas with sparse vegetation. This has led to automated 'tuning' of land surface properties to match the predictions with available data. Some alternatives would be to build statistical LSMs, link the surface moisture formulation with a hydrologic model, or to build a model with simplified physics. The dependence of land-surface fluxes on synoptic flow also needs study. Breakthroughs in remote sensing may help in characterizing the ever changing land surface.

5. It is unclear whether conventional surface boundary layer parameterizations and hydrologic models are valid for sloping terrain. For example, sloping surfaces induce thermal circulation, and surface runoff is dependent on the slope.

6. To address heterogeneity, it will be necessary to make high resolution measurements in the lowest layer (note that there is no surface layer in conventional sense, given the 3D heterogeneity of fluxes). Both vertical and horizontal profiling is needed.

7. In characterizing the marine surface layer, the intricacies of air-sea interactions need to be considered. Some key parameters are the Sea Surface Temperature (SST), surface fluxes, wave properties and breaking of the ocean surface (e.g., sea spray).

Lateral BC

1. Multiple nesting is a natural tool for mesoscale simulations, which is realized using ad-hoc methods. No simple universal answer has emerged on the best nesting method.

2. Horizontal nests are the most common, either one-way or two-way nesting. The latter is computer intense, and parameterizations for up-scaling are not well established. What should be the optimal size of the nests and where should they be located? Steep terrain is a nuisance for nesting. How can the reflections at lateral boundaries be handled and blended with the coarser mesh? What criteria should be used to determine the frequency of saving the coarse mesh output? Can better numerical schemes improve the effectiveness of nesting?

3. Downscaling of mesoscale models can be accomplished using LES or RANS models. How can one ensure that the spin up of high-resolution model is compatible with the output of coarse model?

4. How can parameterizations be developed to be uniformly applicable across nests? What are the best methods for blending the land surface with nest surfaces?

5. Alternative to horizontal nesting, it is possible to consider global models with local mesh refinements to avoid lateral BC? Parameterizations that are valid across grids, described above, will be of help.

6. Techniques for ensemble data assimilation must be developed. This requires overriding of usual data ingestion at the lateral boundaries of mesoscale models. How can lateral boundary conditions be perturbed for ensembles?

7. Carefully planned field experiments must be designed for model validation. Consideration should be given to the standardization of validation methods.

Upper BC

1. Wave radiation is ubiquitous in mountain terrain, and upper boundary conditions need to be designed accordingly. Perhaps the top boundary condition can be located far away (30-40km), where a damping layer can be introduced to absorb the remnant energy.

2. Numerical weather prediction (NWP) models ought to be run for idealized cases to study wave radiation and to understand the design requirements for absorbing filters. Key benchmark cases can be identified for future model verification/evaluations. Specification methods for heterogeneous upper boundary conditions need to be considered.
3. Reflection from the upper boundary is particularly important in vertical nesting, where adaptive refinements (high resolution at low levels) are used to capture phenomena.

C. Model Initialization – Data Sources and Data Assimilation

1. The sophistication of data assimilation methods for mesoscale modeling lags behind those of global models. Data from a suite of platforms operating in mountain terrain

(surface, UAVs, balloons) can be assimilated to mesoscale models, for which new methodologies must be developed. The concept of targeted observing is promising for theater operations.

2. Assimilating surface data tend to wash away in a short period of time. Dense surface networks together with high-resolution grids perform better. Assimilation of large-scale variables, for example, synoptic surface pressure or interpolated weather data, has been more effective. Similarly, profiler data is more effective than surface observations. The satellite data are potentially valuable as an assimilation tool, but their reliability over land is questionable. The surface data are more appropriate for model evaluation and calibration.

3. Available data assimilation methods need to be evaluated for complex terrain. Quality control filters, model-data compatibility, the use of adjoints, non-standard data are all important issues. Ensemble Kalman filter (EnKF) has proven to be beneficial for assimilation of diverse data and ensembles. The latter is particularly helpful because individual realizations are not expected to and usually do not match observations.

4. A dedicated modeling study in conjunction with a carefully planned field study in mountainous terrain is highly recommended to evaluate various assimilation techniques. The field study ought to include representative sites (valleys, peaks, canyons) as well as up-and downstream data stations. Leveraging observations of other field programs (e.g., Dugway and Aberdeen proving grounds, T-REX) as well as inclusion of non standard data must be considered. This effort must span a broader set of issues, for example, investigating comparisons of 4DVAR, ensemble Kalman filtering and 3DVAR.

5. Optimization methods of sensor siting need to be developed for the case of mountainous terrain. There is a possibility that observing large scales may help improve small-scale predictions, which depends on the understanding of the interactions between large and small scales.

6. Low level UAV observations may be assimilated and used for model validation. Dealing with large data rates from a fleet of UAVs, however, is onerous, and thus the UAV weather observations capability is not currently used. Development of cyber-infrastructure will be necessary, which ought to be tested in a mountainous test bed. UAVs also can carry drop sondes for vertical profiling.

7. The viability of a suite of data platforms should be investigated. Microsensors (pressure, temperature, velocities), profiling systems (lidar, sodar, wind/temperature profiler, ATC radars, balloon sondes, kites, acoustic sensors), remote sensors (satellites), mobile platforms, aerostats and UAVs (with turbulence probes, micro-Lidars weighing ~ 6.5 lbs) should be considered. Not all will work in mountainous conditions, but different platforms can be enlisted as needed. Issues regarding data transmission, storage, and database development need to be addressed.

8. The satellite information should be fully exploited for land-surface characterization (moisture, land-use, roughness, snow cover, etc), although the interpretations can be stymied by terrain and clouds.

9. Biases exist in the WRF model with regard to the wind speed, and to a lesser degree for temperature, which can be partly attributed to hot (daytime) and cold (nighttime) model starts. More frequent data assimilation beyond typical 6-12 hour assimilations perhaps might help alleviate the difficulty.

10. Because of the short time scale variability of mountain weather, the model initialization is more crucial than for usual simulations. Careful studies on initialization techniques (either ensemble or adjoint sensitivities), including sensitivities to land-surface are required. Initial tests can be conducted using synthetic data, followed by those with real-data sets.

D. Parameterizations: Clouds, Turbulence, Radiation, Aerosols and Waves

Clouds

1. Location, type, rain rates, visibility (depth, line-of-sight issues) are important parameters akin to clouds, which are determined by processes interacting over a range of space-time scales. Understanding the dynamics and interactions of such processes will be important for cloud parameterizations.

2. An improved understanding of cloud microphysics, including thermodynamics and phase changes, is needed, and better sampling strategies ought to be devised (e.g., continuous versus episodic). Scale dependence of measurements and uncertainties need to be documented.

3. Improved convective parameterizations can usher a new generation of cloud resolving models or high fidelity LES models that may improve predictability, given the dominance of convection in mountainous terrain. Current microphysical schemes need site specific tuning, and their performance in mountainous terrain is particularly poor.

4. Bulk models are the most practical and computationally affordable thus far, compared to bin models.

5. Aerosol plays a major role as cloud condensation nuclei (CCN), and hence in convection. The origins (industrial, fires and smoke), transport and diffusion of aerosols play an important role in visibility prediction. Some air quality models (e.g., CMAQ) currently employ visibility models, but few validation studies have been conducted.

6. Satellite data can play an important role in model validation, but accuracy has been an issue.

Turbulence

1. The classical parameterizations for stable and unstable flat terrain boundary layers (Monin-Obukhov theory) are questionable for mountainous terrain. Assumptions such as constant flux layer, horizontal homogeneity and local equilibrium are not valid for mountainous terrain, calling for new theoretical formulations. Contributing to these factors are the complexities of soil moisture, runoff and thermodynamics. The possibility of formulating thermal and momentum roughness scales for mountain boundary layers should be investigated.

2. Because of the rapidity of space-time variation, adaptive or stochastic sub-grid parameterizations ought to be considered. Extant parameterizations for meso-scale and LES models need to be revisited in light of mountainous terrain flow physics.

3. Little is known on turbulence in the stable boundary layer over steep mountains. Intermittency is expected in stable layers, triggered by additional mechanisms such as

wave breaking and strong near-surface shear. The intermittency of patchy turbulence is dependent on a myriad of factors (energy content, generating mechanism, etc.), which needs to be studied using field measurements. As in oceanic stable layers, the statistical distributions of space-time intermittency are important in eddy-diffusivity parameterizations. Patchy turbulence is an ideal candidate for conditional ensemble predictions.

4. Research on convective driven flow along steep terrain as well as flow separation therein should be intensified. The convective boundary layer is modified by upslope flow, thus making the Monin-Obukhov theory invalid; relevant parameterizations should be developed. Transnational flows that occur between up and down slope flow periods are not well understood.

5. Although the gap and canyon flows may not play a first order role in parameterizations, they are not uncommon and can be hazardous. They cause sudden changes of wind speeds, aerosol concentration and visibility. Conditions for their appearance need to be studied, with the aim of incorporating them into ensemble forecasts.

Radiation

1. Radiation calculations with slopes and shading are computationally expensive; simpler and efficient schemes are needed. These models need to include proper lateral communications.

2. Increased spatial/temporal resolution can enhance the effectiveness of radiation schemes. Vertical resolution near the ground is known to impact boundary layer

temperature profiles, and hence the radiation flux. The profiles in the first 4-5 m of the atmosphere are critical in determining the vertical flux divergence, which drives the slope flows.

3. The lateral inhomogeneities of land use, albedo and snow cover have significant impact on radiation balance. Methods must be developed to incorporate such complexities.

Aerosols

1. Aerosol models that take into account dust entrainment are needed. Currently, most models do not couple flow and dust entrainment, but rely on emission inventories (wind driven, fires, city pollution, sea salt, dust) based on averaged data. Stochastic models ought to be considered given the complexity of aerosol dynamics.
2. Dust deposition is accounted in most regulatory models, but issues remain with regard to the effects of turbulence and lateral inhomogeneities of land use. The formation of secondary aerosols is important as CCN, but they may be inconsequential away from urban areas unless there is strong advection.
3. The radiative properties of aerosols have been intensely studied in the climatic context, but their short space-time scale radiative behavior has received far less attention. The radiative properties and the dynamics of ice nuclei and CCN need further study, especially via measurements.

Waves

1. In NWP models, the drag induced by wavelength less than 5 km or so is neglected, and most mesoscale models use parameterizations that do not properly account for

internal-wave transports (i.e., higher momentum diffusivity compared to scalar diffusivity). The wave excitations both in horizontal and vertical are prevalent in mountainous topography, given the myriad of topographic excitation scales. As such, mountain meteorological models should have accurate wave excitation and energy transport parameterizations that account for a full spectrum of waves.

2. Waves can penetrate the tropopause and affect upper stratospheric circulation, which, in turn impacts the synoptic flow.

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Appendix 1

Agenda

ONR – ARO Workshop on Mountain Meteorology

Overcoming Scientific Barriers to Weather Support

Fiesta Resort & Conference Center   Tempe, AZ

February 1 & 2, 2010

Hosted by University of Notre Dame

SUNDAY January 31
Arrival & check in

MONDAY February 1
0700 Continental Breakfast

0815 Welcome and Opening Remarks - Hosts & Sponsors

0830 Session I - Military Challenges for Weather Support in Mountainous Terrain
Raul Ramirez, AG1, USSOCOM NSWSA1
CWO3 Thomas Muschamp, USMC

0945 Break

1000 DoD Operational Weather Forecasting
Dr. Jim Doyle - NRL-Monterey – Navy approach
Mr. David Keller – AF Weather Agency – AF / Army approach
Mr. Robert Dumais – Army Research Laboratory - Tactical Decision Aids

1145 Lunch

1300 Session II - Subject Matter Topics - A
Introduction
TOPIC: *Model core issues* Moderators: Jim Doyle & Scott Sandgathe
Scribes: Josh Hacker & Stephan deWekker
1500 Break

1520 TOPIC: *Boundary Conditions – lateral, surface, topography, soil moisture*
Moderators: Jim Steenburgh & Dale Durran Scribes: Brian Colle &To Be Confirmed

1730 ADJOURN for day

1830 Reception and Dinner – University of Notre Dame

TUESDAY 2 February

0700-0800 Continental Breakfast

0815 SESSION III - Subject Matter Topics - B
TOPIC*: Initialization – Data sources, Data assimilation,*
Moderators: John Cook & Bob Banta Scribes: Tina Chow & Yansen Wang

0945 Break

1000 TOPIC: *Parameterizations* - *Clouds, Turbulence, Aerosols, Radiation,*
Moderators: Joe Fernando & Bob Walko
Scribes: Rob Swanson & Eric Buch
1145 Lunch

1300 SESSION IV – Opportunities for Basic Research
Recommendations of Each Participant

1445 Break

1500 Prioritize Recommendations

1630 ADJOURN

Appendix 2

Dr. Walter Bach
Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
walter.d.bach@us.army.mil
Phone: (919) 549-4247

Dr. Robert Banta, Research Meteorologist
National Oceanic & Atmospheric Administration
Earth System Research Laboratory
Chemical Sciences Division R/CSD3
325 Broadway
Boulder, CO 80305
robert.banta@noaa.gov
Phone: (303) 497-5535
FAX: (303) 497-5318

CDR Eric Buch, Military Deputy
Ocean and Atmospheric S&T Directorate
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375
eric.buch@nrl.navy.mil
Phone: (202) 404-8162
FAX: (202) 404-8183

Dr. Fotini Katopodes Chow, Assistant Professor
University of California, Berkeley
Dept. of Civil & Environmental Engineering
621 Davis Hall
MC 1710
Berkeley, CA 94720-1710
tinakc@berkeley.edu
Phone: (510) 643-4405
FAX: (510) 642-7483

Dr. Brian Colle, Associate Professor
State University of New York
Institute for Terrestrial & Planetary Atmospheres
Marine Sciences Research Center
119 Endeavor Hall
Stony Brook, NY 11794-5000
bcolle@notes.cc.sunysb.edu
Phone: (631) 632-3174
FAX: (631) 632-6251

Mr. John Cook
Naval Research Laboratory
7 Grace Hopper Avenue, Box 2
Monterey, CA 93943-5506
cook@nrlmry.navy.mil
Phone: (831) 656-4785
FAX: (831) 656-4017

Dr. Stephan de Wekker, Assistant Professor
University of Virginia
Dept. of Environmental Sciences
291 McCormick Rd.
P.O. Box 400123
Charlottesville, VA 22904-4123
dewekker@virginia.edu
Phone: (434) 924-3324
FAX: (434) 982-2137

Dr. Jim Doyle, Meteorologist
Naval Research Laboratory
Mesoscale Modeling Division
Marine Meteorology Division
7 Grace Hopper Avenue, Box 2
Monterey, CA 93943-5502
james.doyle@nrlmry.navy.mil
Phone: (831) 656-4716
FAX: (831) 656-4769

Dr. Robert Dumais
U.S. Army Research Laboratory
CISO-BE
White Sands Missile Range, NM 88002-5501
rdumais@arl.army.mil
Phone: (575) 678-4650

Dr. Dale Durran, Professor and Chair
University of Washington
Dept. of Atmospheric Sciences
Box 351640
Seattle, WA 98195-1640
durrand@atmos.washington.edu
Phone: (206) 543-7440

FAX: (206) 543-0308

CDR Daniel Eleuterio
Office of Naval Research
875 N. Randolph St.
Arlington, VA 22203-1995
daniel.eleuterio@navy.mil
Phone: (703) 696-4303

Dr. Ronald Ferek
Office of Naval Research
Ocean Battlespace Sensing S&T Department
Marine Meteorology, Code 322MM
875 N. Randolph St, Suite 1425
Arlington, VA 22203-1995
ron.ferek@navy.mil
Phone: (703) 696-0518
FAX: (703) 696-3390

Dr. H. Joe Fernando, Professor
University of Notre Dame
Dept. of Civil Engineering & Geological Sciences
156 Fitzpatrick Hall
University of Notre Dame
Notre Dame, IN 46556
Fernando.10@nd.edu
Phone: (574) 631-9346
FAX: (574) 631-2980

Dr. Boris Galperin, Associate Professor
University of South Florida
College of Marine Science
Dept. of Physical Oceanography
140 Seventh Avenue South, MSL 138F
St. Petersburg, FL 33701-5016
bgalperin@marine.usf.edu
Phone: (727) 553-1249
FAX: (727) 553-1189

Dr. Joshua Hacker
Naval Postgraduate School
Dept. of Meteorology
589 Dyer Rd.
Root Hall, Rm 254
Monterey, CA 93943
jphacker@nps.edu
Phone: (831) 656-2722

Dr. Andrew Jones, Senior Research Scientist
Colorado State University
Cooperative Institute for Research in the Atmosphere
1375 Campus Delivery
Fort Collins, CO 80523-1375
jones@cira.colostate.edu
Phone: (970) 491-7808
FAX: (970) 491-8241

Mr. David Keller
AFWA
16th Wx Squadron
Offutt AFB, 68113
kellerd@offutt.af.mil
Phone: (402) 294-1649

CWO3 Thomas Muschamp, Meteorological & Oceanographic Officer
MWSS 372 MWSG-37
3d MAW Box 555861
Camp Pendleton, CA 92055
thomas.muschamp@usmc.mil
Phone: (760) 889-4077

AG1 Raul Ramirez
Naval Oceanography Special Warfare Center
San Diego, CA 92110
raul.ramirez@navsoc.socom.mil
Phone: (619) 537-1013

Dr. Scott Sandgathe, Principal Meteorologist
University of Washington
Applied Physics Laboratory
1013 NE 40th Street
Seattle, WA 98105-6698
sandgathe@apl.washington.edu
Phone: (541) 988-0289
FAX: (206) 543-6785

Dr. Jim Steenburgh, Professor and Chair
University of Utah
College of Mines & Earth Sciences
Dept. of Atmospheric Sciences
135 S. 1460 E, Rm 819
Salt Lake City, UT 84112-0110
jim.steenburgh@utah.edu
Phone: (801) 581-8727
FAX: (801) 585-3681

Lt. Col. Robert Swanson, Jr., Deputy Chief of Staff, G-2
Deputy Director, Army Policy
1000 Army Pentagon
Room 2D383
Washington, DC 20310-1000
robert.t.swanson@us.army.mil
Phone: (703) 695-2726
FAX: (703) 697-7605

Dr. Eric Terrill, Director
Coastal Observing R&D Center
Marine Physical Laboratory
Scripps Institution of Oceanography
Keck Center for Ocean Atmosphere Research
La Jolla, CA 92093-0213
eterrill@ucsd.edu
Phone: (858) 822-3101
FAX: (858) 534-7132

Dr. Robert Walko, Senior Scientist
University of Miami
RSMAS
4600 Rickenbacker Causeway
Miami, FL 33149
rwalko@rsmas.miami.edu
Phone: (305) 421-4621
FAX: (305) 421-4711

Dr. Yansen Wang
U.S. Army Research Laboratory
Adelphi, MD 20783
yansen.wang@ds.arl.army.mil
Phone: (301) 394-1310

Dr. Keith Wilson, Research Physical Scientist
U.S. Army Corps of Engineers
Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory
72 Lyme Rd.
Hanover, NH 03755-1290
D.Keith.Wilson@usace.army.mil
Phone: (603) 646-4764
FAX: (603) 646-4644