MOUNTAIN TERRAIN ATMOSPHERIC MODELING AND OBSERVATIONS PROGRAM

The MATERHORN:

Toward Improving the Prediction of Mountain Weather

by

H.J.S. Fernando

Environmental Fluid Dynamics Laboratories
Department of Civil & Environmental Engineering and Earth Sciences
and
Aerospace & Mechanical Engineering
University of Notre Dame

A Multidisciplinary University Research Initiative (MURI)

Aimed at

Improved weather prediction in complex terrain

ONR FY 2011 MURI TOPIC #7:

Improved Meteorological Modeling in Mountain Terrain

(Topic Chiefs: Dr. Ronald J. Ferek and Dr. Daniel Eleuterio, ONR)

Additional support: Army Research Office (Gordon Videen and Walter Bach)

www.nd.edu/~dynamics/Materhorn

Principal Investigators:

H.J.S. Fernando

(ND)

Eric Pardyjak

(UU)

Stephan De Wekker

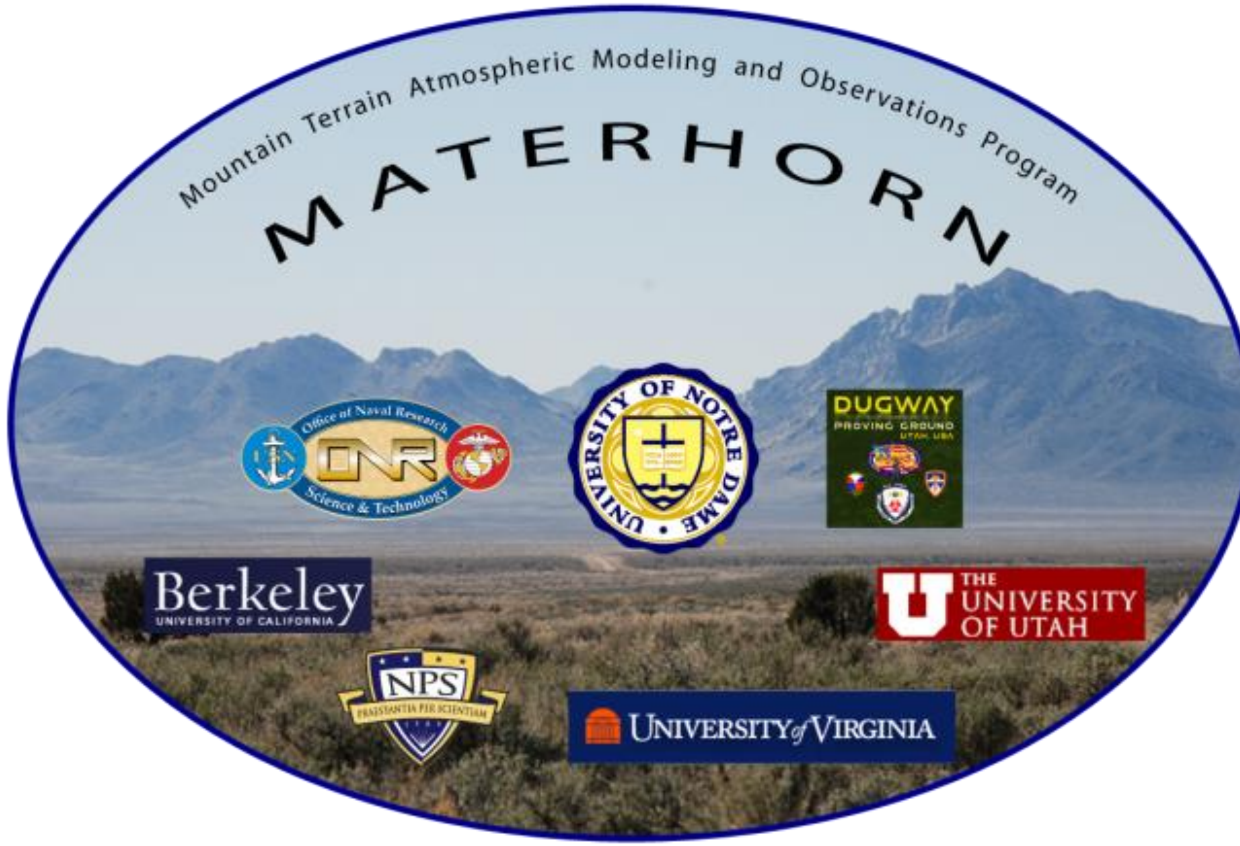
(UVA)

Josh Hacker

(NPS/NCAR)

Tina Katopodes Chow

(Berkeley)



Advisory Committee

- Vanda Grubišić
- Dave Emmitt
- John Pace

Why a multidisciplinary approach?

- Maturity and community advancement of state-of-the-science mesoscale models such as the Weather Research and Forecast model (WRF) and COAMPS
  - Yet , mountain terrain predictions leaves much to be desired
- New observational capabilities have arrived – were ready for MATERHORN IOP deployment (e.g., radiometers, sensor networks, DTS, small UAVs)
- Probabilistic (ensemble) and adjoint (deterministic) methods are both making progress – need to identify sensitivity to initial conditions, use observations, and identify model parameters
- Need for new instrumentation - push the frontiers – needed mechanical, optical and electrical engineers and innovators
- Hope that the total will be larger than the sum of the parts
- Collaboration is enlightening – those with same goals, different skill sets – diversity improves the quality

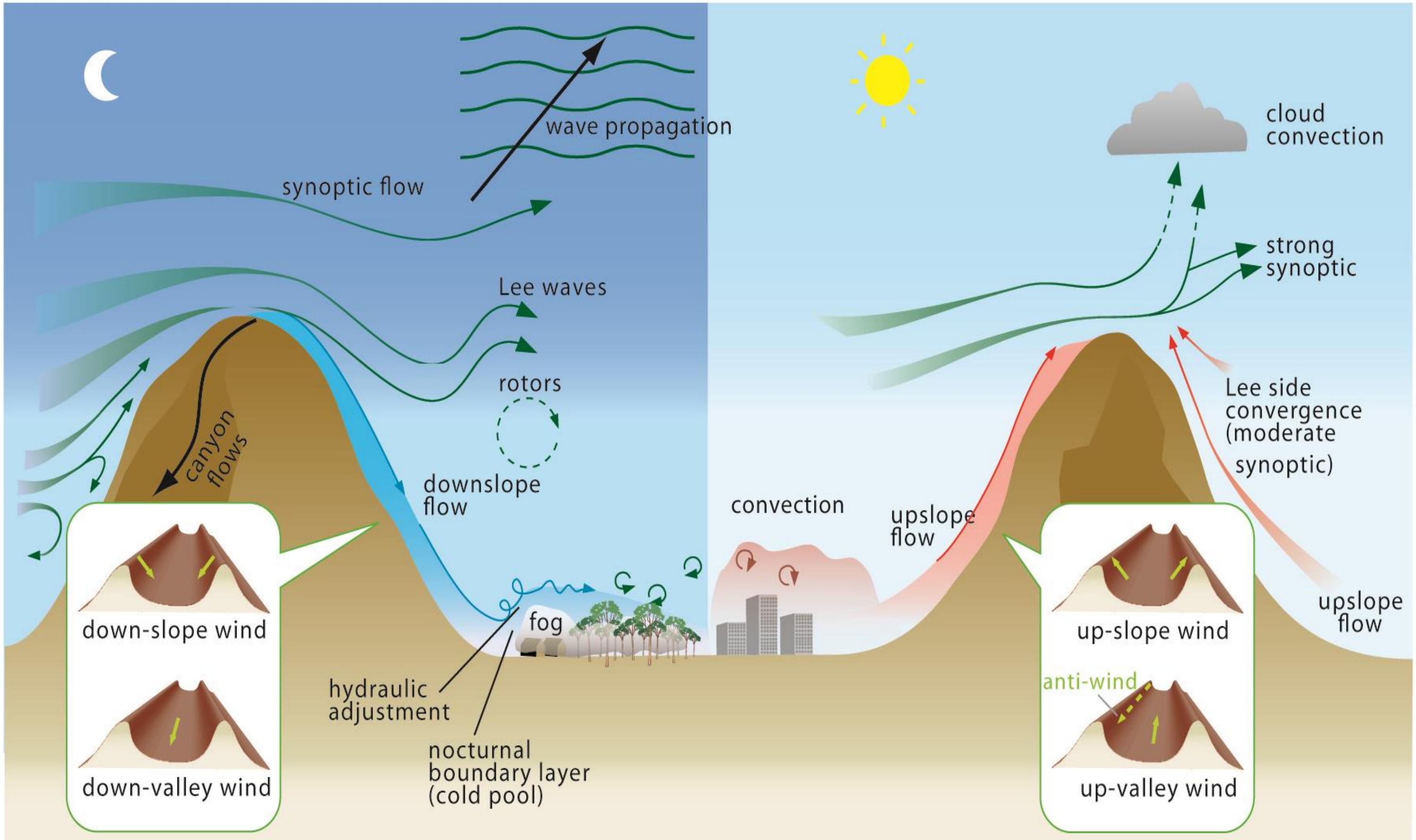
Some Scientific Barriers

- Predictability of near-surface atmospheric wind and temperature in complex terrain – poor
- Accurate measurement of model relevant parameters have been lean - soil properties and the surface energy balance over extended periods
- Near-surface temperature forecasts over arid regions are very sensitive to soil moisture
- Need to identify, understand and remedy model deficiencies –structural, physics and dynamcs

Barriers .....

- Ultra high-resolution (50 m horizontal or finer) simulations have been nearly impossible over complex terrain
- Issues remains on turbulence closure modeling, terrain representation and numerical methods (What is the best? – e.g., terrain-following vs. immersed boundary method)
- Nocturnal predictions are not satisfactory -- unknown physical processes?

Mountain terrain processes



Look at meso-scale to Kolmogorov scale

Fernando, Ann Rev Fluid Mech. 2010

How about scale interactions?

MATERHORN has four components working symbiotically across institutions and disciplines

Modeling (Hacker)

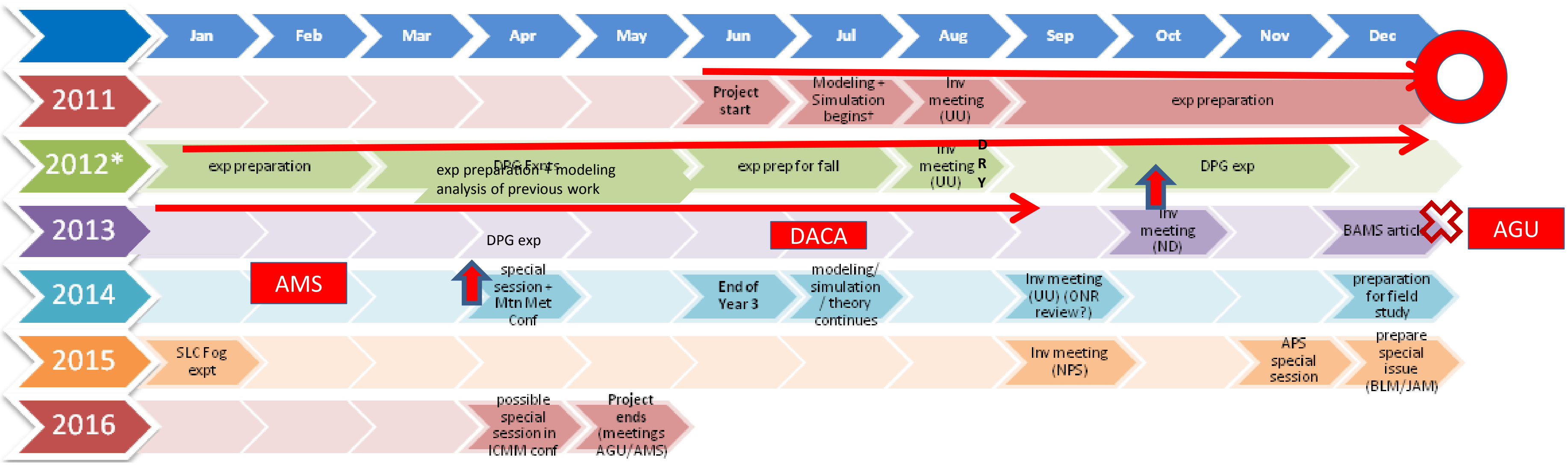
Experiments (Pardyjak)

Technology (Fernando)

Parameterizations (Fernando)

Timeline

Special Session on Complex Terrain (DeWekker & Chow) – AGU Fall SF 2011
Special session on Atmospheric Observations and Modeling in Complex Terrain (Fernando) – AMS Annual Meeting, New Orleans, 2012
A special session on “Atmospheric boundary layers in complex terrain and over ice, snow and vegetated surfaces” at the Davos Atmosphere and Cryosphere Assembly (DACA), 8-12 July 2013 (de Wekker)
A special session on “Research on Improving Weather Prediction for Mountain Terrain,” 2013 Fall AGU Meeting , - Fernando et al.
A special session on “THE MATERHORN PROJECT” at the 92nd AMS Meeting, January 22-26, 2012, - Di Sabatino and Ferek



25 Aug. - 28 Aug. 2012: MATERHORN-X-DRY
25 Sept. – 25 Oct. 2012: MATERHORN-X-FALL
1 May– 30 May 2013: MATERHORN-X-SPRING

MATERHORN-M

Accomplishments

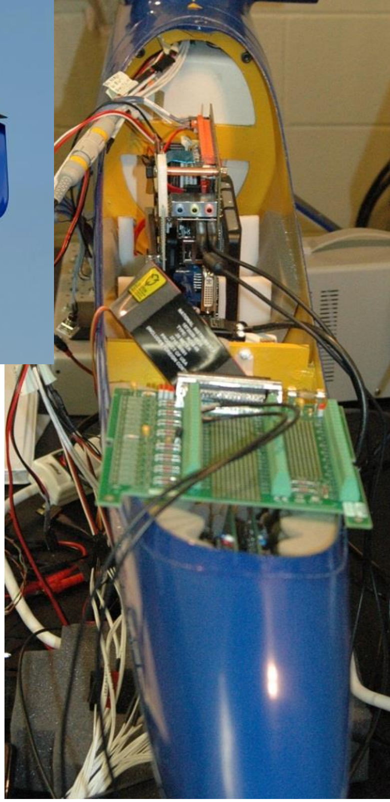
MATERHORN - M

- WRF and COAMPS - more prone to forecast error when predicting in complex terrain than over flat terrain
- High fidelity flow physics and thermodynamics are very important
- Assimilation of near-surface observations can improve short-range forecasts
- Ensemble methods appear superior to 3D variational methods
- Near-surface temperature forecasts - very sensitive to soil moisture
- Probabilistic methods for predicting observation impact and determining optimal observation siting appear tractable for short-range, near-surface forecasts
- The immersed boundary method (IBM) implemented in WRF model can be used to get 50m resolution in complex tarrain

MATERHORN-T

Accomplishments

Will be on display



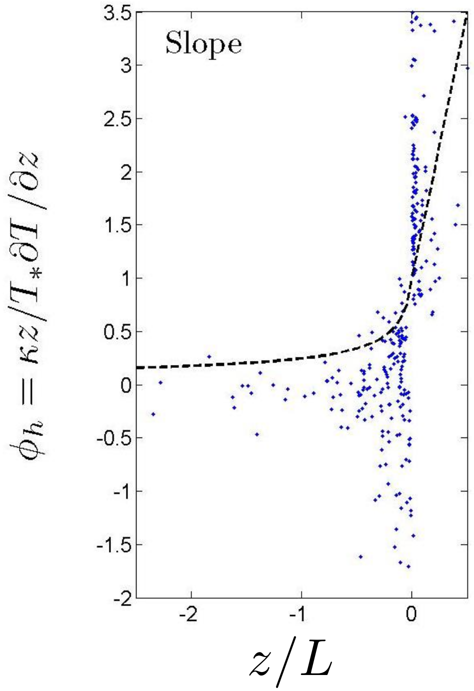
- **<u>Unmanned Aerial Vehicle</u>**
  - Temperature, humidity, wind velocity
  - Turbulent components (combo probe) up to Kolmogorov
  - Onboard data acquisition
  - Automated flight tracks
  - Fog droplet size distribution (FASS)

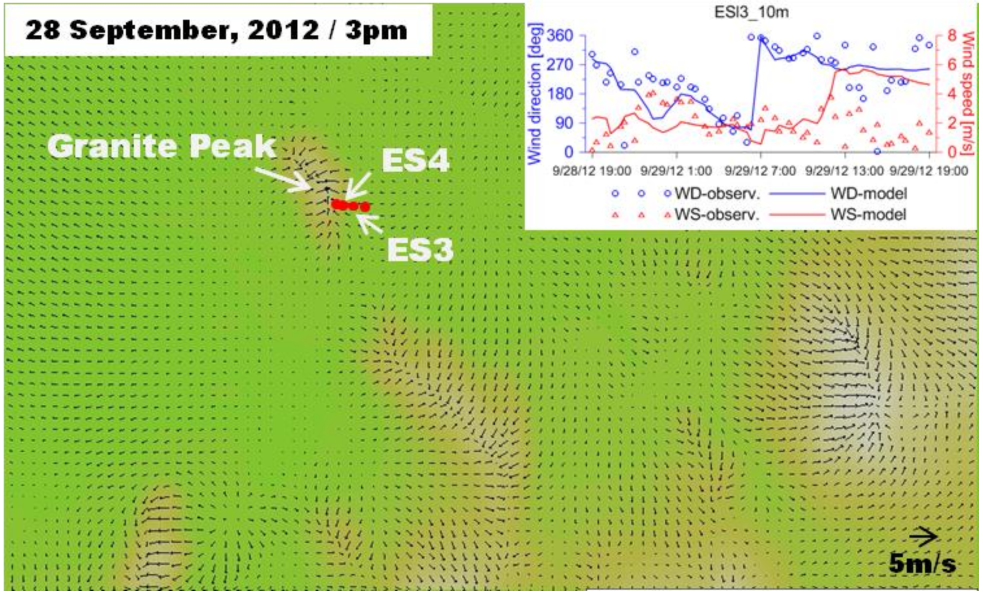
- **<u>Sonic-hotwire Combo System</u>**
  - Developed and deployed
  - unique turbulence information, dissipation scales
    - Allow myriad of turbulence and multiscale studies

MATERHORN-P

Accomplishments

Accomplishments: MATERHORN - P





•**Evaluated existing boundary layer parameterizations using field data** - YSU (YonSei University), MRF (Medium Range Forecast), MYJ (Mellor-Yamada-Janjic), BouLac (Bougeault-LaCarrere), QNSE (Quasi-Normal Scale Elimination) and ACM2 (Asymmetric Convective Model)

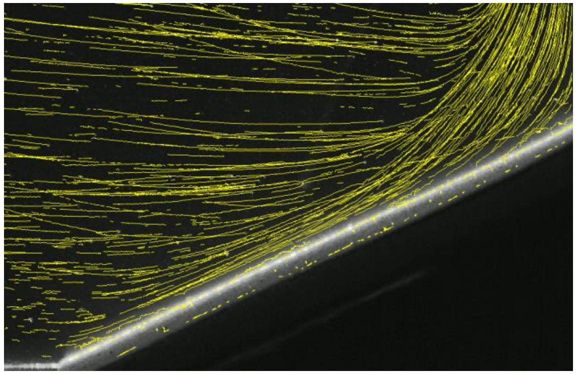
•**Evaluating Monin-Obukhov Similarity Theory –** Failure during transition periods at all sites; failure at night on slope

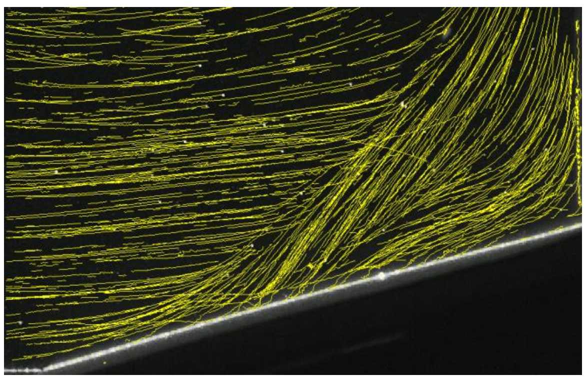
• **Development of new parameterizations** – In progress

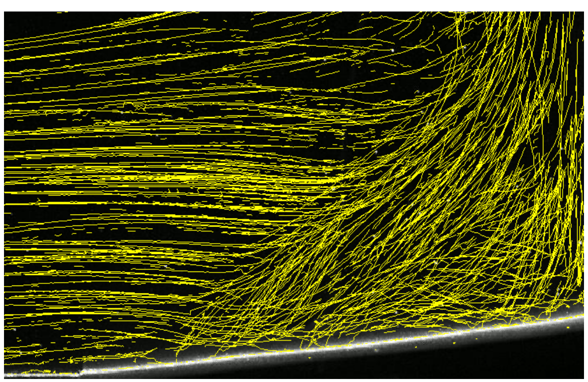
Laboratory - Flow Separation

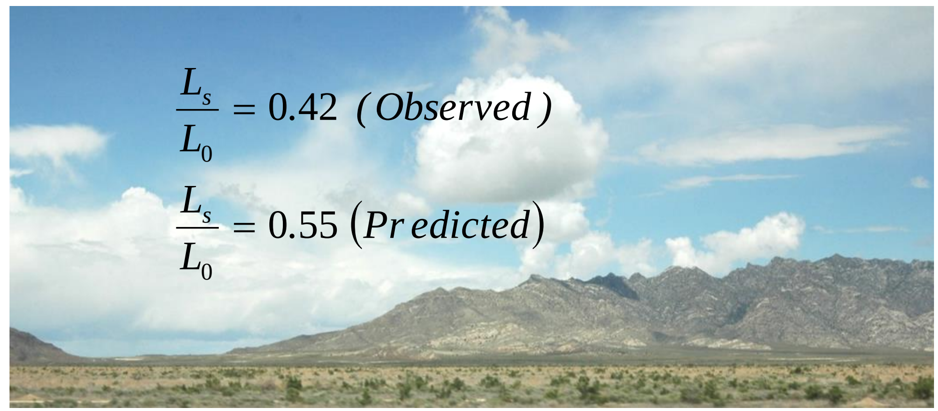
$$\frac{L_s}{L_0} = \left[1 + \Pi \frac{\sin^{1/4} 2\beta_s}{\sin \beta_s} \right]^{-1}$$

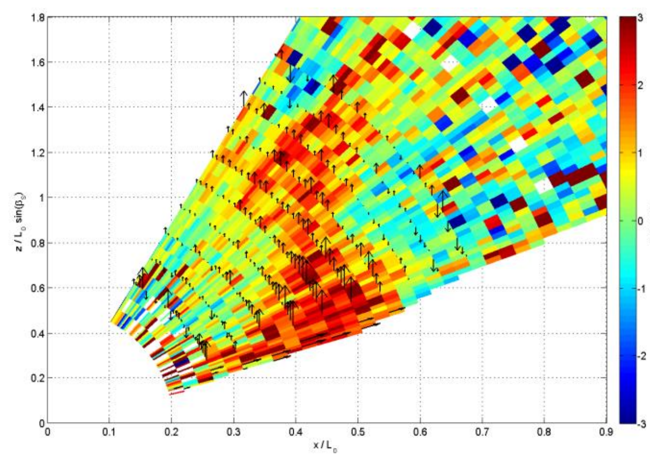
Theoretical











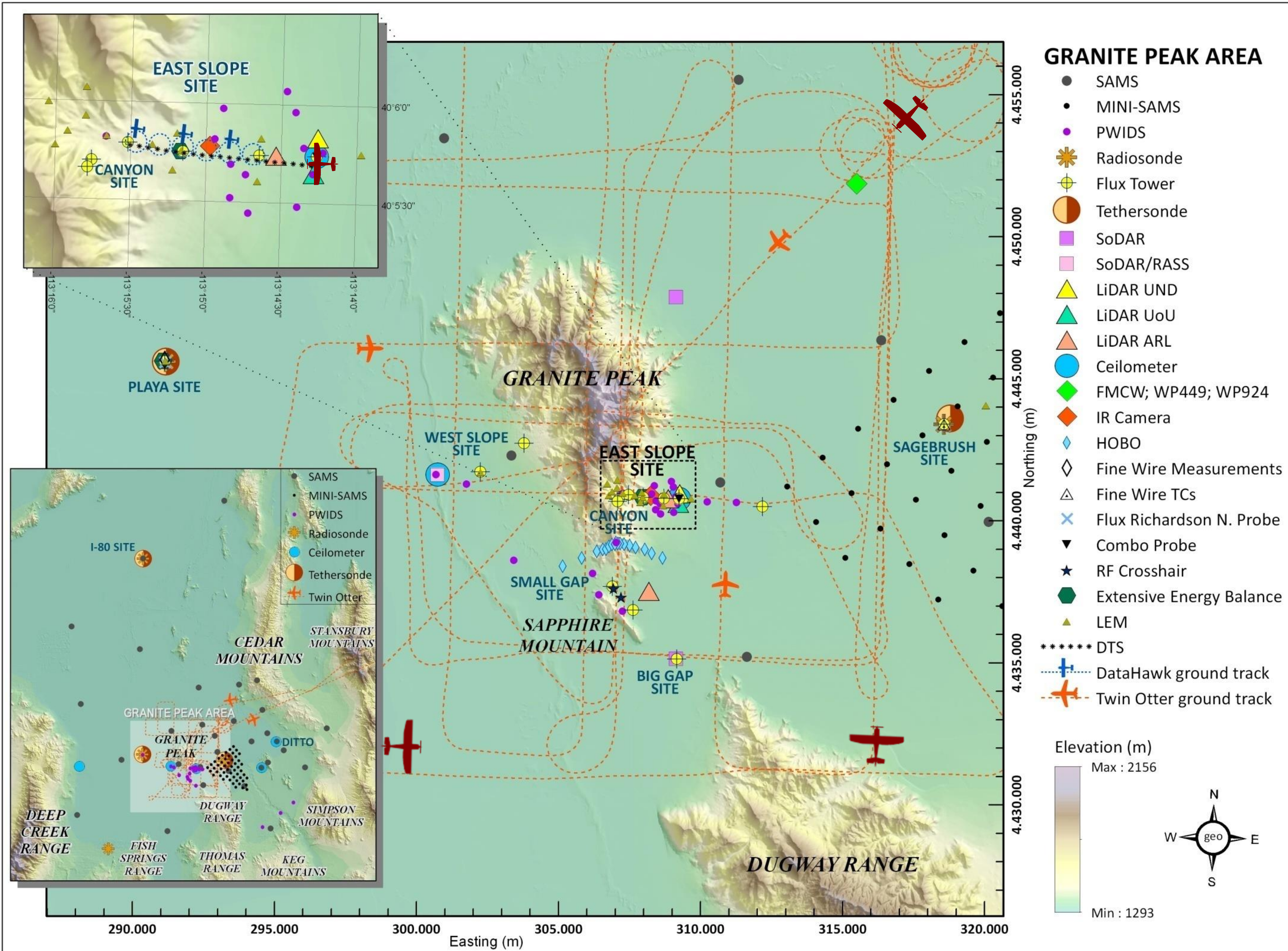
MATERHORN-X

Accomplishments

MATERHORN – X (Autumn & Spring)

GMAST - US Army Dugway Proving Ground

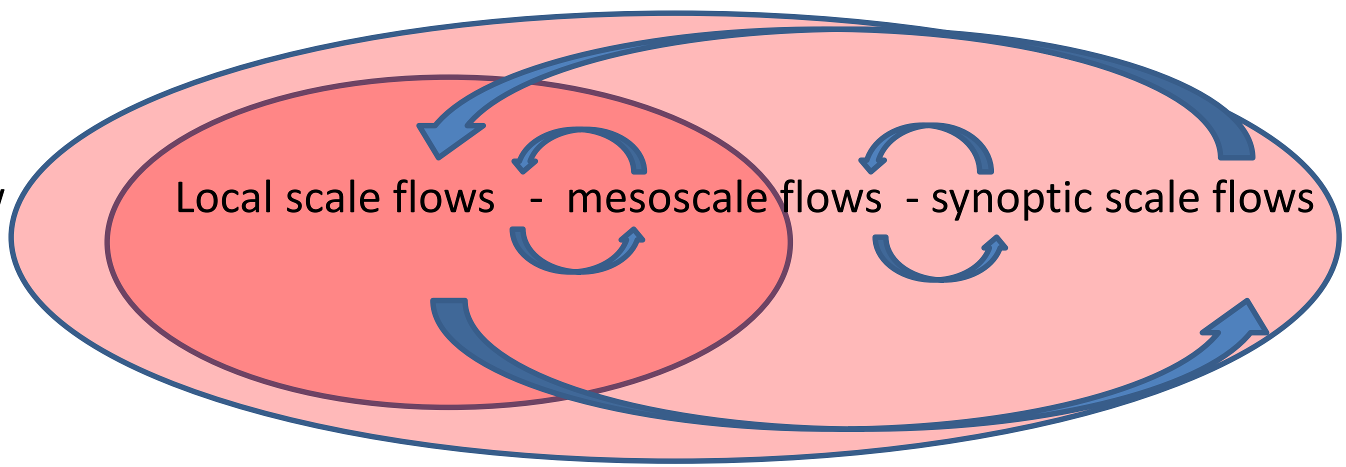

Granite Mountain
Test Bed [GMAST]
US Army Dugway Proving Ground


GRANITE PEAK AREA
SAMS
MINI-SAMS
PWIDS
Radiosonde
Flux Tower
Tethersonde
SoDAR
SoDAR/RASS
LiDAR UND
LiDAR UoU
LiDAR ARL
Ceilometer
FMCW; WP449; WP924
IR Camera
HOBO
Fine Wire Measurements
Fine Wire TCs
Flux Richardson N. Probe
Combo Probe
RF Crosshair
Extensive Energy Balance
LEM
DTS
DataHawk ground track
Twin Otter ground track
Elevation (m)
Max : 2156
Min : 1293
N
W
E
S
geo
EAST SLOPE SITE
CANYON SITE
40°6'0"
40°5'30"
-113°16'0"
-113°15'30"
-113°15'0"
-113°14'30"
-113°14'0"
PLAYA SITE
GRANITE PEAK
WEST SLOPE SITE
SMALL GAP SITE
SAPPHIRE MOUNTAIN
BIG GAP SITE
SAGEBRUSH SITE
DUGWAY RANGE
I-80 SITE
Twin Otter
CEDAR MOUNTAINS
STANSBURY MOUNTAINS
GRANITE PEAK AREA
DITTO
DEEP CREEK RANGE
FISH SPRINGS RANGE
THOMAS RANGE
KEG MOUNTAINS
SIMPSON MOUNTAINS
4.455.000
4.450.000
4.445.000
4.440.000
4.435.000
4.430.000
Northing (m)
290.000
295.000
300.000
305.000
310.000
315.000
320.000
Easting (m)

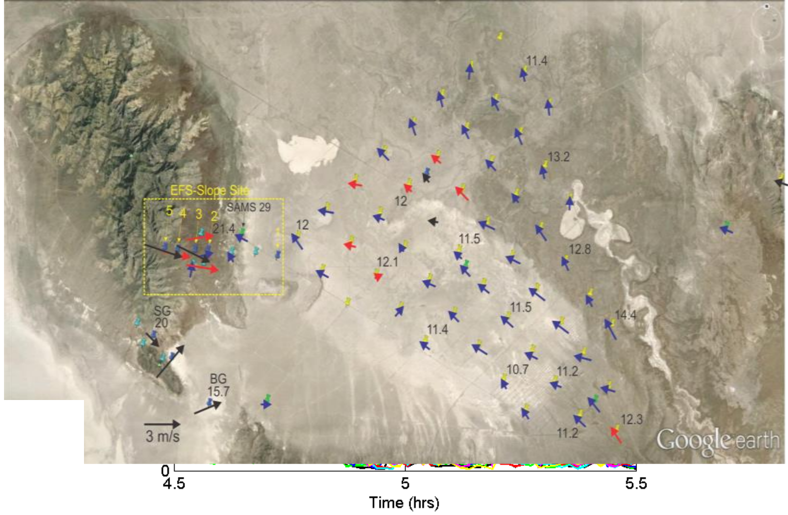
Key Results

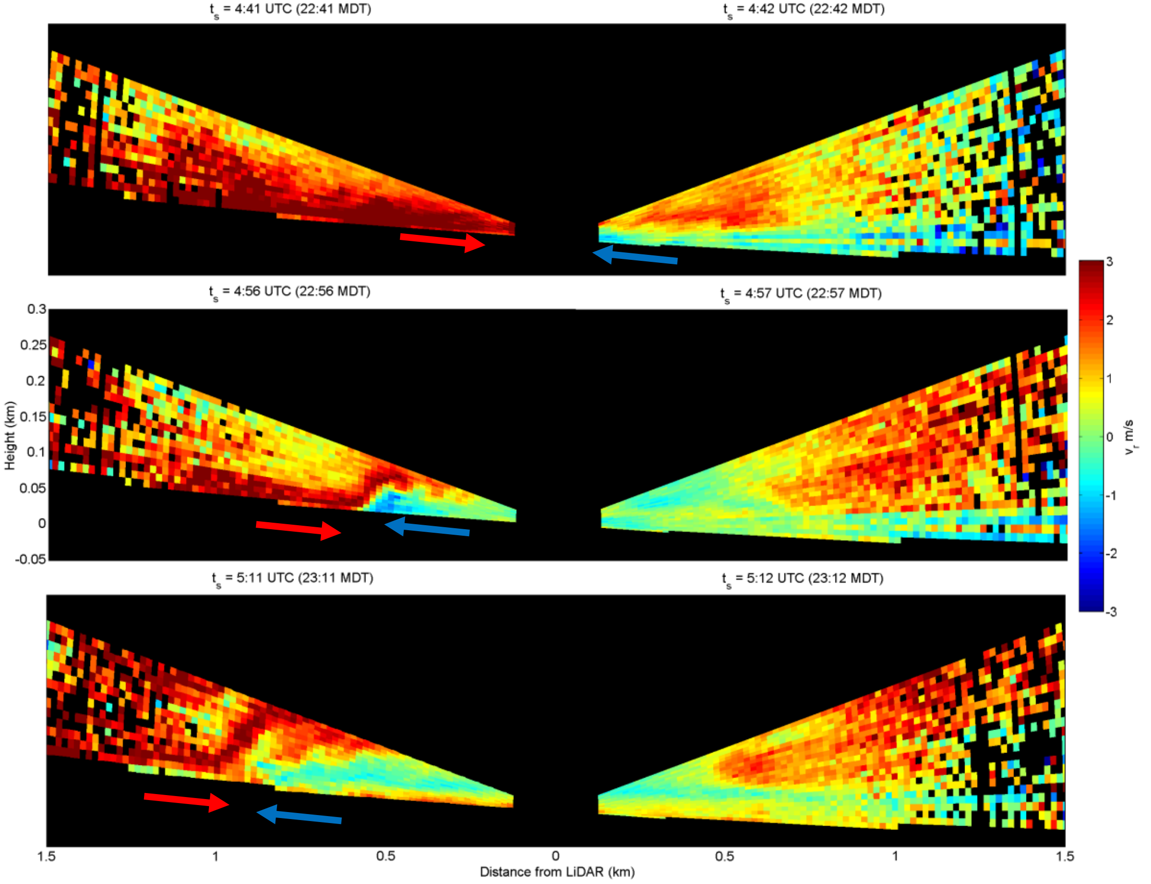
- Unprecedented instrumentation allowed probing from the regional scale to millimeter scales, systematically – Unique Hallmarks of MATERHORN – presented at recent meetings
- Delineate local forcing mechanisms (shadows, topographic inhomogeneities)
- Understanding the energy cascades, momentum transfer in the atmosphere, near the mountains, from regional to local
- Retrieval algorithms were developed – airborne Lidar, Combo

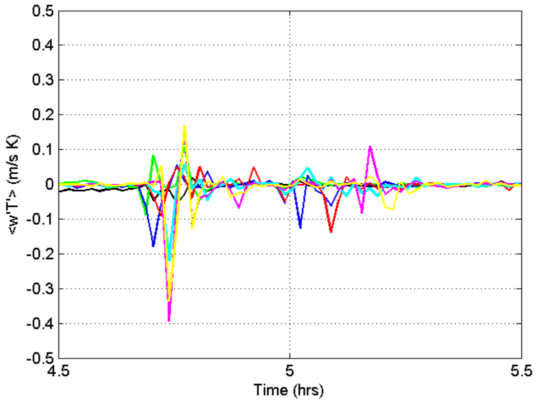
Multi-scale flow interactions

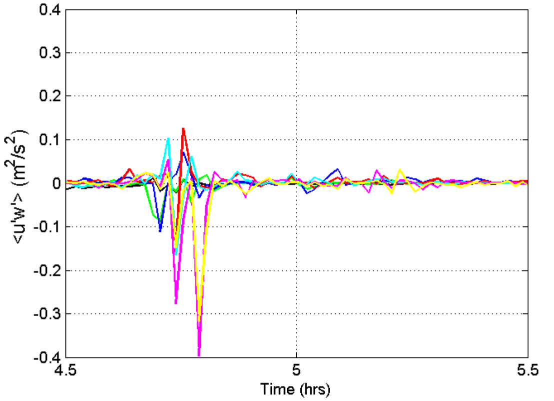


Gravity Current Collisions (Hocut and Hoch)

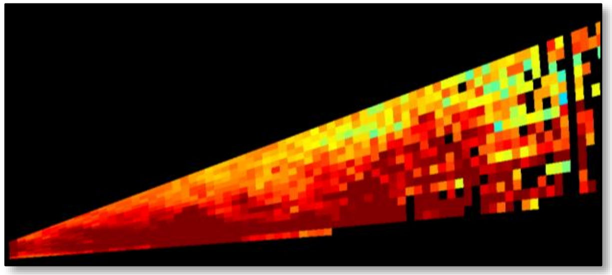




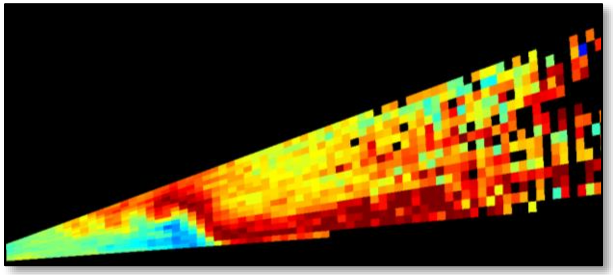




Gravity Currents Collide



4:41 UTC (22:41 MDT)



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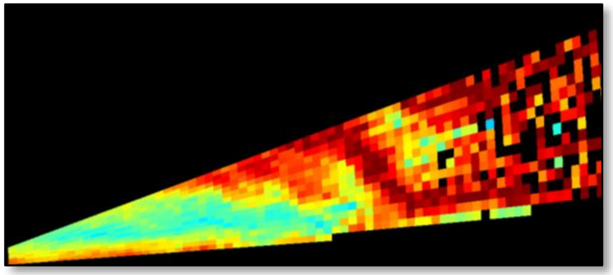

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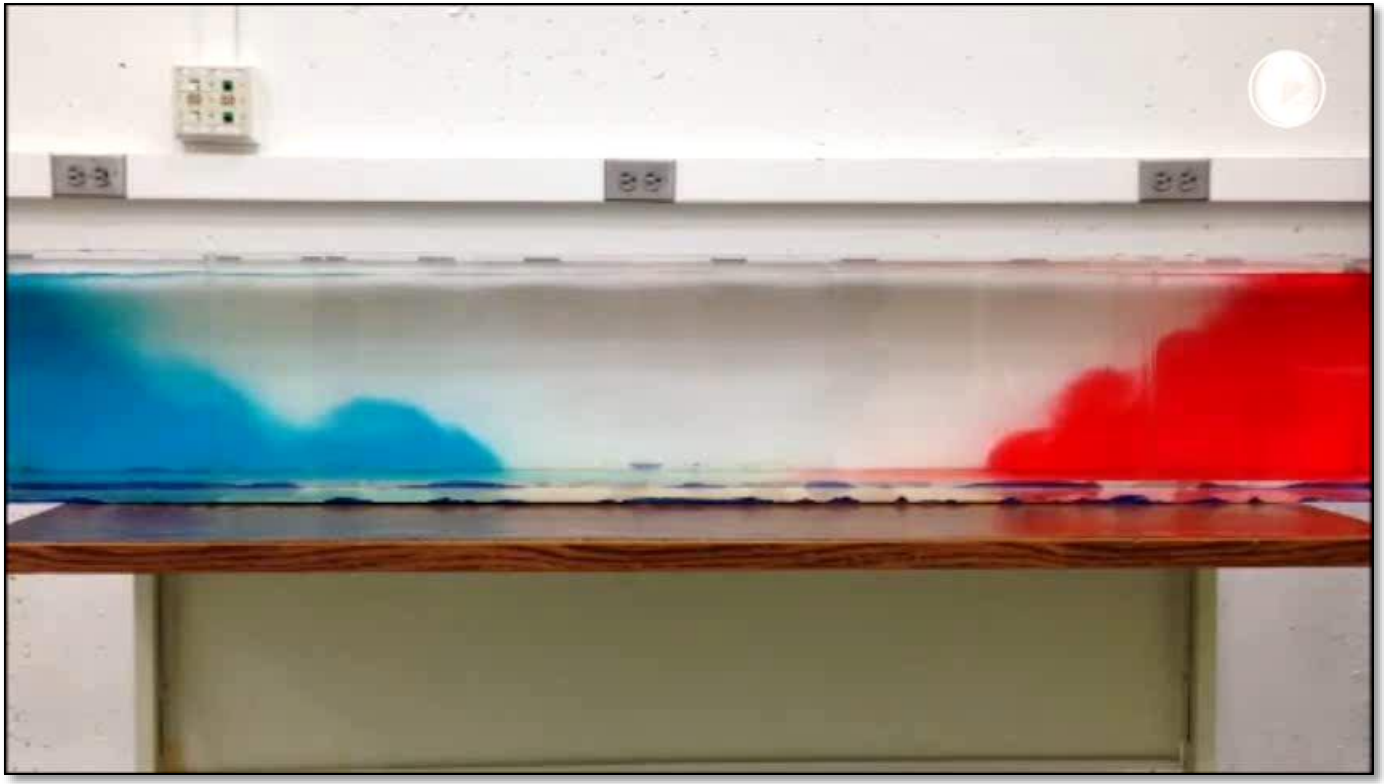
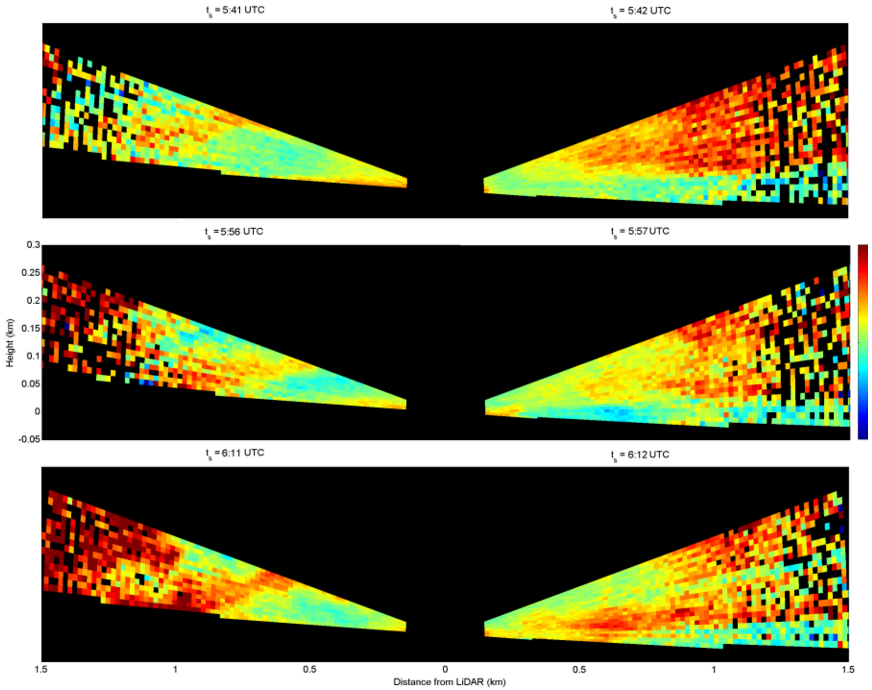
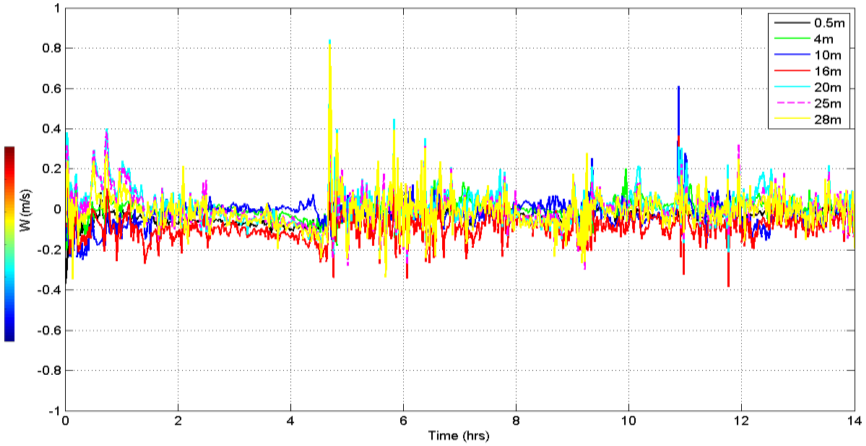
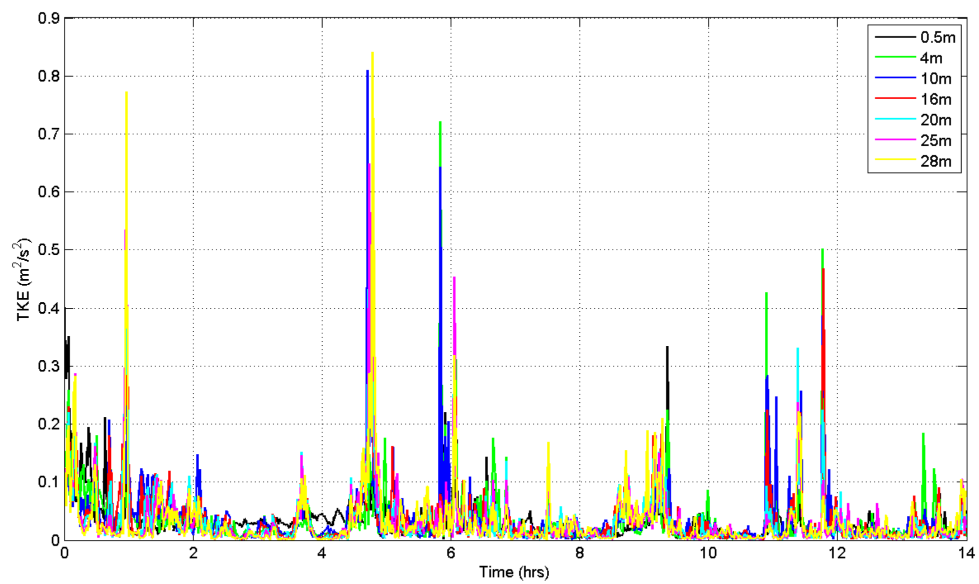


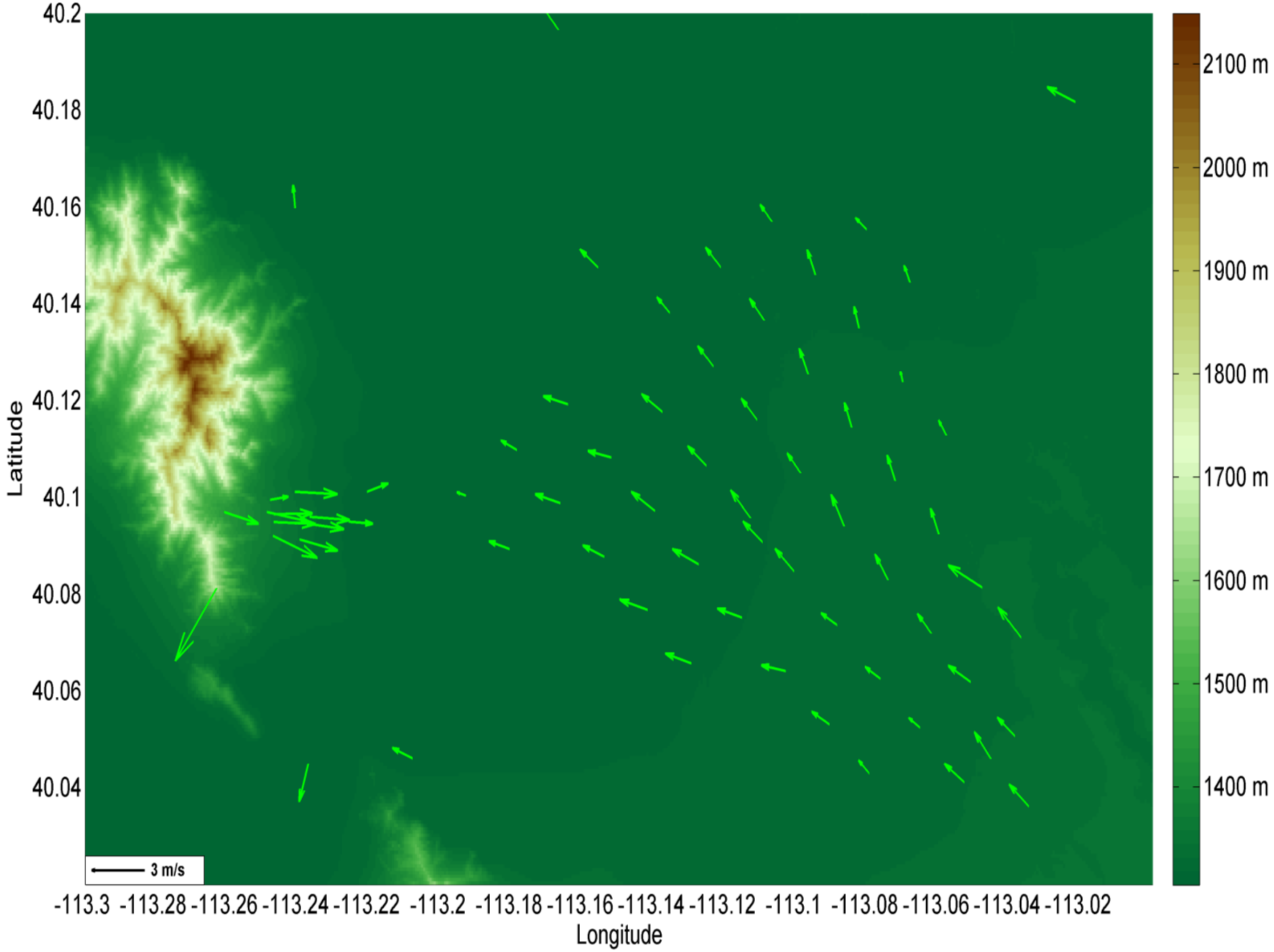




Secondary Collisions



Proper Orthogonal Decomposition of Velocity Vectors



10/19/2012 21:59 MDT

10/19/2012 03:59 UTC

Summary

- Senior PIs: 11
- Research faculty: 4
- Technical staff: 8
- Post docs: 8
- Graduate Students : 18 PhD and 3 MS (Total 21)
- Undergraduate Students: 13
- Collaborators (original proposal): 5
- Collaborators joined: 11

(total: 67)

Additional Funding

- Army Research Office
- Air Force Weather Agency
- University of Utah (Research Office)
- University of Notre Dame (Research Office)
- Wayne and Diana Murdy Endowment at Notre Dame

PUBLICATIONS (past two years)

- Journal publications: 16
- Journal Papers under Review or Revision: 8
- Conference (full length) papers: 4
- Conference Presentations: 54
- Awards: 1 Senior Faculty; 4 Students (best conference paper awards)
- Recognitions: 1 Senior Faculty

AMS special collection on "MATERHORN" – Zhaoxia Zhang

- 1. Fernando et al. – Materhorn; An Overview (BAMS), To be submitted to BAMS in 2013
- 2. Masey, J., J. Steenburgh et al., Sensitivity of Near-Surface Temperature Forecasts to Soil Properties over a Sparsely Vegetated Dryland Region, To be submitted to JMAC in August 2013
- 3. Hacker, J., and others, The potential utility of high-resolution ensemble sensitivities during weak flow in complex terrain. To be submitted to MWR or WAF in August 2013
- 4. Wang et al., Atmospheric boundary layer wind characterization during MATERHORN using triple Doppler wind lidars. To be submitted to JAMC in October 2013 5. Laura Leo et al. Downslope flow, internal waves and mixing in katabatic currents, To be submitted to JAS in 2013
- 6. Pratt, T., N. Dodson, Z. Lin, S. Silliman, S. Di Sabatino, L. Leo, and P. Yang, Polarization Characterization of Microwave Reflections for Local and Field-Scale Remote Sensing of Soil Moisture. To be submitted to JTECH in 2013
- 7. Pratt, T., Z. Lin, S. Di Sabatino, L. Leo, and J. Bryant, Y. Sun, Temperature Sensitivity of Polarimetric RF Remote Sensing to Soil Dielectric Properties. To be submitted to JTECH in 2013
- 8. Pu Z. and others. A real-time WRF forecast during the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program: Performance and evaluation with observations, To be submitted to WAF in 2013
- 9. Zhang, H. and Z. Pu, Predictability of Atmospheric Conditions over Complex Terrain with Ensemble Kalman Filter Assimilation of Observations during MATERHORN. To be submitted to MWR or JAMC in 2013.
- 10. Pal, De Wekker et al. : Investigation of the spatio-temporal variability of the atmospheric boundary layer depths over mountainous terrain observed with a suite of ground-based and airborne instruments during the MATERHORN field experiment, JAMC (October 2013),
- 11. De Wekker, Emmitt, Pal et al. Wind structure in the boundary layer around an isolated mountain from airborne measurements during the MATERHORN field study, JAMC (October 2013)
- 12. De Wekker, Liu, Knievel, et al. An evaluation of the operational DPG RTFDDA-VLES using airbone Doppler lidar data, MWR (December 2013)
- 13. Liu, Knievel, De Wekker et al., Assimilating airborne Doppler lidar data in the operational DPG RTFDDA. MWR (December 2013)
- 14. Nadeau, N., E. Pardyjak, C. Hang and D. Jensen, Soil moisture dynamics and evaporation in arid alpine environments, To be submitted to JMAC in summer 2014
- 15. Dimitrova et al. – Modeling of basin scale circulation during MATERHORN, To be submitted to JAMC in 2013/2014
- 16. T. Katopodes et al., Immersed boundary method for WRF applied to complex terrain", To be submitted to MWR in 2014
- 17. T. Katopodes et al., "Slope cooling and drainage flow with LES, To be submitted to JMAC in 2014.
- 18. Zhang, H., Z. Pu and X. Zhang, 2013: Examination of errors in near-surface temperature and wind from WRF numerical simulations in regions of complex terrain. *Wea. Forecasting.* **28**, 893-914.

BLM Issue (Di Sabatino)

1) Fernando and Team "Scaling of Upslope Flows in Complex Terrain" - (tentative title)- Yes
2) Hunt et al. "Stable stratification and flow separation: theory and verification" (tentative title)- Yes
3) Di Sabatino, Leo et al. "“Analyses of evening transition periods from MATERHORN-X” (tentative title) - Yes
4) Dimitrova, Silver "on B-L parameterizations within WRF“ _ Yes
5) Sandip PAL et al. "evening transitions - morning transition" ???
6)Pardyjak and Team "application and limitation of MOST theory" ???
7) Pardyjak and Team "Shadow fronts etc..." - Yes
8) Hoch et al - "energy balance..." ???
9) Hocut et al. "valley flow interactions - mechanisms" ???
10) Grachev et al. " Turbulence spectra and analyses in slope and valleys…“ - Yes
11) De Wekker et al. "BL parametrisations in convective conditions" ???
12) Katopodes-Chow and TEAM "LES applications and analyses" - Yes
13) Dale et al. "Analyses of DATAHAWK during MATERHORN"???
14) Thompson el al. “On flow separation under stable conditions: results from flow visualization in Materhorn X” (Tentative Title) - Yes

Special Issue of the Journal of Environmental Fluid Mechanics

Eric Pardyjak

Inspirational


KEEP
CALM
AND
CARRY
ON


Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.
Winston Churchill
Former Prime Minister of the UK
(1874-1965)
QuoteHD.com


[redacted]
keep going.
— Winston Churchill

B: University Teams

- University of Notre Dame

  PIs: H.J.S. Fernando (Civil & Environmental Engineering and Geosciences), T. Pratt (Electrical Engineering; radar remote sensing), P. Dunn (Mechanical Engineering; aerosols and fog) (Total 3)

  Senior Visitors: Eliezer Kit (Tel Aviv), Julian Hunt (London), S. DeSabatino (Lecce), R. Dimitrova (ND, WRF Simulations)

  Technical/Research Staff: M. Zenk (Aerospace Engineering; UAV, Pilot), S. Coppersmith (Electrical Engineering; instrumentation), Neil Dodson (Research Engineer), Leonard Montenegro (Research Engineer), Orson Hyde (Technical Assistant) (Total 6)

  Post Docs: Dan Liberzon, Laura Leo, Charles Retallack (Total 3)

  Graduate Students: Jordan Bryant (MS, ESTEEM Fellow), Patrick Conry (PhD, Schmidt Fellow), Chris Hocut (PhD), Zi Lin (MS), Kelly McEnerney (PhD), Zachariah Silver (PhD), Michael Thompson (MS) (Total 7)

  Undergraduate Students: (Jordan Bryant), Greg Brownell, Andrew Harper, Mike Higginson, Kevin Peters, Kristin Stryker, Capt. Samuel White, (Patrick Conry), Rich Strebinger, Sean Coppersmith (Total 9)

B: University Teams

- Naval Postgraduate School

  PIs: – Joshua Hacker (Atmospheric Sciences; mesoscale modeling) (Total 1)

  Technical/Research Staff: – Mary Jordan (Total 1)

  Post Docs:– Jared Lee, Walter Kolczynski (partly supported), (Total 2)

  Graduate Students:) – Maj. Paul Homan, Capt. Sean Wile (Total 2 PhD)

- University of California, Berkeley

  PIs: – Fotini Katopodes Chow (Civil Engineering, LES and Mesoscale modeling) (Total 1)

  Technical/Research Staff: – none (Total 0)

  Post Docs:– none (Total 0)

  Graduate Students:) – Jason Simon, Jingyi Bao (Total 2 PhD)

B: University Teams

- **University of Utah**

  PIs: – Eric Pardyjak (coordinator, Mechanical Engineering; field lead), S. Hoch (Atmospheric Sciences, observations), Z. Pu (Atmospheric Sciences; DA, ensemble forecasting), J. Steenburgh (Atmospheric Sciences; modeling) and D. Whiteman (Atmospheric Sciences; observations) (Total 5)

- **Technical/Research Staff**: Caleb Fallgatter (Total 1)
- **Post Docs:** Vigneshwaran Kulandaivelu (Total 1)
- **Graduate Students:** – Chaoxun Hang (PhD), Estel Blay Carreras (PhD), Matthew Jeglum (PhD), Derek Jensen (PhD), Jeff Massey (PhD) , Hailing Zhang (PhD), Xuebo Zhang (PhD), Tim Price (PhD) (Total 8)
- **Undergraduate Students:** Nipun Gunawardena, Christan Holbert (Total 2)

- **University of Virginia**

  PIs: Stephen de Wekker (Atmospheric Sciences; Aerosol Lidar, model evaluation, optimal siting) (Total 1)
  Technical/Research Staff: – none (Total 0)
  Post Docs:– Zeljko Vecenai, Sandip Pal (Total 2)
  Graduate Students: – Temple Lee (PhD), Mark Sghiatti (MS) (Total 2)
  Undergraduate Students: - Nikita Dodbele, Max Newman, Ian deBoisblanc (total 3)

11 Other Collaborators – via Proposals

- Dr. Nick Ovenden University College, London, U.K. (Host: Notre Dame)
- Dr. Andrey Grachev, CIRES, NOAA, Boulder, Colorado (Host: Notre Dame)
- Professor Joachim Reuder, University of Bergen, Norway (Host: Utah)
- Professor Chad Higgins, Oregon State University, Corvallis, Oregon (Host: Utah)
- Dr. Stefano Serafin, University of Vienna, Austria (Hosts: Virginia and California, Berkeley)
- Dr. Dorita Rostkier-Edelstein, Environmental Sciences Division, IIBR, Israel (Host: Naval Postgraduate School)
- Professor Marcus Hultmark, Princeton University (Host: Utah)
- Dr. David J. Gochis, National Center for Atmospheric Research (Host: Virginia)
- Dr. Dave Emmitt, Simpson Weather Associate (Host: Virginia) – Twin Otter
- Professors Ben Balsley and Dale Lawrence, University of Colorado (Host: Notre Dame) - UAV
- Daniel Nadeau, École Polytechnique De Montreal, Canada (Host: Utah) – total 12

(Additional funding for collaborators were provided by Air Force Weather Agency and Army Research Office)

Collaborators (7)

(listed in the Proposal)

- James Doyle (Naval Research Laboratory)
- John Pace (US Army Dugway Proving Grounds)
- Dragan Zajic (US Army Dugway Proving Grounds)
- Yansen Wang (Army Research Laboratory)
- Julian Hunt (University of Cambridge, University College, London)
- Eliezer Kit (Tel Aviv University, University of Notre Dame)
- David Emmitt, Simpson Weather Associates

E. Potential Breakthroughs

- Significant improvements in understanding forecast errors in near-surface atmospheric temperature and winds
- Significant improvements in the forecasting of near-surface temperatures, atmospheric winds, and turbulence especially at night and during the early morning
  - Through improved data assimilation
  - Through identification of model deficiencies, and objective parameter tuning specifically targeted at land-atmosphere interactions and soil characteristics such as soil moisture
  - Through better observation siting
- Significant improvements in nocturnal forecasts using better sub-grid models
  - Use high resolution observations of fast processes
  - Theoretical Understanding

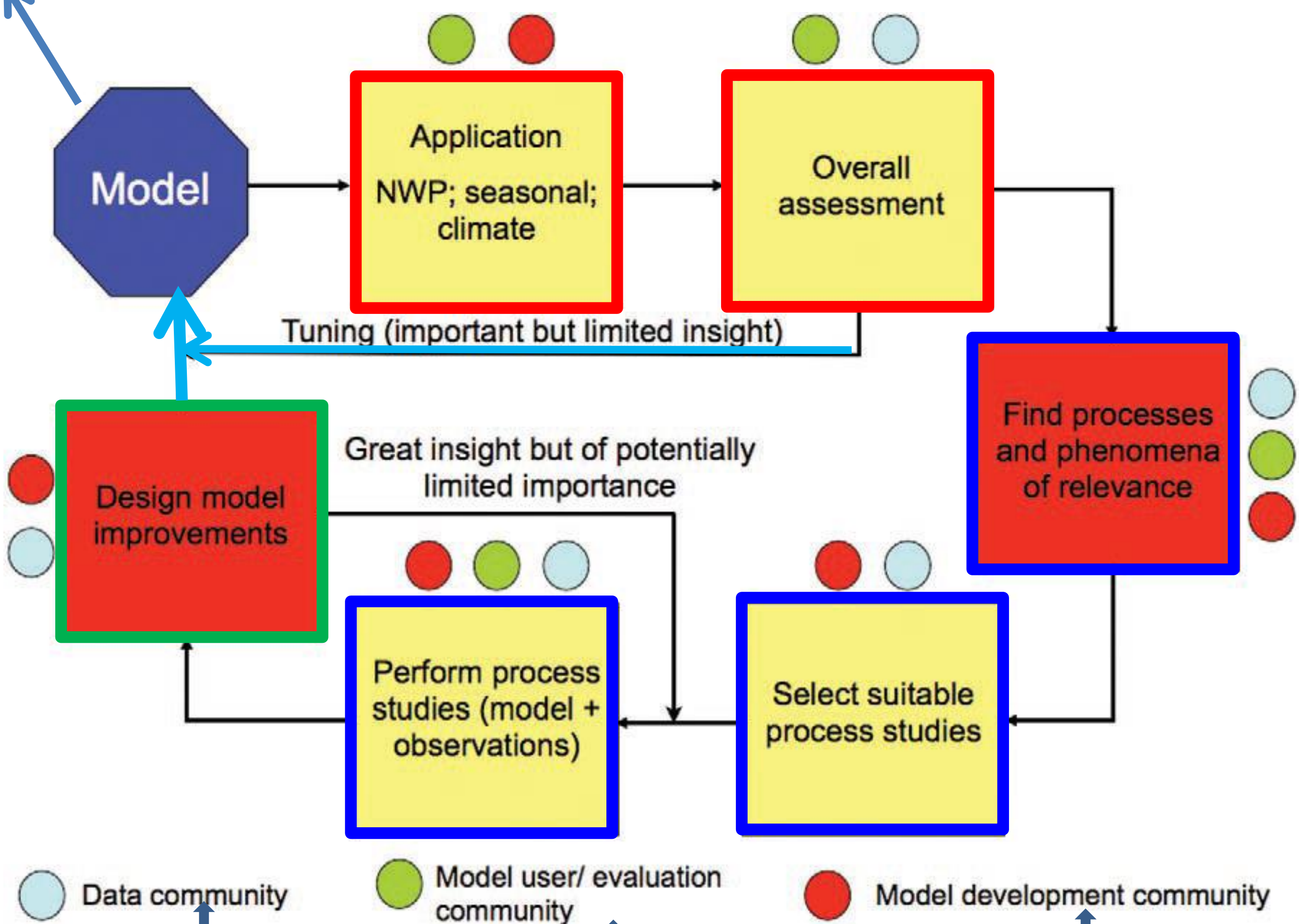
E. Potential Breakthroughs

- Vastly improved numerical techniques for LES of complex terrain flows
  - ultra high resolutions can be achieved
  - New processes and insights on high frequency processes
- New atmospheric small scale turbulence measurments technologies
  - Already great strides have been made
- New automated RF based moisture measurement technology
  - Moisture is a key variable for complex terrain
- Introduction of UAV based atmospheric measurement platforms for fine-scale quantities
  - A Pandora box! -- numerous opportunities for atmospheric sciences

(New paradigm proposed by Jakob; BAMS, 2010)

Improved Modeling of Complex Terrain Weather

A2: Approach



Materhorn - X
Materhorn - T

Materhorn - P (M)

Materhorn - M

Modus Operandi

- Assemble a group of skilled researchers with synergy - atmospheric scientists, fluid dynamicists, numerical and theoretical analysts, engineers and applied mathematicians
- Tap into best human resources, multiple universities
- Embrace all methodologies - laboratory experiments, high resolution numerical simulations, theoretical advances and sophisticated field experiments
- Integrate systematically - A new paradigm?
- Leverage alternative resources – DOD (Navy, Army and Air force), NOAA, NCAR and other US and foreign universities

B. MURI Team - PIs

PI: Dr. Harindra Joseph Fernando (Wayne and Diana Murdy Endowed Professor of Engineering & Geosciences, University of Notre Dame)

Co Pis:

Dr. Joshua Hacker (Naval Post Graduate School; Currently Deputy Director, National Security Applications Program, Research Applications Lab at NCAR)

Dr. Fotini Katopodes Chow (Associate Professor, Civil & Environmental Eng., University of California, Berkeley)

Dr. Eric Pardyjak (Professor, Mechanical Engineering, University of Utah)

Dr. Stephan F.J. de Wekker (Associate Professor, Atmospheric Sciences, University of Virginia)

D: Scientific accomplishments MATERHORN-X

- Two state-of-the-science field campaigns completed – unique access to the US Army Dugway Proving Ground - best complex terrain experiments ever conducted
  - Autumn (Sep 25 to Oct 31, 2012; Quiescent and dry) and Spring (May 01 –May 31, moisture, synoptic), about 45 participants
  - 100 TB data, repository at Notre Dame, investigator/collaborator access
  - EOS, Transactions of the American Geophysical Union – In Press

    <u>Referee 1</u> - "*a very extensive and truly unique study of mountain meteorology that merits featuring in EOS*";

    <u>Referee 2</u> – "*It clearly demonstrates that MATERHORN opens outstanding opportunities for better understanding the nature and principally improved forecasting of fine features of the mountain weather and climate*"
  - Bulletin American Meteorological Society– A proposal has been accepted for a comprehensive article

Potential DOD Transitions

- Improvements to WRF and COAMPS forecasts, which are the two models we are using: both are currently used by military operationally.
- Battlefield decision making aids – based on extensive observational experience
- Ultra-high resolution modeling – local forecasting for weather sensitive weapons
- UAV technology products – a future data assimilation tool - useful for theater scale predictions

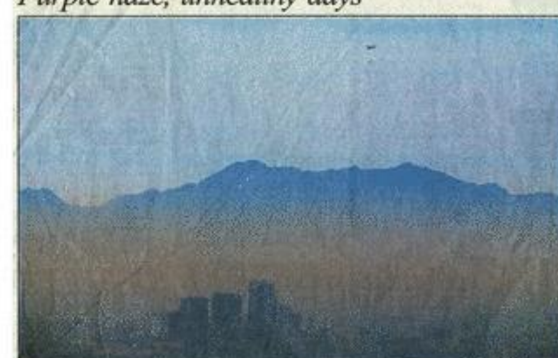
F. Societal Importance

Recent resurgence of interest in improving weather prediction in mountainous (and complex) terrain

- More than 50% of cities are in complex terrain (air pollution, accidental spills, visibility, agriculture, capricious weather)
- Aircraft safety
- Mountain (alpine) warfare is the most dangerous type of combat

Phoenix Brown Cloud

Purple haze, unhealthy days



From the *Arizona Republic*

Scientific Objectives

- Identify and study the limitations of current state-of-the-science mesoscale models for mountain-terrain 1 km scale weather prediction. What are scientific and computational knowledge gaps?
- Study known unknowns; uncover hidden physical processes, delve into them using laboratory studies, high-resolution numerical simulations (LES); develop high fidelity parameterizations
- Bridge science gaps, identify processes across scales, delineate their contributions to basic momentum and heat transfer processes
- Develop new computational and technological tools to help realize leaps in predictability
- Transition new knowledgebase to improve predictive models (WRF and COAMPS)
- Evaluate models with new and existing observations

D: MATERHORN - M

- State-of-the science mesoscale models (WRF and COAMPS) are more prone to forecast error when predicting in complex terrain than over flat terrain
- Flow physics and thermodynamics matter most!
- Assimilation of near-surface observations can improve short-range forecasts and ensemble methods appear superior to 3D variational methods
- Near-surface temperature forecasts over arid regions are very sensitive to soil moisture
- Probabilistic methods for predicting observation impact, and determining optimal observation siting, in weakly-forced flows appear tractable for short-range, near-surface forecasts
- The immersed boundary method (IBM) implemented in WRF model can be used to get 50m resolution in complex tarrain

H. Special Sessions

- A special Session on Complex Terrain flows , 2011 Fall AGU Meeting (de Wekker and Chow)
- “Atmospheric Observations in Mountainous Terrain” at the 92nd American Meteorological Society Annual Meeting, January 22-26, 2012), Fernando
- A special session on “Atmospheric boundary layers in complex terrain and over ice, snow and vegetated surfaces” at the Davos Atmosphere and Cryosphere Assembly (DACA), 8-12 July 2013 (de Wekker)
- A special session on “Research on Improving Weather Prediction for Mountain Terrain,” 2013 Fall AGU Meeting , - Fernando et al. (37 papers)
- A special session on “THE MATERHORN PROJECT” at the 92nd American Meteorological Society Annual Meeting, January 22-26, 2012, Atlanta, the 18th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA . - Di Sabatino and Ferek (14 papers)

H. Major reviews or meetings (Dates and locations)

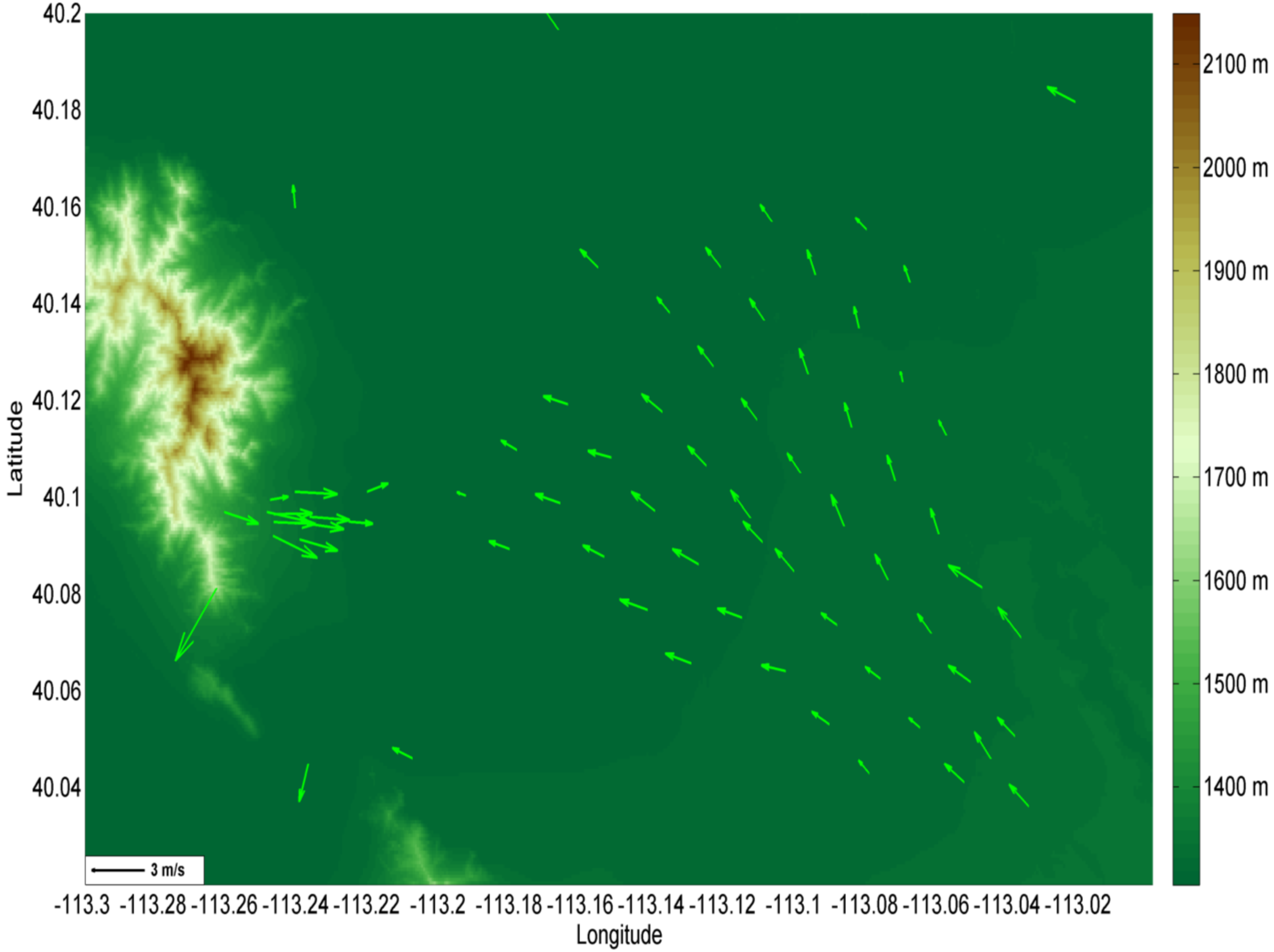
- Kickoff Meeting and field trip to GMAST (September 8, 2011), University of Utah (43 participants)
- 1st Investigator Meeting, University of Utah, August 12, 2012 (44 participants)
- Materhorn-X2 planning meeting, March 1, 2013, University of Utah (18 participants)
- 2nd Investigator Meeting, University of Notre Dame, September 6, 2013 (today)
    - Presentations are in www.nd.edu/~dynamics/materhorn

11 Other Collaborators – via Proposals

- Dr. Nick Ovenden University College, London, U.K. (Host: Notre Dame)
- Dr. Andrey Grachev, CIRES, NOAA, Boulder, Colorado (Host: Notre Dame)
- Professor Joachim Reuder, University of Bergen, Norway (Host: Utah)
- Professor Chad Higgins, Oregon State University, Corvallis, Oregon (Host: Utah)
- Dr. Stefano Serafin, University of Vienna, Austria (Hosts: Virginia and California, Berkeley)
- Dr. Dorita Rostkier-Edelstein, Environmental Sciences Division, IIBR, Israel (Host: Naval Postgraduate School)
- Professor Marcus Hultmark, Princeton University (Host: Utah)
- Dr. David J. Gochis, National Center for Atmospheric Research (Host: Virginia)
- Dr. Dave Emmitt, Simpson Weather Associate (Host: Virginia) – Twin Otter
- Professors Ben Balsley and Dale Lawrence, University of Colorado (Host: Notre Dame) - UAV
- Daniel Nadeau, École Polytechnique De Montreal, Canada (Host: Utah) – total 12

(Additional funding for collaborators were provided by Air Force Weather Agency and Army Research Office)

Proper Orthogonal Decomposition of Velocity Vectors



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