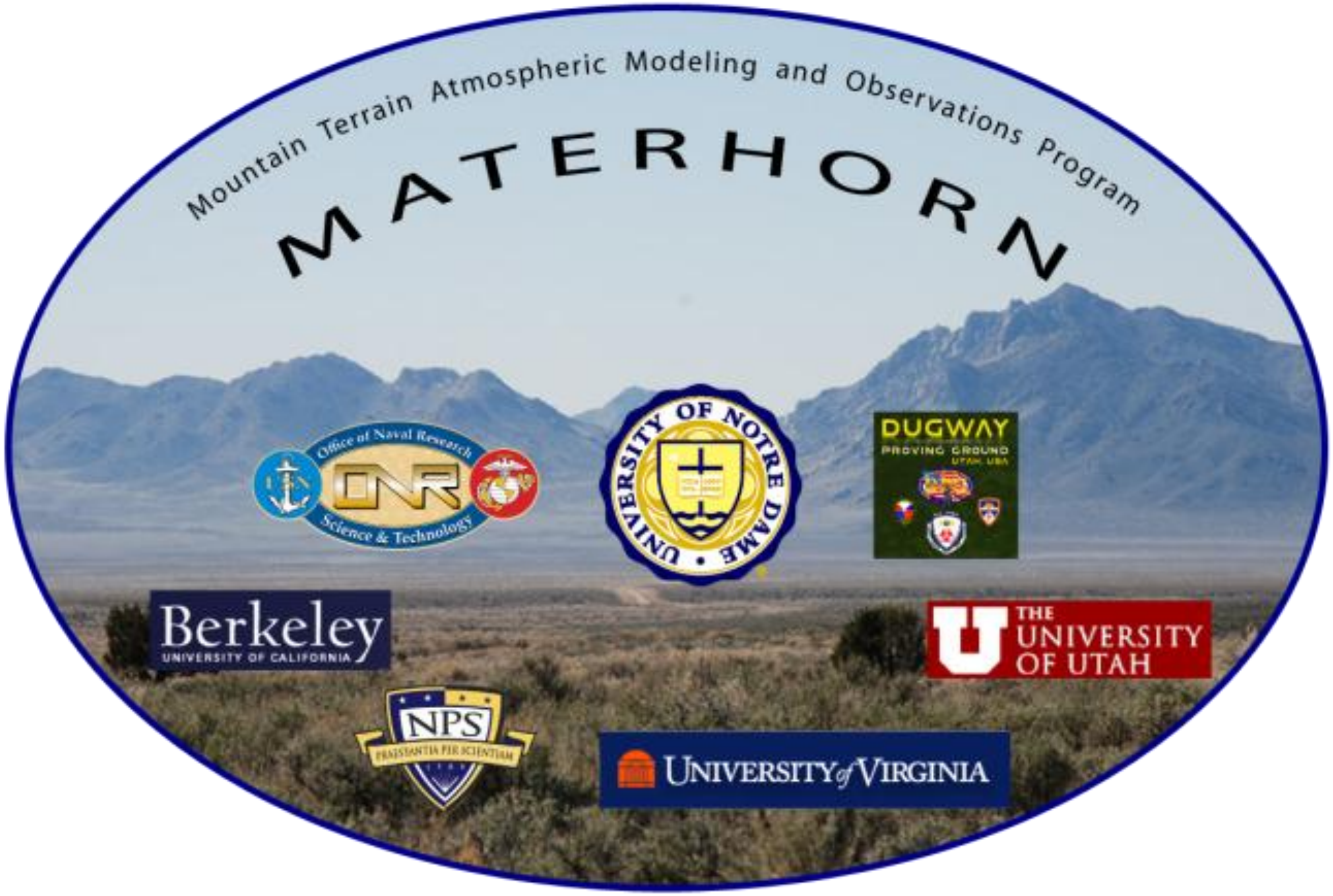


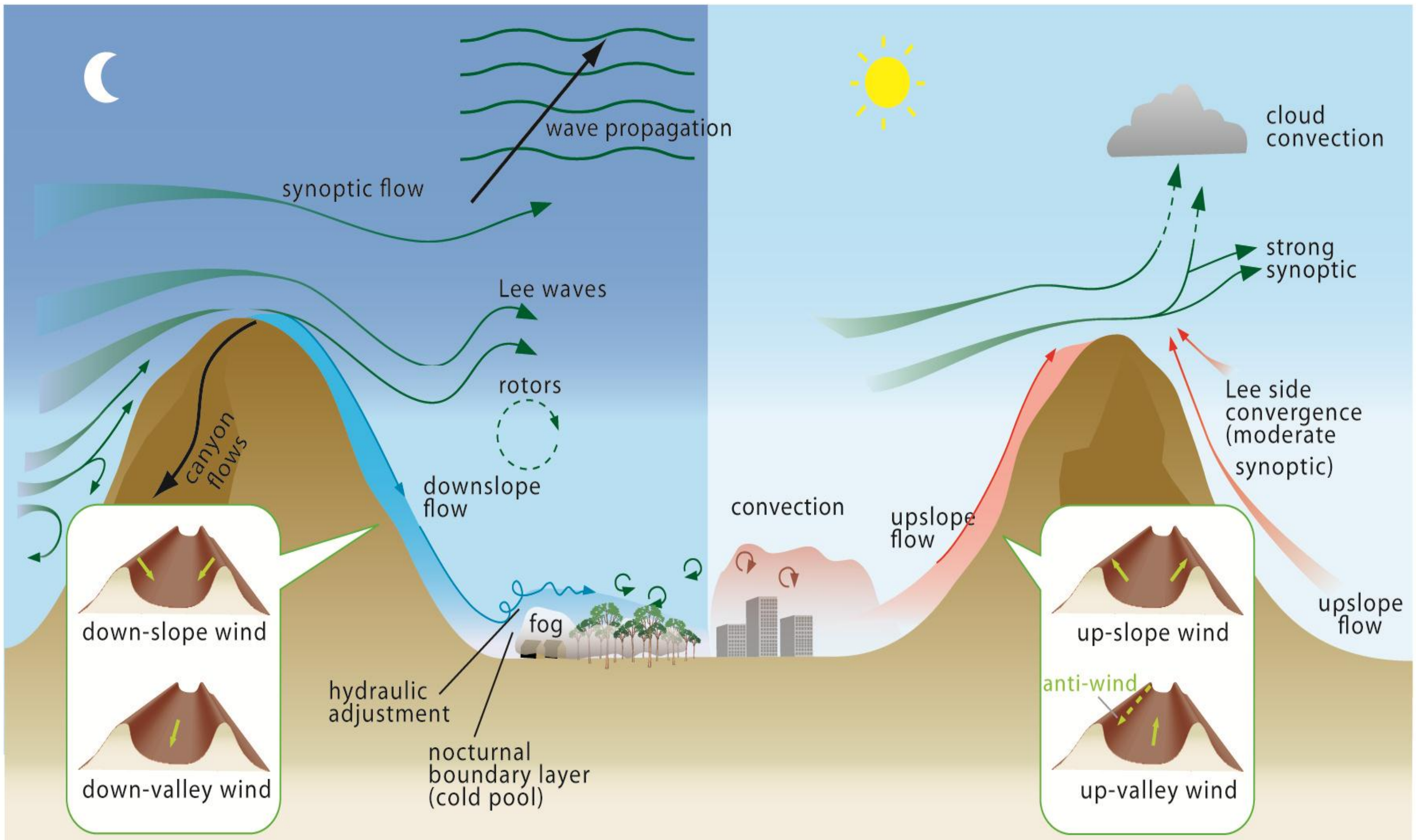
www.nd.edu/~dynamics/Materhorn

ONR FY 2011 MURI TOPIC #7:

Improved Meteorological Modeling in Mountain Terrain

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

Atmospheric Processes in Mountain Terrain



Fernando, Ann Rev Fluid Mech. 2010

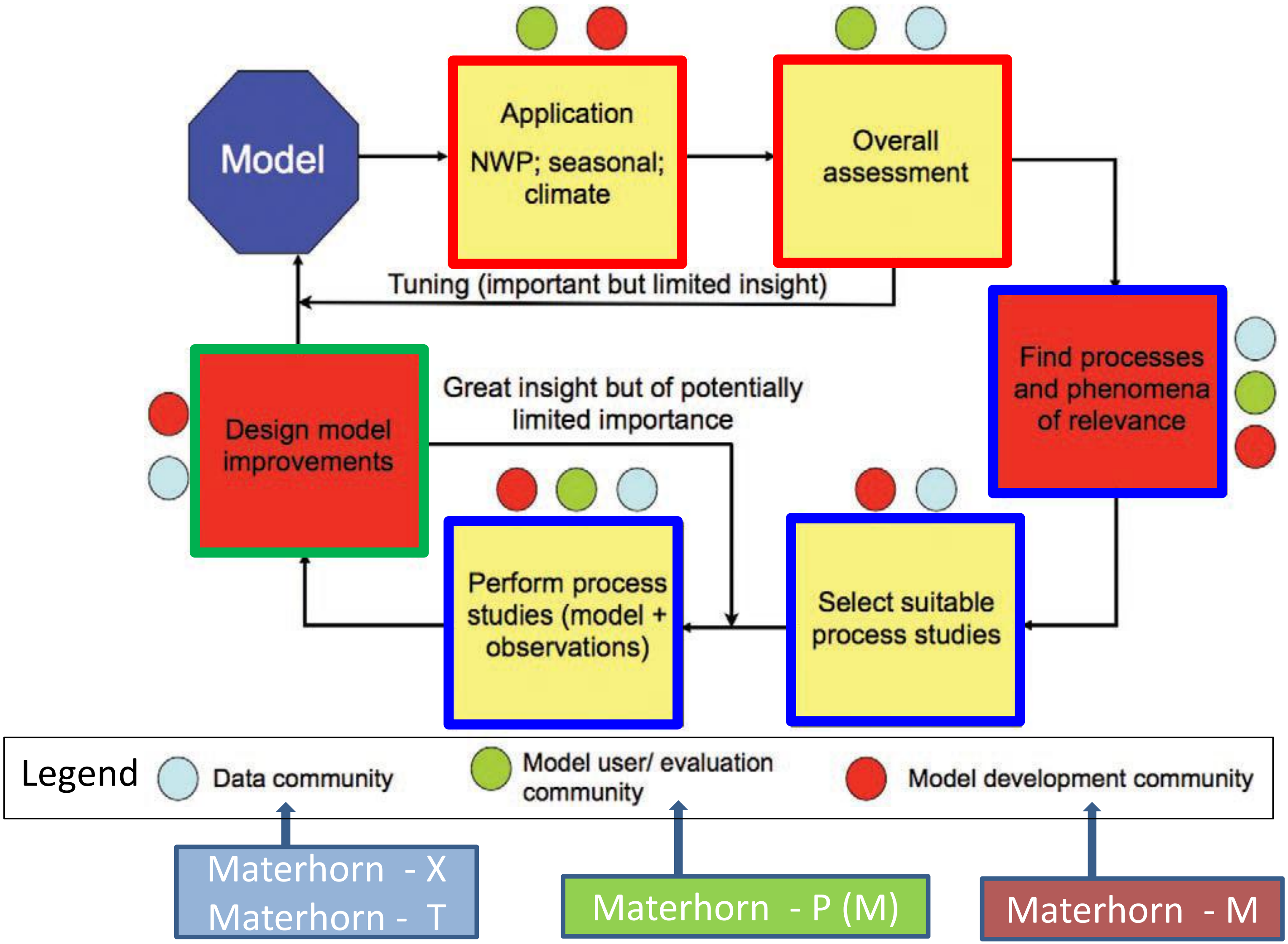
Look at meso-scale to Kolmogorov scale (100km to 1 mm)

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

Integrated Approach

(New paradigm proposed by Jakob; BAMS, 2010)



MURI Team - PIs

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

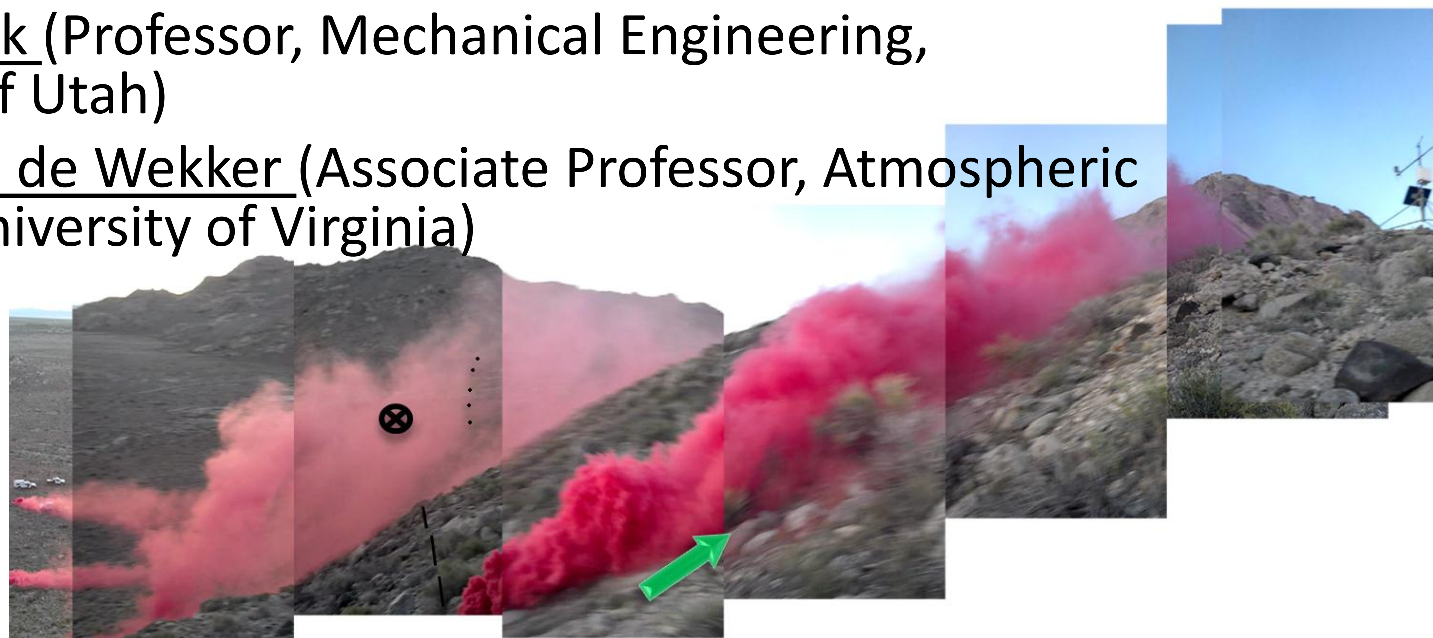
Co PIs:

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)



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), Scott Coppersmith (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)

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)

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 de Boisblanc (total 3)

Collaborators

Listed in Original Proposal

- James Doyle (Naval Research Laboratory)
- John Pace (US Army Dugway Proving Grounds), Dragan Zajic (US Army Dugway Proving Ground)
- 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 (Host: Virginia) – Twin Otter

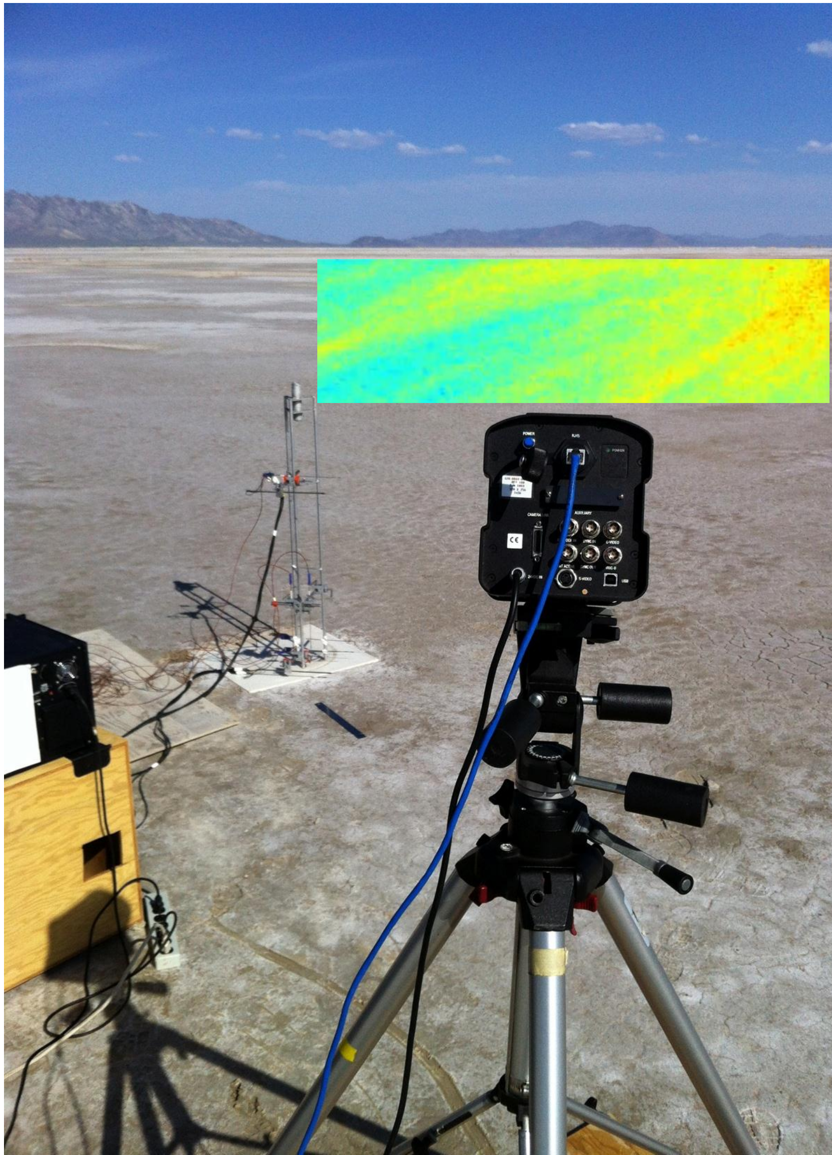
Names in Red: Additional funding for collaborators were provided by Air Force Weather Agency and Army Research Office

Additions – 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)
- Professors Ben Balsley and Dale Lawrence, University of Colorado (Host: Notre Dame) - UAV
- Daniel Nadeau, École Polytechnique De Montreal, Canada (Host: Utah)

Team Summary

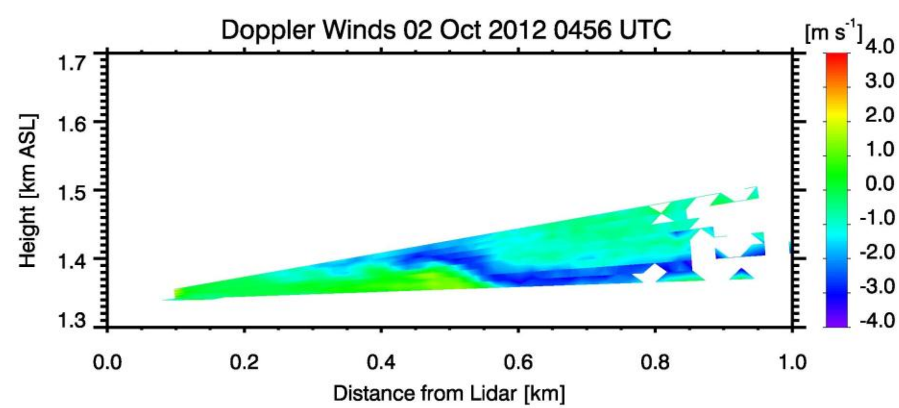
- Senior PIs: 11
- Research faculty: 4
- Technical staff: 8
- Post docs: 8
- Graduate Students : 18 PhD and 3 MS (Total 21)
- Undergraduate Students: 13
- Collaborators (proposal): 7
- Collaborators joined: 11



Total: 70

Project Scientific Issues - Barriers

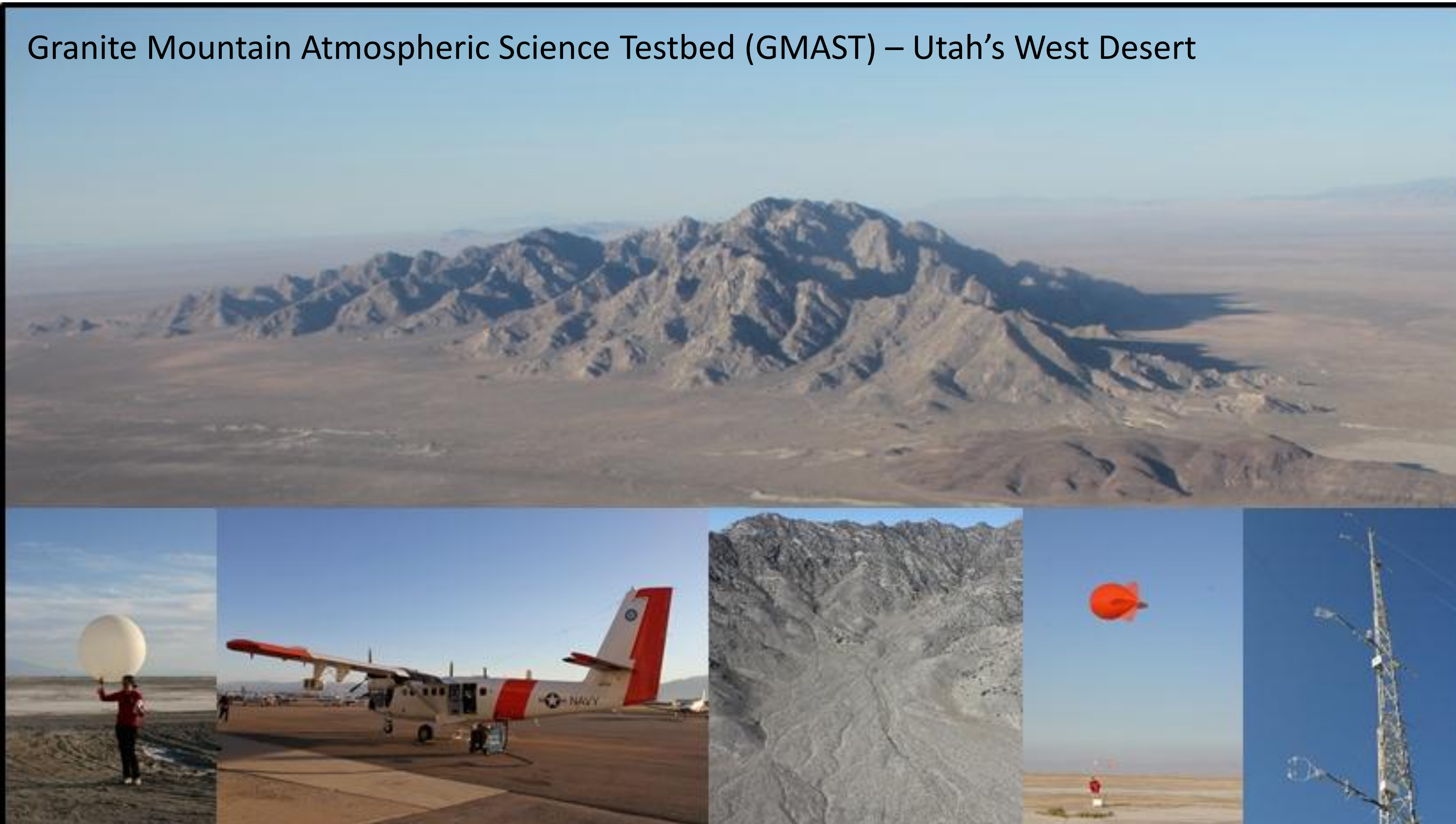
- Atmospheric Predictability in complex terrain – poor
- Accurate measurement of model-relevant soil properties and the surface energy balance over extended periods – difficult
- Model deficiencies – structural and physical – insufficiently understood

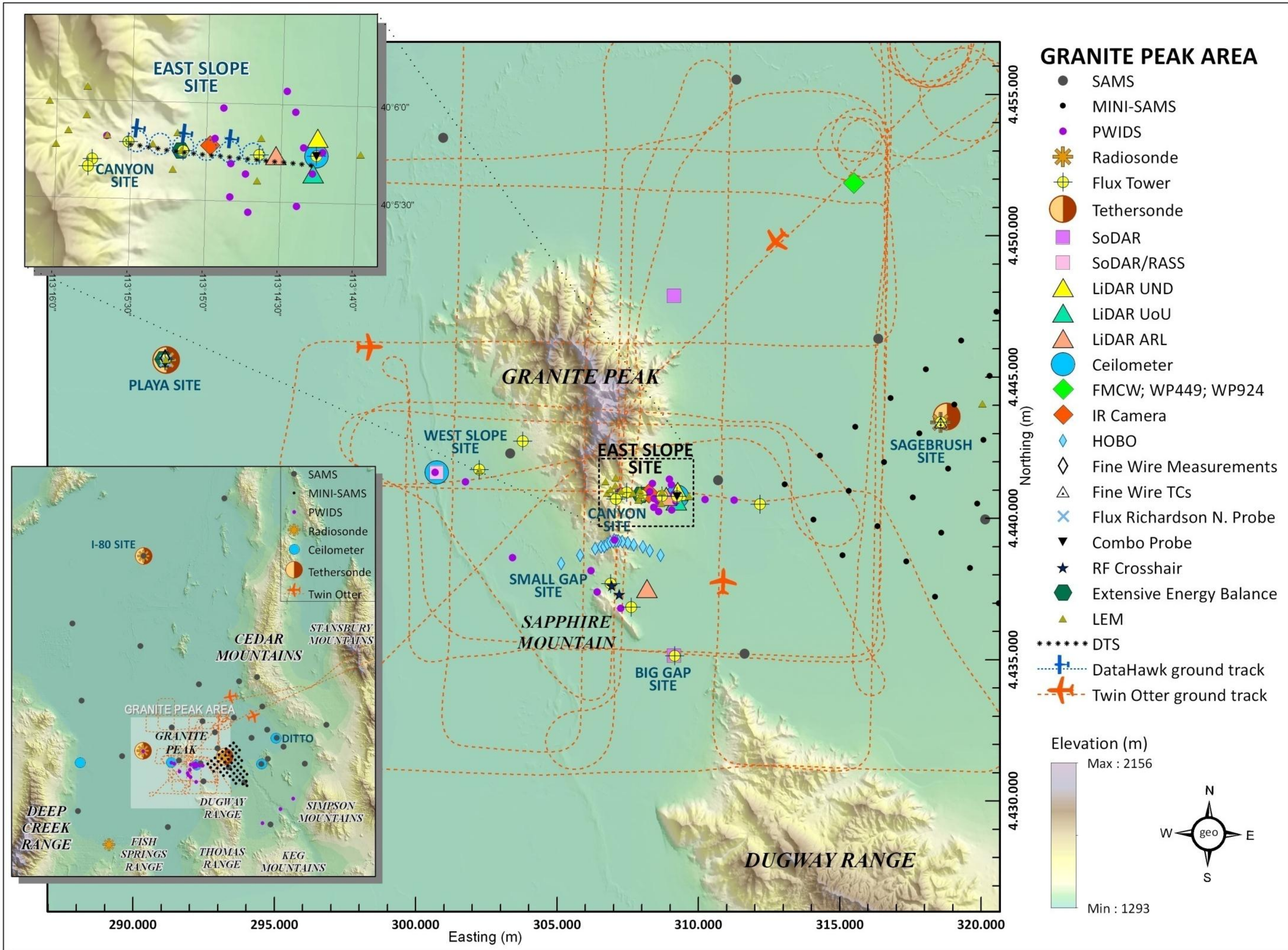


Project Scientific Issues - Barriers

- Ultra high-resolution (LES, 50 m horizontal or finer) simulations over complex terrain are extremely challenging
- "Terrae Incognitae" exist for turbulence closure schemes and other earth science processes that must be modeled – matching models with ever increasing grid resolutions
- Unknown physical processes and interactions - intense events, spasmodic fluxes and contributions – Should be in the models!

Major Scientific Accomplishments
MATERHORN – X (Autumn & Spring)
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
SAGEBRUSH SITE
SMALL GAP SITE
SAPPHIRE MOUNTAIN
BIG GAP SITE
DUGWAY RANGE
Northing (m)
4.455.000
4.450.000
4.445.000
4.440.000
4.435.000
4.430.000
Easting (m)
290.000
295.000
300.000
305.000
310.000
315.000
320.000
SAMS
MINI-SAMS
PWIDS
Radiosonde
Ceilometer
Tethersonde
Twin Otter
I-80 SITE
CEDAR MOUNTAINS
STANSBURY MOUNTAINS
GRANITE PEAK AREA
GRANITE PEAK
DITTO
DUGWAY RANGE
SIMPSON MOUNTAINS
DEEP CREEK RANGE
FISH SPRINGS RANGE
THOMAS RANGE
KEG MOUNTAINS

Major Scientific Accomplishments
MATERHORN-X

- Autumn: Sep 25 to Oct 31, 2012 - Quiescent and dry
- Spring: May 01 –May 31 - moisture, synoptic - ~45 participants
  - 100 TB data repository at Notre Dame, investigator/collaborator access
  - EOS, Transactions of the American Geophysical Union – *In Press*

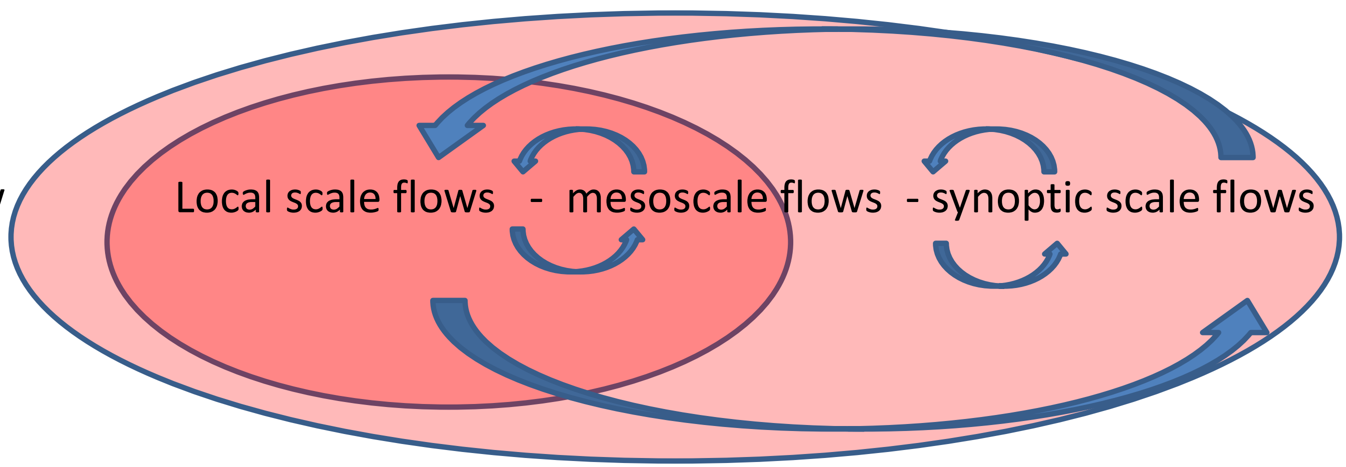
    Referee 1 - "*a very extensive and truly unique study of mountain meteorology that merits featuring in EOS*";

    Referee 2 – "*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

Key Results: MATERHORN - X

- 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, solar cycle, topographic complexities)
- Understanding atmospheric circulations in mountains from regional to local scales
- Airborne Doppler lidar retrieval algorithms were developed

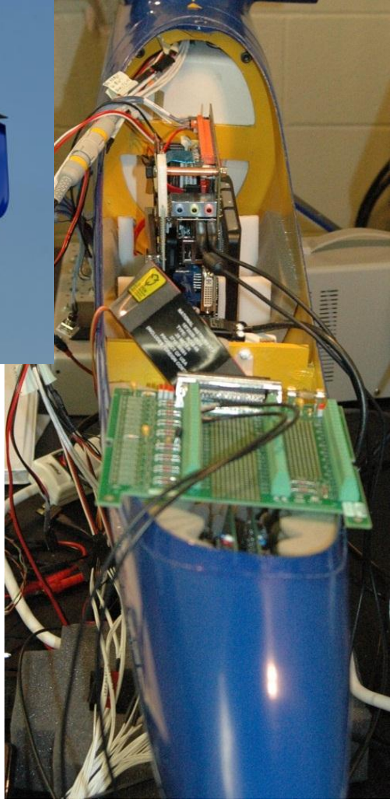
Multi-scale flow interactions



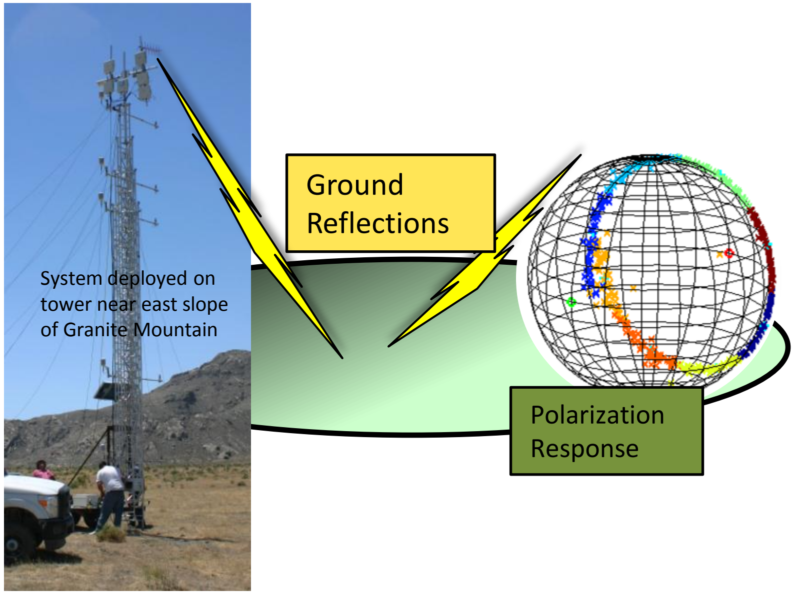
Accomplishments: MATERHORN - M

- Probabilistic/ensemble methods of assimilation of near-surface and other observations can predict observation impact, determine optimal observational siting, and improve short-range forecasts over complex terrain
- Near-surface temperature forecasts are very sensitive to soil moisture and can be improved over dry land regions by improving soil moisture analyses and using techniques that more accurately simulate energy transfers between the land surface to the atmosphere
- The immersed boundary method implemented in the WRF model can be used for highly detailed (~50 m) simulations in complex terrain

Accomplishments: MATERHORN-T



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



- **Designed, Constructed and Deployed <u>three-frequency sensor systems to collection RF polarimetric data – for moisture</u>**
  - Extensive data, two MATERHORN sites, moisture calibration
  - Developed theoretical electromagnetic modeling

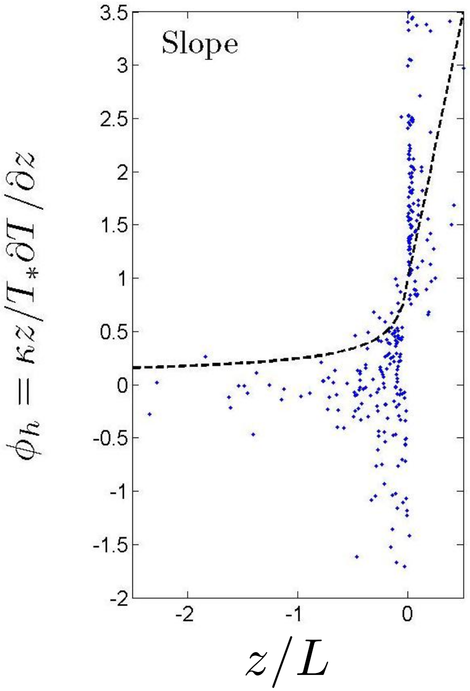
Accomplishments: MATERHORN-T

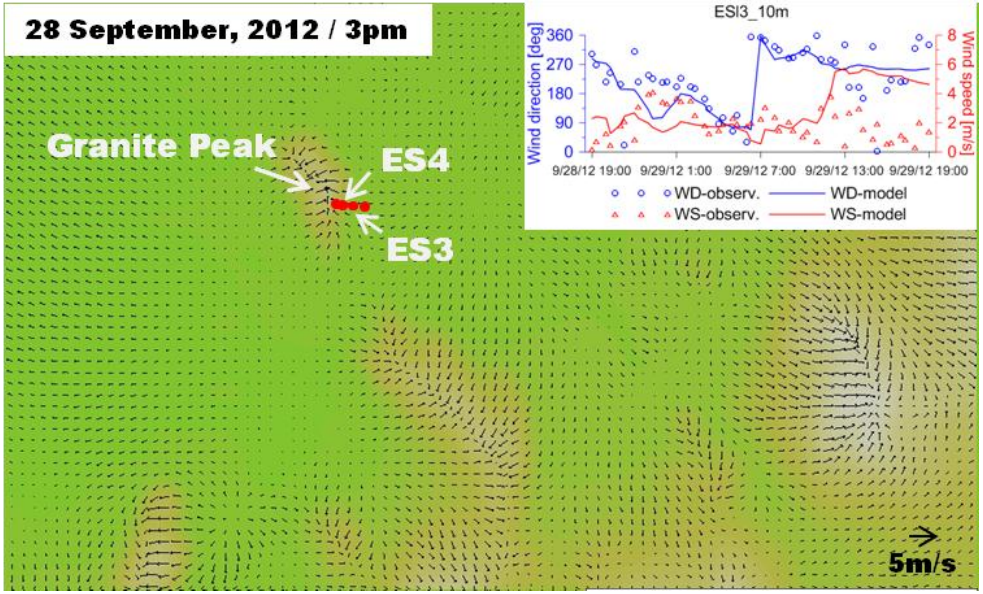
- **<u>Sonic-hotwire Combo System</u>**
  - Developed and deployed
  - Extensive data, unique turbulence information, dissipation scales
    - Allow myriad of turbulence and multiscale studies

- **<u>Fog Aerosol Sampling System (FASS)</u>**
  - Developed the system
  - State of the art – on a UAV
  - Testing for FOG experiment

FASS can measure fog concentrations in flight at small spatial and temporal scales.

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

• **Develop new parameterizations** – In progress

Potential Breakthroughs

- 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
- Improved theoretical understanding of key processes
- Vastly improved numerical techniques for LES of complex terrain flows
- New atmospheric small scale turbulence measurements technologies
- New automated RF based moisture measurement technology

Budget Summary

Institution	06/01/11-09/30/11	10/01/11-09/30/12	10/01/12-09/30/13	10/01/13-05/31/14	06/01/14 09/30/14	10/01/14 09/30/15	10/01/15-05/31/16
Notre Dame	372,827	463,050	433,754	189,766	280,308	476,325	221,077
Utah	295,138	534,697	512,859	329,788	155,311	503,047	324,888
NPS	61,138	187,145	198,990	145,149	83,774	211,045	141,335
Berkeley	65,512	124,801	138,972	59,254	75,760	147,533	63,903
Virginia	42,007	84,745	100,110	35,404	49,192	91,336	37,025
Total	**886,622**	**1,394,438**	**1,384,685**	**759,361**	**644,355**	**1,429,286**	**788,228**

Total for the first <u>three years</u>: **$ 4,375,106**
Total for the <u>optional years</u>: **$ 2,861,859**
<u>Total</u> : **$7,236,965**

Major Reviews and Meetings

- Kickoff Meeting and field trip to GMAST (September 8, 2011), University of Utah (43 participants)
- 1st Investigator Meeting, University of Utah, August12, 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 (pending)
    - Presentations are in www.nd.edu/~dynamics/materhorn

Special Conference Sessions

- A special Session on Complex Terrain flows , 2011 Fall AGU Meeting.
- "Atmospheric Observations in Mountainous Terrain" at the 92nd American Meteorological Society Annual Meeting, January 22-26, 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
- A special session on "Research on Improving Weather Prediction for Mountain Terrain," 2013 Fall AGU Meeting , - H.J.S. Fernando et al. (Approved)
- A special session on "THE MATERHORN PROJECT" at the 94th American Meteorological Society Annual Meeting, February 2-6, 2014, Atlanta, the 18th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA (Approved)

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

Questions

Project Scientific Issues
Why a multidisciplinary approach?

- <u>Weather Prediction Models</u> integrate different components of the Earth system
- <u>New instrumentation and observational capabilities</u>, push the frontiers – need mechanical, optical and electrical engineers
- <u>Data assimilation and identification of model inadequacy</u> requires integration amongst applied mathematicians, modelers and experimentalists

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

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