Spatial Variability of Turbulent Kinetic Energy around an Isolated Mountain

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MATERHORN Investigator's Meeting

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Introduction

- Turbulent processes important for:
  - Pollution dispersion
  - Convection
  - Cloud formation
  - Atmospheric turbulence
- Number of previous studies on boundary layer (BL) turbulence in flat homogeneous terrain
  - BL turbulence is generally well understood in these areas
- Less research on BL turbulence in complex terrain
  - Not well understood

Introduction

The spatial variability of turbulence in complex terrain influenced by:

- Horizontal surface heterogeneities
- Terrain air flow modification
- Thermally driven wind systems

- Understanding and documenting turbulence over complex terrain can:
  - Provide verification for models
  - Improve the parameterization and representation of turbulence processes in numerical models

Goal

Characterize and document the spatial variability and structure of boundary layer turbulence in complex terrain

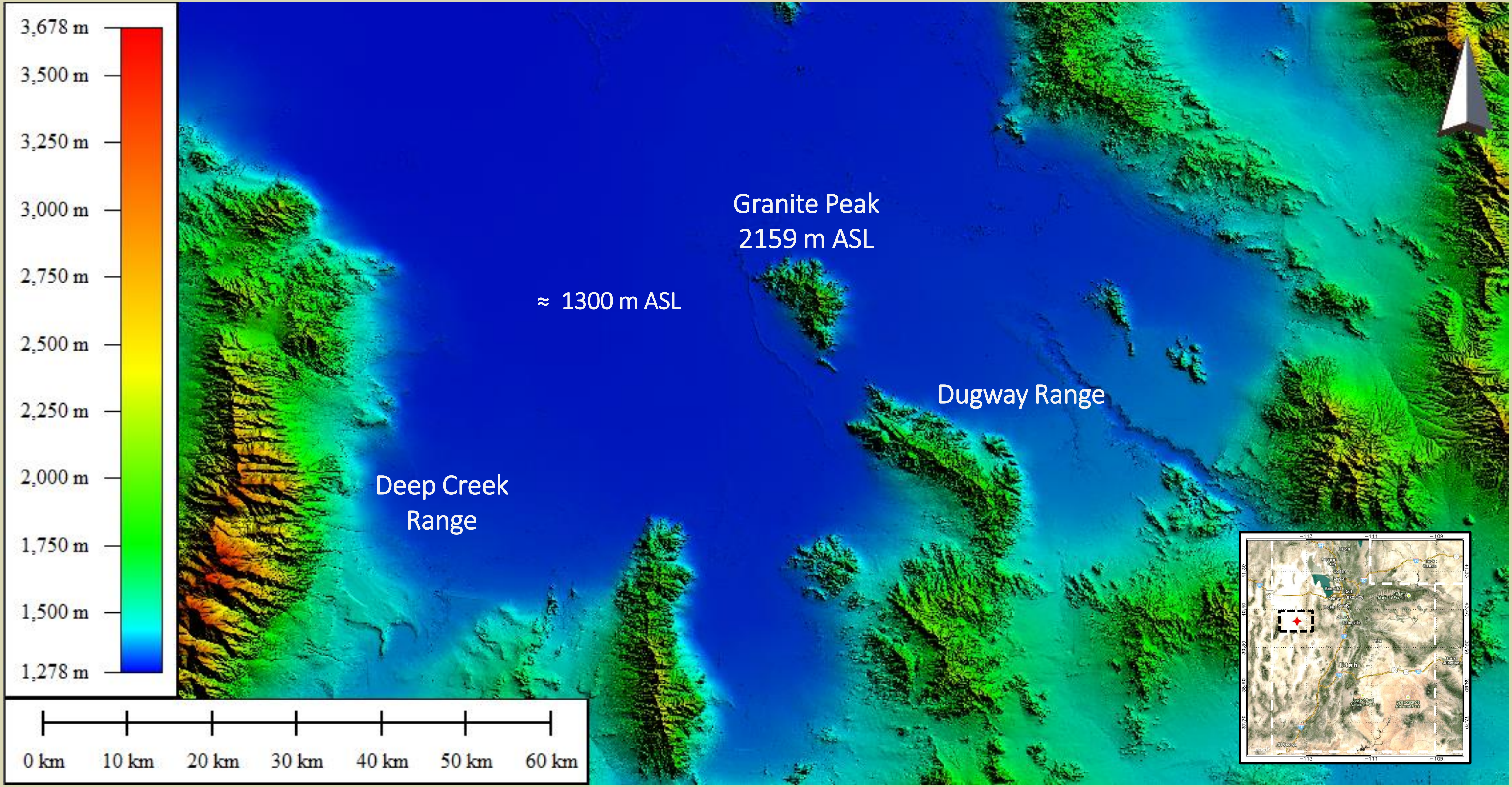
Introduction

Mountain **T**errain **A**tmospheric **M**odeling and **O**bservations (MATERHORN) program

- **Fall 2012 MATERHORN-X** : airborne *In situ* meteorological measurements over an isolated Granite Peak, Utah and surrounding area

MATERHORN-X data set

- Provides an opportunity to investigate the influence of complex terrain on **BL** turbulence


3,678 m
3,500 m
3,250 m
3,000 m
2,750 m
2,500 m
2,250 m
2,000 m
1,750 m
1,500 m
1,278 m
0 km
10 km
20 km
30 km
40 km
50 km
60 km
Granite Peak
2159 m ASL
≈ 1300 m ASL
Dugway Range
Deep Creek
Range

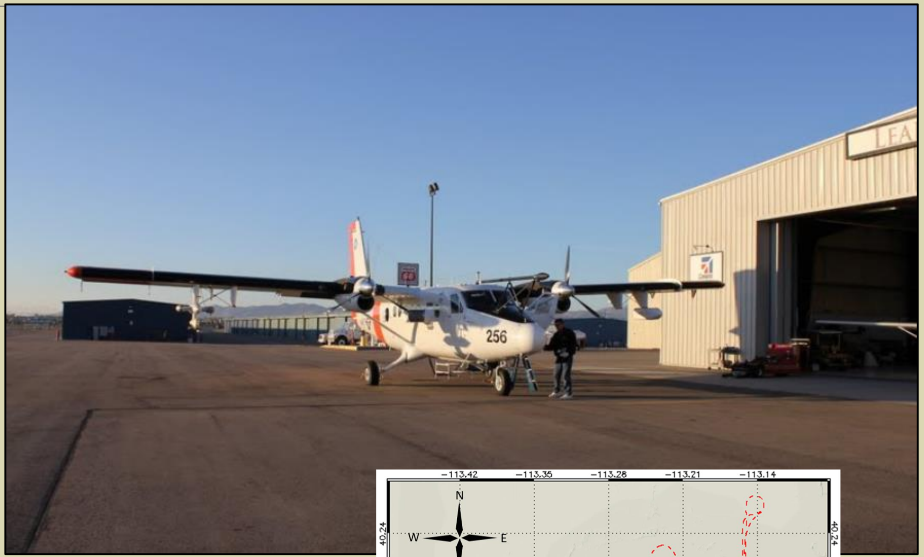
MATERHORN-X: Twin Otter Flight Summary

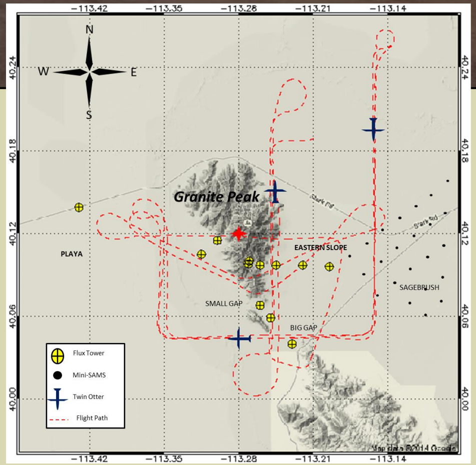
Twin Otter airborne observations are from

- Six Navy Twin Otter flights flown between 5-18 Oct. 2012
- Participated in 4 IOPs
- Missions lasted ~ 4 hours
- Flight legs 1500-2500 m ASL and 10-20 km long
- Co-funded by ONR and ARO

Observations Include:

- *In situ* 10 Hz temp, humidity, wind components, wind direction
- Twin Otter Doppler Wind Lidar (TODWL) wind profiles

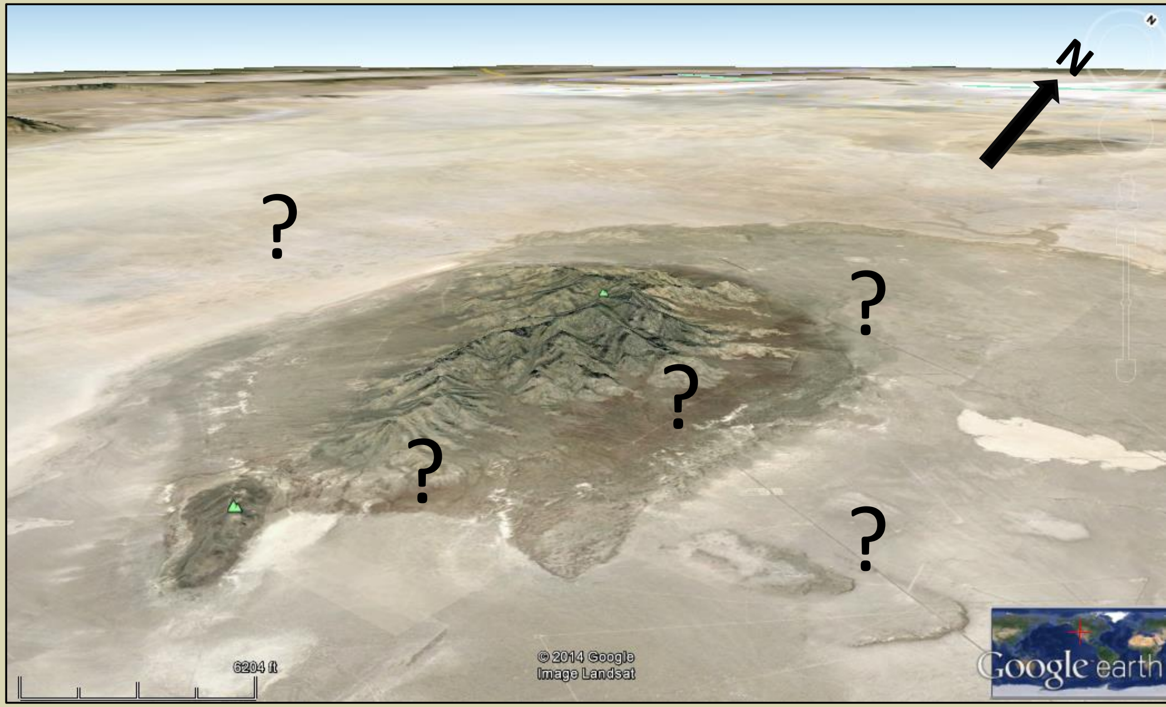




Question

Processes over mountainous terrain are known to influence the spatial variability of turbulence

What is the spatial variability of turbulence in terms of TKE around Granite Peak?



Question

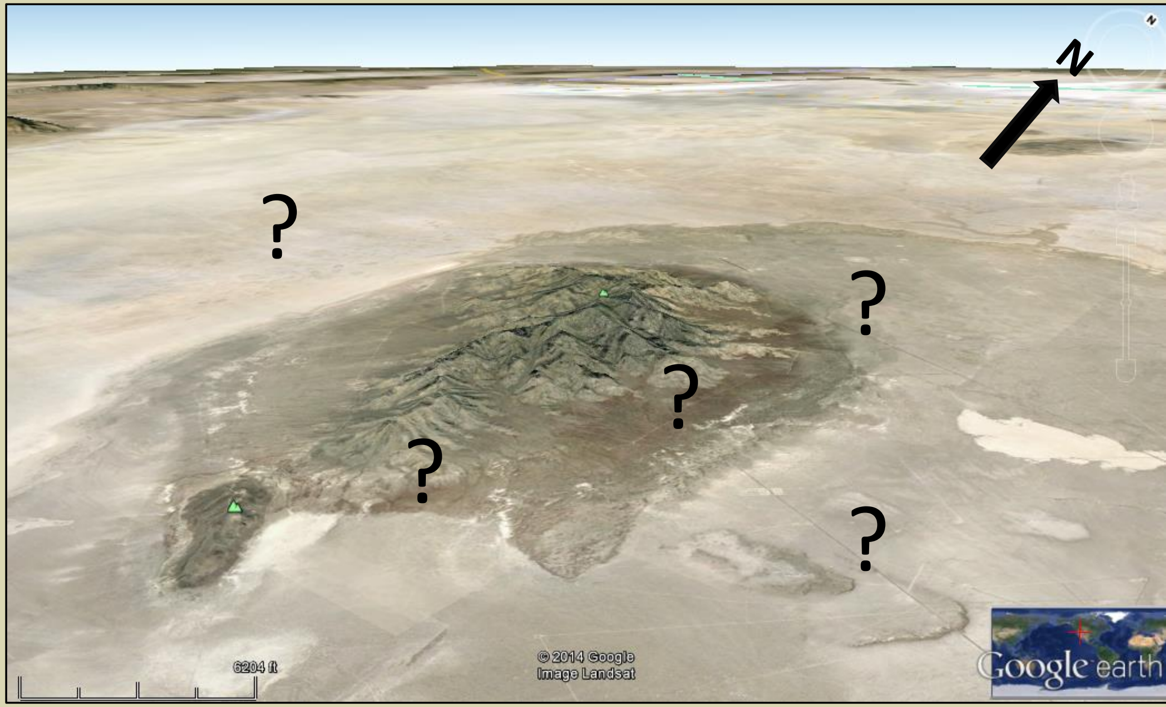
Why TKE?

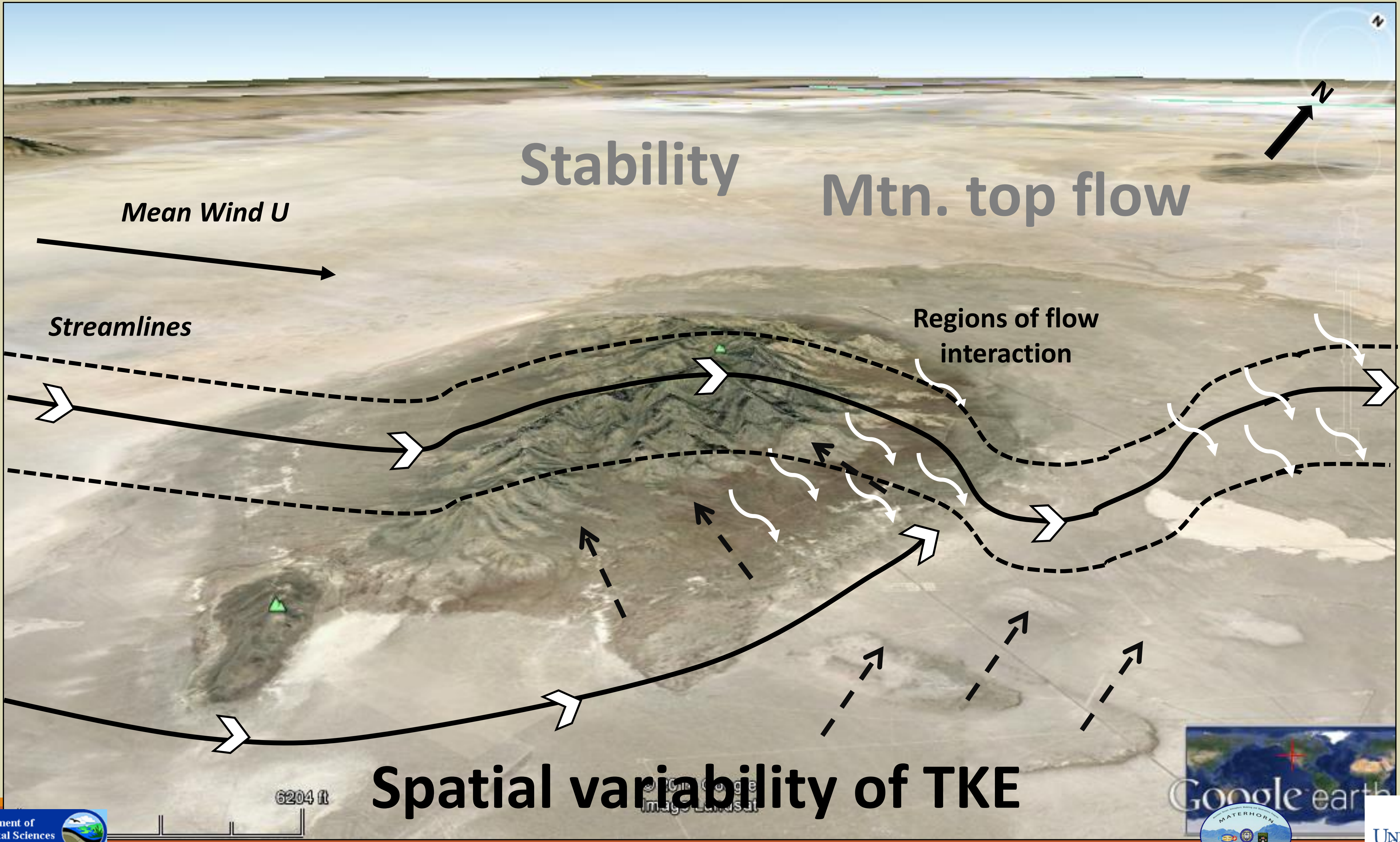
- Many models are based on TKE similarity functions formulated over idealized topography (Rotach, 1995).
- Nature of TKE over highly complex terrain cannot be assumed to be the same as that over flat homogeneous terrain (Weigel et al., 2006).
- Spatial variability and dominant scales that contribute to the production of TKE over mountainous terrain remains greatly unknown

Objectives

Utilize MATERHORN aircraft observations to investigate:

1. **Turbulence averaging length over Granite Peak**
2. **Spatial variability of TKE**
3. **Resolve scales of turbulence**




Stability
Mtn. top flow
Mean Wind U
Streamlines
Regions of flow
interaction
Spatial variability of TKE
6204 ft
Google earth

Approach and Methods

1. Select IOPs to Investigate
2. Select TO flight legs
3. Turbulence averaging length over complex terrain
4. Investigate the spatial variability of TKE
5. Resolve scales of turbulence

Approach and Methods: *Selected IOPs*

IOP Number	Date	Time of Twin Otter Fligths [MDT]	Prevailing Synoptic Conditions (700 mb)	Type	Flight Legs	RS	Last Precip
IOP 4	6-Oct	1415 -1710 MDT	NW flow 7-10 m/s	Quiescent	SG, PYA, GP, GRNT Mtn	SG, PYA	25-Sep
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IOP 6	14-Oct	800-1200 MDT	NW flow 5-7 m/s	Quiescent	SG, PYA, GP, ESLP, GRNT Mtn	SG, PYA	12-Oct
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Afternoon Mission (IOP 5, 9-Oct)

Morning Mission (IOP 5, 10-Oct)

Approach and Methods: *Selected IOPs*

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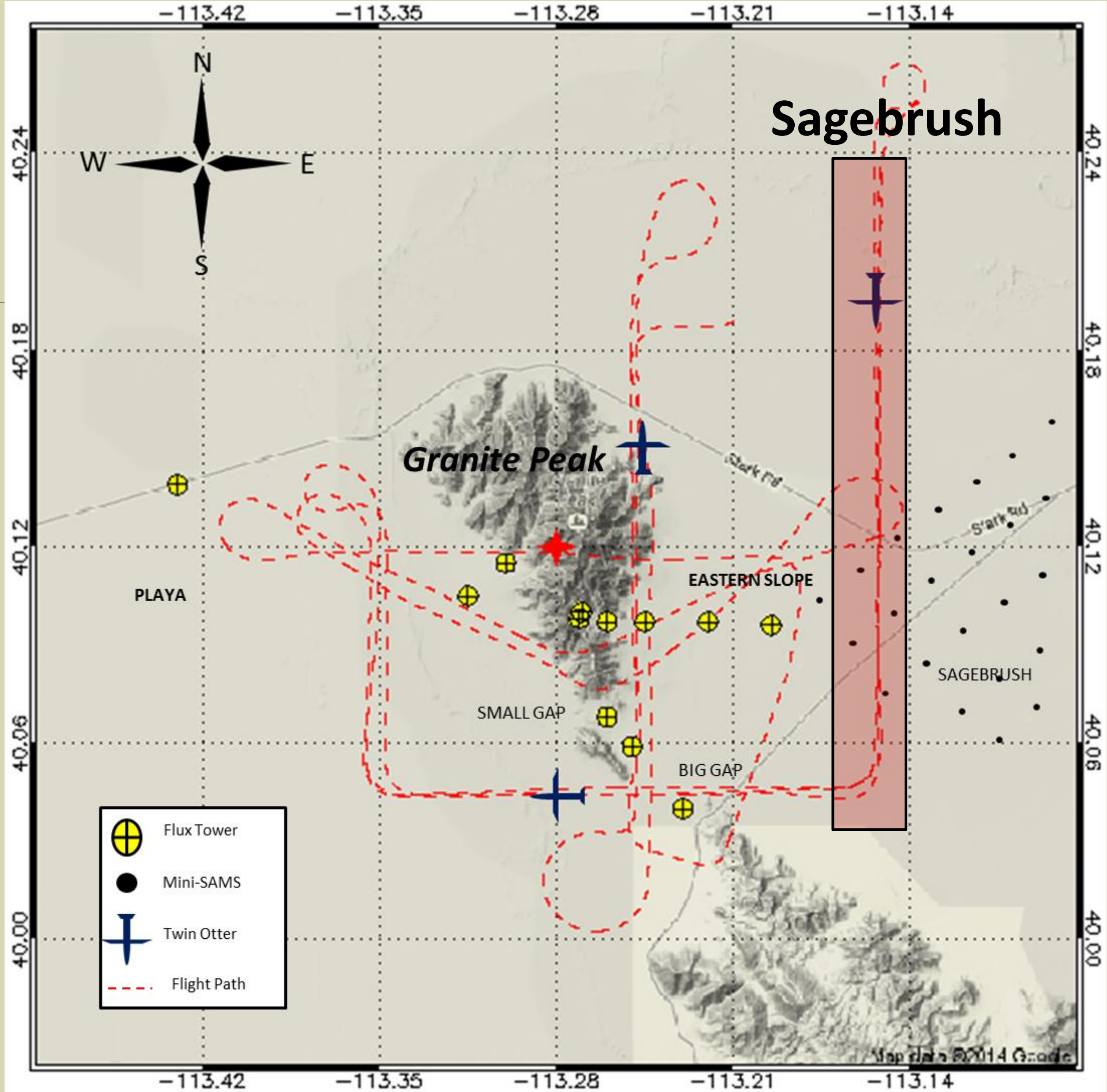
Weak mtn. top flow

Moderate Mtn. top flow

Approach and Methods: *Selected Flight legs*

Focus will be on turbulence analysis over:

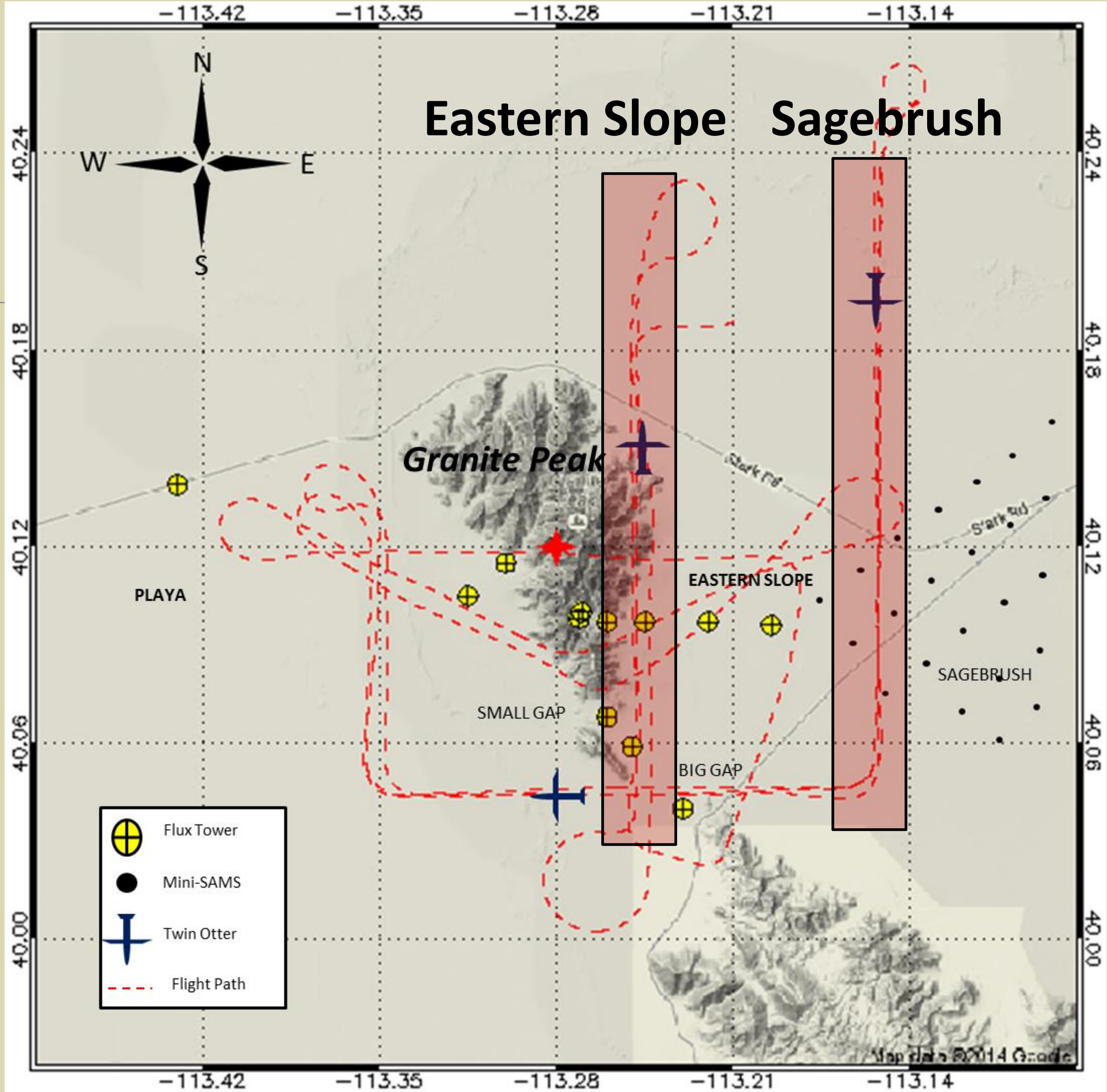
- **Sagebrush**



Approach and Methods: *Selected Flight legs*

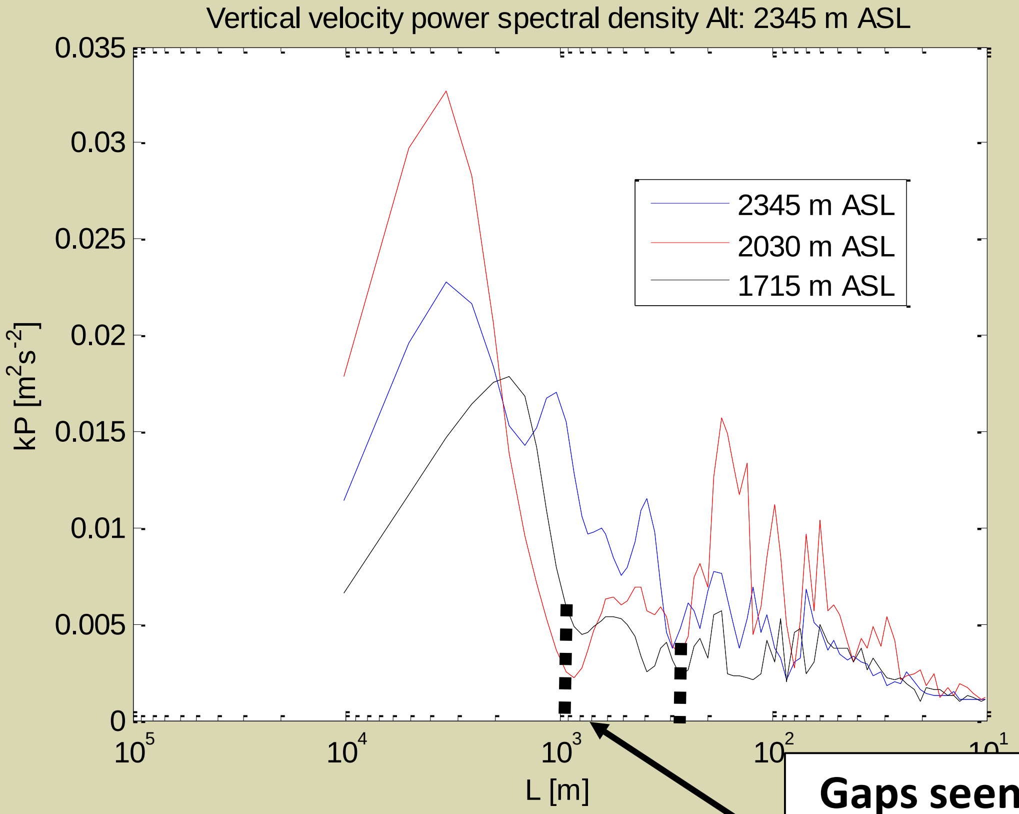
Focus will be on turbulence analysis over:

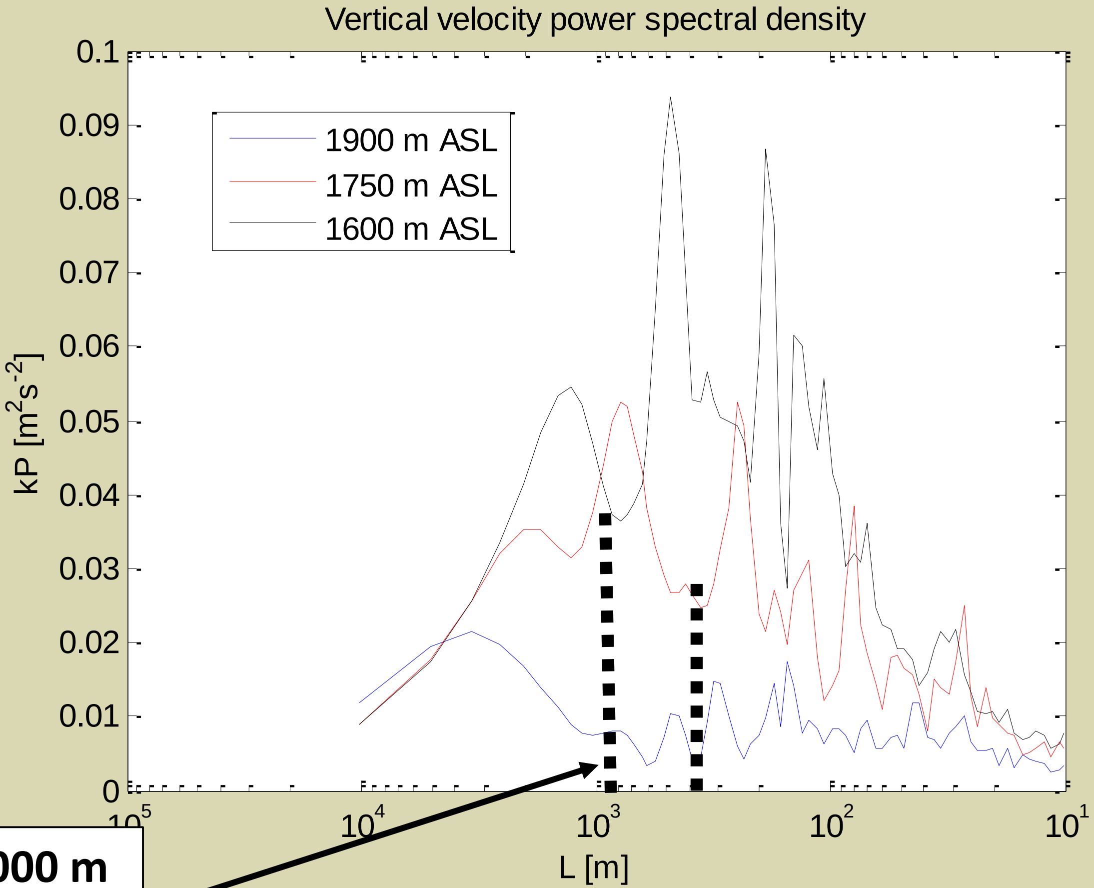
- **Sagebrush**
- **Eastern Slope**



Approach and Methods: *Averaging Length*

Example: Fourier Spectral Analysis





Gaps seen near 1000 m and 900 m for w on Oct. 09 and Oct. 10. Unclear

Approach and Methods: *Averaging Length*

- Most likely averaging length from the power spectra is given by
  - Gap seen at approximately 900 m and 1000 m
- Inhomogeneous and non-stationary nature of PBL turbulence
  - Makes defining the spectral gap unclear
- To alleviate this problem dilemma
  - Use the moving average method

Approach and Methods: *Averaging Length*

Moving average used to calculate perturbations from aircraft data

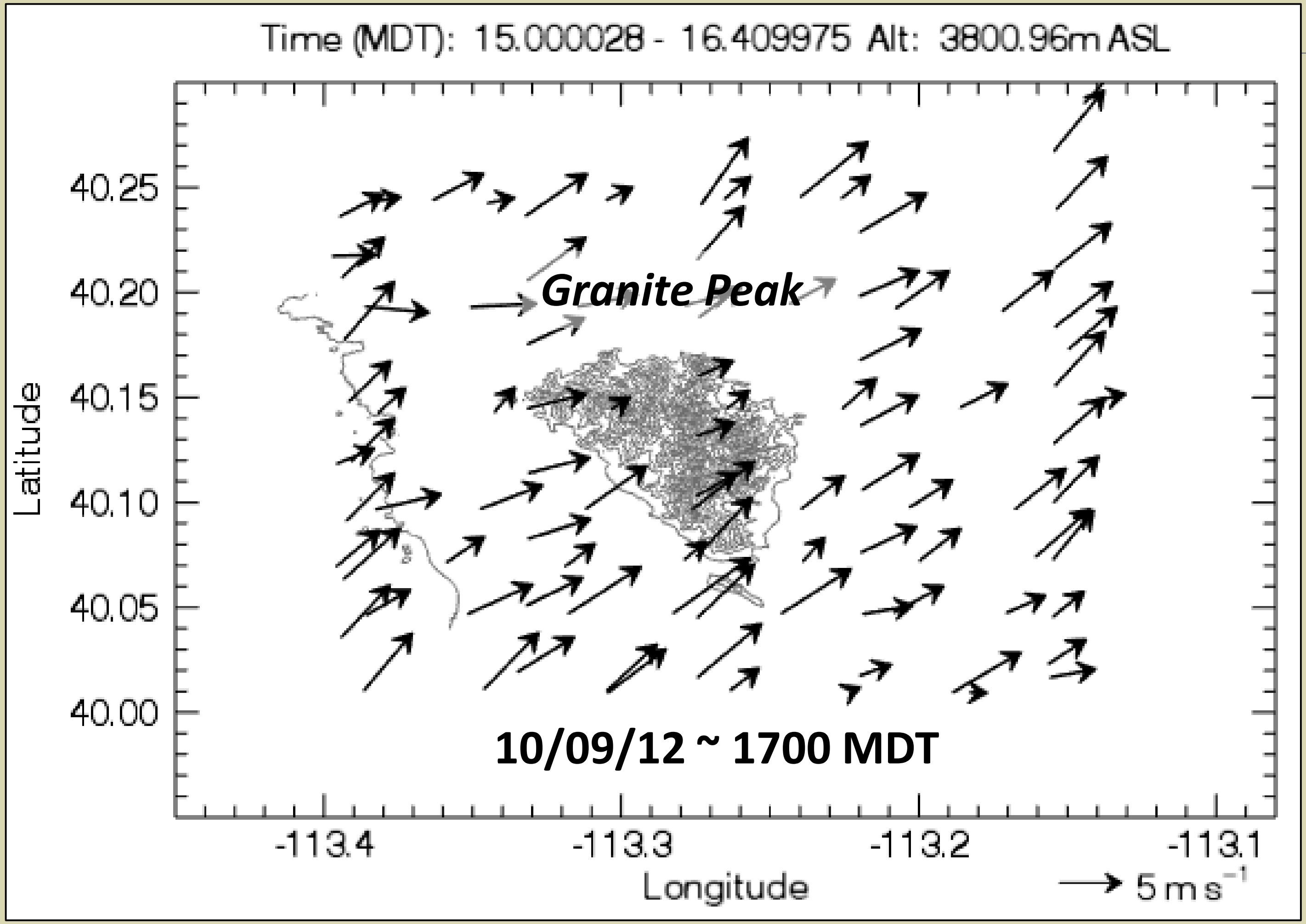
Work still being done on determining averaging length

- For this study we us 1.5 km from sensitivity tests and past research
  - Vickers and Mahrt (1997)
  - Vecenaj et al. (2012)
  - Foken et.al. (2005)

- TKE was calculated from perturbations of the wind components (w', u', v')

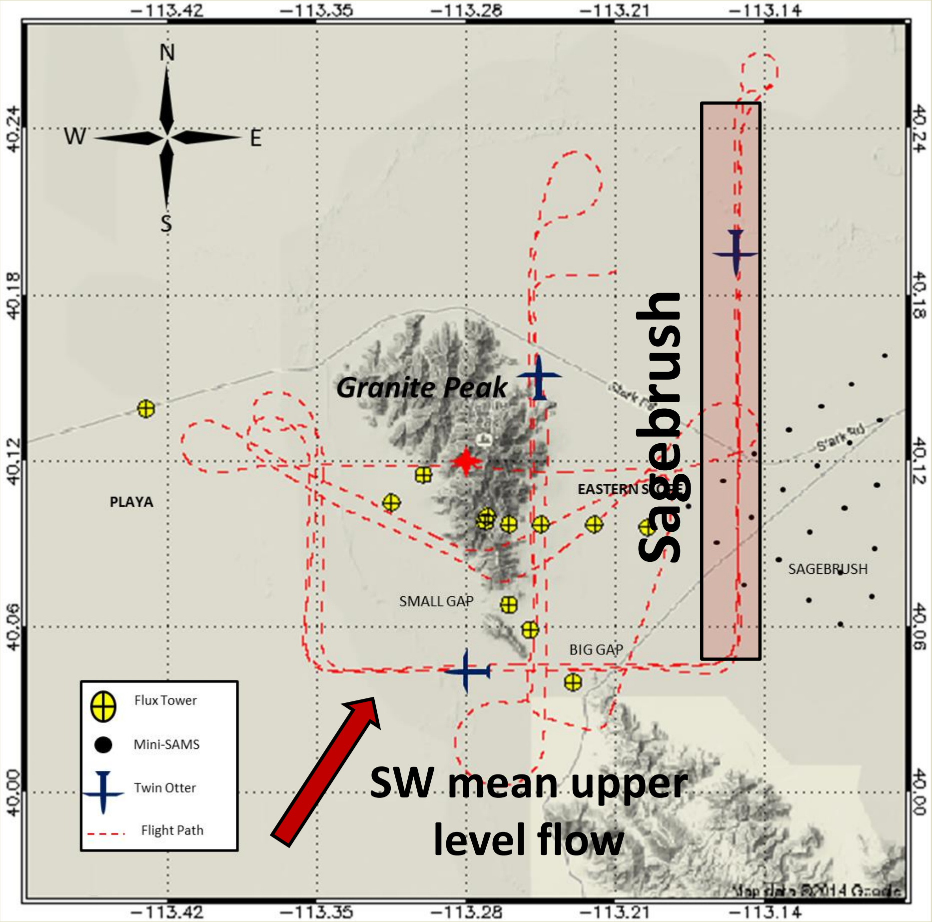
$$\bar{e} = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

Case Study: Oct. 9 Afternoon

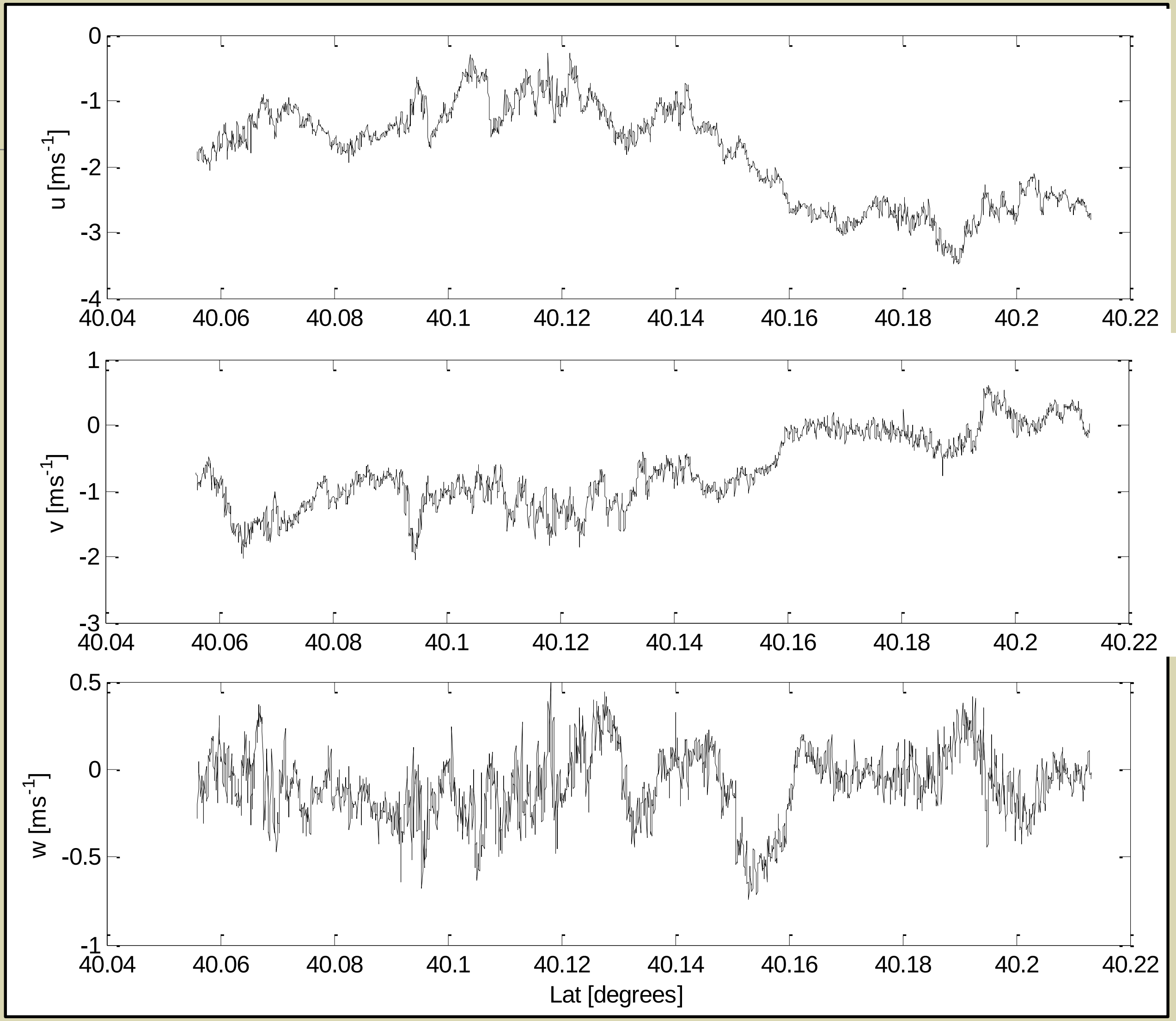


- Prevailing synoptic flow
  - W-SW 4-6 ms^{-1}
  - Transitional period

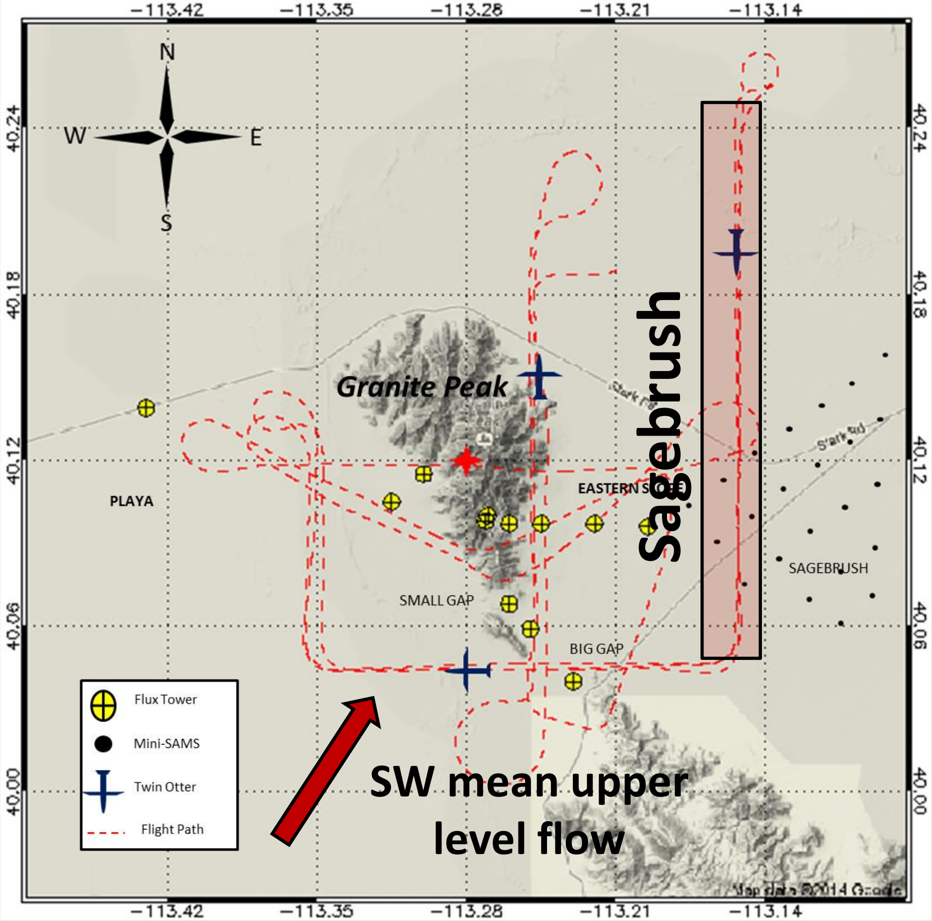
Air Flow



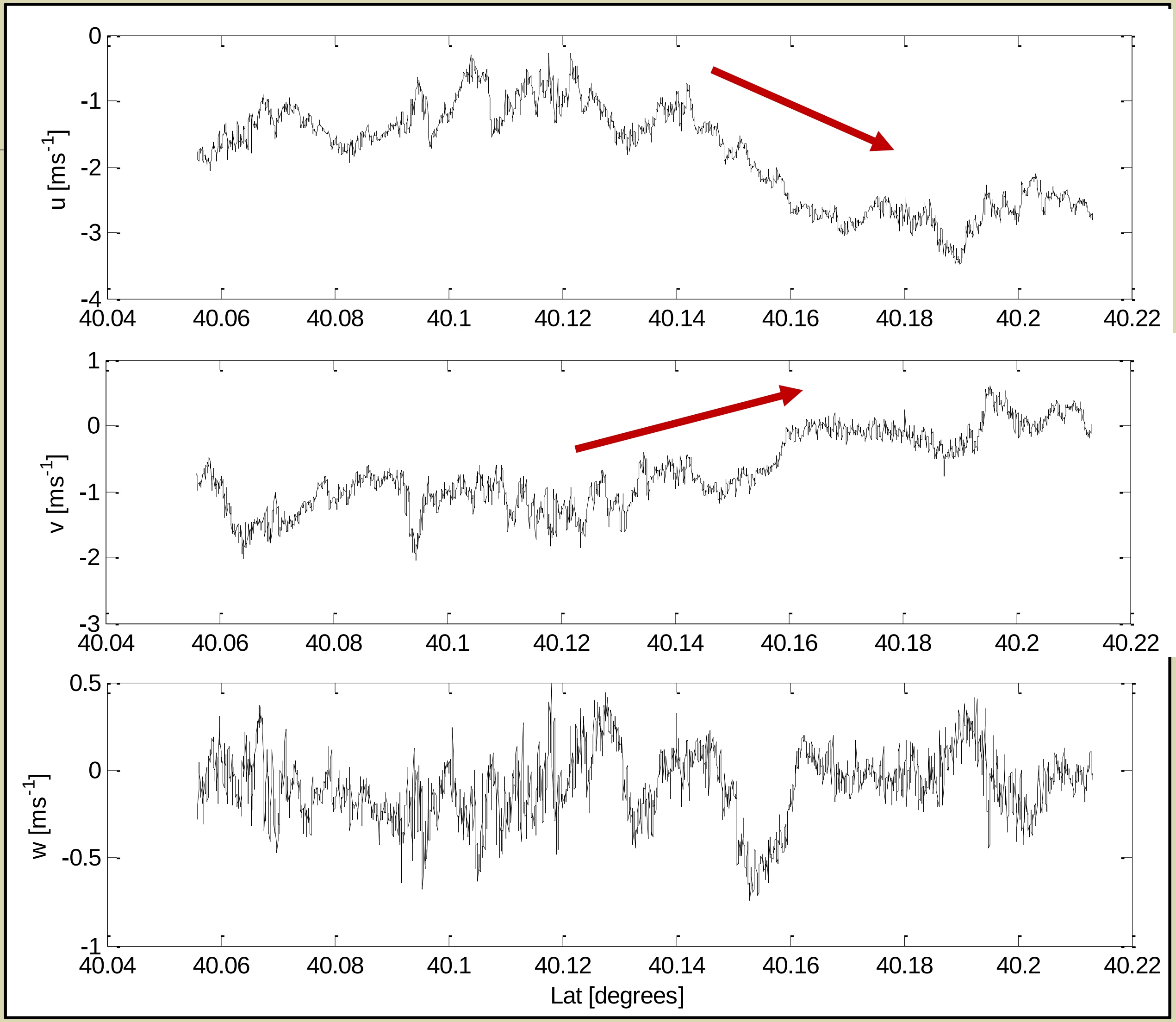
Sagebrush 1720 m ASL



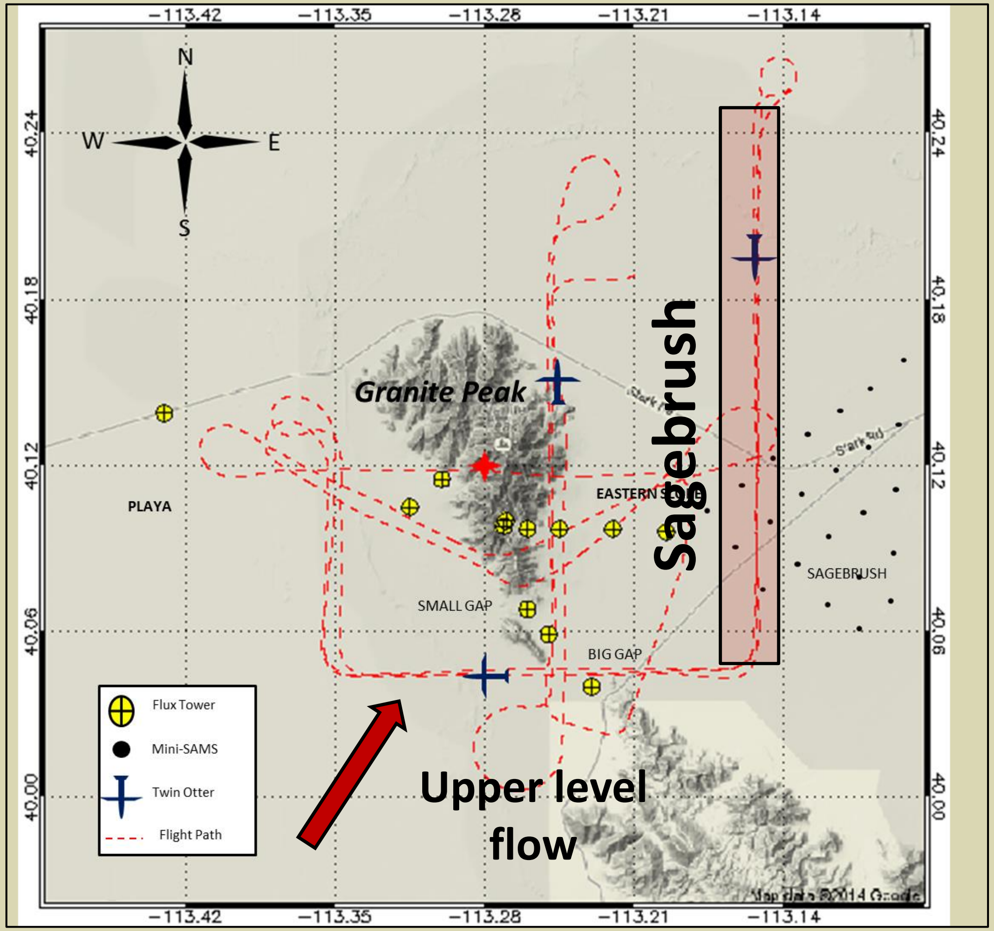
Air Flow

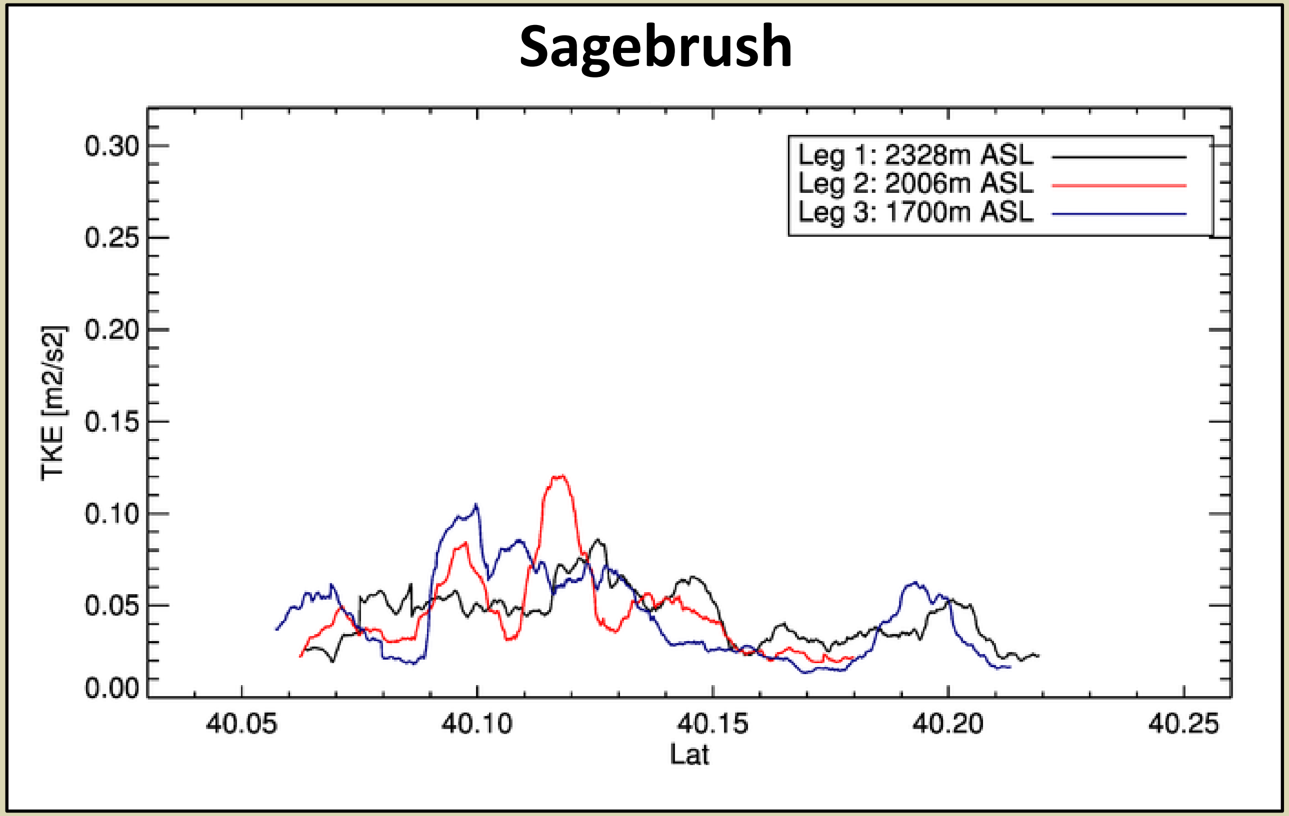


Sagebrush 1720 m ASL



Spatial variability of turbulence





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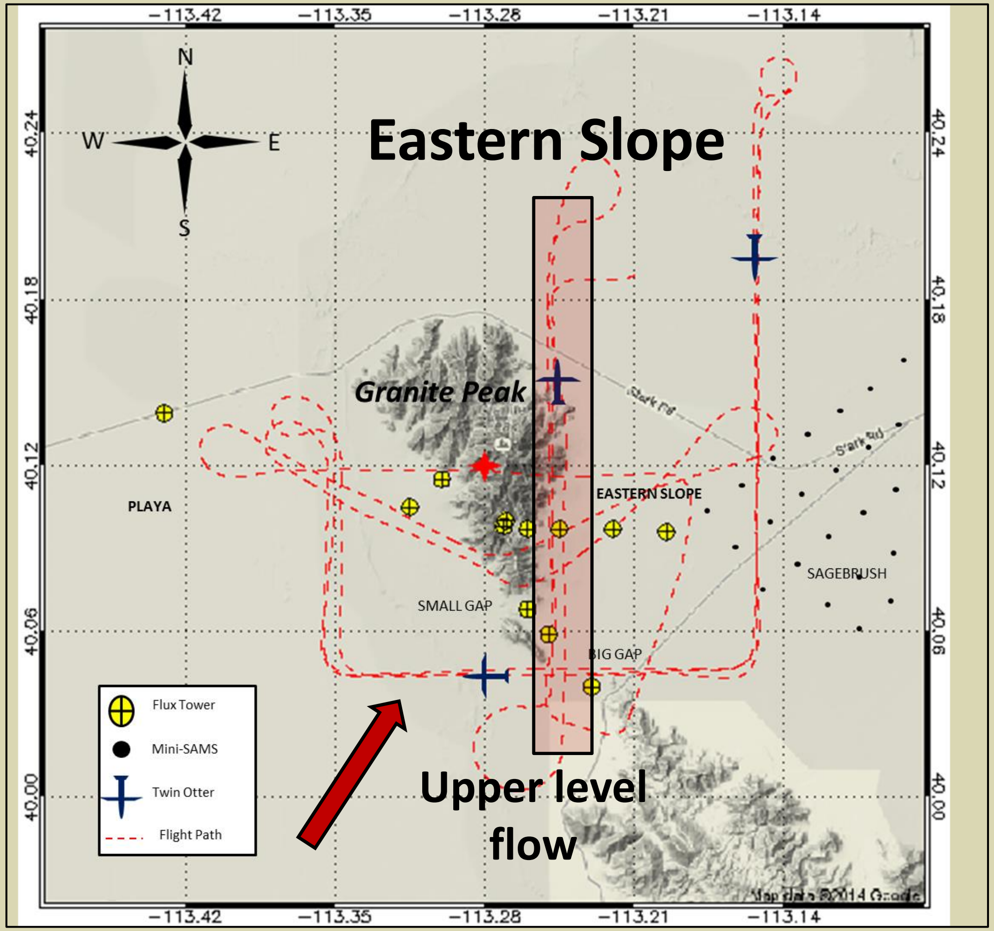
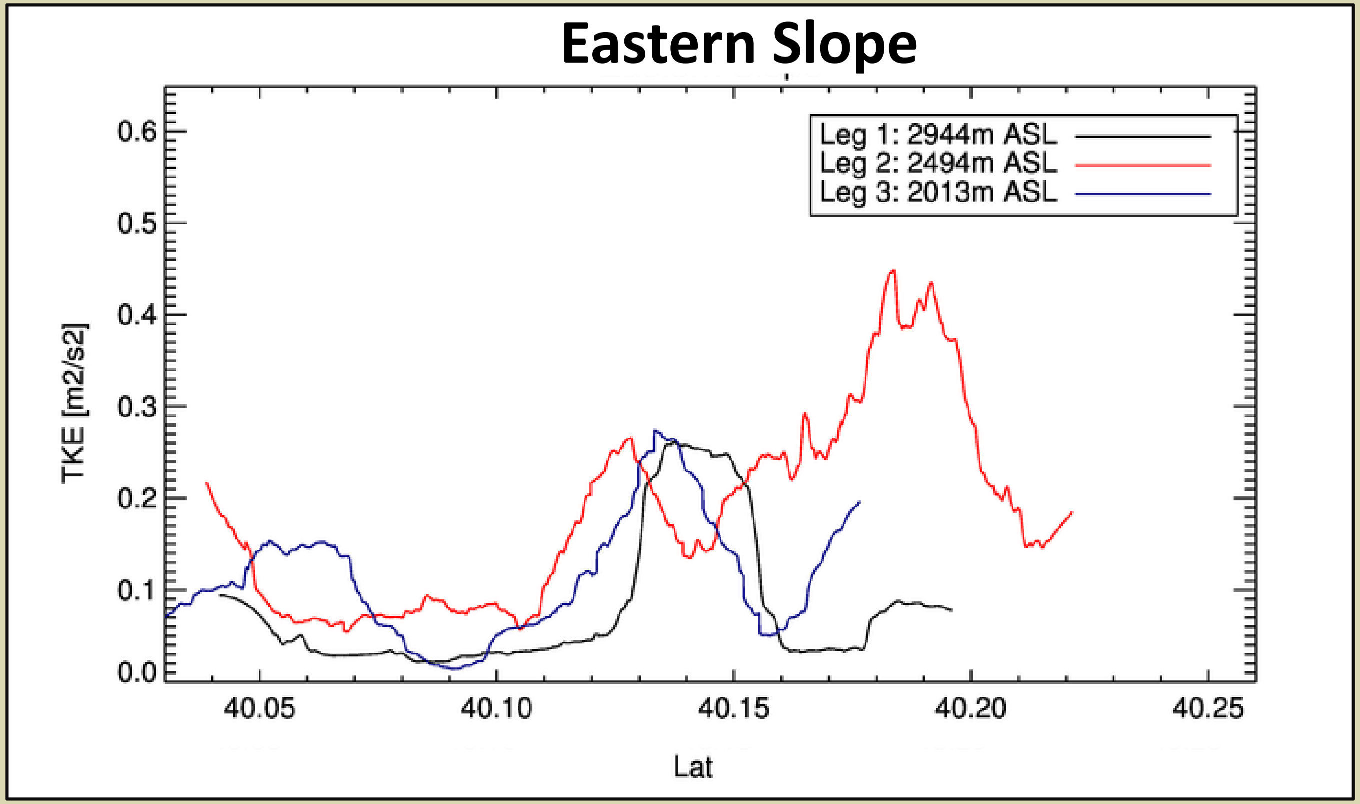
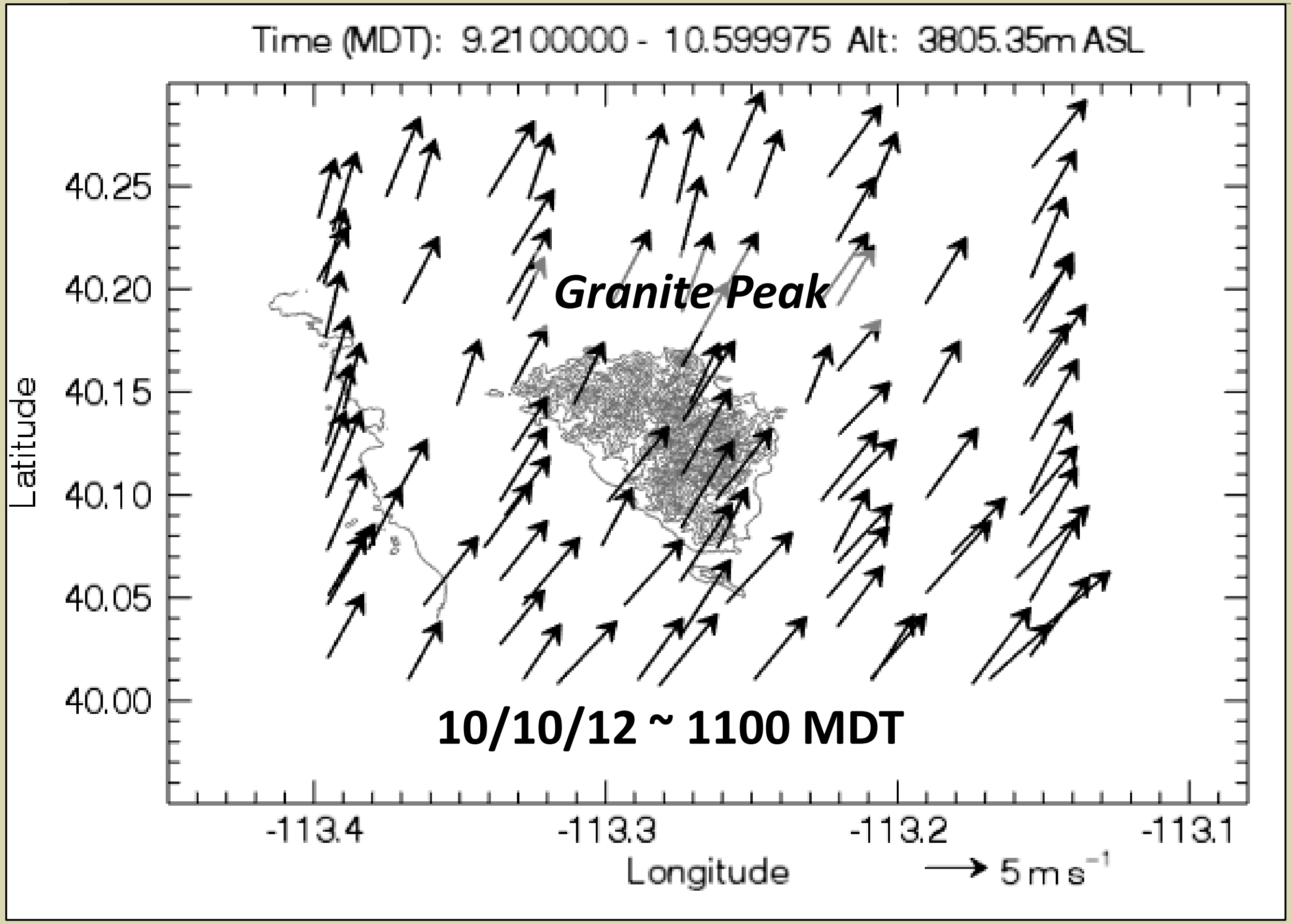


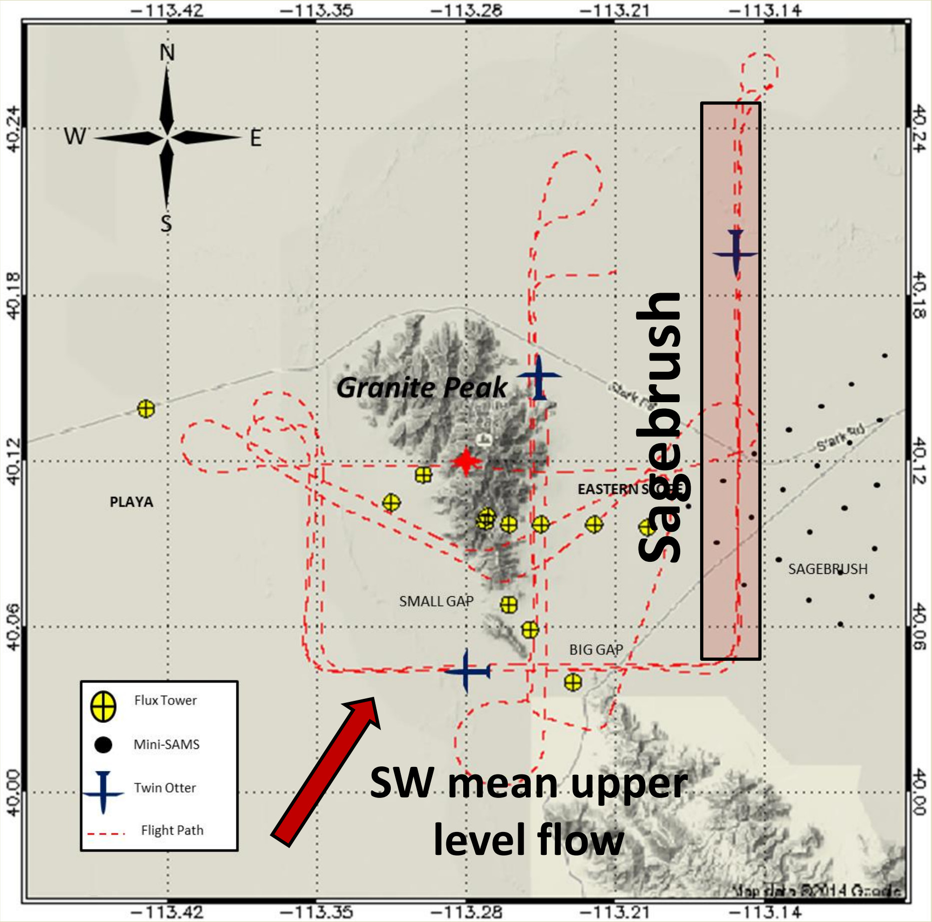


Case Study: Oct. 10 Morning

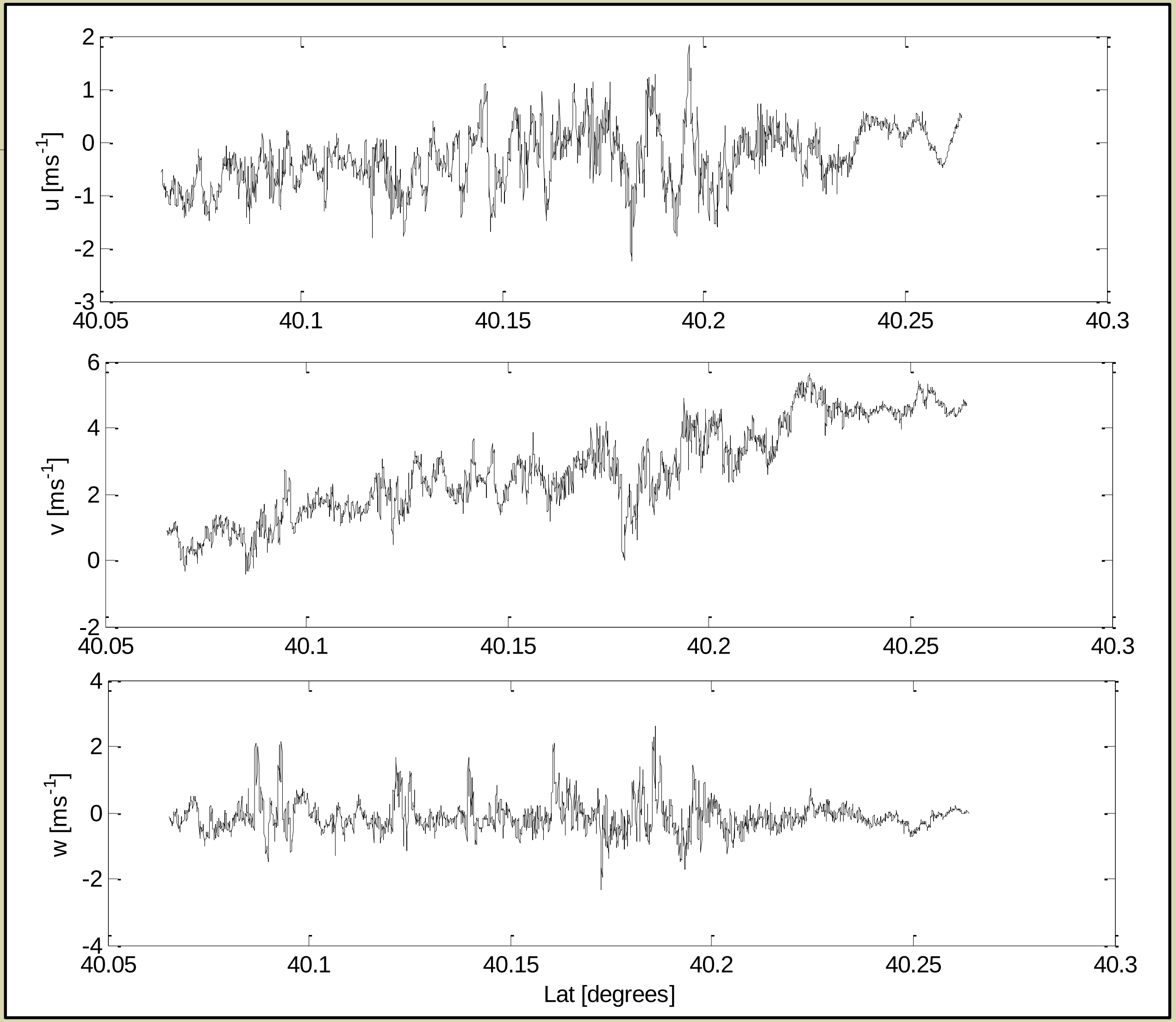


- Prevailing synoptic flow
  - W-SW 6-9 ms^{-1}
  - Transitional period

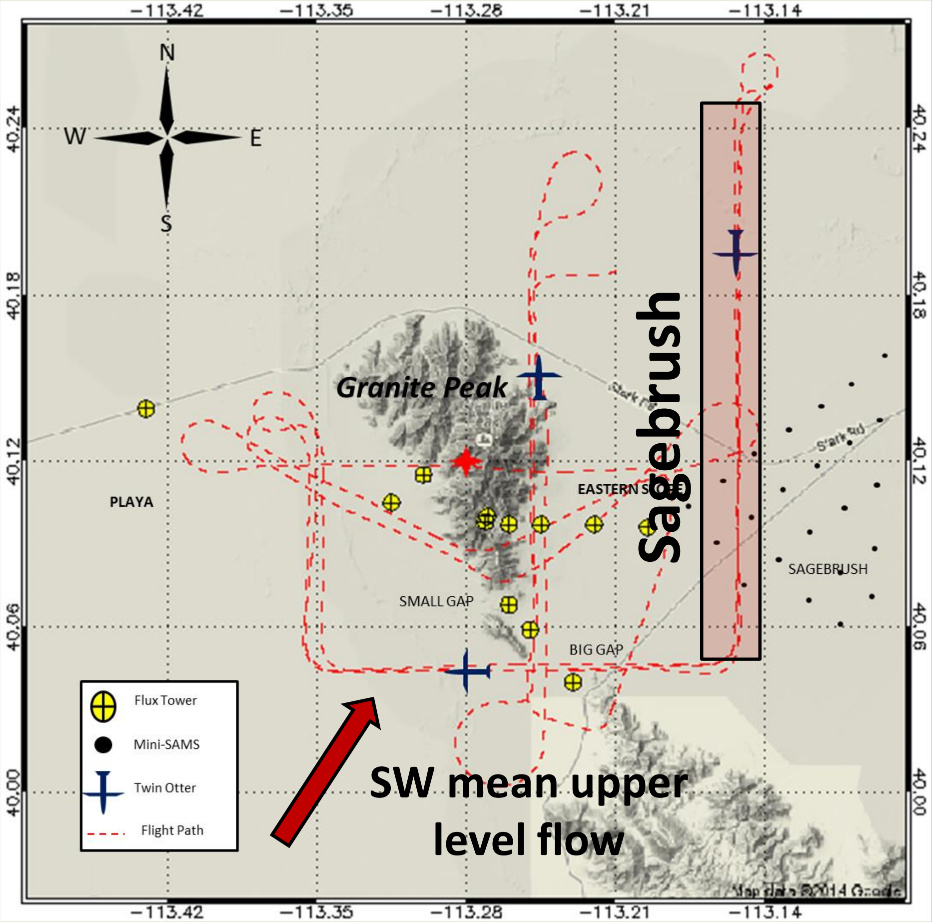
Air Flow



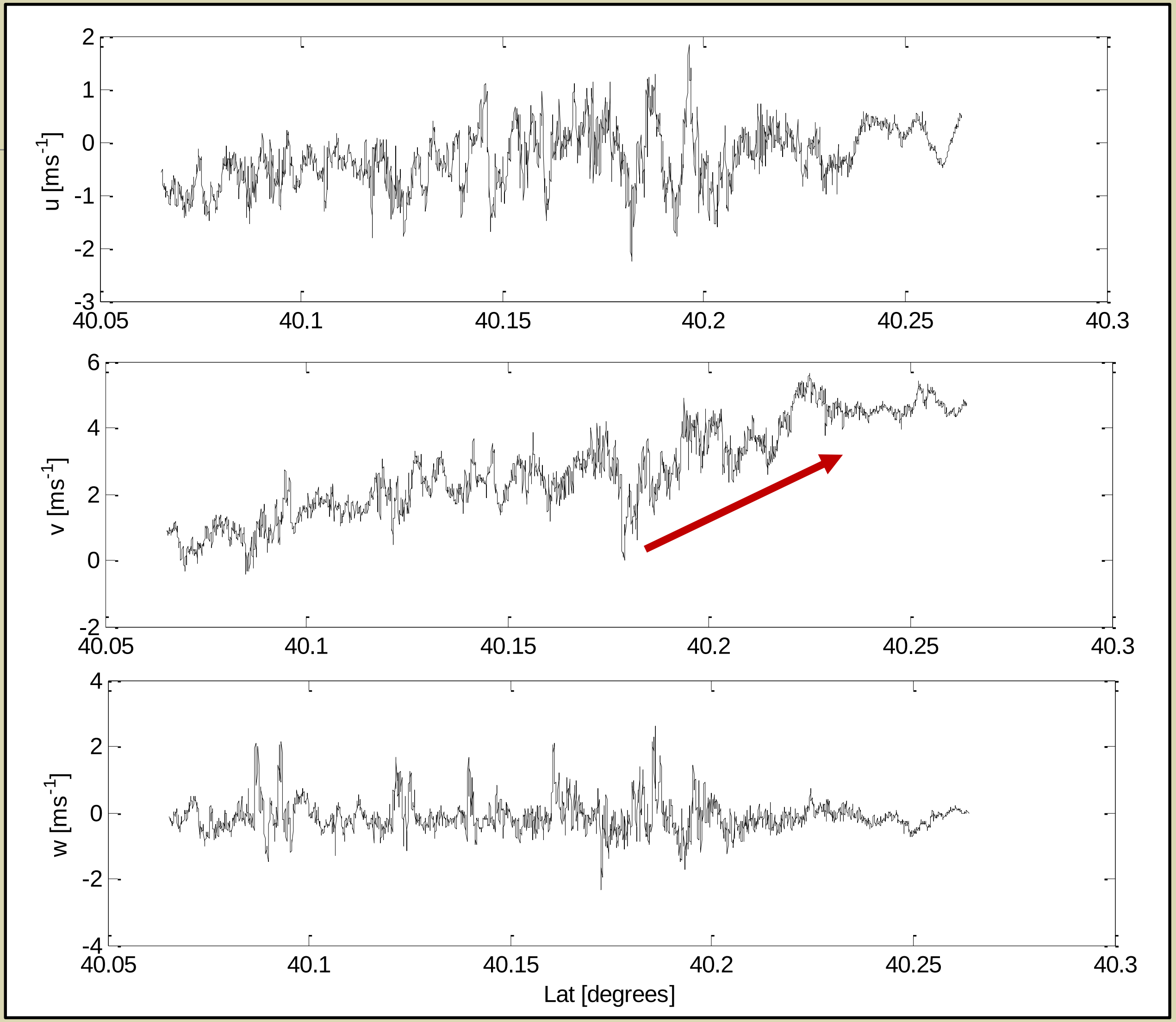
Sagebrush 1720 m ASL



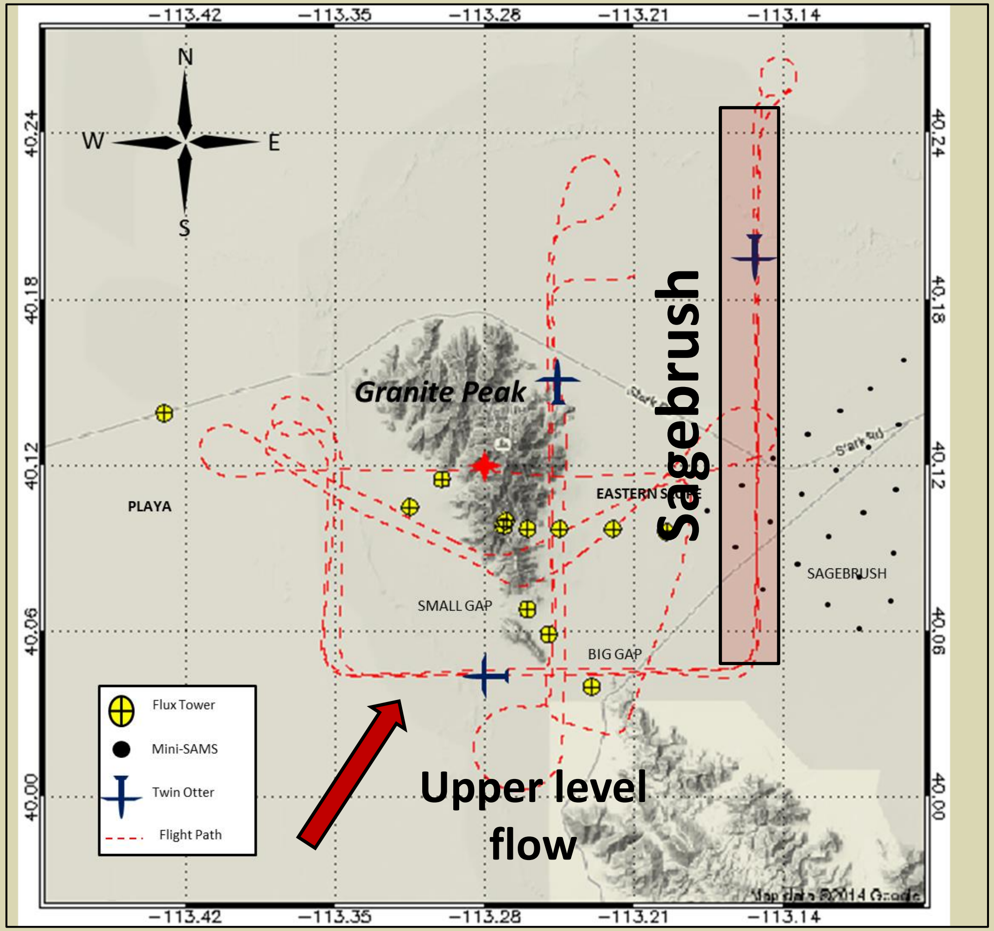
Air Flow

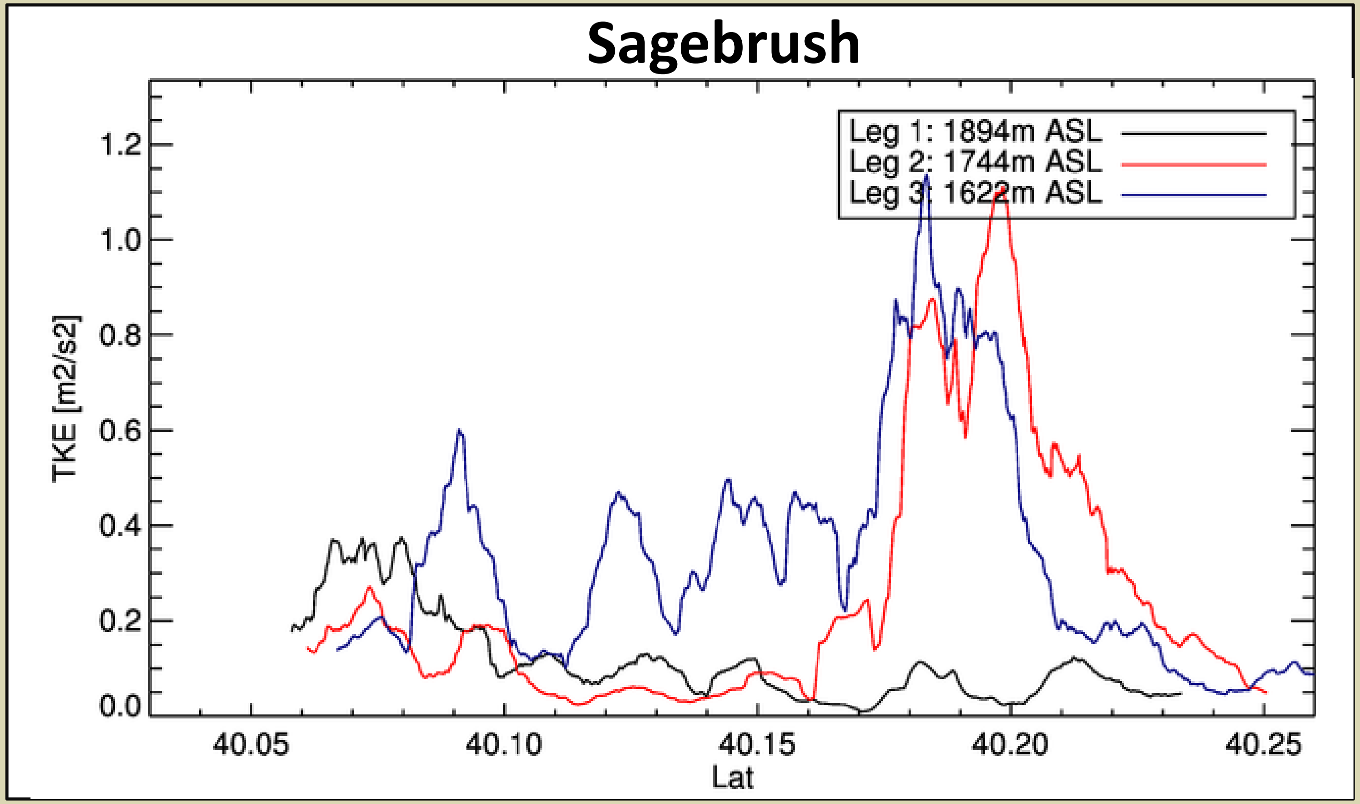


Sagebrush 1720 m ASL



Spatial variability of turbulence





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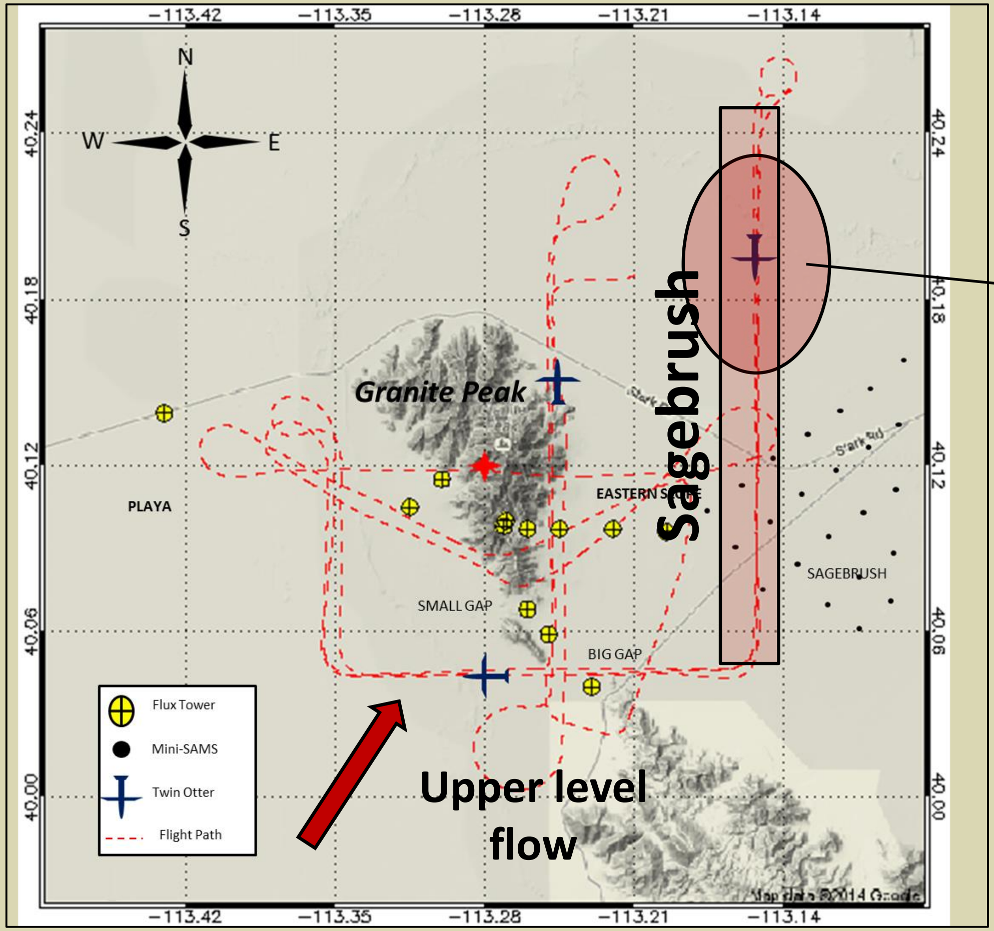
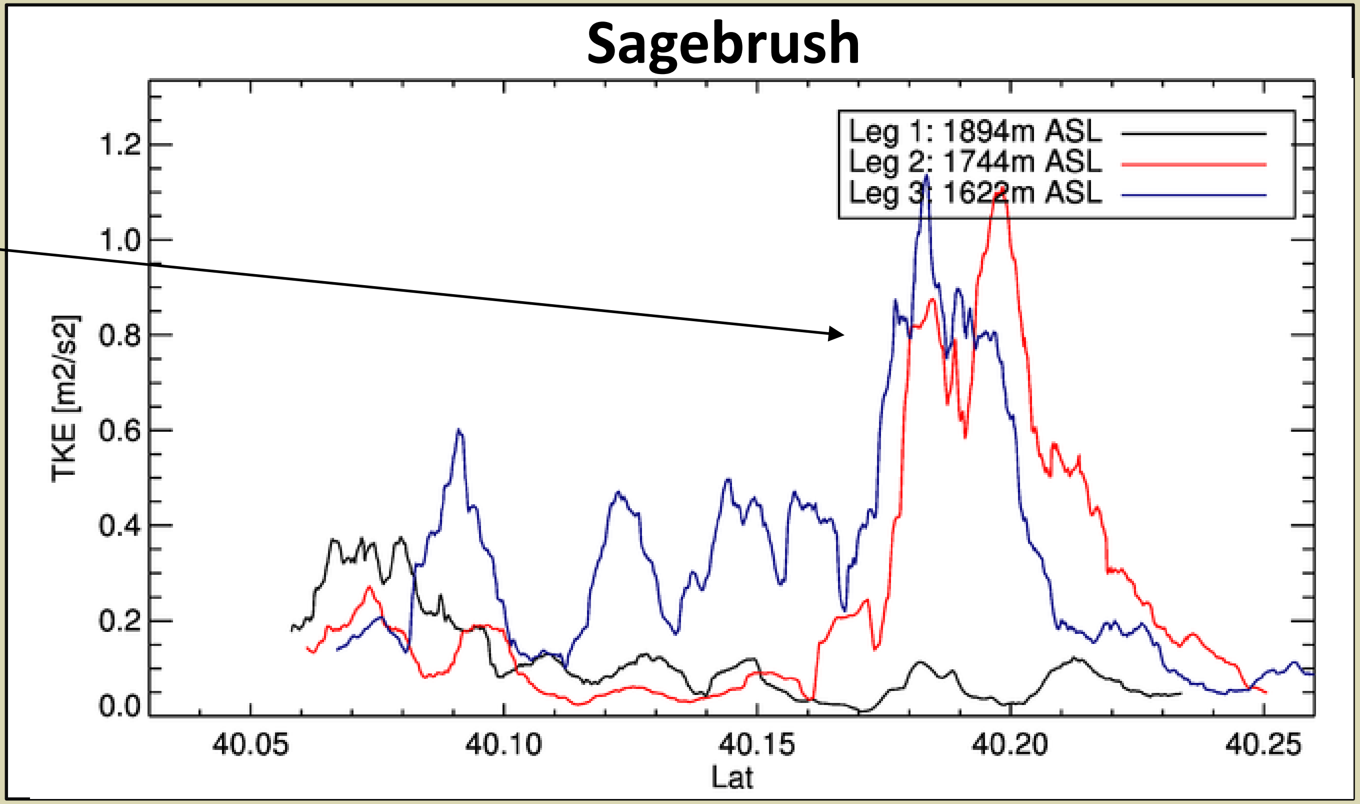
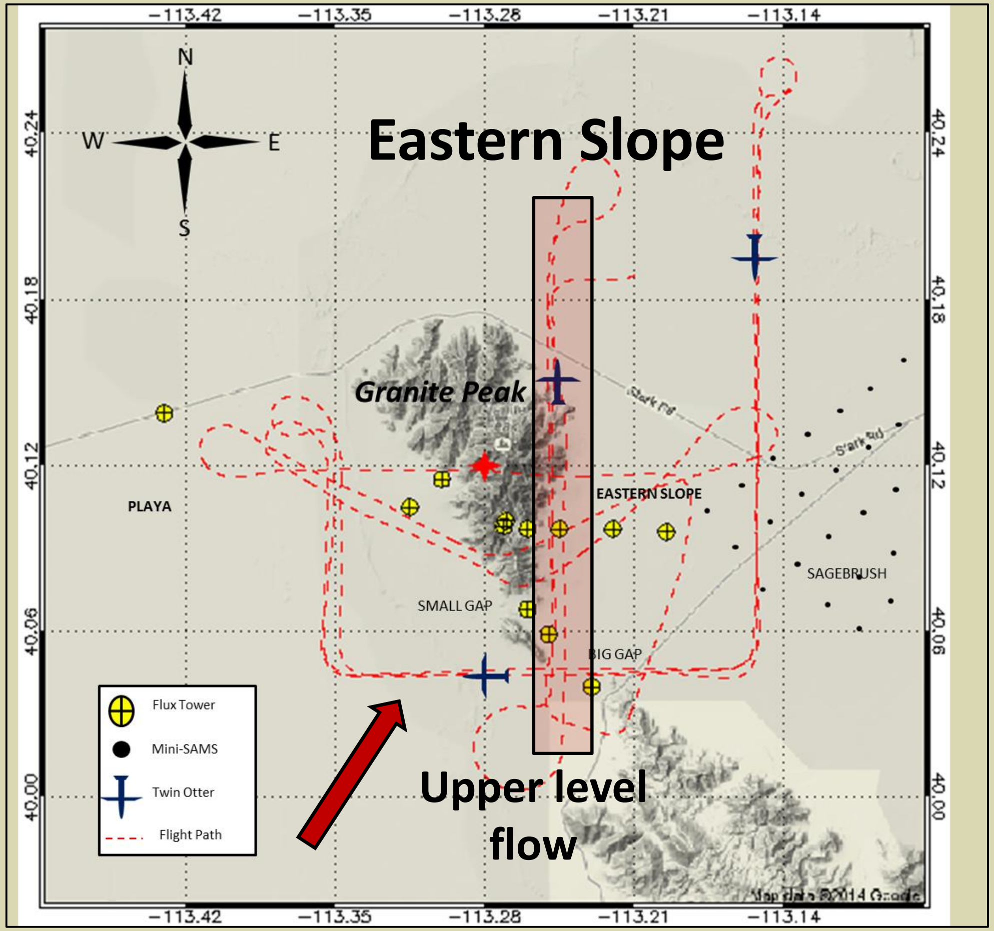
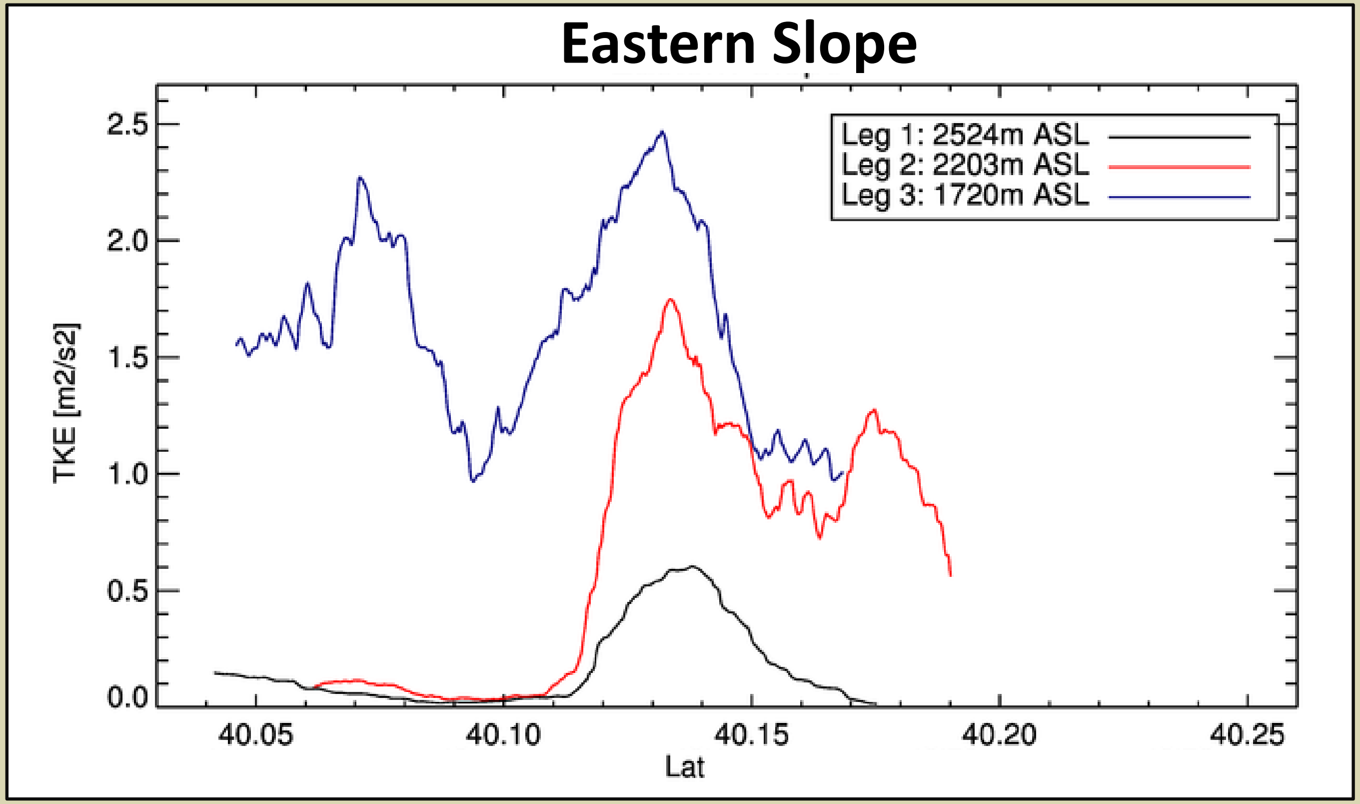




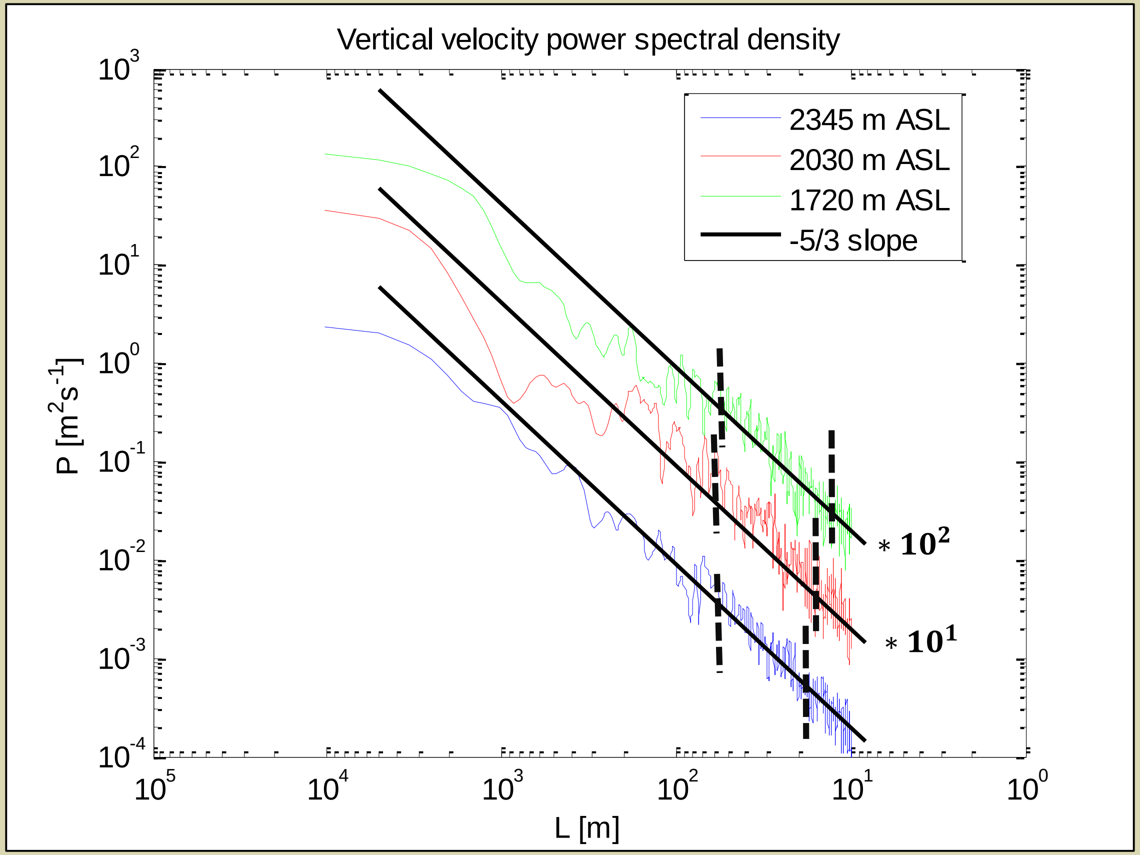
Spatial variability of turbulence

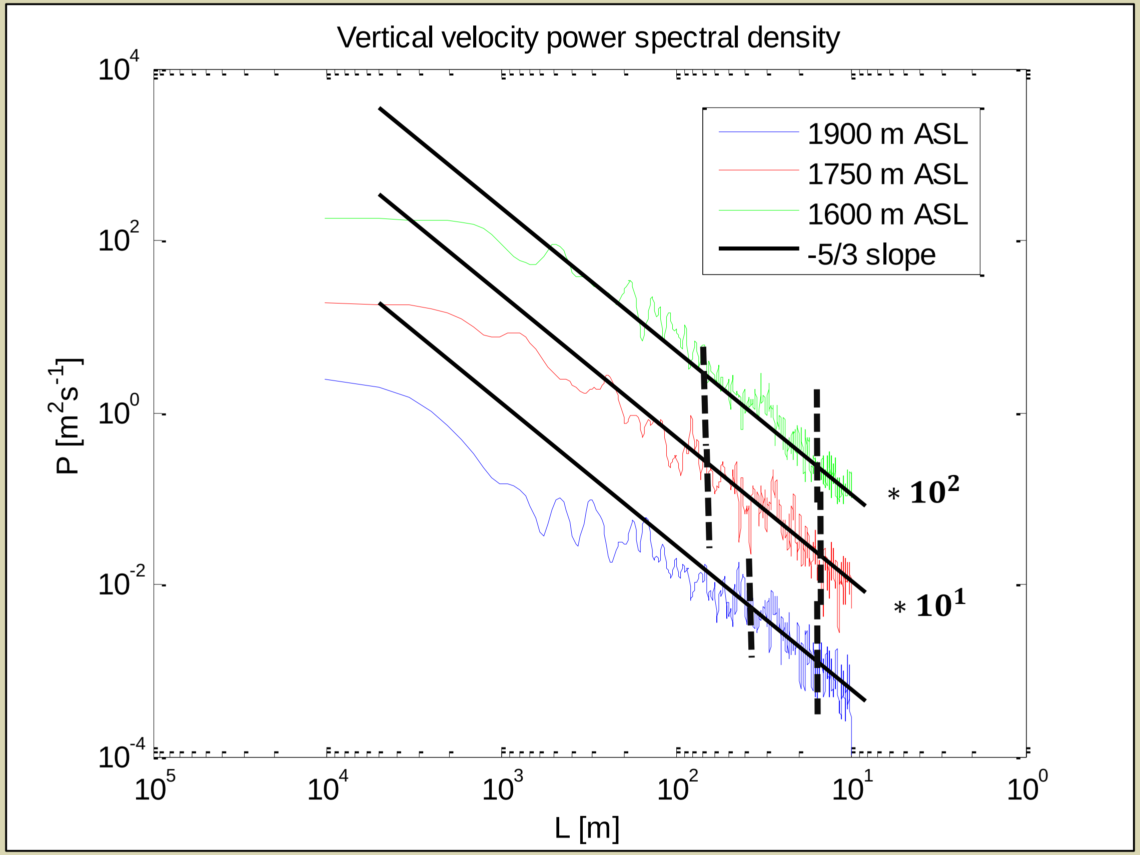




Spectral Analysis

Dotted lines represent Inertial subrange





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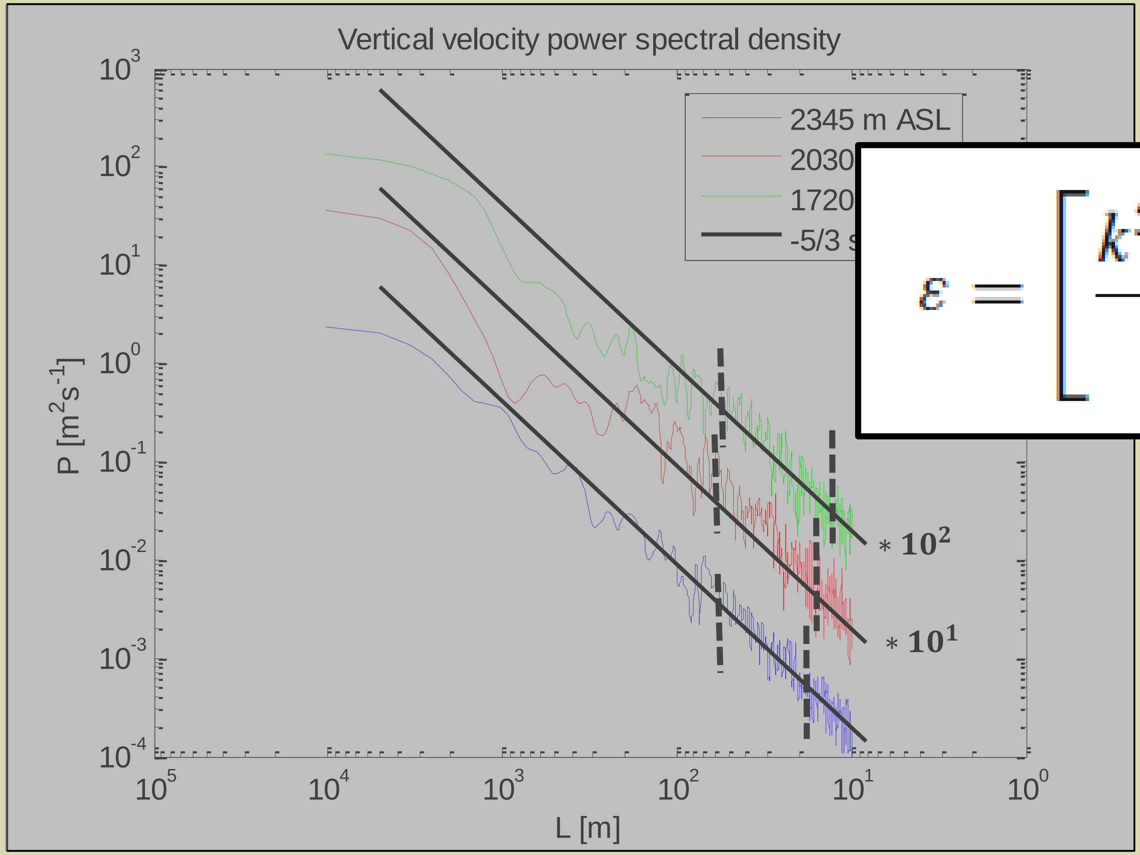
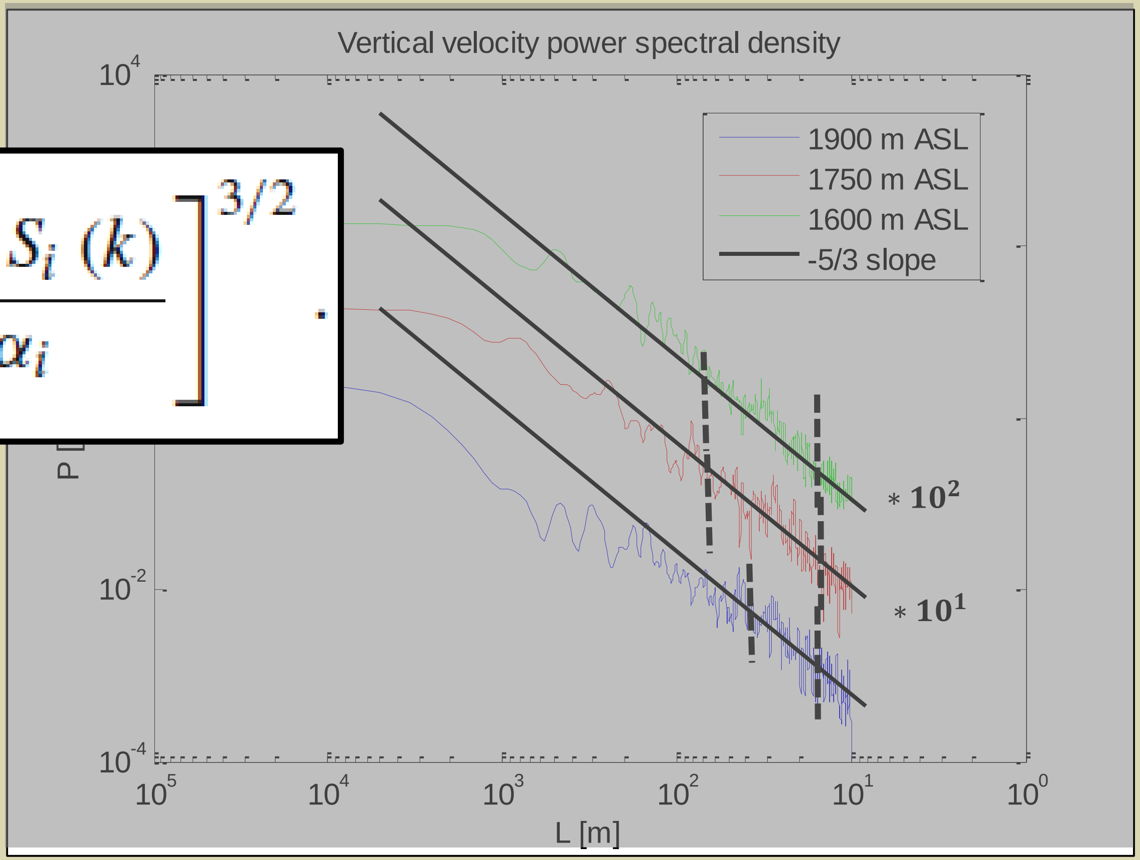


$$\varepsilon = \left[\frac{k^{5/3} S_i\,(k)}{\alpha_i} \right]^{3/2} .$$



Discussion and Conclusion

- **Determination of averaging length is not straight forward**
  - **Moving average method works well for characterizing the spatial variability of TKE**
- **Stronger lower level and mountain top level flow on Oct. 10 than Oct. 9**
  - **Relatively smaller values of TKE during weaker mountain top flow on Oct. 09**
  - **TKE varies as function of distance away from Granite Peak (Eastern Slope => Sagebrush)**
- **Spectral analysis**
  - **Resolve scales of turbulence**
- **What are the physical processes responsible for influencing the spatial variability of TKE?**

Future Work

- Investigate the physical mechanisms that are contributing to the spatial variability of turbulence
  - TKE structure
  - Contribution of shear and buoyancy mechanisms
- Continue spectral analysis on all three wind velocity components
- Investigate flight legs from other IOPs

Acknowledgments

Advisor and collaborators

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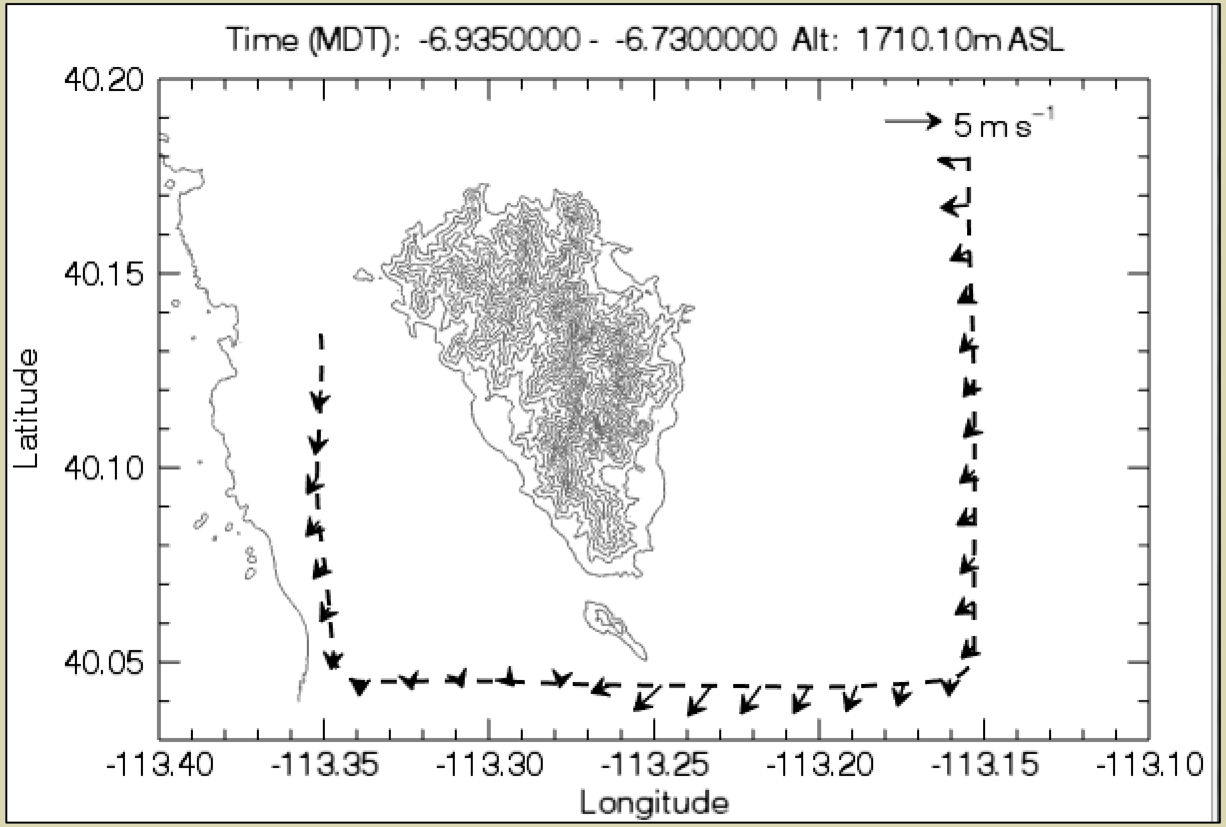
Office of Naval Research and NSF

Environmental Sciences group at the Army Research Office

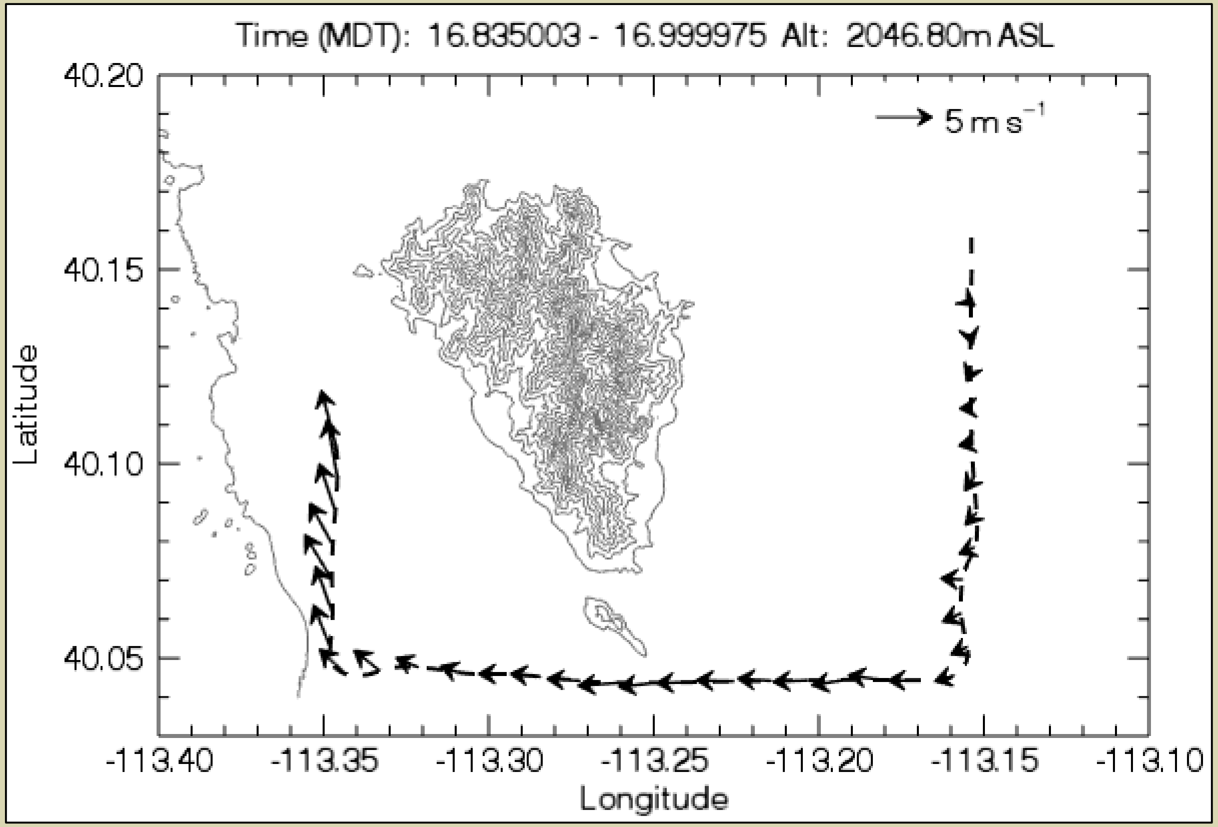
MATERHORN community, De Wekker lab group, and University of Virginia Environmental Sciences Department

Dept.Envl.Sci.

Air Flow

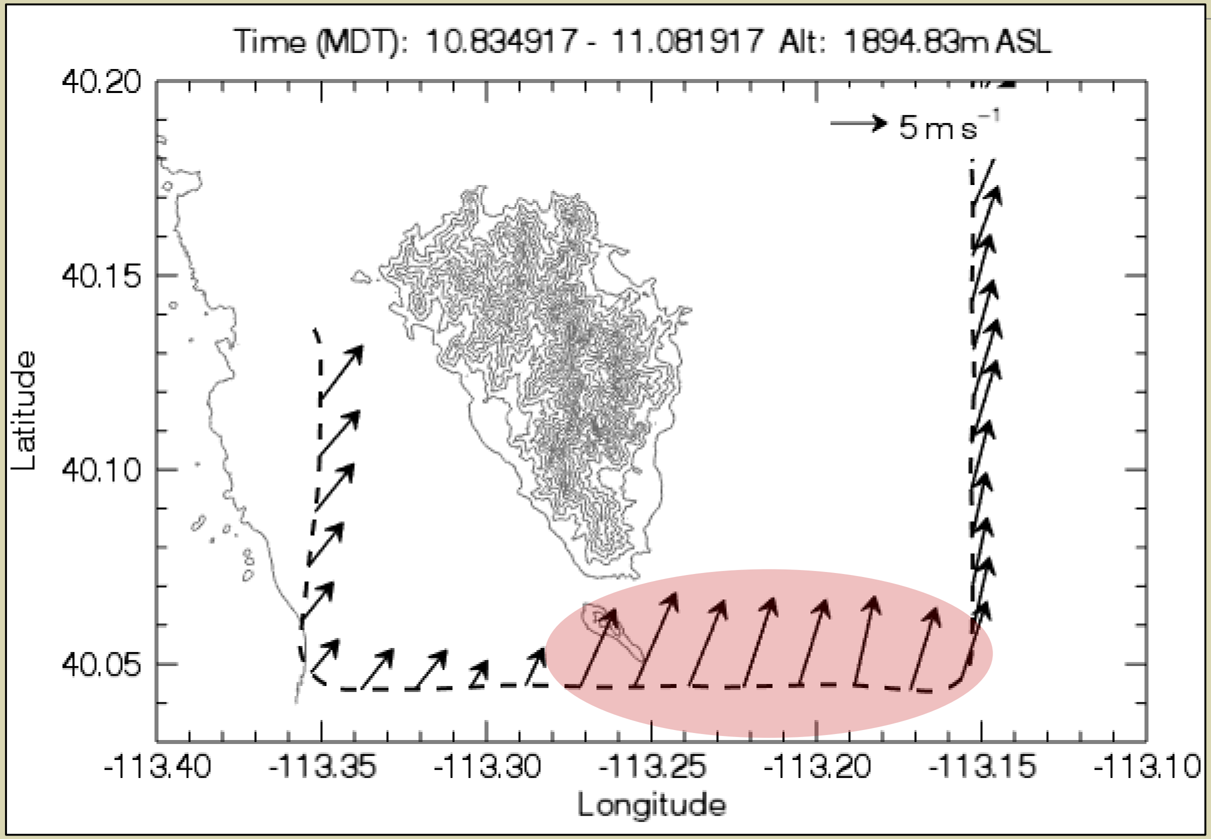


121009 Lower Level winds ~ 1700 m ASL in situ winds

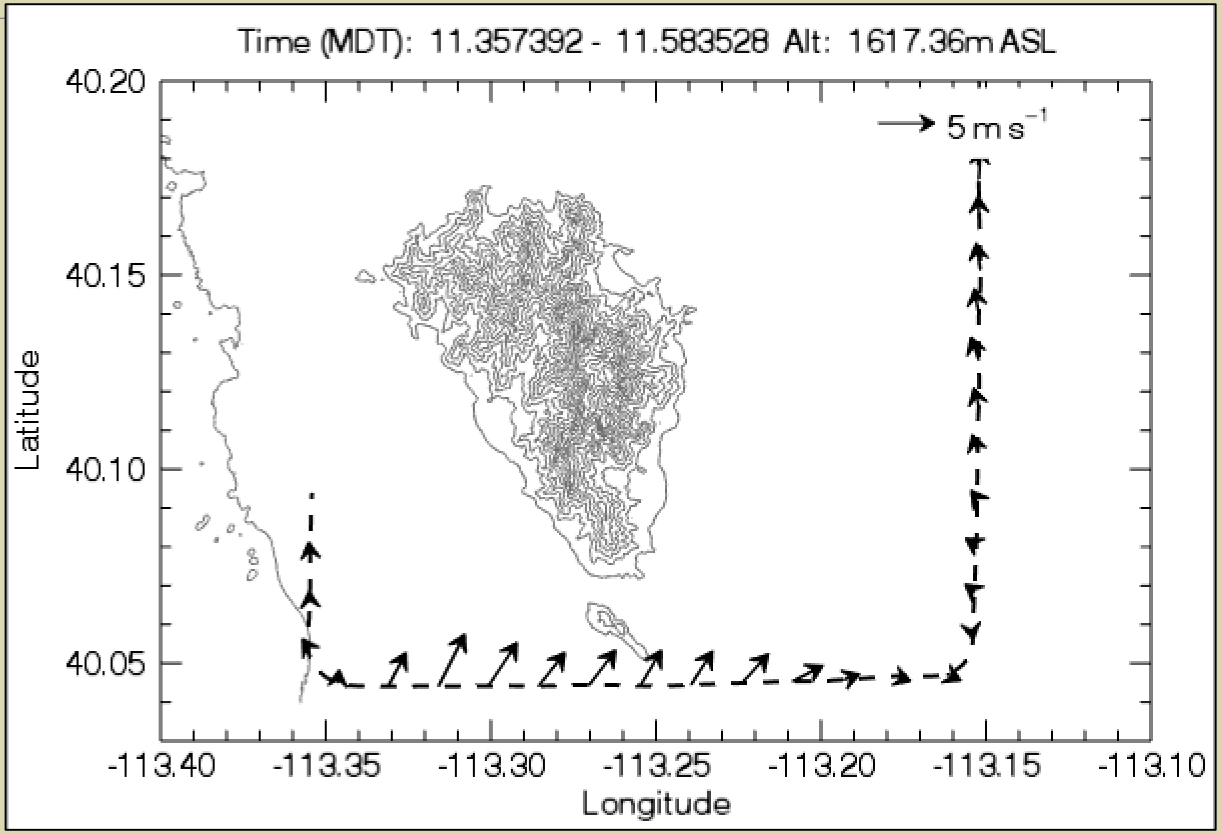


121009 Lower Level winds ~ 2050 m ASL in situ winds

Air flow



121010 Lower Level winds ~ 1900 m ASL in situ winds



121010 Lower Level winds ~ 1620 m ASL in situ winds

Approach and Methods: *Spatial Variability of TKE*

The spatial variability of TKE was evaluated as follows:

- Moving averaging method for data series and calculate respective perturbations of meteorological variables

- TKE profiles from aircraft are compared across flight days

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Approach and Methods

Pick selected IOPs with similar conditions

- Mean flow
- Synoptic conditions

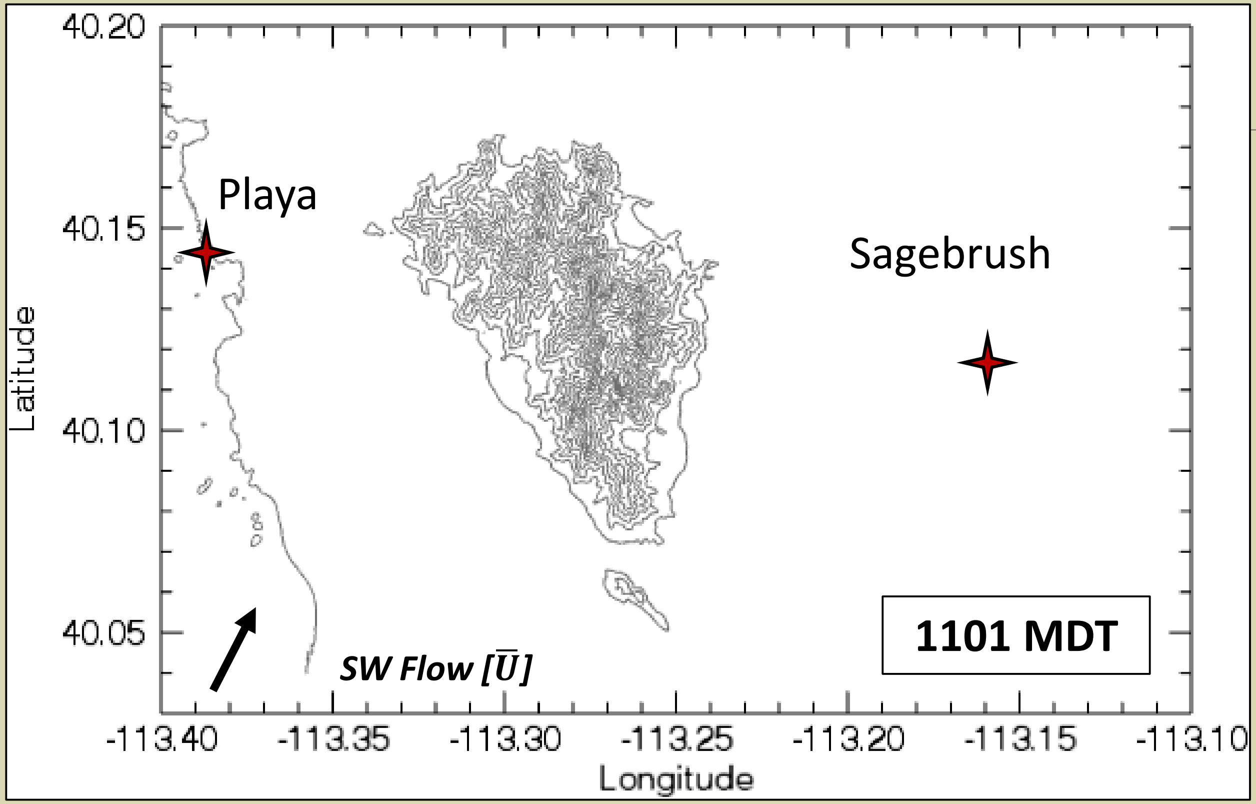
Select TO flight legs in regions around Granite Peak

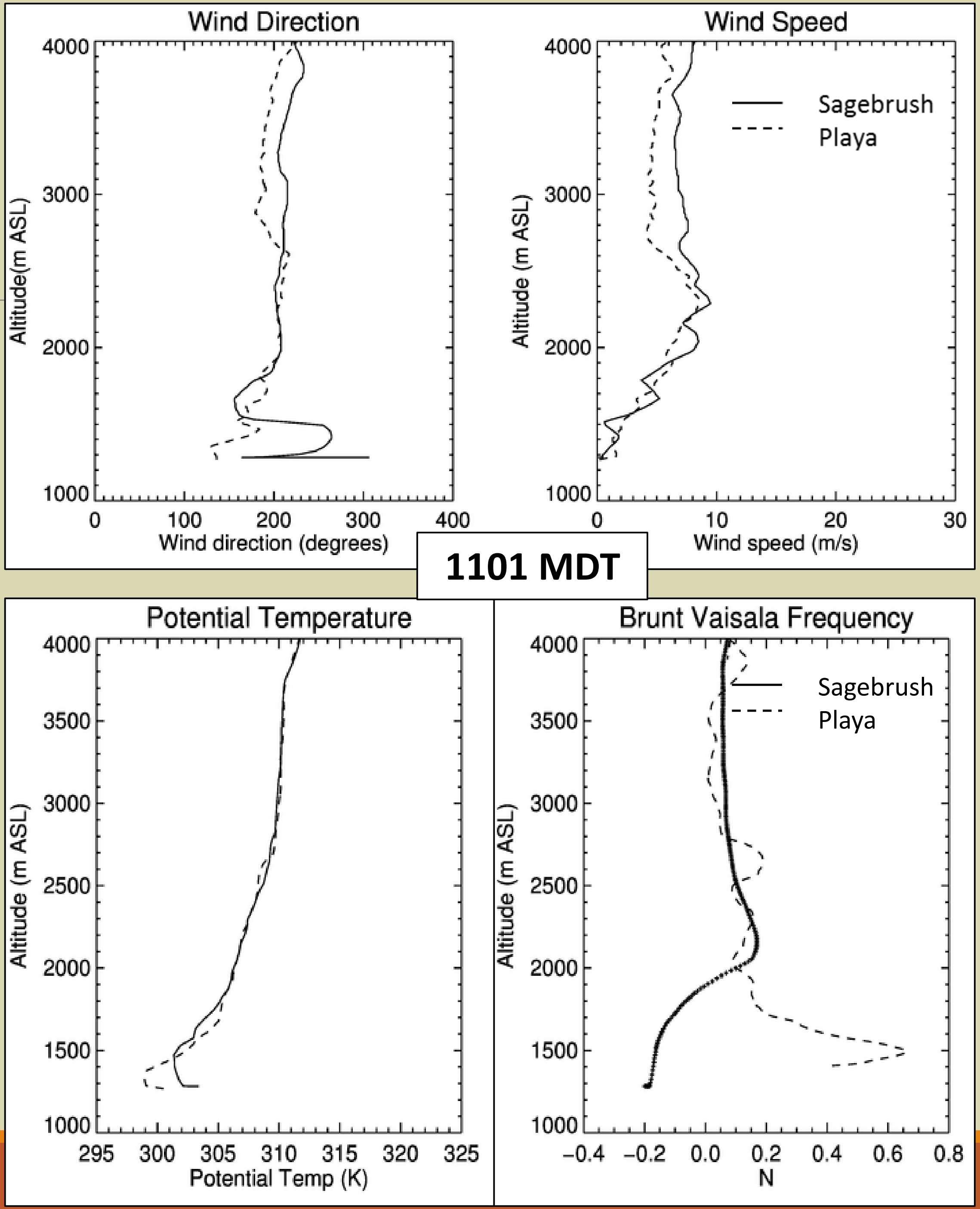
- Areas hypothesized that flow-terrain interactions will produce spatial variability in turbulent features

Investigate TO *in situ* observations of wind velocity components (w, u, and v)

- Determine prominent features in turbulent wind field
- Develop profiles turbulent kinetic energy (TKE)
- Determine prominent features in TKE

Mean State Conditions: Oct. 10





$\bar{U}$ 2000 m ASL

Playa: 8.1 m/s

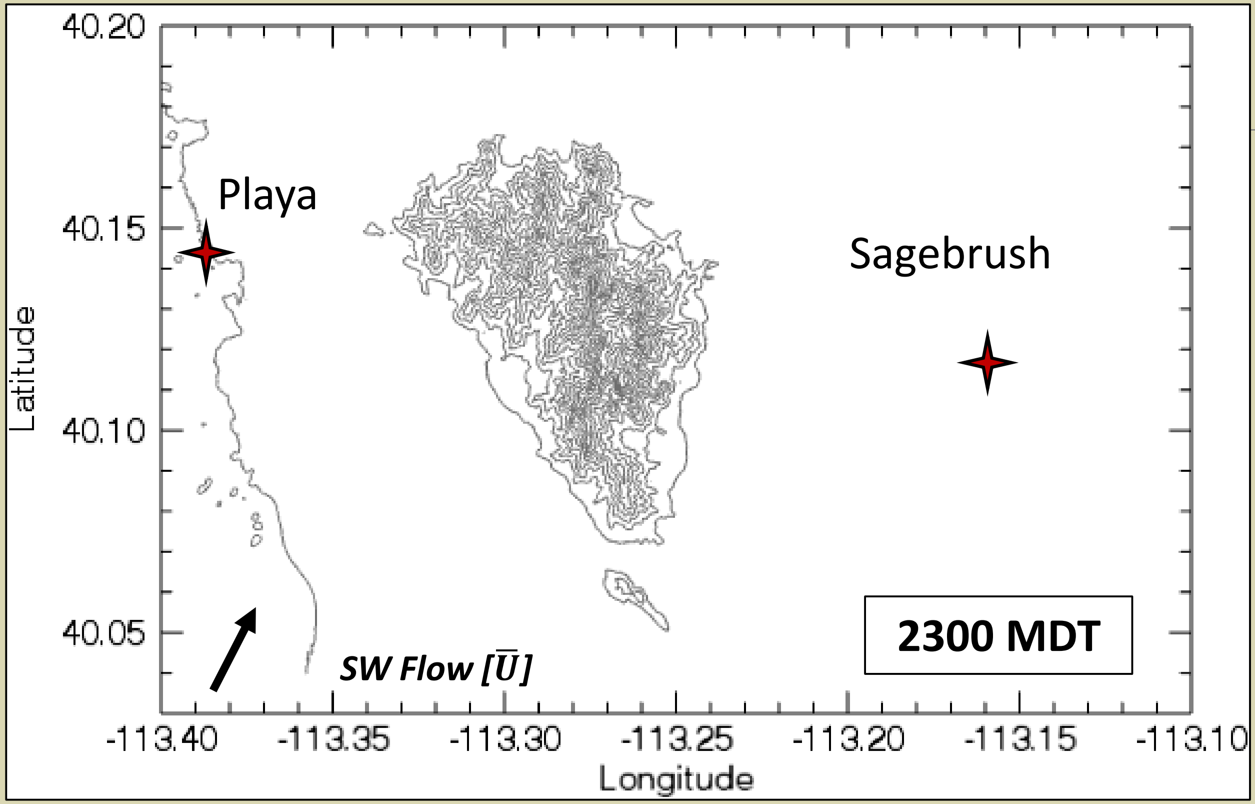
Sagebrush: 6.0 m/s

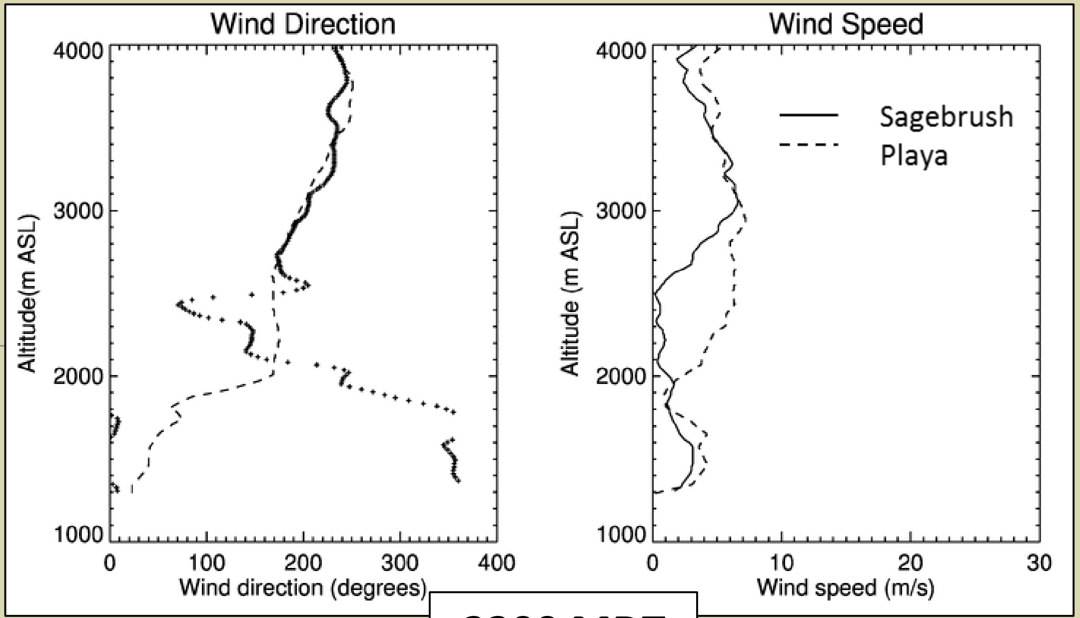
Surface Temp

Playa: ~ 17 C˚

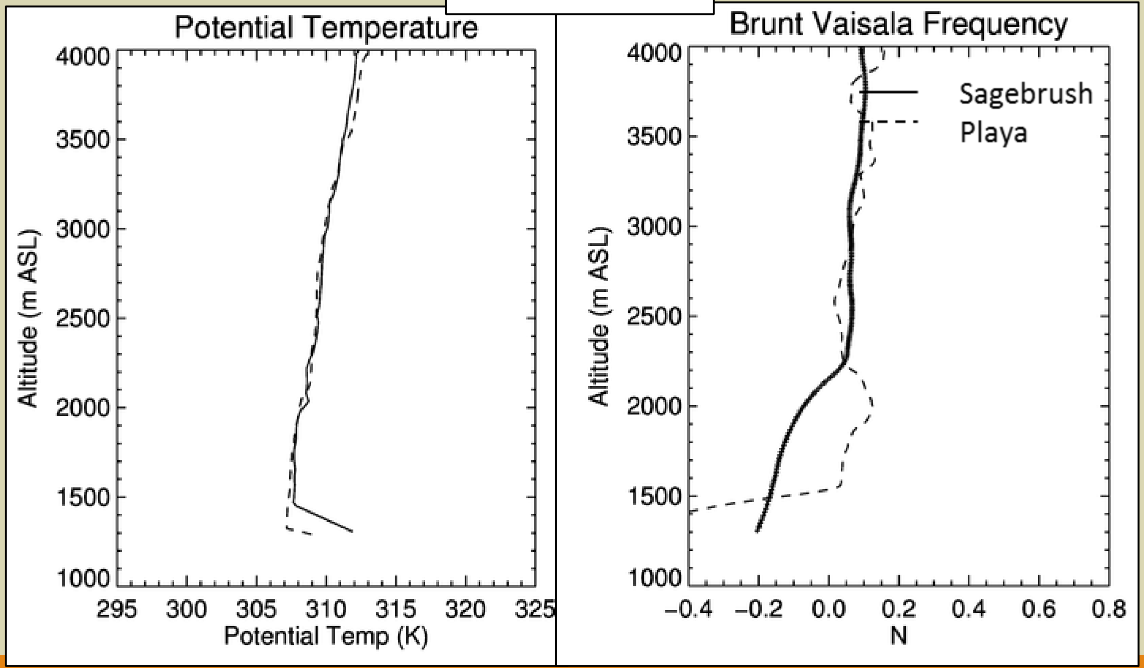
Sagebrush: ~ 21 C˚

Mean State Conditions: Oct. 9





2300 MDT



$\bar{U}$ 2000-3000 m ASL

Playa: 8.1 m/s

Sagebrush: 6.0 m/s

Surface Temp

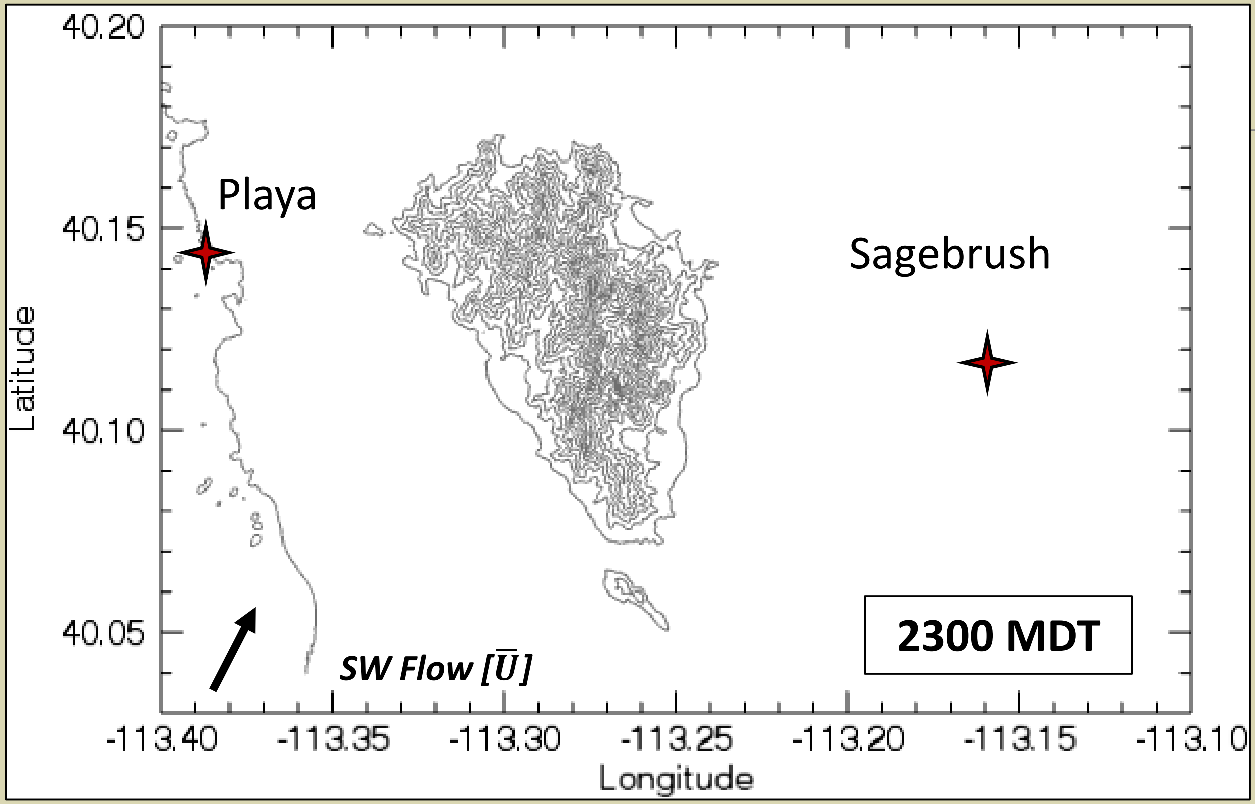
Playa: ~ 23 C˚

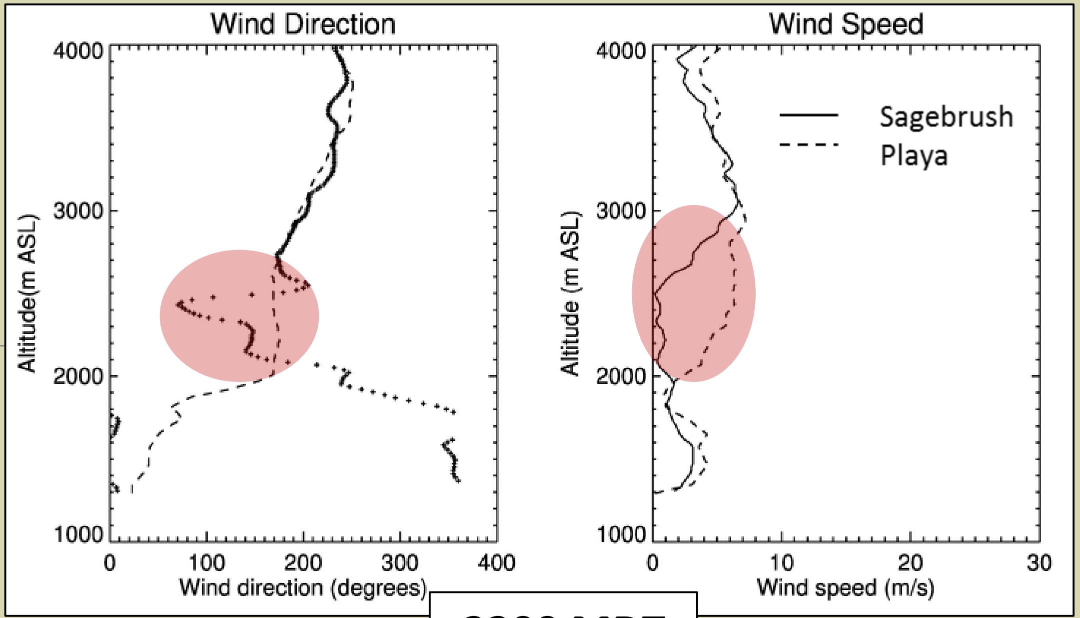
Sagebrush: ~ 27 C˚

Department of Environmental Sciences

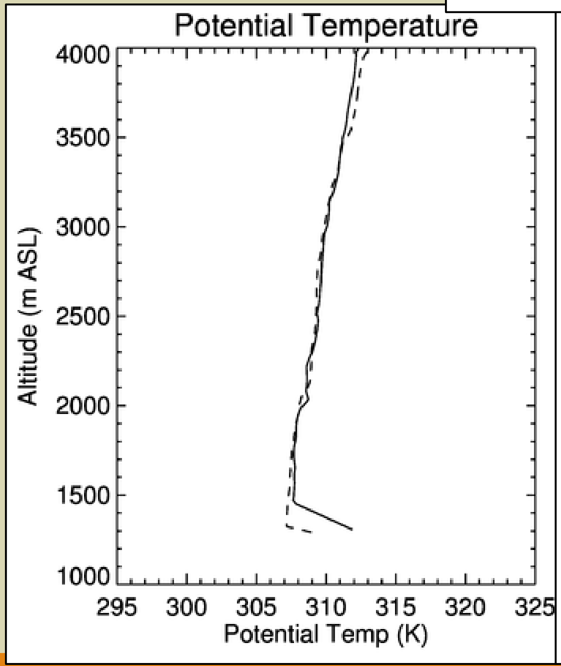
University of Virginia

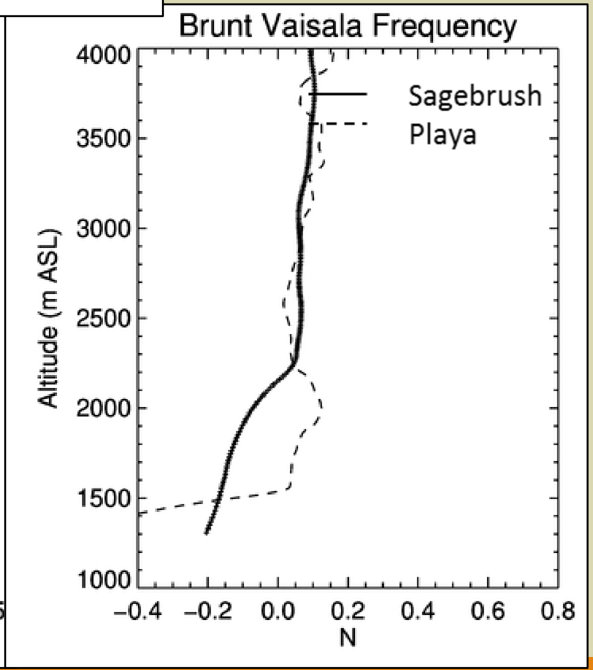
Mean State Conditions: Oct. 9





2300 MDT





$\overline{U}$ 1950-2100 m ASL

Playa: 6 m/s

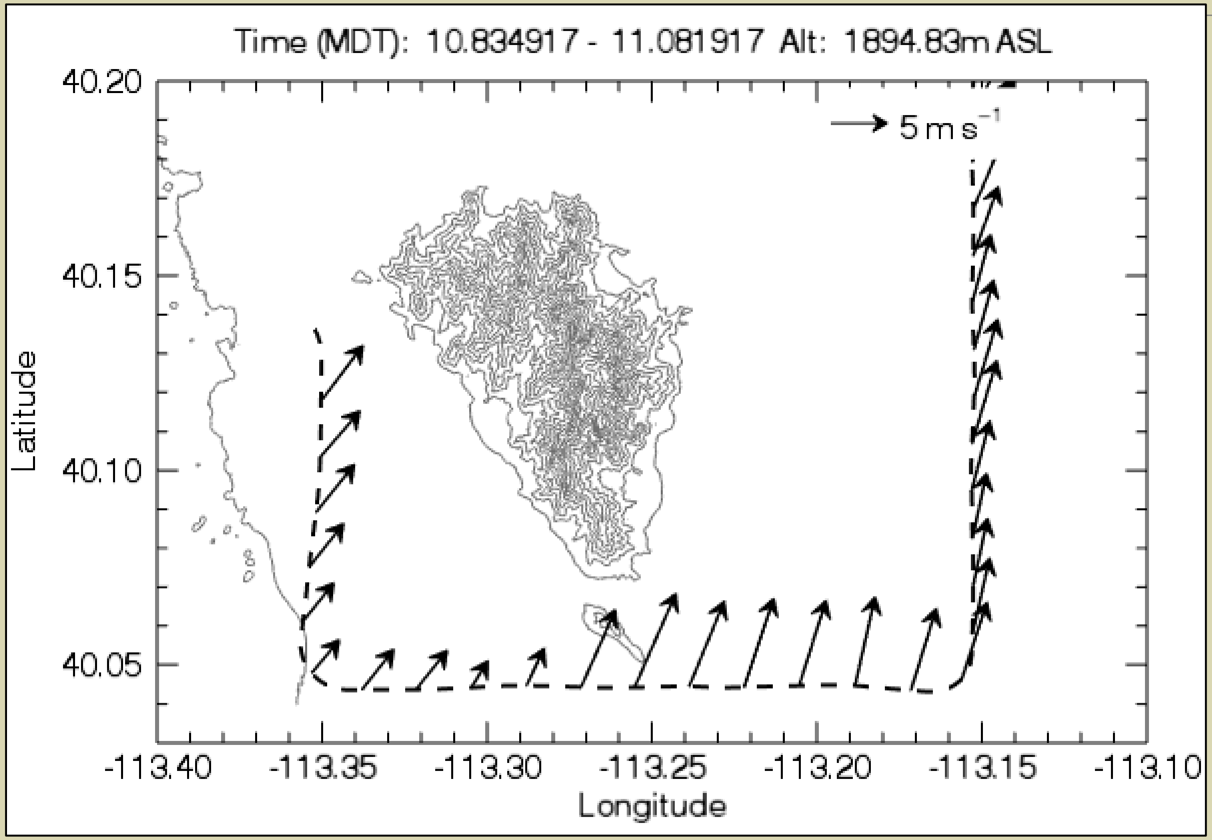
Sagebrush: 1-2 m/s

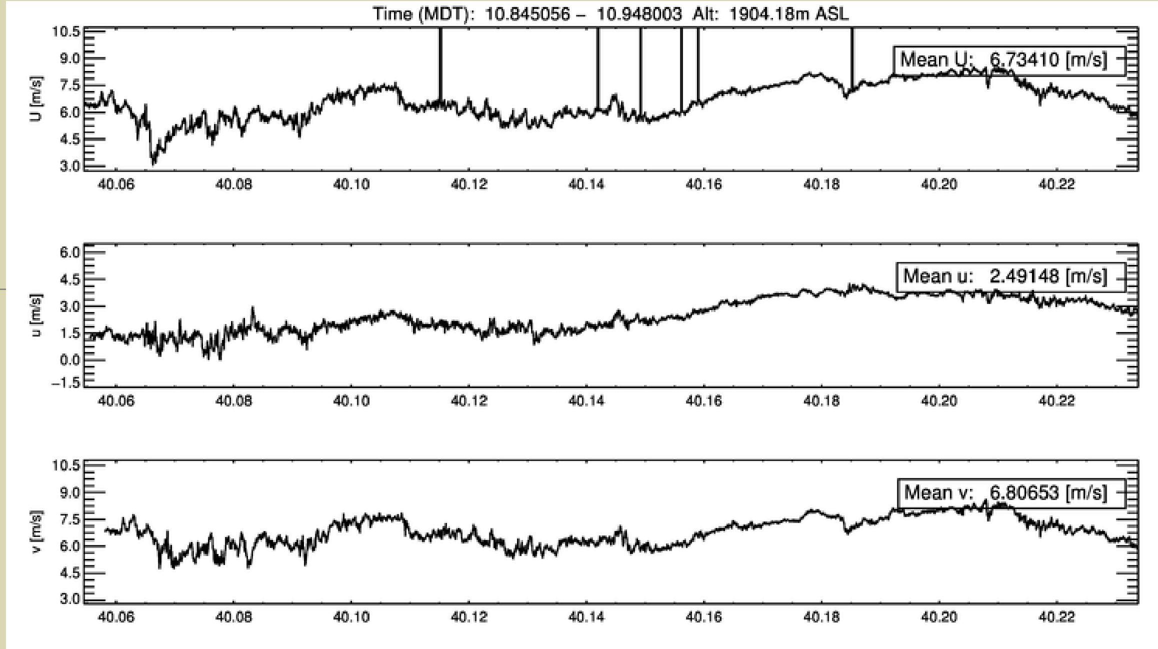
Surface Temp

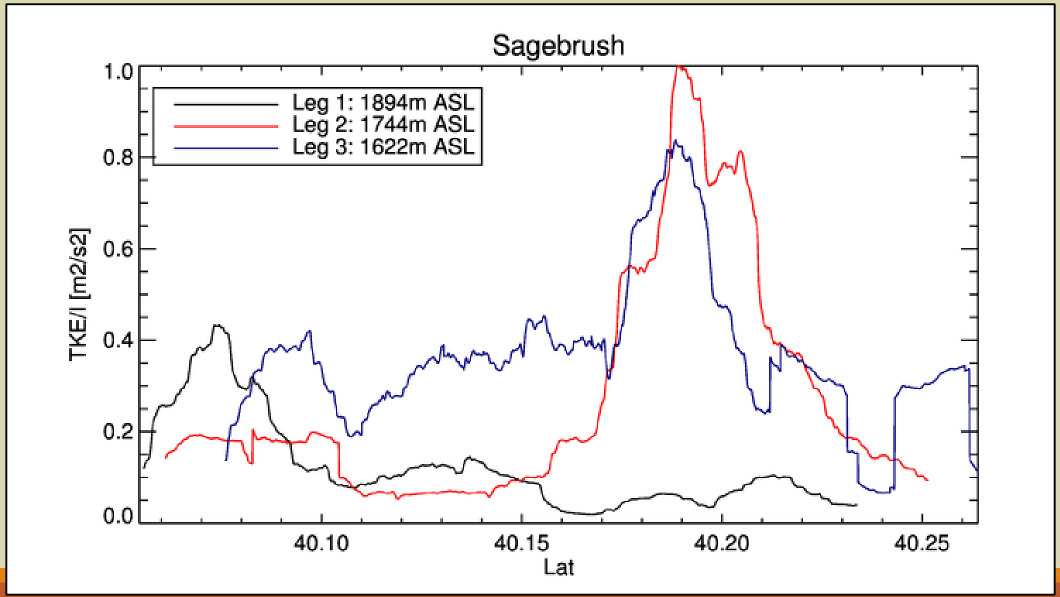
Playa: ~ 22 C˚

Sagebrush: ~ 26 C˚

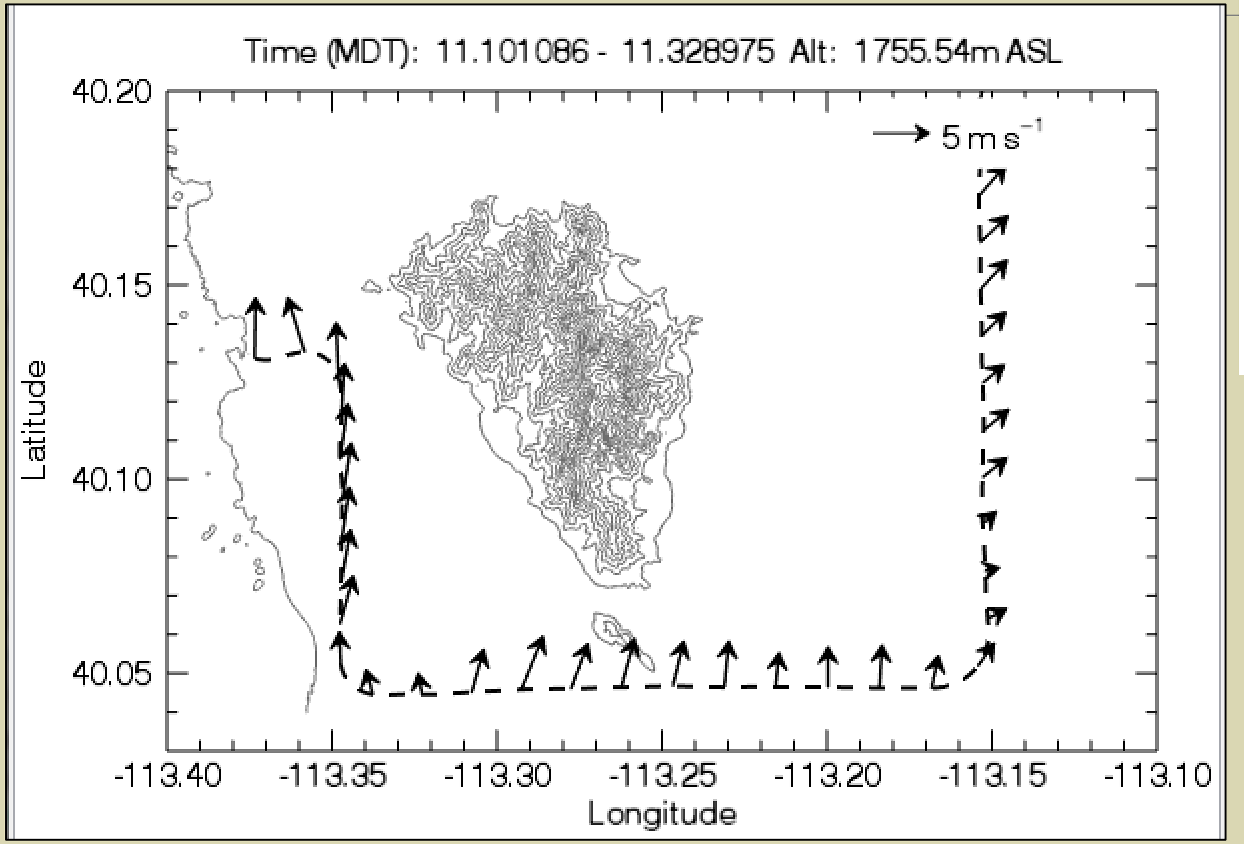
10.10

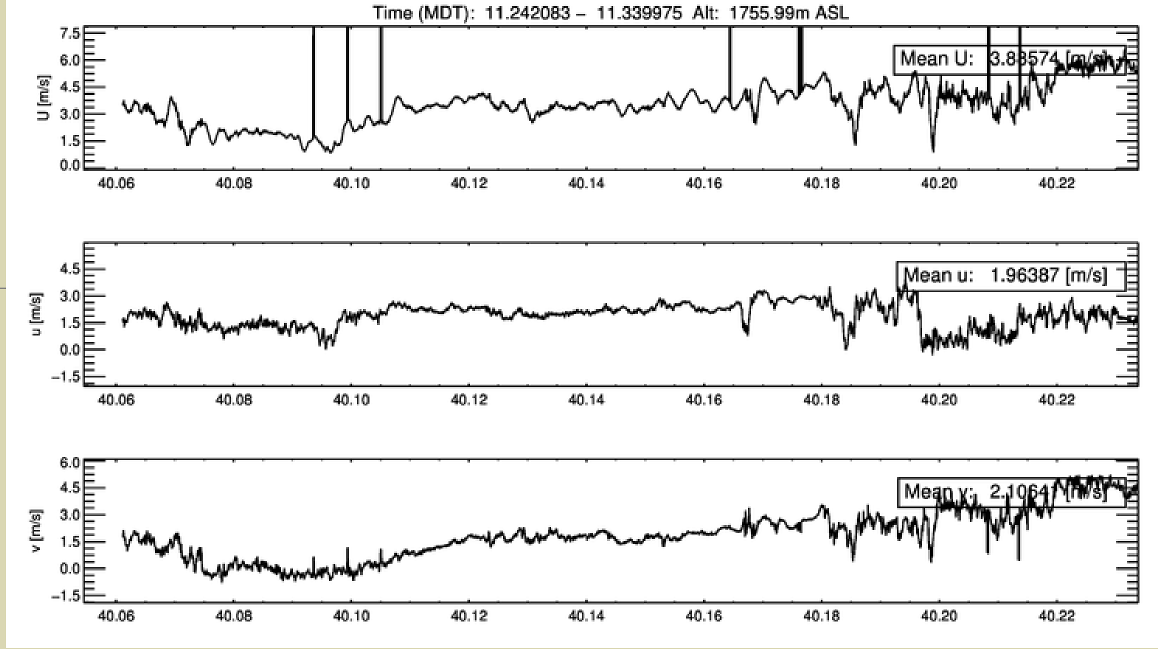

Time (MDT): 10.834917 - 11.081917 Alt: 1894.83m ASL
5 m s⁻¹
Latitude
Longitude
40.20
40.15
40.10
40.05
-113.40
-113.35
-113.30
-113.25
-113.20
-113.15
-113.10

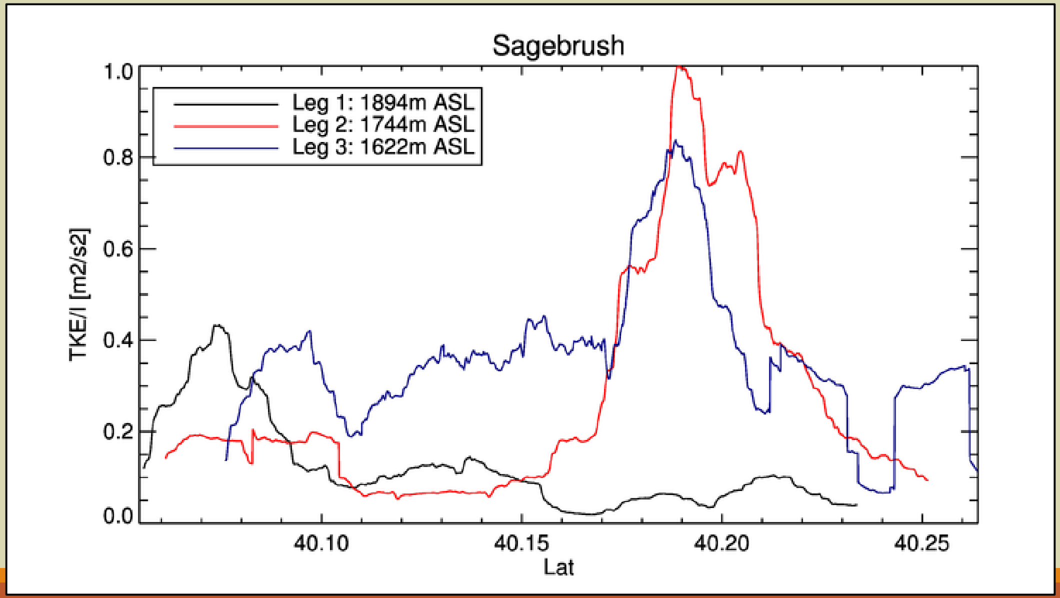

Time (MDT): 10.845056 – 10.948003 Alt: 1904.18m ASL
U [m/s]
Mean U: 6.73410 [m/s]
u [m/s]
Mean u: 2.49148 [m/s]
v [m/s]
Mean v: 6.80653 [m/s]
40.06
40.08
40.10
40.12
40.14
40.16
40.18
40.20
40.22


Sagebrush
Leg 1: 1894m ASL
Leg 2: 1744m ASL
Leg 3: 1622m ASL
TKE/l [m2/s2]
Lat
1.0
0.8
0.6
0.4
0.2
0.0
40.10
40.15
40.20
40.25

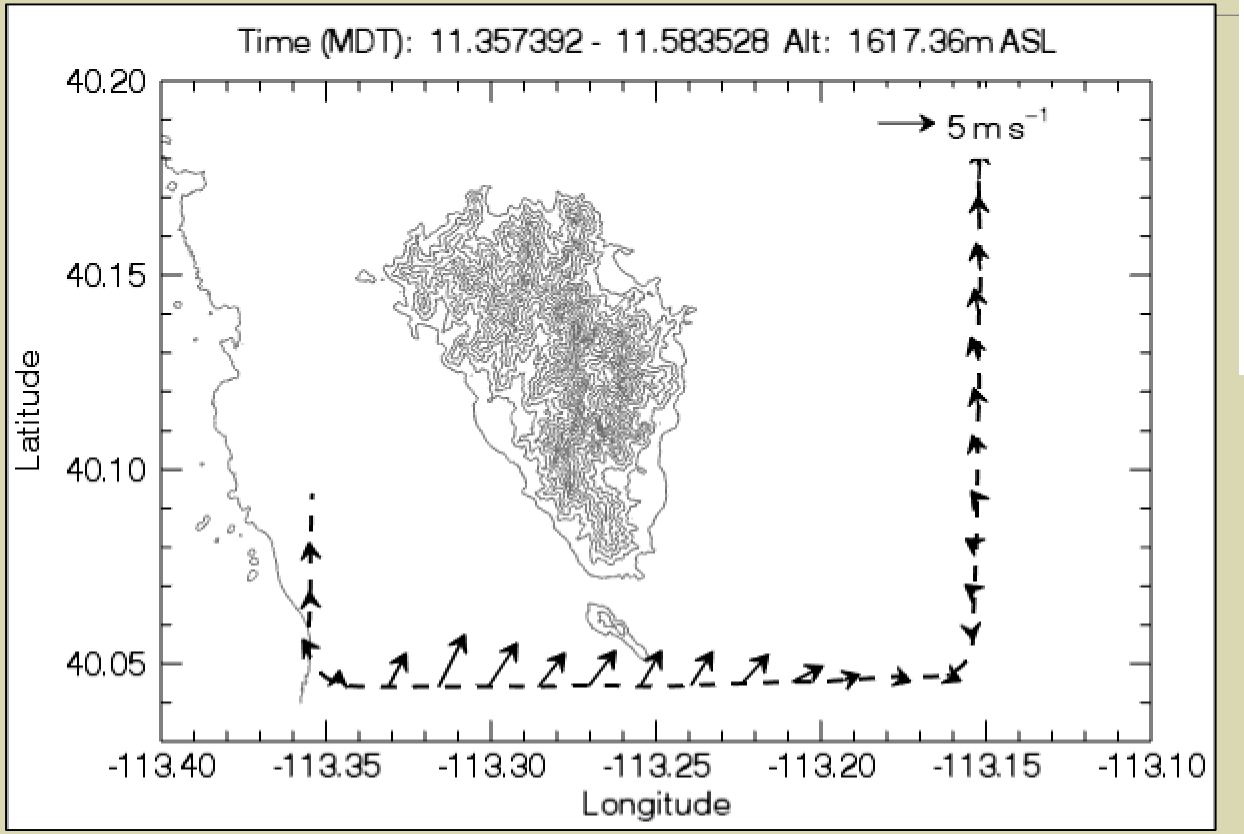
10.10


Time (MDT): 11.101086 - 11.328975 Alt: 1755.54m ASL
5 m s⁻¹
Latitude
40.20
40.15
40.10
40.05
-113.40
-113.35
-113.30
-113.25
-113.20
-113.15
-113.10
Longitude

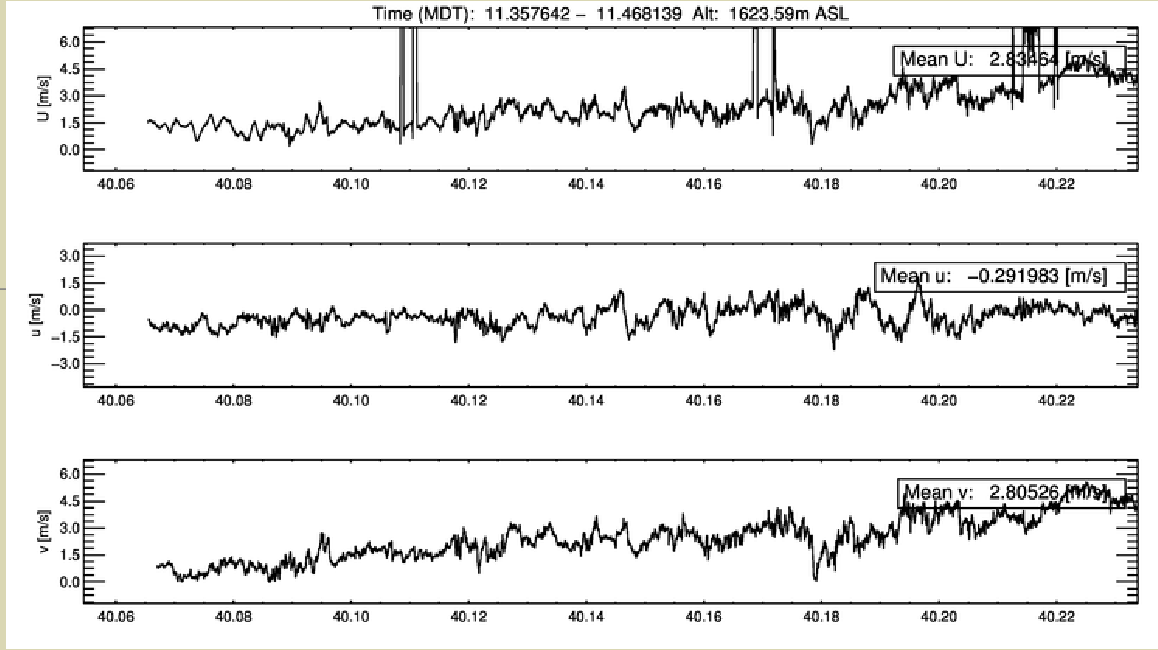

Time (MDT): 11.242083 – 11.339975 Alt: 1755.99m ASL
U [m/s]
Mean U: 3.83574 [m/s]
u [m/s]
Mean u: 1.96387 [m/s]
v [m/s]
Mean v: 2.10641 [m/s]
40.06
40.08
40.10
40.12
40.14
40.16
40.18
40.20
40.22


Sagebrush
Leg 1: 1894m ASL
Leg 2: 1744m ASL
Leg 3: 1622m ASL
TKE/l [m2/s2]
Lat
40.10
40.15
40.20
40.25

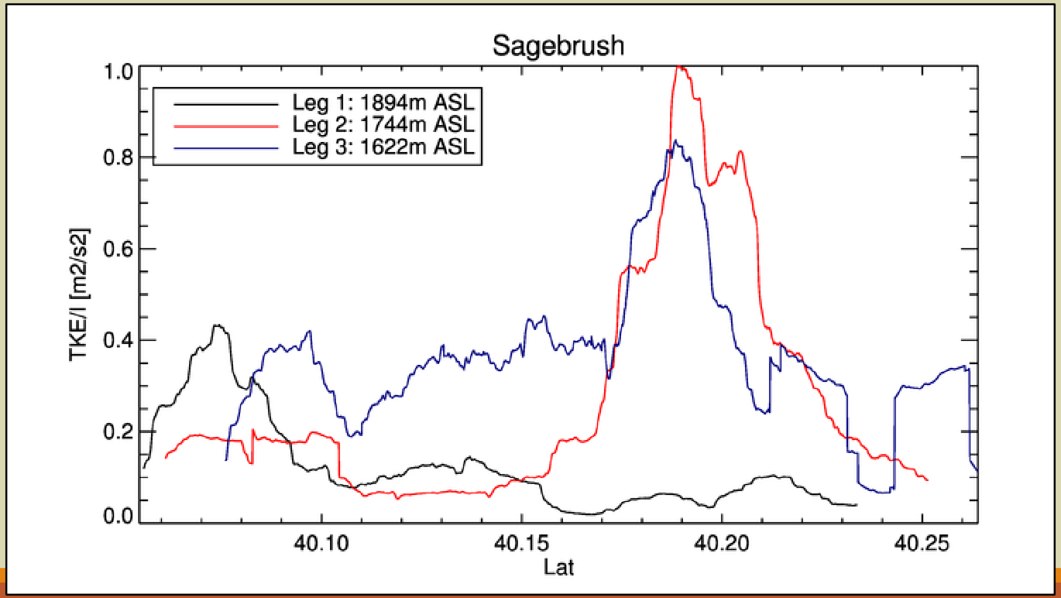
10.10



Time (MDT): 11.357392 - 11.583528 Alt: 1617.36m ASL
5 m s⁻¹
Latitude
Longitude
40.20
40.15
40.10
40.05
-113.40
-113.35
-113.30
-113.25
-113.20
-113.15
-113.10



Time (MDT): 11.357642 – 11.468139 Alt: 1623.59m ASL
U [m/s]
Mean U: 2.83464 [m/s]
u [m/s]
Mean u: −0.291983 [m/s]
v [m/s]
Mean v: 2.80526 [m/s]

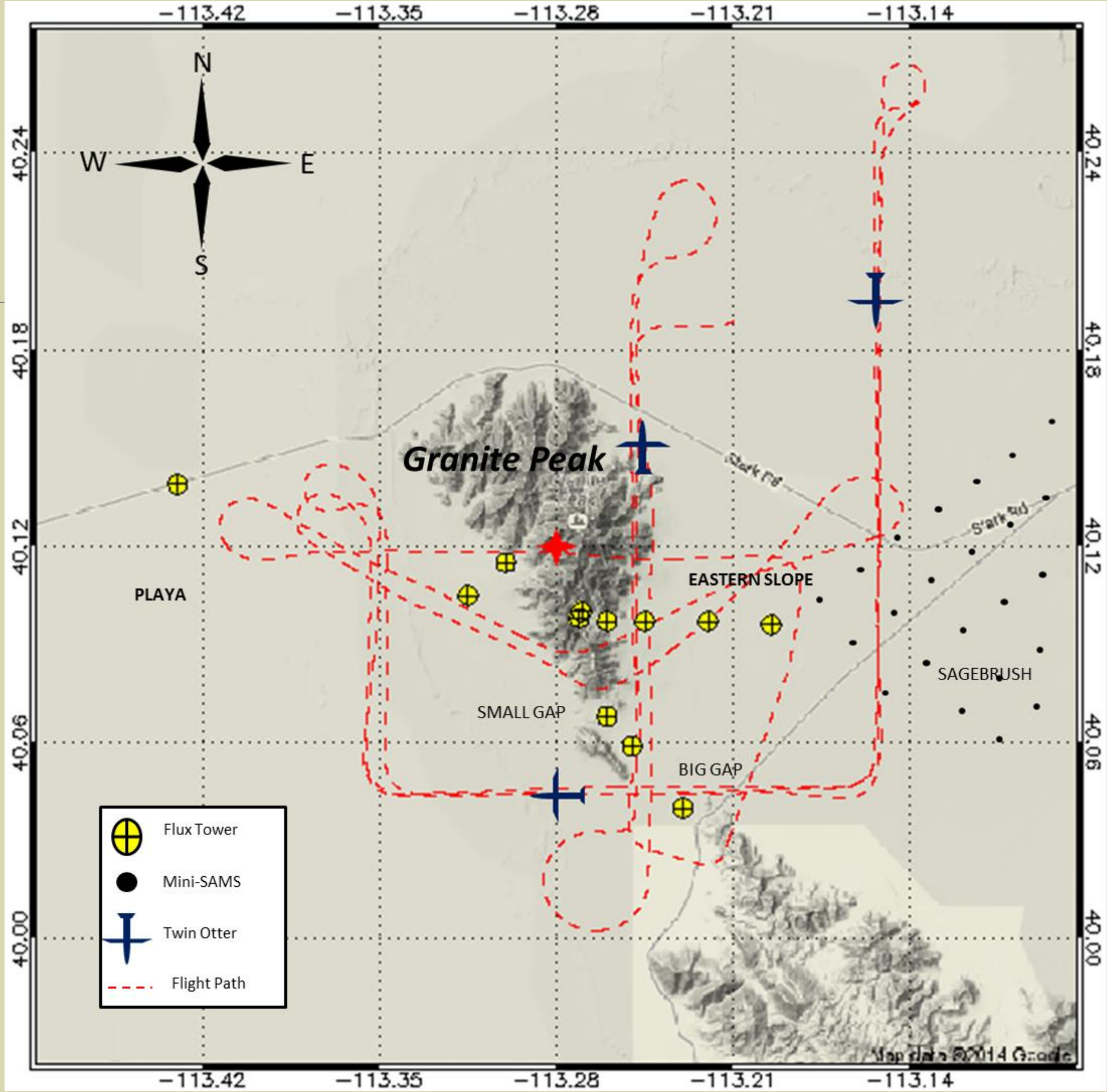


Sagebrush
Leg 1: 1894m ASL
Leg 2: 1744m ASL
Leg 3: 1622m ASL
TKE/l [m2/s2]
Lat

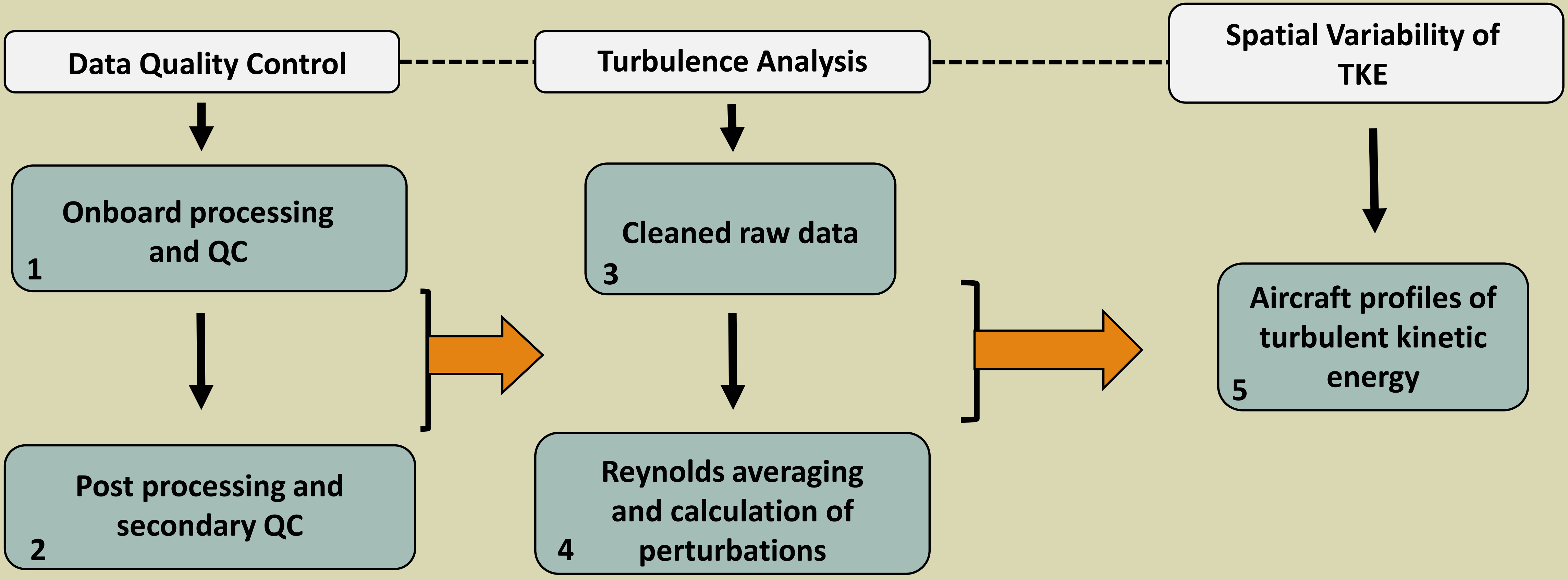
Twin Otter Flight and Site Overview

Aircraft flew over five key areas:

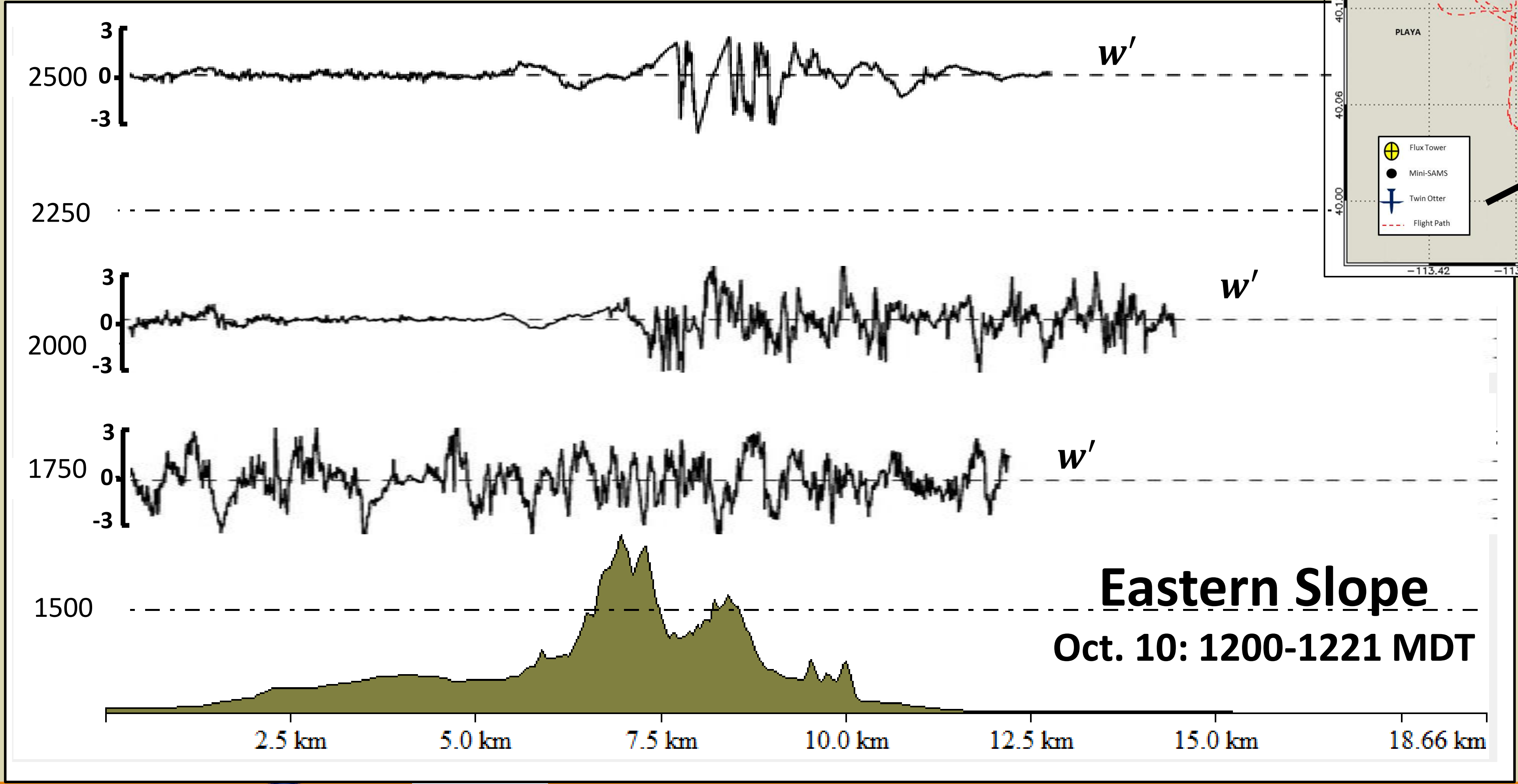
- **Playa**
- **Granite Peak**
- **Sagebrush**
- **Gap (*Small/Big*)**
- **Eastern Slope**

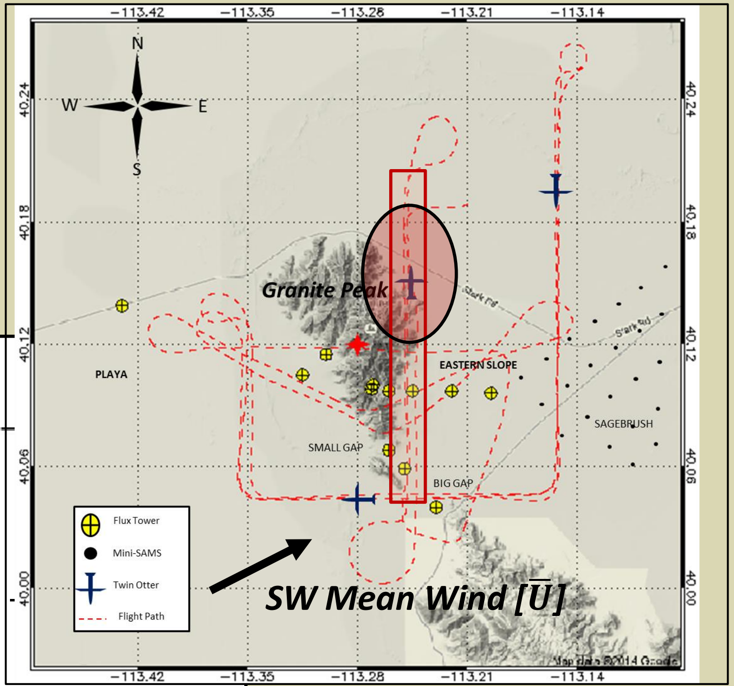


Approach and Methods: *Analysis*

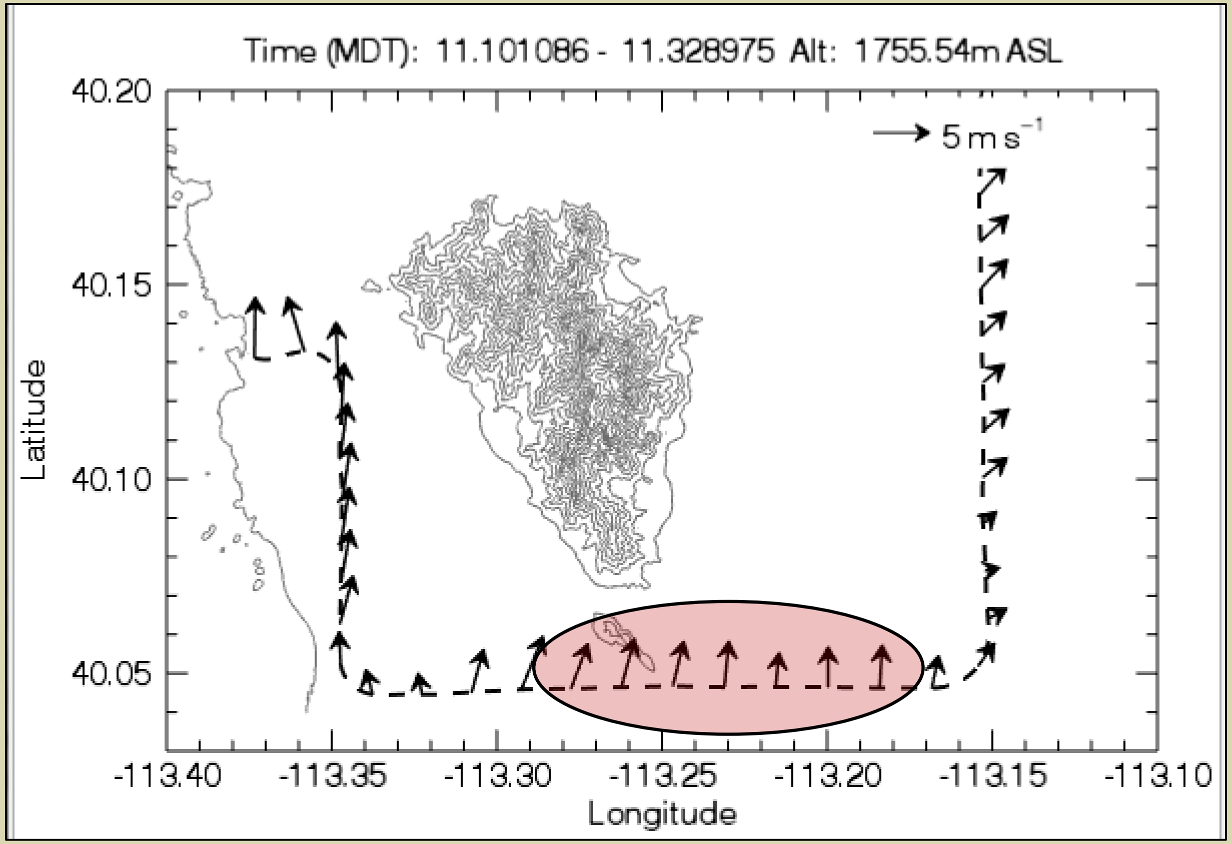


Example: *Spatial variability of turbulence*



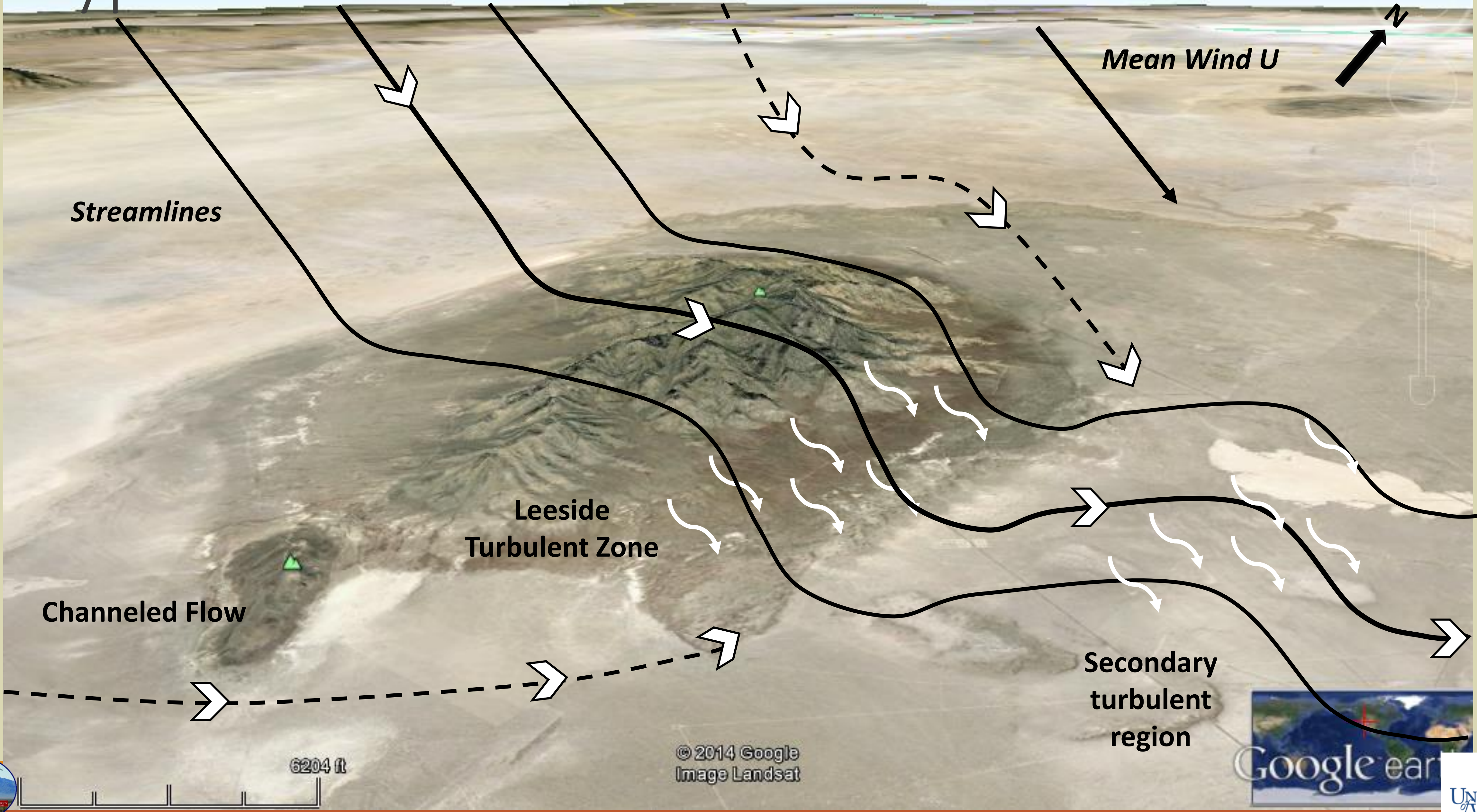


w’ shown for stacked flight legs over the Eastern Slope.



Time (MDT): 11.101086 - 11.328975 Alt: 1755.54m ASL
5 m s⁻¹
40.20
40.15
40.10
40.05
Latitude
-113.40
-113.35
-113.30
-113.25
-113.20
-113.15
-113.10
Longitude

Hypothesis



University of Virginia

Introduction

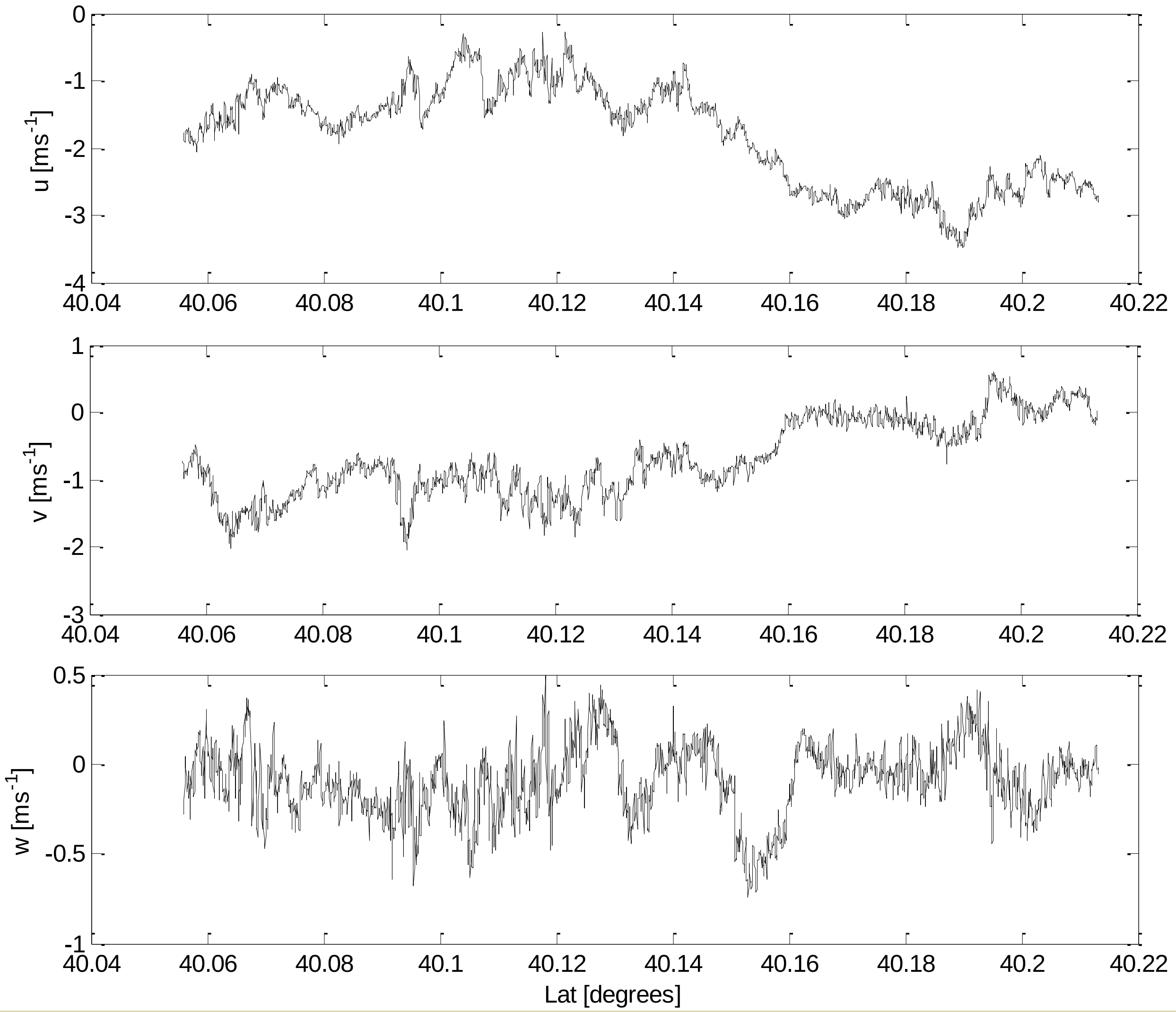
Orlanski, 1975

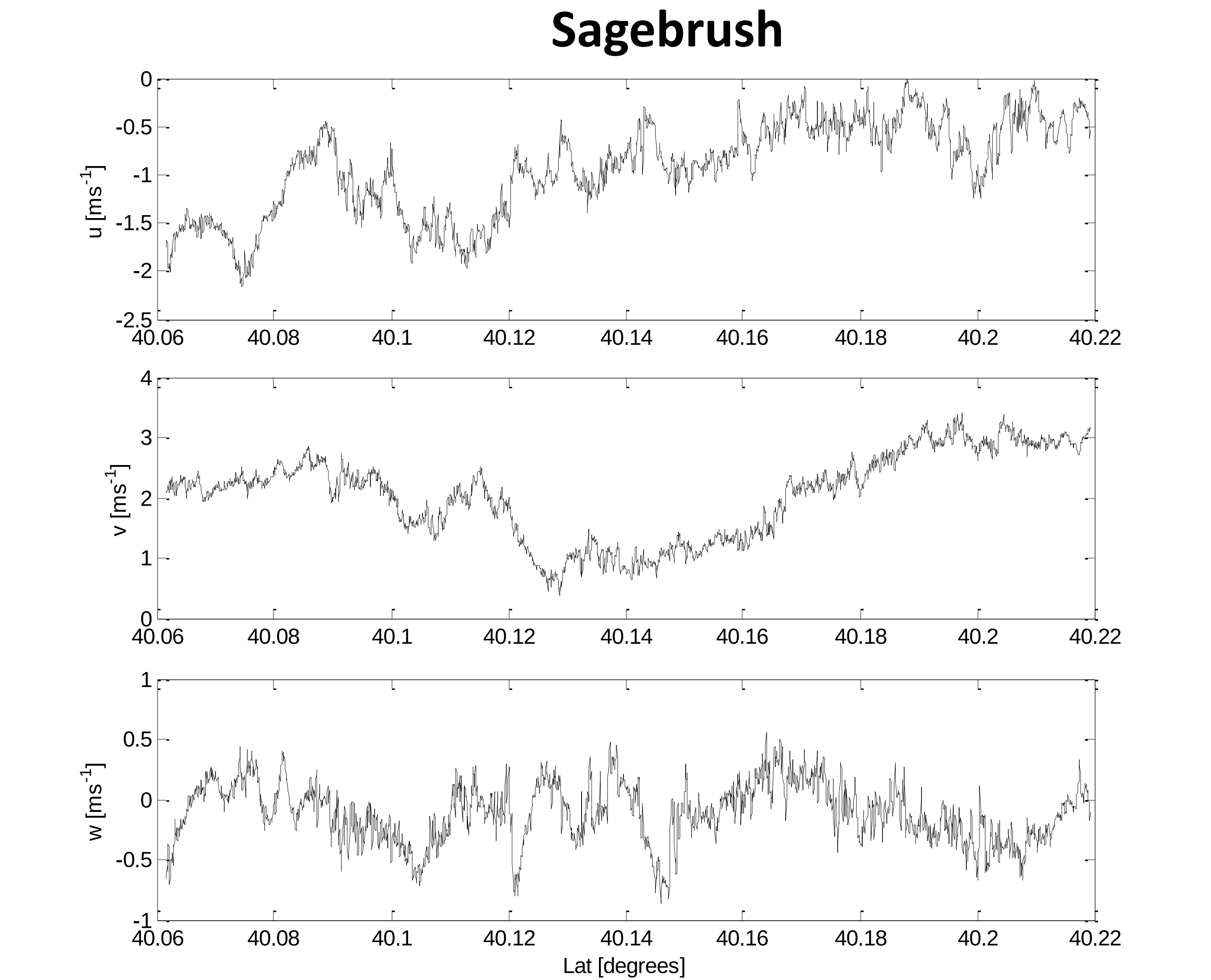
Understanding of how turbulence is affected by interactions with complex terrain has been a challenge for boundary layer meteorology, and more work is needed in this research area

Rotach and Zardini, 2007

There is a virtual absence of knowledge concerning the turbulence structure in the boundary layer over complex terrain

Sagebrush


u [ms-1]
v [ms-1]
w [ms-1]
Lat [degrees]
0
-1
-2
-3
-4
1
0
-1
-2
-3
0.5
0
-0.5
-1
40.04
40.06
40.08
40.1
40.12
40.14
40.16
40.18
40.2
40.22



Sagebrush
u [ms-1]
v [ms-1]
w [ms-1]
Lat [degrees]
0
-0.5
-1
-1.5
-2
-2.5
4
3
2
1
0
1
0.5
0
-0.5
-1
40.06
40.08
40.1
40.12
40.14
40.16
40.18
40.2
40.22