The nature of turbulence in a daytime boundary layer around an isolated mountain

MATERHORN Fall Campaign, 2012

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Introduction

- Numerous studies have interpreted their data in terms of turbulent kinetic energy (TKE) and associated transport and production terms to describe the structure of turbulence within the boundary layer.
- However, these studies have been mainly over flat homogeneous terrain. TKE budget terms remain poorly defined over complex terrain.

Introduction

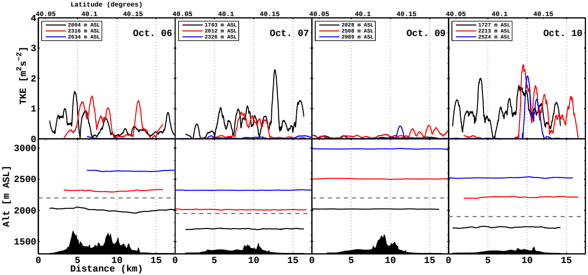
Motivation

- TKE and associated budget terms are important because they allow us to understand the sources and sinks of turbulence within the CBL.
- It is in the interest of modelers to have observations of the magnitude and spatial variability of the TKE budget terms for comparisons with numerical simulation (Lothon et al., 2003).

Introduction

Motivation

- Objectives of Part I:
  - Determine an appropriate turbulence averaging length for complex terrain airborne data-set
  - Distinguish spatial variability of TKE within and above the CBL over an isolated mountain
- Isolated mountain, Granite Peak, and associated flow processes affected the magnitude and spatially variability of TKE within and above the CBL.



Introduction

Objectives

- In continuation of Part I, Part II investigates the mechanisms and sources of turbulence?
- Illustrate the relative importance and localization of various terms of the TKE budget equation

  Objectives
  1) What are the dominant mechanisms of turbulence production/destruction
  2) What is the relative magnitude of the TKE budget terms
  3) How do the TKE budget terms spatially vary?

- **Fall 2012 MATERHORN experiment**: 10Hz in-situ aircraft data, Doppler wind Lidar, and surface meteorological observations

Methods and Approach

Interpretation of the TKE budget equation

- TKE budget equation (Karacostas and Marwitz, 1980):

$$\frac{\partial \overline{e}}{\partial t} = \frac{\tau}{\rho}\frac{\partial U}{\partial z} - \frac{\partial}{\partial z}\left[\frac{1}{\rho}(\overline{w'p'} + \overline{w'e})\right] + g\frac{\overline{w'\theta_v'}}{\overline{\theta_v'}} - \epsilon \qquad (1)$$

- Focusing on the shear production, buoyancy production/destruction, and dissipation terms, Eq. 1 becomes:

$$0 = \frac{\tau}{\rho}\frac{\partial U}{\partial z} + g\frac{\overline{w'\theta_v'}}{\overline{\theta_v'}} - \epsilon + R \qquad (2)$$

Methods and Approach

Interpretation of the TKE budget equation

Shear Production

- Calculated from the Reynolds stress, $\tau = \overline{w'u'} + \overline{w'v'}$, estimated from flight leg observations
- Shear, $\frac{\partial U}{\partial z} = \frac{\partial u}{\partial z} + \frac{\partial v}{\partial z}$, estimated as the mean vertical gradient from stacked flight legs

Buoyant production - destruction

- Heat flux $\overline{w'\theta_v'}$ estimated w and θ_v series from each flight leg
- Mean $\overline{\theta_v}$ averaged in 500 m segments

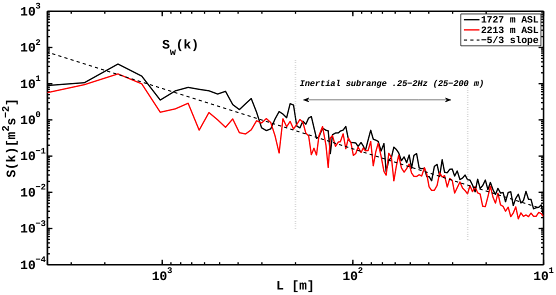
***All fluctuations were calculated with a 500 m averaging length**
***Overbars represent a 500 m spatial average**

Methods and Approach

Interpretaton of the TKE budget equation

Dissipation (ϵ)

- Kolmogorov turbulence spectrum, the inertial subrange lies where the wind velocity spectrum has a -5/3 slope.



Methods and Approach

Interpretation of the TKE budget equation

- Eddy dissipation range 25-200 m.
- **Two methods for calculating w variance in inertial subrange**
  1) **Vecenaj et al. (2012):** w time series split into 500 m (100 data points) segments. FFT within each segment. Variance in the inertial subrange is accounted for by integrating the spectral energy between 2-.5 Hz.

$$\epsilon = \left[\frac{\lambda^{5/3} S_i(\lambda)}{\alpha} \right]^{3/2} \tag{3}$$

  2) **Hahn (1980):** Estimation of the variance at each observation point. High pass butterworth filter. Only frequencies between 0.5-2 Hz are passed, and then squaring the terms to get variance

$$\epsilon = \frac{2\pi}{V_a} \left[\frac{S_i(\lambda)}{\alpha} \right]^{3/2} \tag{4}$$

Case study

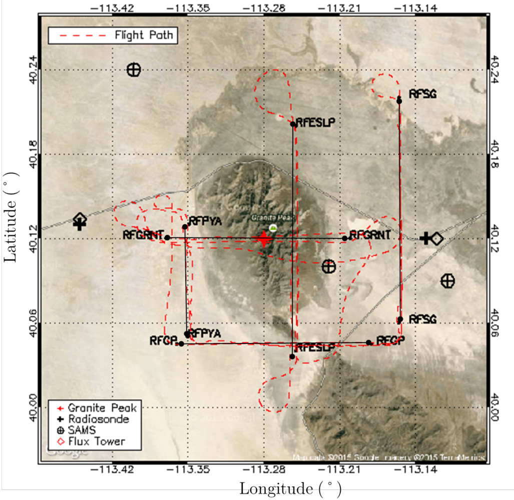
Selected flight legs for investigation

- Selected *Eastern Slope* and *Granite Peak* flight legs during the October 10 and 17 flight periods

Flight times

10Oct: 1151-1318 MDT

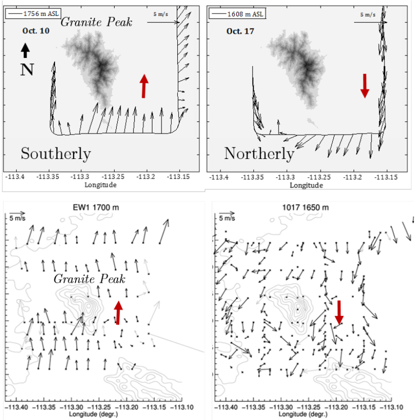
17Oct: 1551-1700 MDT



Case study

Ambient conditions 10Oct and 17Oct

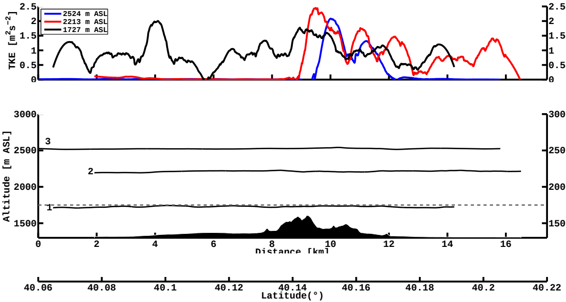
- **10Oct** surface $H = 75 Wm^{-2}$; Southerly lower level flow; CBL wind shear $2.0 \times 10^2 s^{-1}$
- **17Oct**: surface $H = 90 Wm^{-2}$; Northerly lower level flow; CBL wind shear $2.0 \times 6.6 \times 10^2 s^{-1}$



Results

Eastern Slope 10Oct

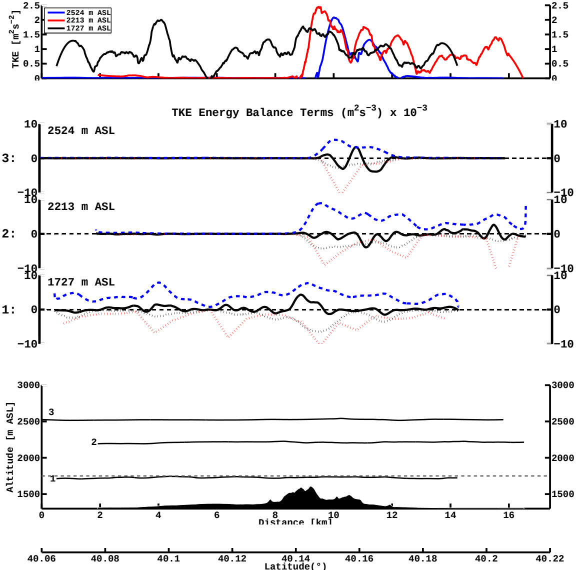
- Localized region of increased TKE over and in the wake of the underlying ridge.
- What are the mechanisms?



Results

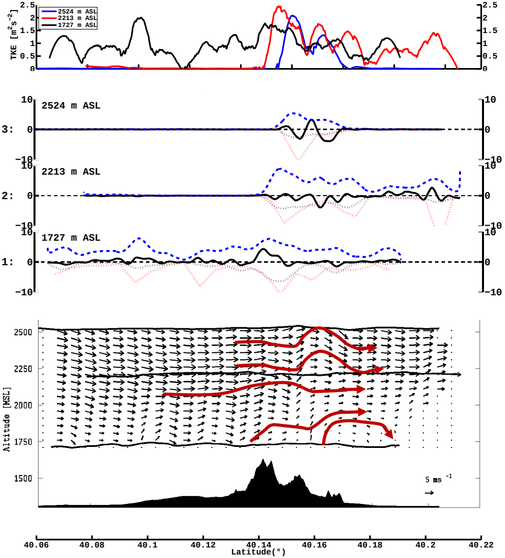
- Localized region of increased TKE at upper flight levels
- Larger shear production, especially at mid and upper flight legs
- Maximum buoyancy production over small ridge

*** Shear production:** *blue dotted*
Buoyant production/destruction: *black solid*
Dissipation (Vecenaj, 2012): red dotted
Dissipation (Hahn, 1980): black dotted



Results

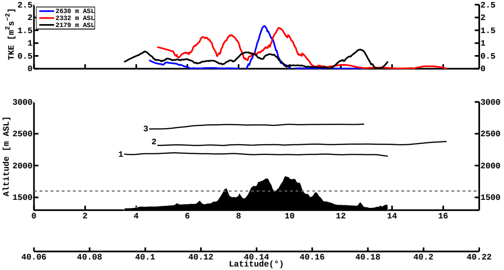
- Ambient flow conforms to underlying terrain
- Upwelling on windward side of ridge and down-welling in the wake of ridge
- Increase TKE and shear production coincide with small wave feature



Results

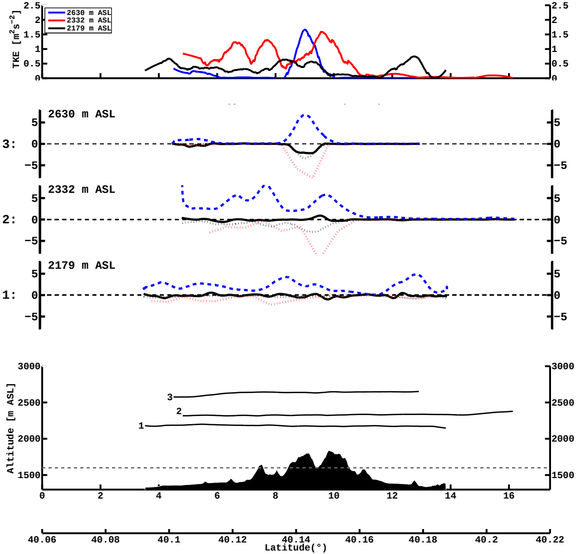
Eastern Slope 17Oct

- Large TKE a mid flight level
- Isolated turbulent patch over ridge at upper level (2 m^2s^{-2})



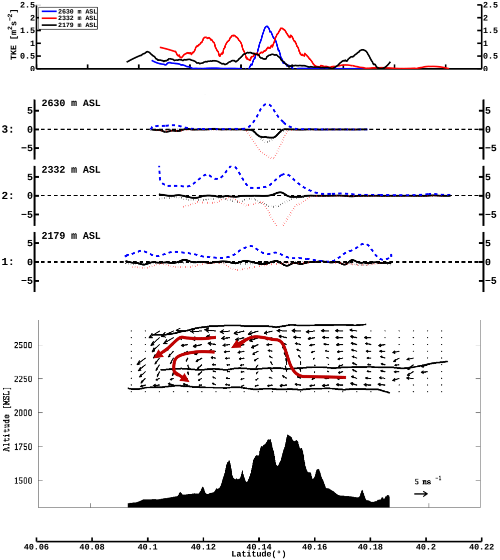
Results

- Positive maximum in shear production over ridge
- Buoyancy production is mainly negative at mid and upper levels
- Shear production correlates well with TKE



Results

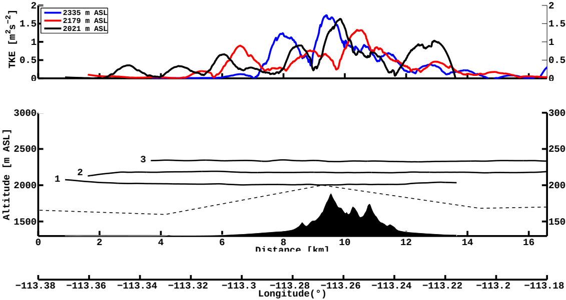
- Some upward motion over ridge at lower levels
- down-welling of faster moving flow in wake of ridge
- Significant vertical wind gradient at mid and upper flight levels



Results

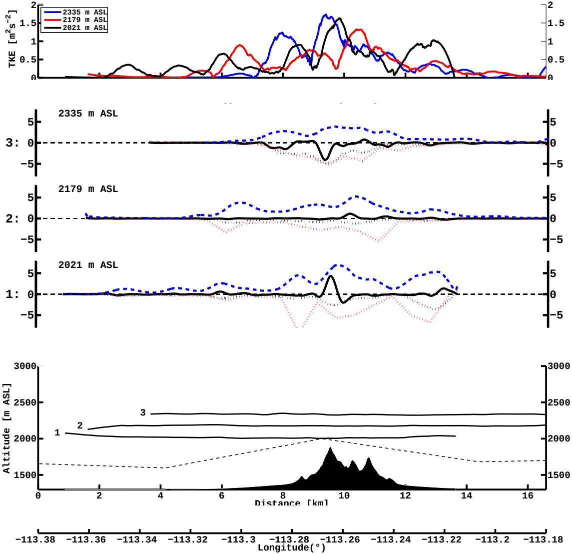
Granite Peak 17Oct

- Large values of TKE over Granite Peak. Even at upper flight levels
- Distribution of TKE seem to be terrain following
- Related to terrain following CBL top (z_i)?



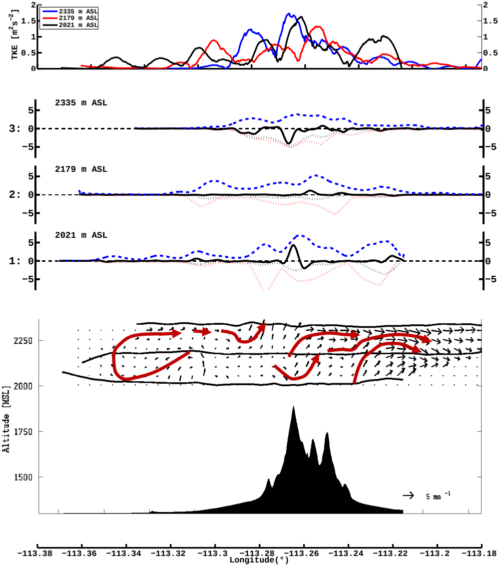
Results

- Shear production largest at lower levels and over Granite Peak
- TKE correlates well with shear production and underlying terrain
- Buoyancy production is relatively small



Results

- Upward motion at upper level, while weak downward motion at lower levels
- Higher momentum air from aloft mixed down over ridge top
- TKE and positive shear peak in shear production on the wake of the mountain are associated with flow features



Key findings

- Magnitude of shear production and dissipation is $10^{-3}\ m^3 s^{-3}$; buoyancy $10^{-4}\ m^3 s^{-3}$
- Underlying terrain has strong influence on TKE production mechanisms
- Positive shear and buoyancy production maxima associated with ridge top
- Dissipation correlates well with TKE.

Conclusions

- Magnitude of terms comparable to previous studies over complex terrain (e.g. Lothon et al, 2003; Karacostas and Marwitz, 1980; Hahn, 1980)
- Even with relatively weak (5 ms^{-1}) lower level flow buoyancy production was small while shear production was dominant mechanism
- Departure from the conceptual picture of turbulence structure over flat homogeneous terrain (e.g. Kaimal, 1976)
    - Contrary to the CBL over flat terrain, shear production is the dominant source of turbulence even above the surface layer
    - Variability of production mechanisms are direct result of topographical variations