Thermal Imaging and Surface Turbulence Characteristics

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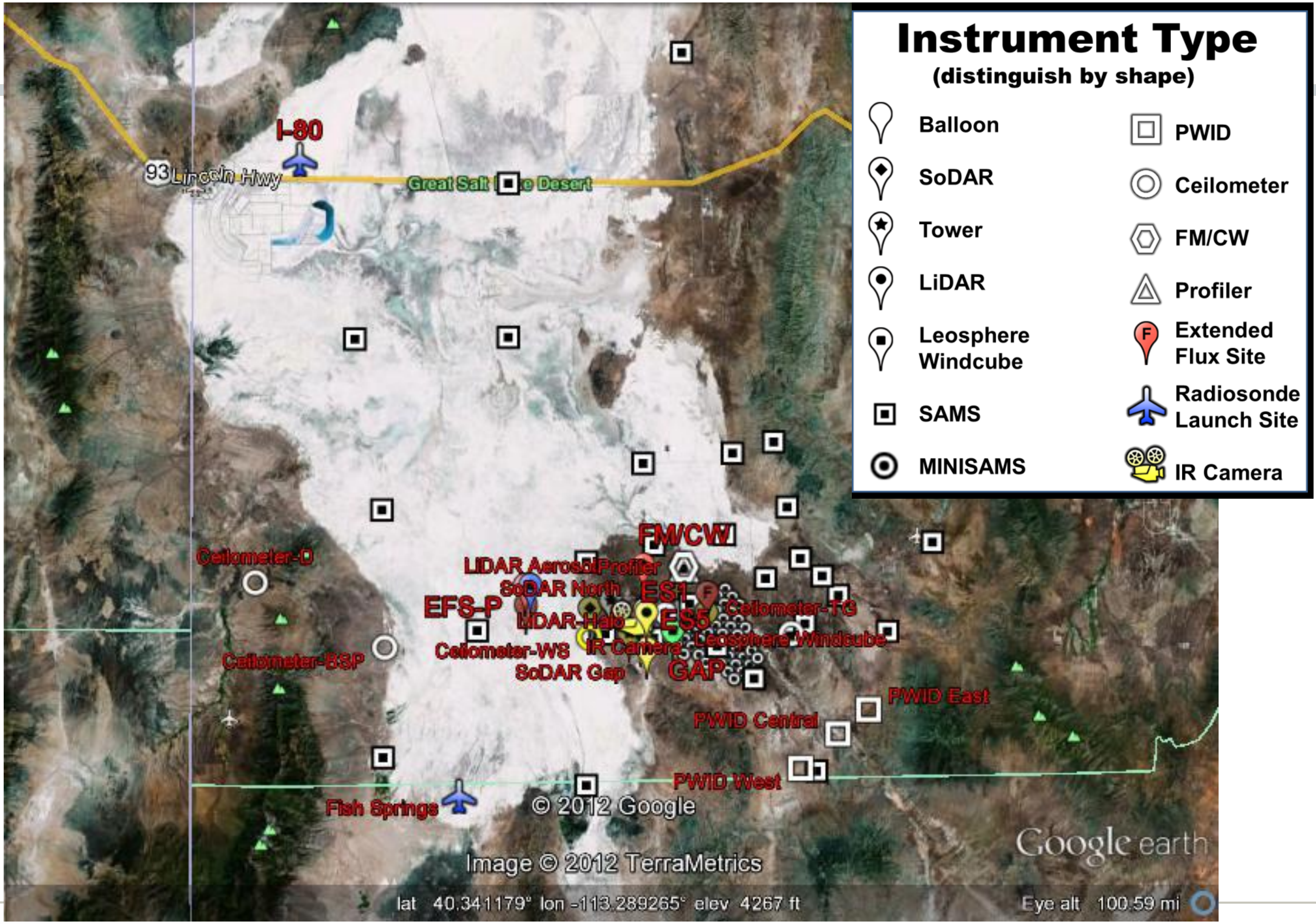
Many Scales of MATERHORN



MATERHORN-X Spring Summary

IOP Summary Table (TB - tethered balloon, RS - radiosounding, NP - North Playa, SB - Sage Brush, CP - Callao Point C, ES - East Slope, SWG - Southwest of Granite Peak; NWG - North West Granite)

IOP Number	Dates and Time of Experiment in Mountain Daylight Time (UTC - 6)	TB	RS	Type	Flights	Last Precip
IOP 1	1400 MDT May 1 - 1400 MDT May 2	Playa, SB	Playa, SB	Moderate/ Quiescent	None	April 20
IOP 2	1400 MDT May 4 - 1400 MDT May 5	Playa, SB, ES	Playa, SB	Moderate	None	
IOP 3	0500 MDT May 7 - 1700 MDT May 7	None	SWG	Moderate	None	May 6
IOP 4	1400 MDT May 11 - 1400 MDT May 12	Playa, SB, ES	Playa, SB	Quiescent	None	May 7*
IOP 5	1200 MDT May 13 - 1200 MDT May 14	None	NWG, Playa	Moderate/ Transitional	None	
IOP 6	1200 MDT May 16 - 1200 MDT May 17	Playa, SB	Playa, NWG, Delta	Moderate/ Transitional GBCZ	None	
IOP 7	1715 MDT May 20 to 1400 MDT 21 May	Playa, SB	Playa, NWG, SB	Sandwhich Quiescent	None	May 18, 19
IOP 8	1400 MDT May 22 to 1400 MDT May 23	Playa, SB	Playa, NWG, Delta	Moderate	None	
IOP 9	1000 MDT May 25 to 1000 MDT May 26		Playa, SB	Moderate	None	
IOP 10	1400 MDT May 30 to 1000 MDT May 31	Playa, SB	Playa, SB	Moderate	None	May 28

*Note that the precipitation on May 7 was just local convection not sustained or range wide

Playa Site Introduction

- Playa at Dugway is a real-world idealized flat plate turbulence experiment (M. Metzger, The near-neutral atmospheric surface layer: Turbulence and non-stationarity, 2007)
- $0.2 < z_o < 0.5$mm roughness for 35-140 km (21-87 mi)
- Thermal camera co-located with hotwire-cold wire, tethered balloon, soil sampling, radiation balance, and 30m flux tower
- Near surface flux and turbulence measurements should yield important clues to fundamental physics involved in surface energy balance

Research Question

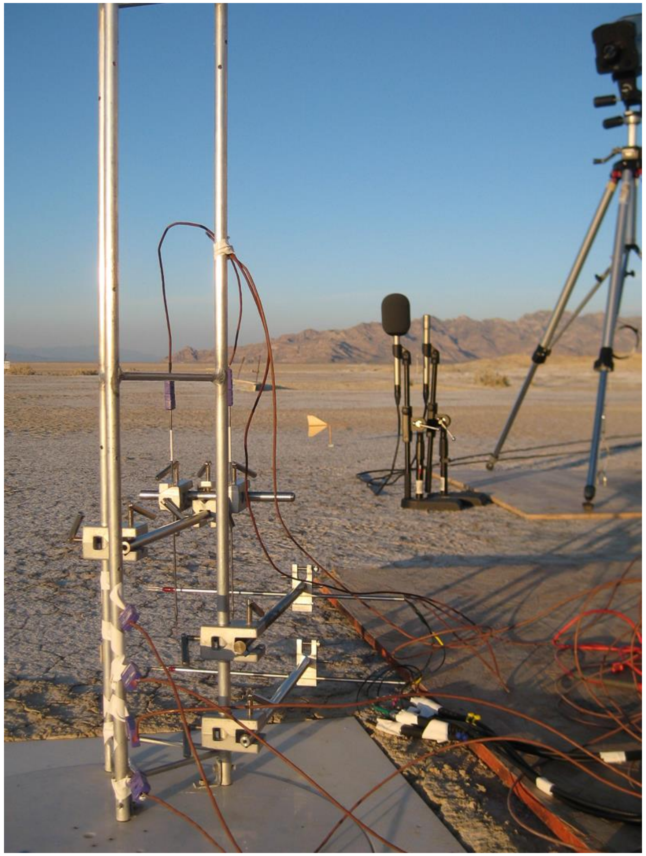
- Temporal and spatial variations in surface temperature measured from a thermal camera correlate directly with atmospheric turbulence at the surface.
- Better understand small scale surface processes both temporally and spatially. Linking surface energy balance with small scale turbulence processes.
- Fishing Expedition…

IOP 9 Conditions

- Moderately strong SW winds, clear skies
- Selected period: 20:57:22 – 21:17:22 UTC
- L = -4 m to -8.5 m (unstable)
- Avg U mag (0.61 m) = 5.46 m/s

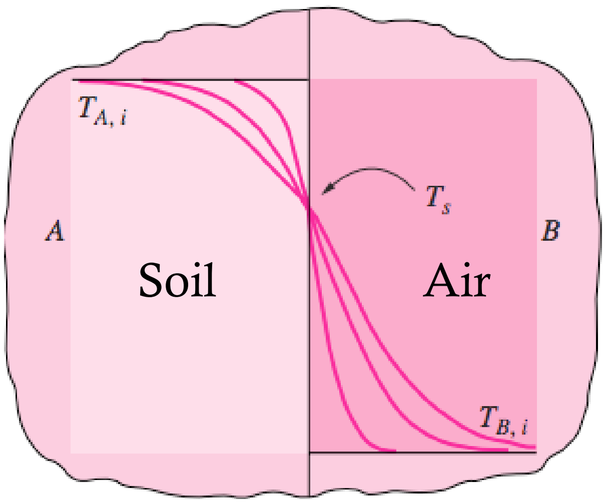
Thermal Imagery Introduction

- FLIR Systems ThermoCAM SC4000 IR Camera
- 320x256 resolution, 20 Hz
- Sensitivity +/- 0.1°C
- Preliminary data: Non-calibrated images, can be post calibrated from radiation measurements
- Absolute temperatures are not as critical as relative sensitivity
- Dataset: 18 hours FLIR video, ~215 GB raw video, ~700 GB MAT files



Theory Introduction

- Semi-Infinite solid thermal conduction problem provides framework for understanding thermal camera signal
- Very near the surface, thermal conductivity in the air and soil interact to determine surface temp
- Thermal admittance difference acts as a weighting factor for the interface temperature
- If thermal admittances and temperatures sufficiently differ, subtle changes in air temperature (turbulence) will be visible in the surface temperature
- A_{soil}=5314 W m^{-2} K^{-1} A_{air} = 162.17 W m^{-2} K^{-1}



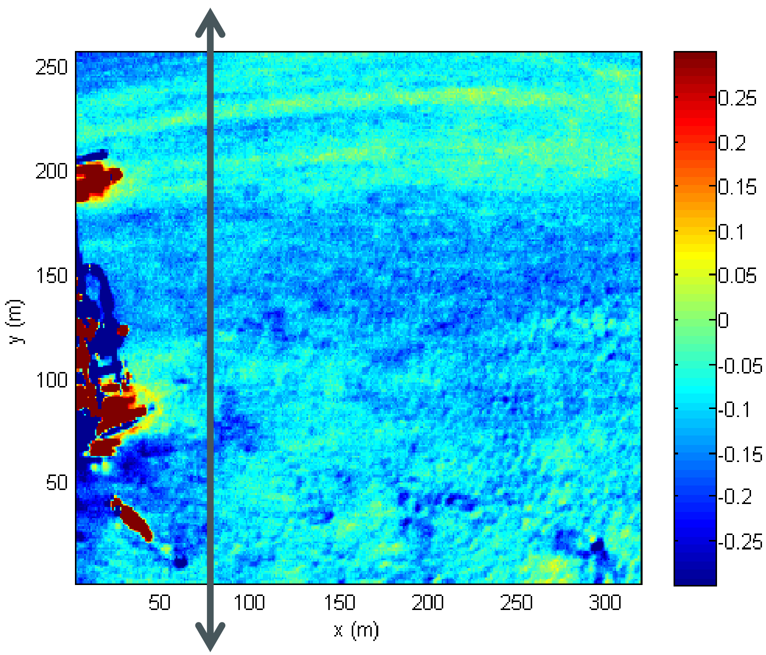
A_{soil} A_{air}

$$T_s = \frac{\sqrt{(k\rho c_p)_A}T_{A,i} + \sqrt{(k\rho c_p)_B}T_{B,i}}{\sqrt{(k\rho c_p)_A} + \sqrt{(k\rho c_p)_B}}$$

Cengal and Ghajar, 2005

Thermal Image Processing Methods
Camera Perspective Correction

Before Correction



After Correction

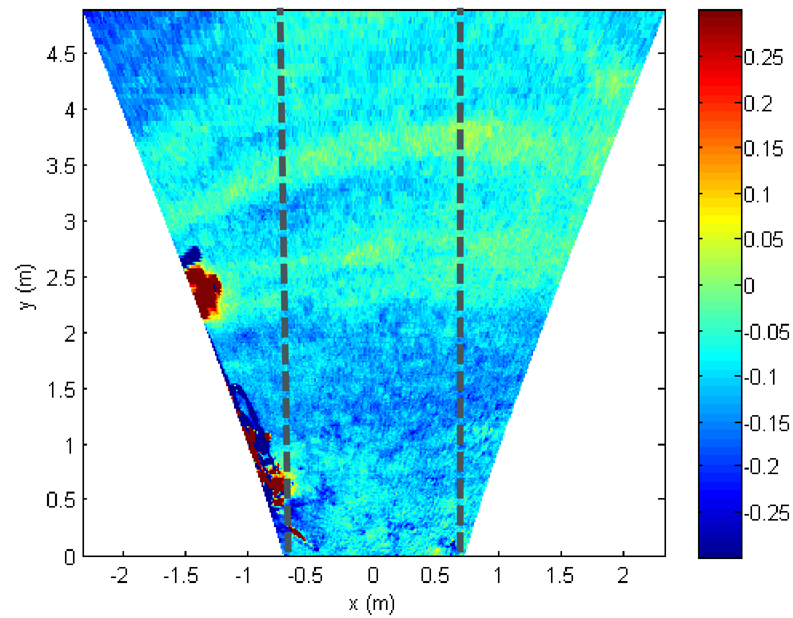


Image was then transformed into constant mesh grid for calculations

Image Processing Methods

Temperature Deviations

- Temperature deviation calculated by subtracting 20 min pixel mean from each pixel in each frame
- Full-field de-trending required for transition periods

$$T_s'(x,y,t) = T_s(x,y,t) - \frac{1}{n}\sum_{t=1}^{n} T_s(x,y,t_n)$$

Spatial-Temporal Correlation

- Correlation is calculated for each pixel as a function of Δx and Δy
- This correlation is spatially averaged, then time averaged

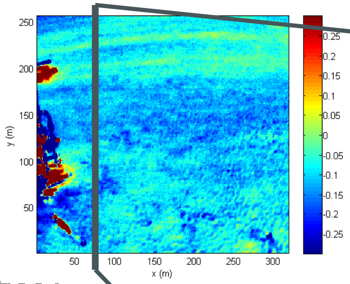
$$\rho_{xy}(\Delta x, \Delta y, t) = \frac{\overline{T_s'(x,y,t)T_s'(x+\Delta x, y+\Delta y, t)}}{\sigma_{Ts}^2}$$

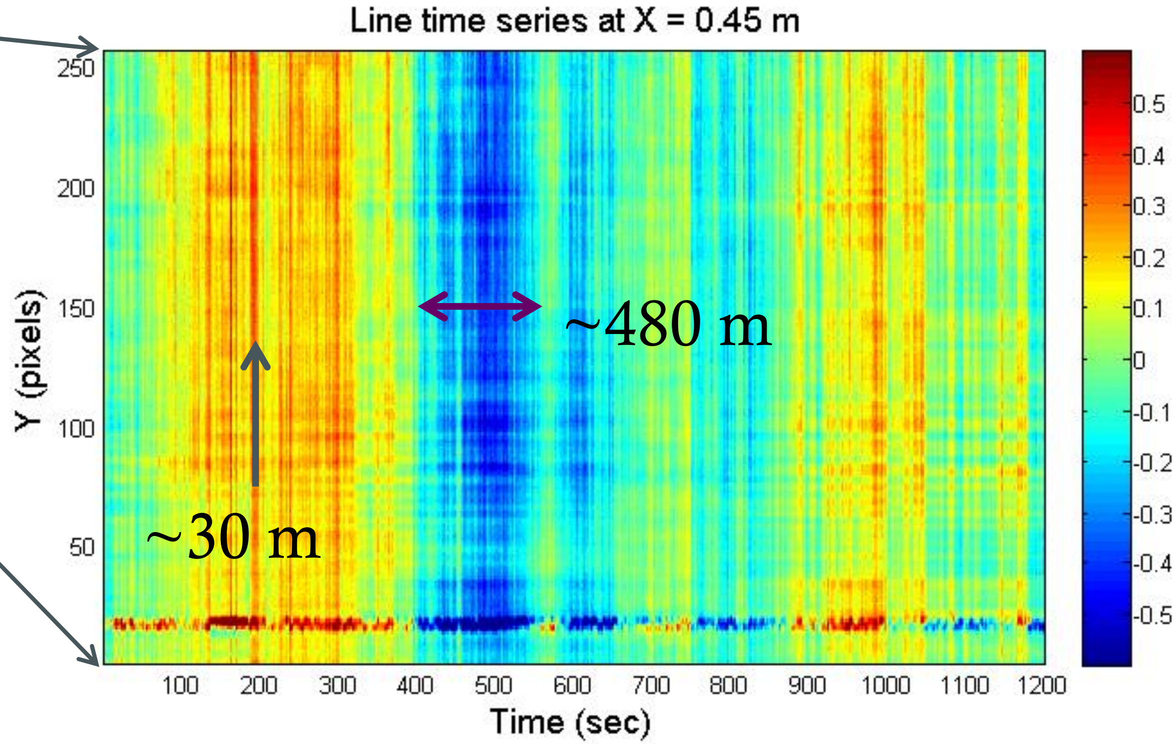
$$\langle \rho_{xy}(\Delta x, \Delta y, t) \rangle$$

Reference: A. Garai et al, 2012

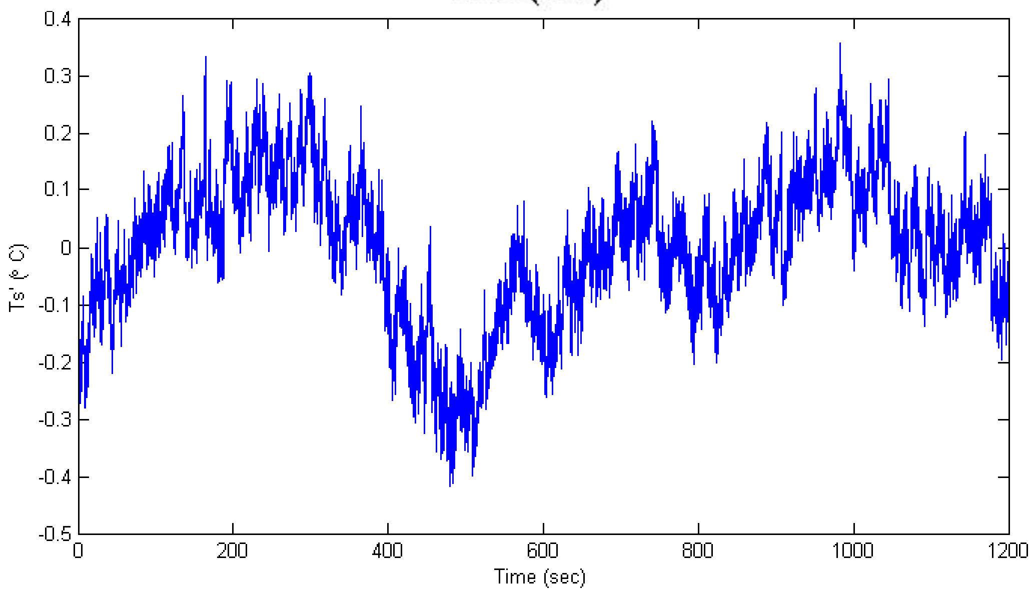
Temperature Fluctuation Video

Link to online video: http://youtu.be/s-tLMti_Tmk

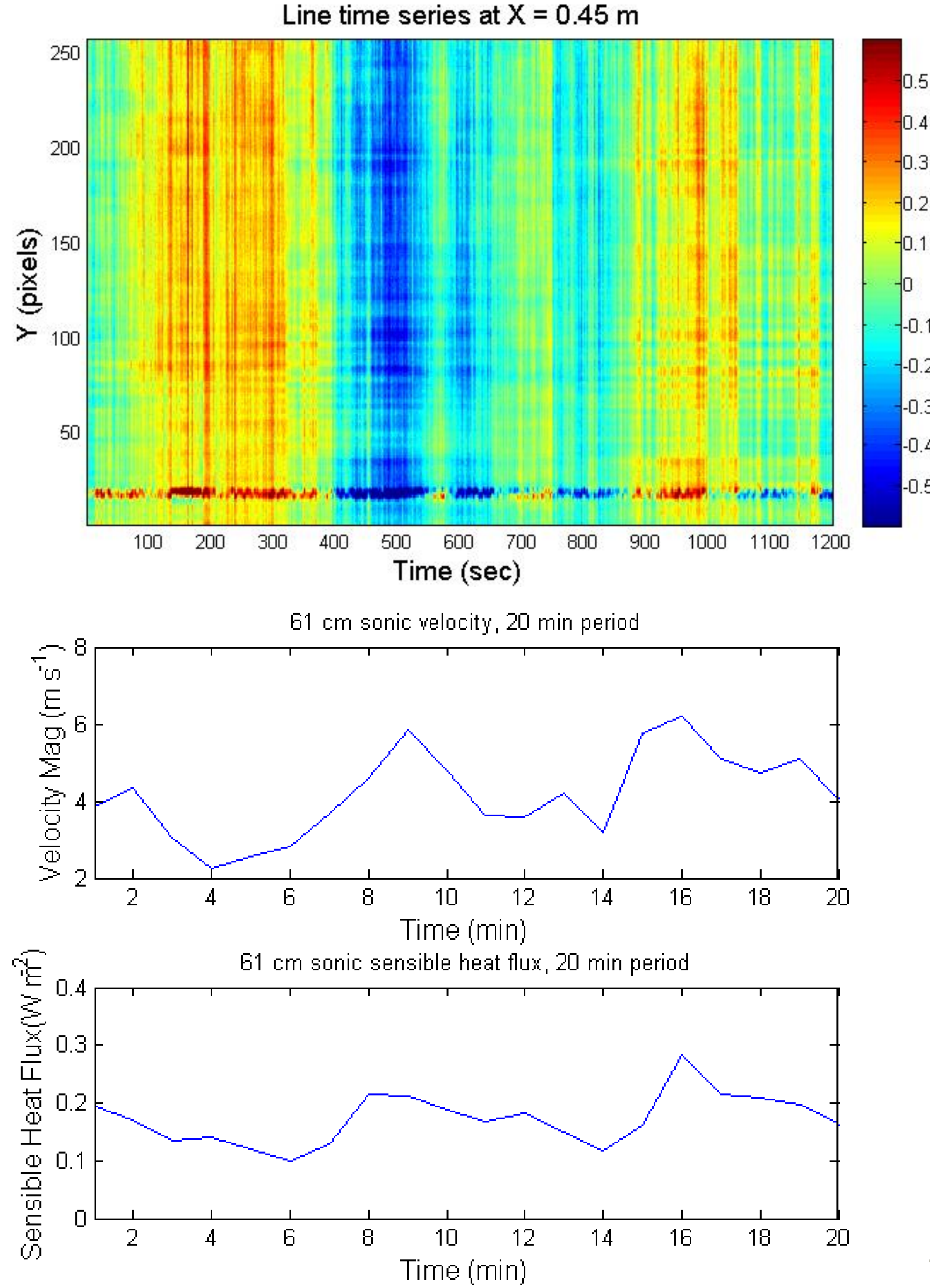


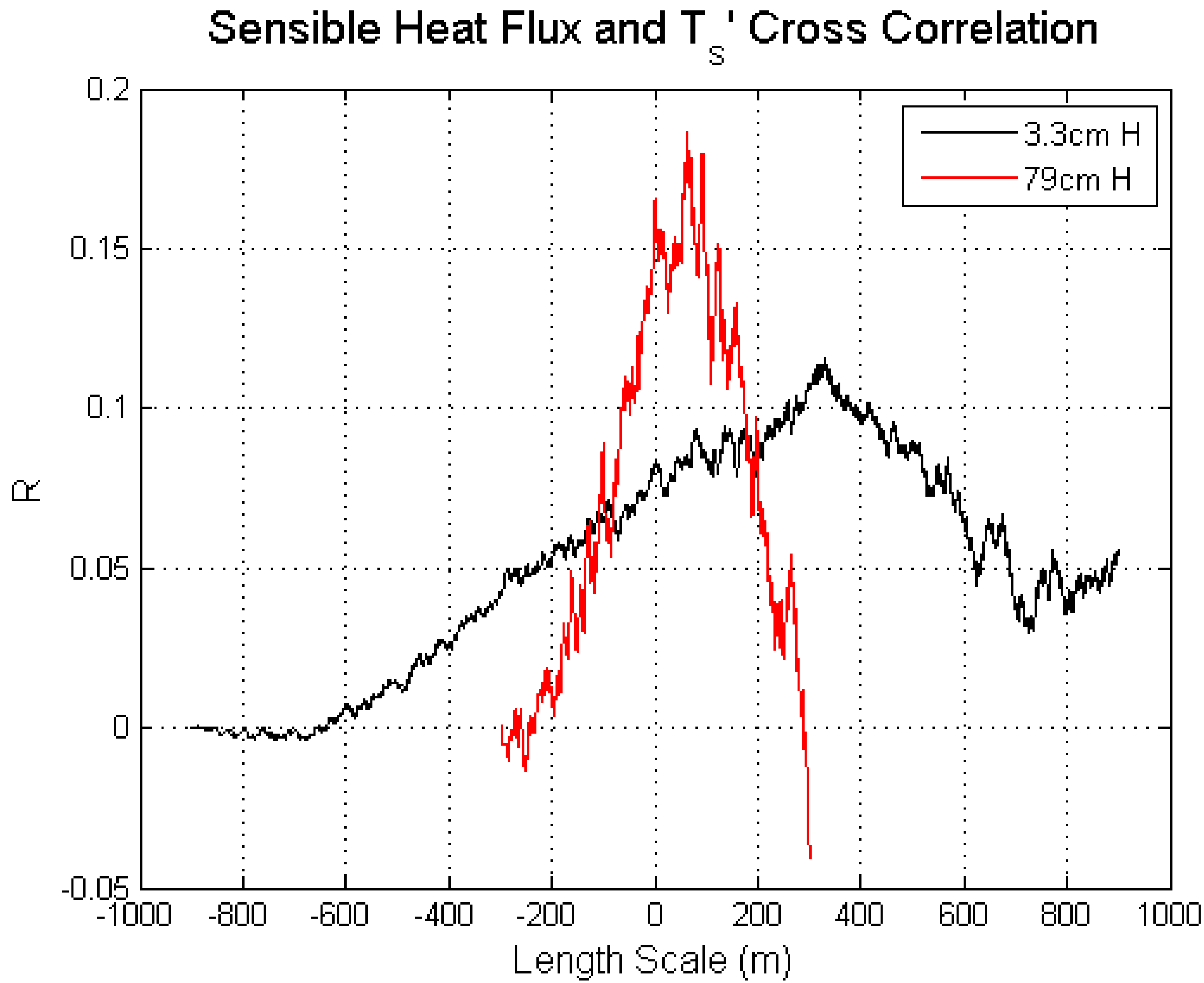


- Many resolved scales!
- Horizontal streaks are persistent surface features (more moisture)
- Vertical banding are time-varying turbulent structures

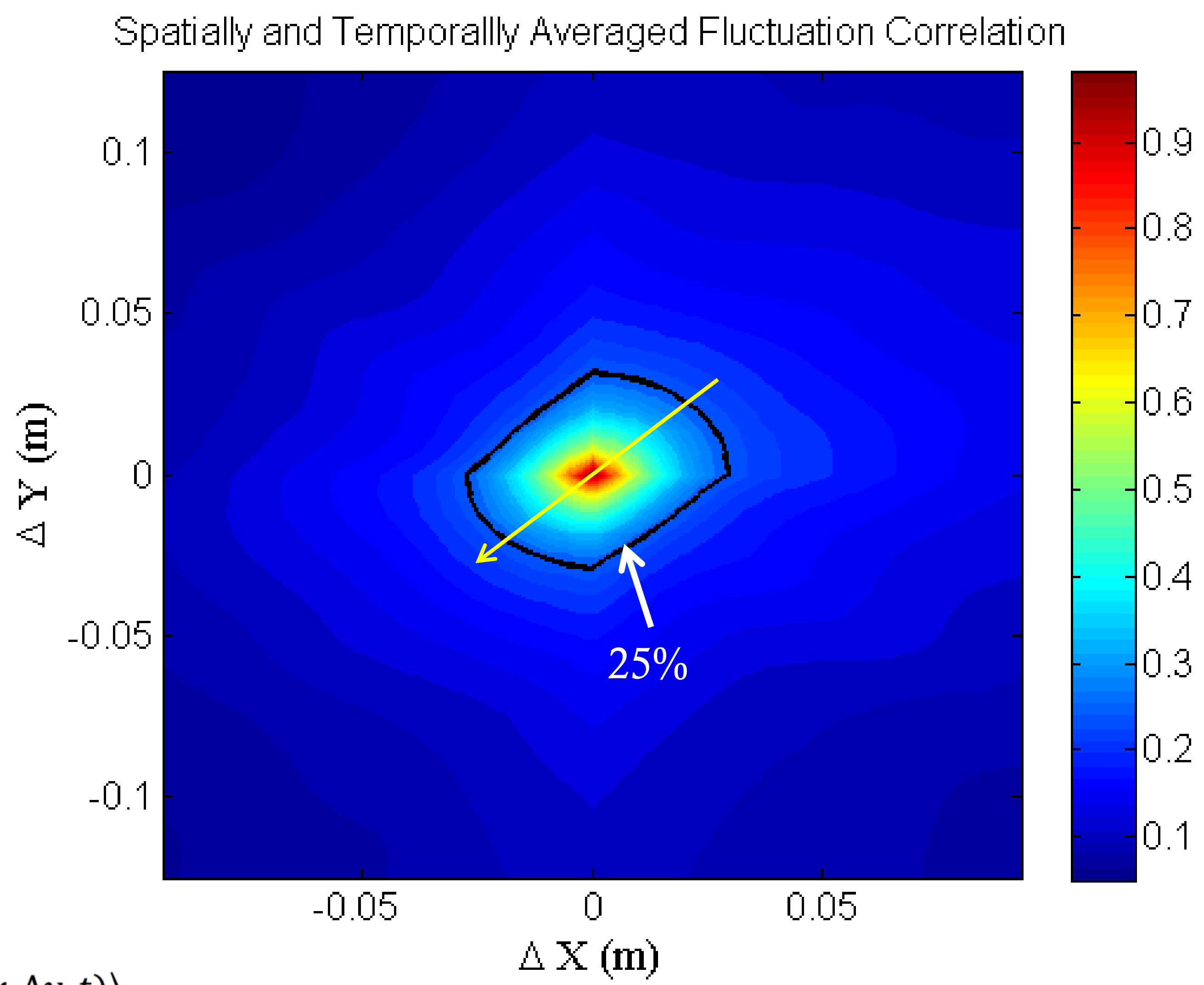


- Cooling periods are associated with high winds
- Sonic anemometer (~100 m downwind) shows obvious correlations
- Sonic 1 min avg H shows some trends, but not as conclusive





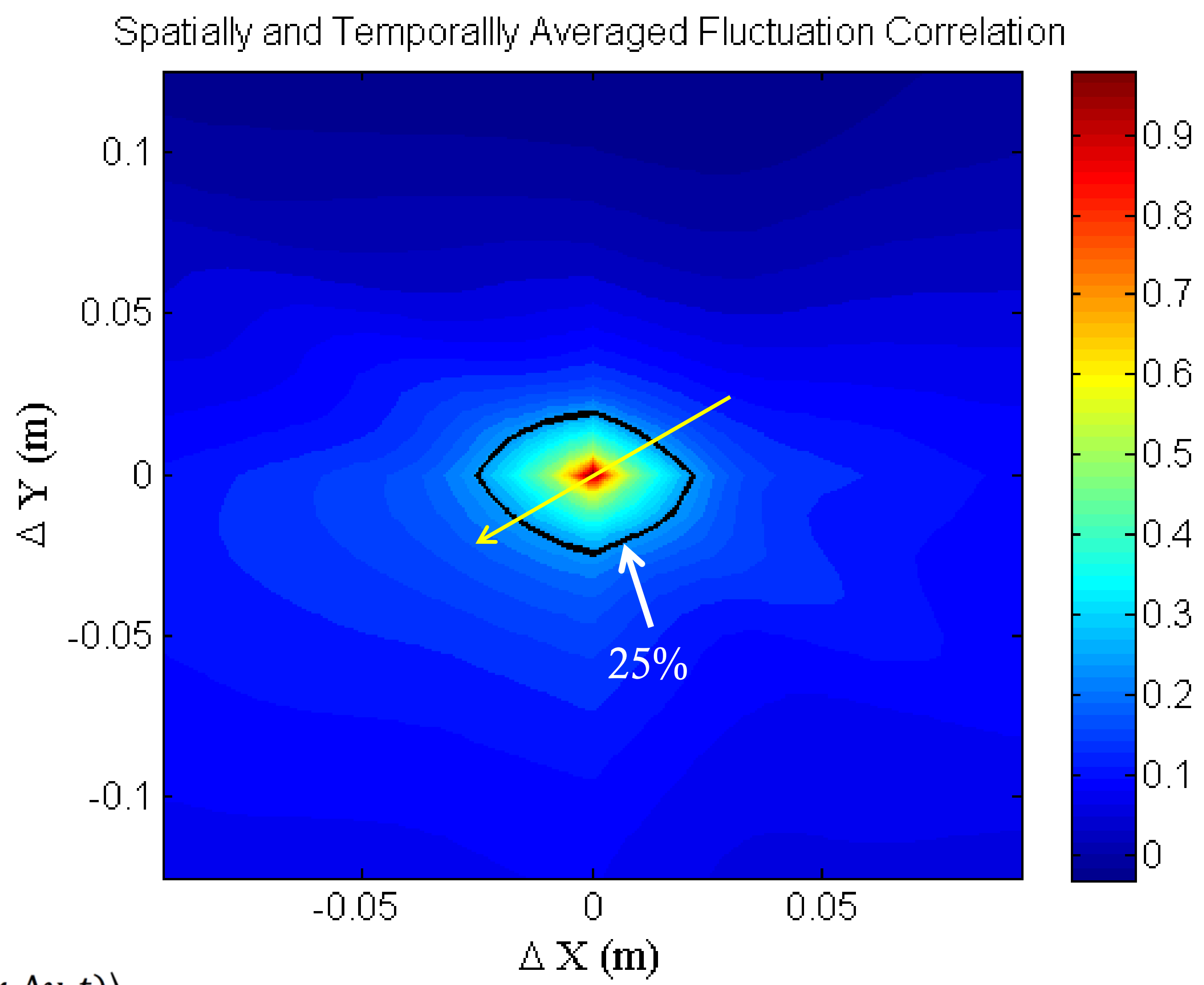
Cross correlation with hotwire measured sensible heat flux



$\langle \rho_{xy}(\Delta x, \Delta y, t) \rangle$

$$\rho_{xy}(\Delta x, \Delta y, t) = \frac{\overline{T_s'(x,y,t)T_s'(x+\Delta x, y+\Delta y, t)}}{\sigma_{Ts}^2}$$

L = -5.34 m



$\langle \rho_{xy}(\Delta x, \Delta y, t) \rangle$

$$\rho_{xy}(\Delta x, \Delta y, t) = \frac{\overline{T_s'(x,y,t)T_s'(x+\Delta x, y+\Delta y, t)}}{\sigma_{Ts}^2}$$

L = -4.29 m

Conclusions

- Surface temperature responds measurably to turbulent fluctuations
- Time averaged spatial turbulence structures are elongated in the streamwise direction (see A. Garai et al. 2013)
- Round shapes correspond to unstable convective structures while elongated shapes relate to more neutral conditions
- Correlation with near-surface sensible heat flux demonstrates complex lag, further investigation required…

Future Work

- Process more data from different stability regimes
- Transient conduction model to quantify time lag and other dynamics of FLIR signal

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Questions?

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- Garai, A., Pardyjak, E., Steeneveld, G. J., & Kleissl, J. (2013). Surface Temperature and Surface-Layer Turbulence in a Convective Boundary Layer.*Boundary-Layer Meteorology*, 1-22.