An atmospheric surface layer study: The Idealized horizontal Planar Array experiment for Quantifying Surface Heterogeneity (IPAQS)

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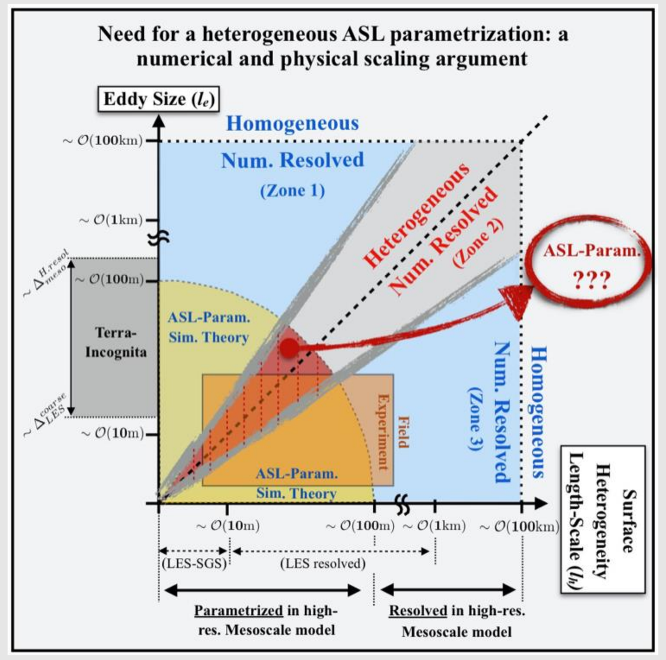
Abstract

Numerical weather prediction models rely heavily on boundary-layer theories, which poorly capture the interactions between the Earth's heterogeneous surface and the internal boundary layers aloft. Further, in relation to these theories, there remains outstanding questions that still require new understanding, such as the closure of the surface energy balance, advection quantification, and surface-flux interaction. We hypothesize that under certain conditions of unstable and neutral stratification, surface thermal heterogeneities can significantly influence the flow structure and alter momentum and scalar transport. To be able to access this hypothesis, we designed the Idealized horizontal Planar Array experiment for Quantifying Surface heterogeneity (IPAQS). IPAQS took place during the summers of 2018 and 2019 at the Great Salt Lake Desert playa in western Utah at the U.S. Army Dugway Proving Ground's Surface Layer Turbulence and Environmental Test (SLTEST) facility. The site is characterized by a long uninterrupted fetch with uniform surface roughness and large thermal and moisture heterogeneities covering a wide range of scales. Observations were made with an array of 2-m high, temporally-synchronized, fast-response sonic anemometers, and finewire thermocouples, which were deployed on a coarse grid covering an area of 800 m x 800 m with 200-m spacing. Results provide valuable insight into the spatial and temporal evolution of the flow. Fine-scale turbulence was measured using Nano-Scale Thermal Anemometry Probes (NSTAP). Meanwhile, larger-scale turbulence was captured with Doppler wind LiDARs. Presented is an overview of the experiment and initial results.

Project Overview

Study and characterize Atmospheric Surface Layer (ASL) processes associated with surfaces with high spatial temperature and moisture heterogeneity to improve ASL parametrizations for high-spatial-resolution mesoscale simulations.



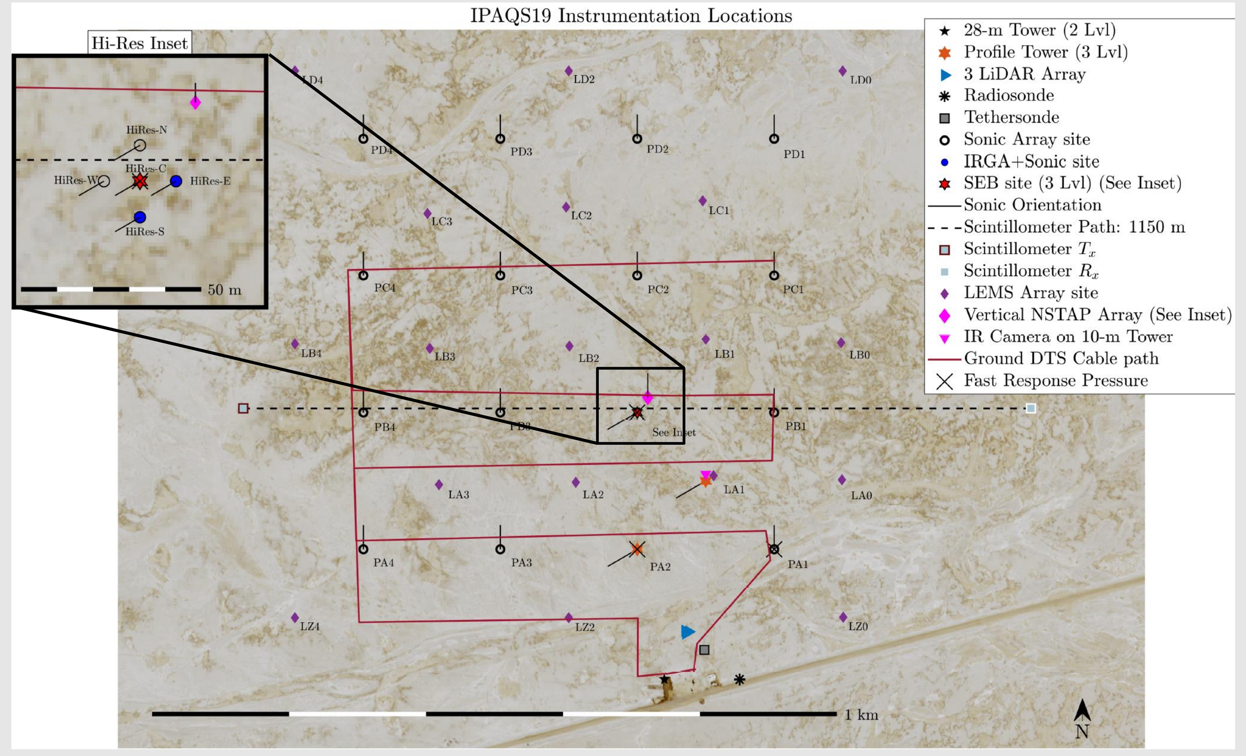
Specific Goals for the IPAQS project

1. Study the spatiotemporal structure of the surface temperature and moisture fluctuations and relate them to the scalar fluxes in the ASL
2. Extend traditional ASL formulations, such as MOST, to account for the energy transport from surface heterogeneity.
3. Incorporate novel techniques to help accomplish goals 1-2 through a two-year field study
4. Utilizing LES and mesoscale simulations validate the **new ASL parameterization**

Field Campaign Location: U.S. Army Dugway Proving Ground, UT

(Above) SLTEST location and photo of the experimental site. Note the site's key characteristics of uniform surface roughness and variable salt-clay surface.

IPAQS Deployment



(Above) Experimental layout of the 800 m x 800 m horizontal array which included 31 3D sonics and 18 2D sonics deployed on 36 2-m masts, 3 10-m towers with profiles, and one 28-m tower

Instrument Close-ups

Quantifying Surface Temperature Heterogeneity

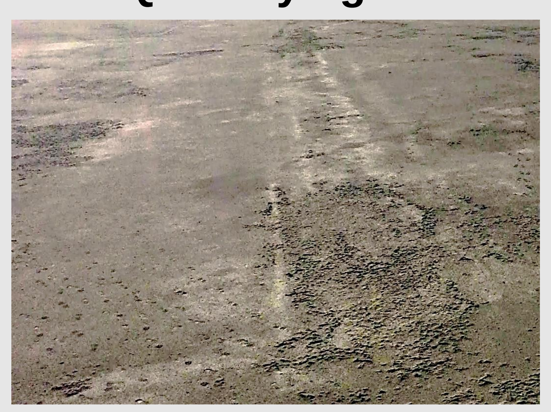
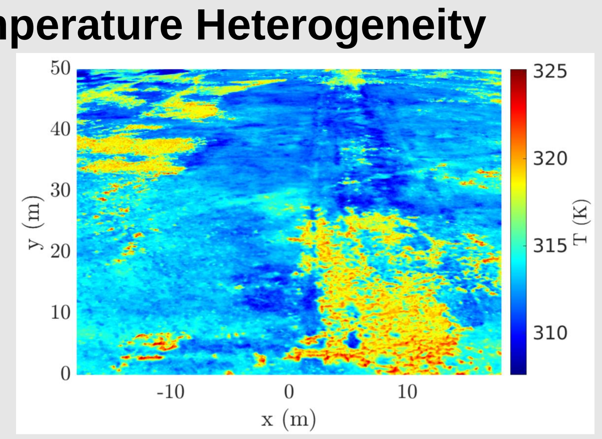


Photo of the playa surface illustrating variations in surface albedo



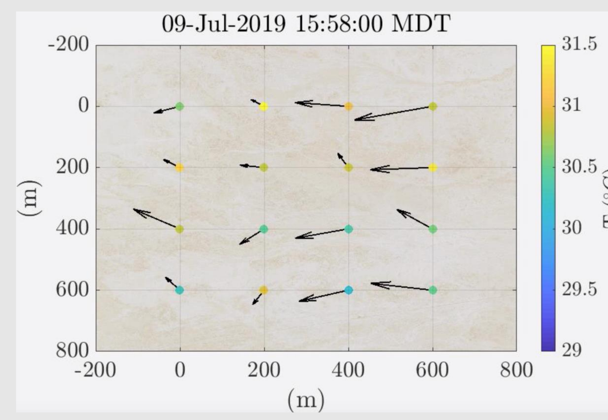
Thermal infrared image of the same photo on the left illustrating the surface temperature heterogeneity

Studying Surface Heterogeneity

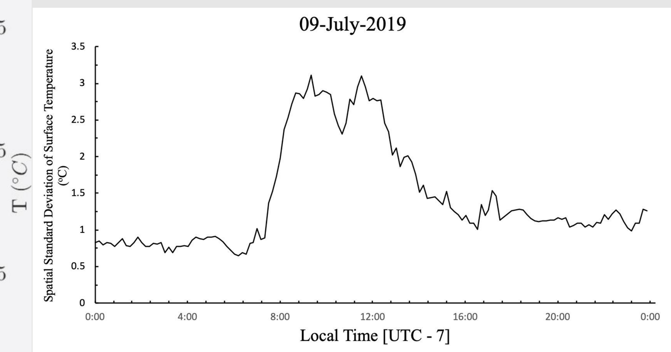
What is the role of the spatial heterogeneity on the surface energy budget? Let's take a step back and study the **temperature tendency** budget:

$$\frac{\partial\overline{\theta}}{\partial t}+\overline{u}_j\frac{\partial\overline{\theta}}{\partial x_j}=-\frac{\partial\overline{u_j'\theta'}}{\partial x_j}+\frac{L_vE}{\rho C_p}+\frac{\partial R_j}{\partial x_j}$$

Spatial Variability of mean quantities



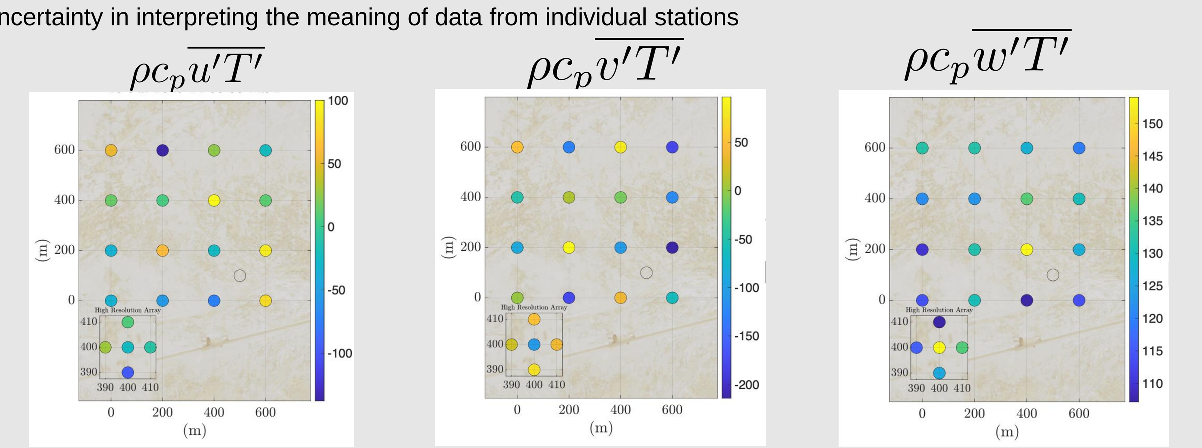
1-min average of 2-m winds and temperatures over the array



The spatial standard deviation of surface temperature collected from iButton data over the entire array (30-stations). Note the strong diurnal pattern.

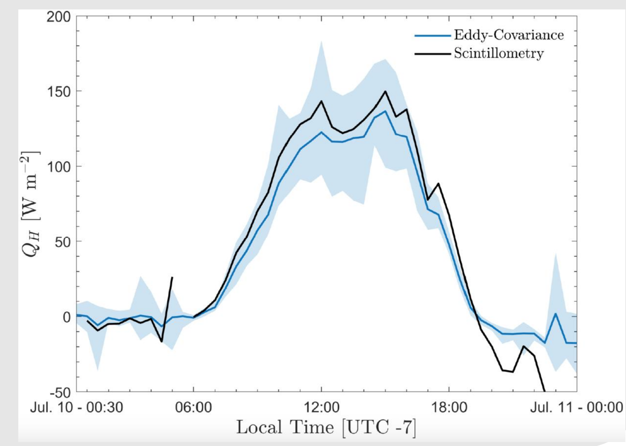
Turbulent heat-flux heterogeneity

The spatial variability of the fluxes is directly coupled to closure of the energy balance. This large variability creates uncertainty in interpreting the meaning of data from individual stations

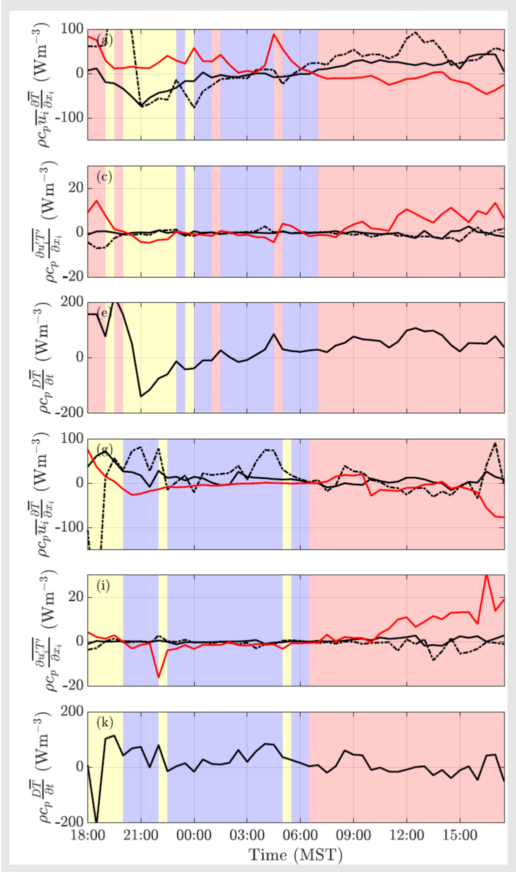


Scintillometer

The scintillometer's spatially-averaged sensible heat flux is shown with a spatial average of the sensible heat flux calculated using the array of 2-m sonic anemometers and fine-wire thermocouples (Eddy-covariance).



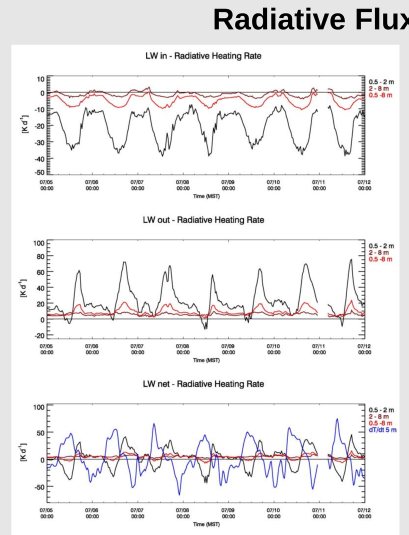
Heterogeneity: mean temperature advection and flux divergences



Advection and turbulent flux divergences between convective and non-convective days:

Results between convective and non-convective days illustrate that mean heating through horizonal advection is stronger on convective days. We hypothesize that local surface heterogeneities are generating stronger persistent air temperature differences during periods with weak winds compared to days with strong winds. This suggests that local advection effects are more likely to contribute more to the energy balance on highly convective days.

Radiative Flux Divergence

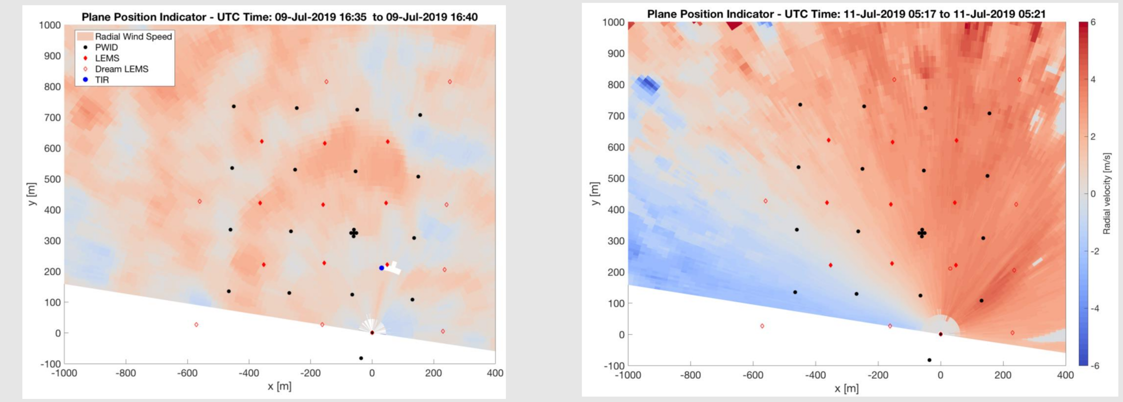


Radiative heating & cooling dominate near the surface. In the morning, when the convective boundary layer is shallow, but the strongest heating is observed, radiative transport cools the near-surface layer. In the afternoon & early evening, radiative heating dominates, again working against the observed temperature tendency. Above 2 m, a weak radiative warming occurs throughout the diurnal cycle, but the bulk (2-8 m) layer still mirrors the near-surface (0.5-2 m) radiative heating & cooling cycle.

Quantifying heterogeneity: Dispersive fluxes

Dispersive fluxes arise from the space decomposition of the time-averaged flow variables (denoted by a double-prime) and are a measure of the covariance between mean spatial differences in the velocity and temperature field. The playa's surface characteristics lead to large surface thermal heterogeneity and provide the means to produce large dispersive fluxes.

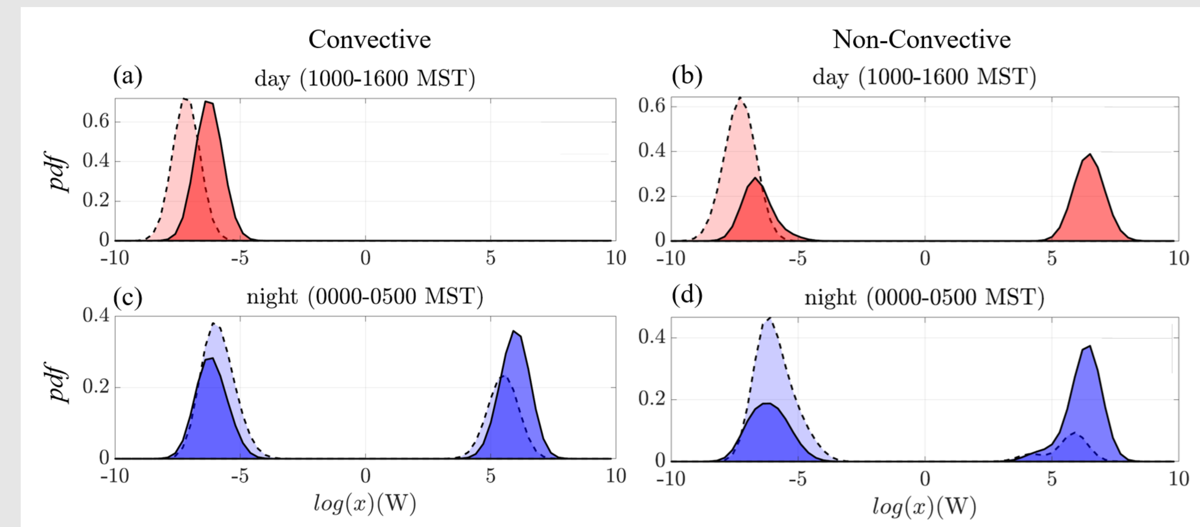
$$\frac{\partial\langle\overline{T}\rangle}{\partial t}+\langle\overline{u_j}\rangle\frac{\partial\langle\overline{T}\rangle}{\partial x_j}=-(\rho c_p)^{-1}\frac{\partial\langle\overline{R_j}\rangle}{\partial x_j}-\frac{\partial\langle\overline{u_j'T'}\rangle}{\partial x_j}-\boxed{\frac{\partial\langle\overline{u}_j''\overline{T}''\rangle}{\partial x_j}}$$



Plane Position Indicator (PPI) scans over the experimental site. (left) Illustrates scans during convective and (right) during stable conditions. The convective period reveals cells of the order of $\sim 10^2$ m, meanwhile during stable thermal conditions (nighttime) the vertical transport of heat reverses sign causing a reduction in turbulence production, a more stratified flow structure, and a larger mean wind speed.

Control volume analysis: relevance of the Dispersive fluxes

A control volume analysis over a 400 m x 400 m x 2 m portion of the array illustrates the importance of the dispersive fluxes (solid black lines) compared to the mean advection (dashed black lines). Cases are divided between convective days and non-convective days and between night and day.



Summary Points

- IPAQS is allowing us to use some of the best available technology through collaborations to understand and quantify the impact of heterogeneity from the Kolmogorov scale to km scales as never before in an idealized setting
- Results will compliment other current projects (i.e. CHEESEHEAD), which will also tackle similar issues in more complex settings
- Preliminary analyses indicate that strong surface heterogeneity has an imprint on the ASL even in this idealized setting
- Develop a modeling framework to most effectively take advantage of our new understanding to improve NWP

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