"Simultaneous Direct Heat and Carbon Dioxide Flux at a Turbulence Free Surface"

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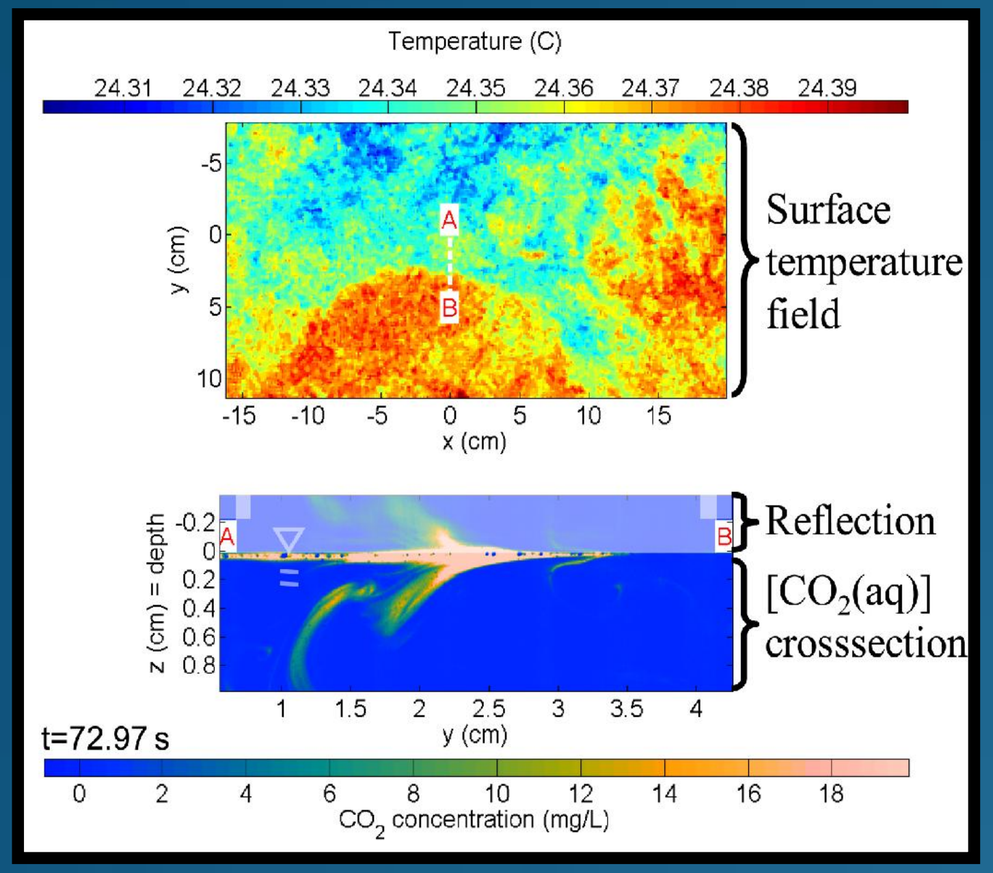
Background

Purpose: The purpose of this experiment is to fully quantify and evaluate heat and gas transfer under turbulent conditions, as well as increase understanding of the interaction between the atmosphere and water at their boundary surfaces.



Since surface water temperatures are slightly cooler than bulk water temperatures (4), the infrared camera employed allows one to locate the boils and upwelling events based on the minute temperature fluctuation they produce at the surface. From this one can measure the size, intensity, duration, and motion of such boils, determine the heat flux that occurs, and eventually compare such measurements to the intensity of CO_2 injections taking place directly below the surface in that area.

The image above reveals the mechanism by which CO_2 gas gets pulled into the bulk. The turbulent mixing of the water thins the concentrated boundary layer (the atmosphere has been stocked with pure CO_2 in order to aide the transfer), which is then "swept" into the bulk by the downward flow of water caused by turbulence. The overall goal of these experiments seeks to determine if the mechanisms of heat and CO_2 transfer are similar. Specifically, here we aim to quantify both transfers' scales, or characteristic size of their transfer events.

Conclusions

Results: Since the same turbulence that causes the concentrated boundary layer to be swept away into the bulk, simultaneously brings warmer bulk water to the surface, we can identify periods of heavy turbulent mixing through autocorrelation analysis and its corresponding integral length scales.

Next Steps: Further analysis can be done on the covariances of the near-surface vertical velocity (determined from the surface elevation derivative) with simultaneous temperature to determine the direction and scale of the heat flux. Additionally, comparisons of the integral length scales and covariance estimates between the surface temperature and subsurface CO_2 measurements will complete the study.

Acknowledgements

I would like to thank the following people/resources for their help :
NSF for their generous grant this summer, , my Advisor, Chris Zappa, Deborah Lebel, and Scott Brown, for help in MATLAB,Evan Variano, for access to data/figures and helpful review/advice, Lamont-Doherty Earth Observatory

References:

1. Varian, E., Cowen, E., A Random-Jet-Stirred Turbulence Tank, Cornell (DeFrees Hydraulics Laboratory) 2006.
2. Brown, S., Dinh, E. H, Characterization of Parameters Affecting Noise and Calibration Data of a CEDIP Jade III LWIR Imager , Columbia (Lamont) 2007.
3. Varian, E., Cowen, E, Quantitative Imaging of CO2 Transfer at an Unsheared Free Surface, Cornell (DeFrees Hydraulics Laboratory) 2007.
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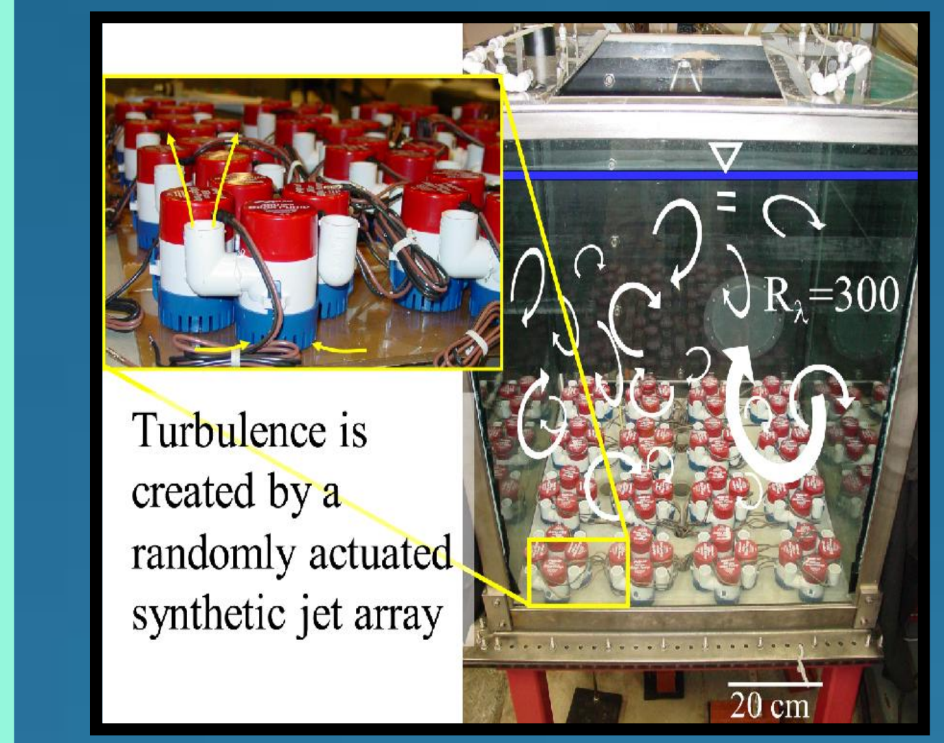
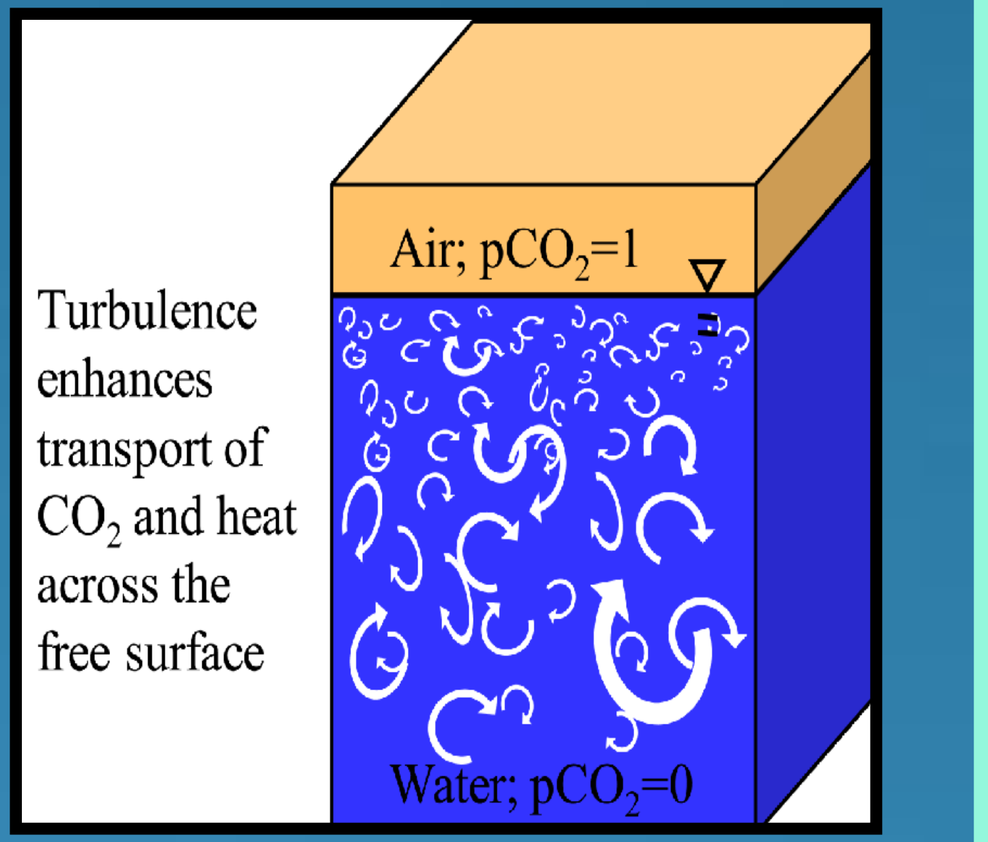
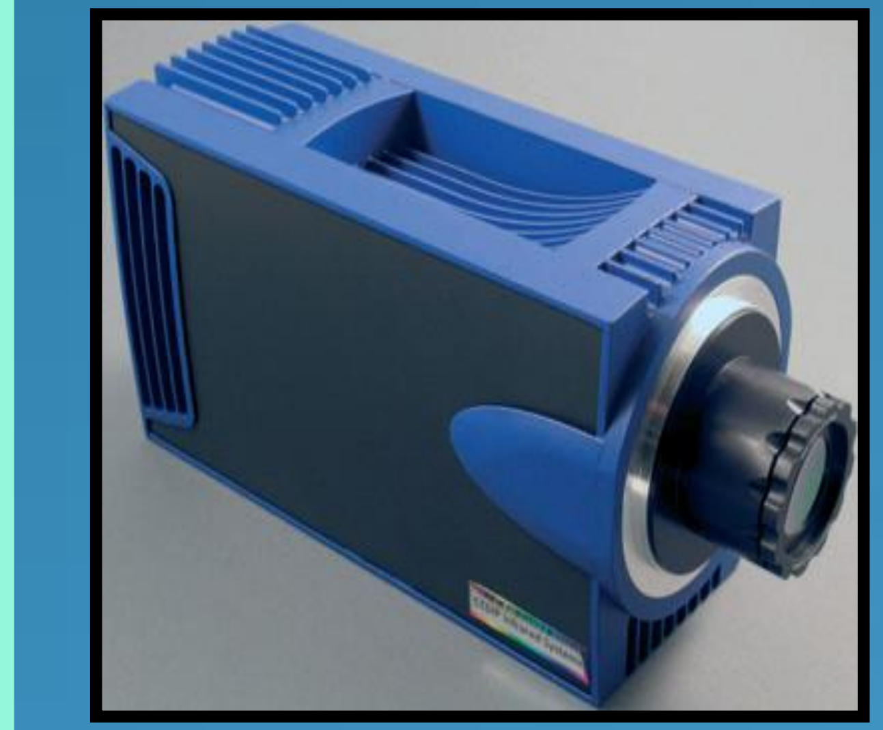
Methods



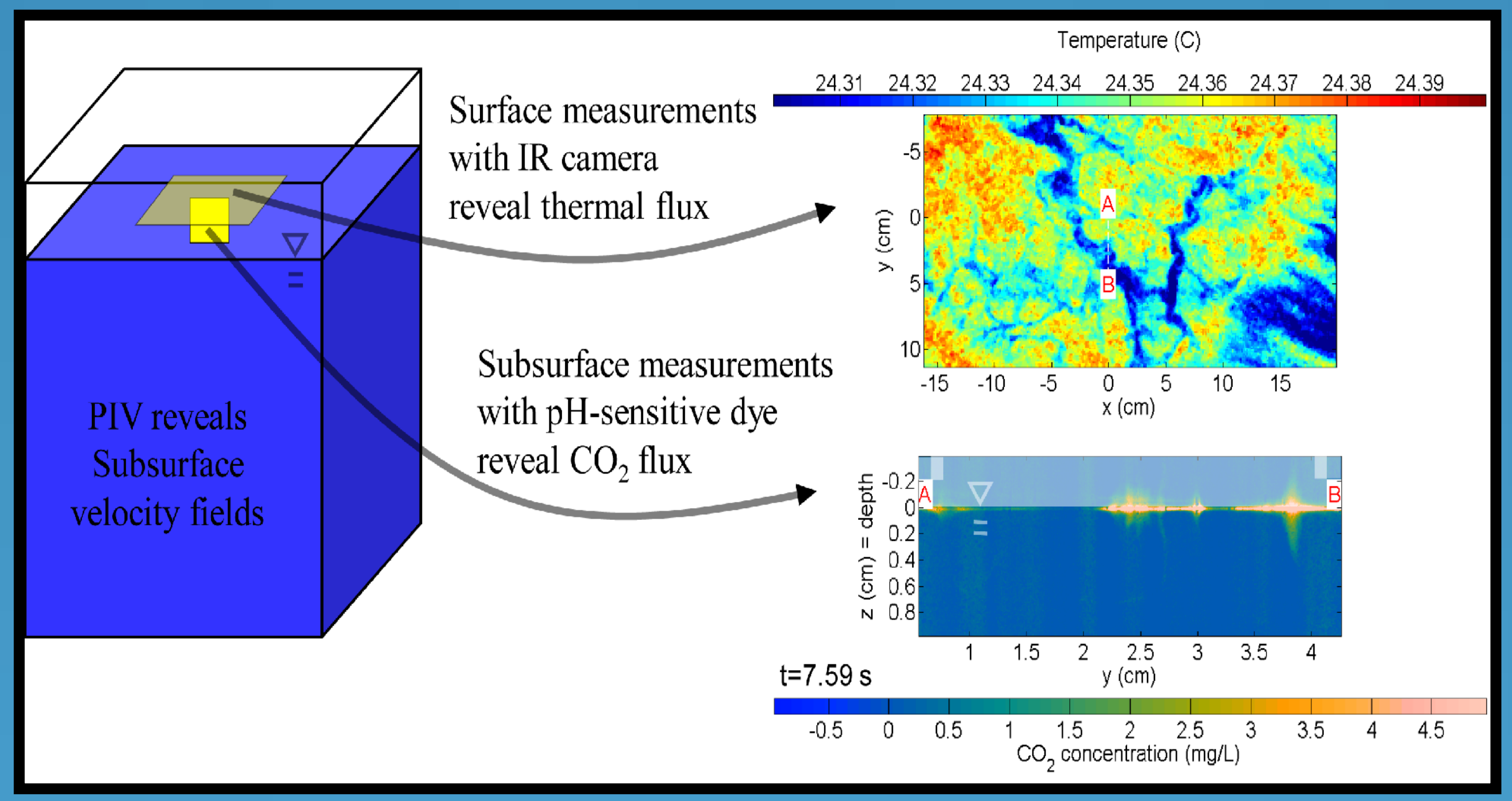
The set-up of the tank is as follows: the bottom grid (80 x 80cm) is covered with 64 evenly distributed synthetic jets (i.e. no integrated flux). They fire on random intervals with an average time engaged at approximately 1.5 s. While this set-up does not produce perfectly random flow within the entire tank, especially the bottom 60 cm nearest the jets, it does come remarkably close in the final 20 cm before the surface (fortunately, the most relevant to our purposes). (1)

The tank's design creates as near as possible random (turbulent) water flow, i.e. no mean shear water flow. Using the Reynold's number as a measure for such randomness (with a high Reynold's number indicating more random, or turbulent, flow and a low Reynold's number indicating uniform, or shear, flow), the tank has performed well producing an experimentally-observed Reynold's number of 6440 (4000 is generally the cut-off for dominantly turbulent flow). (1)





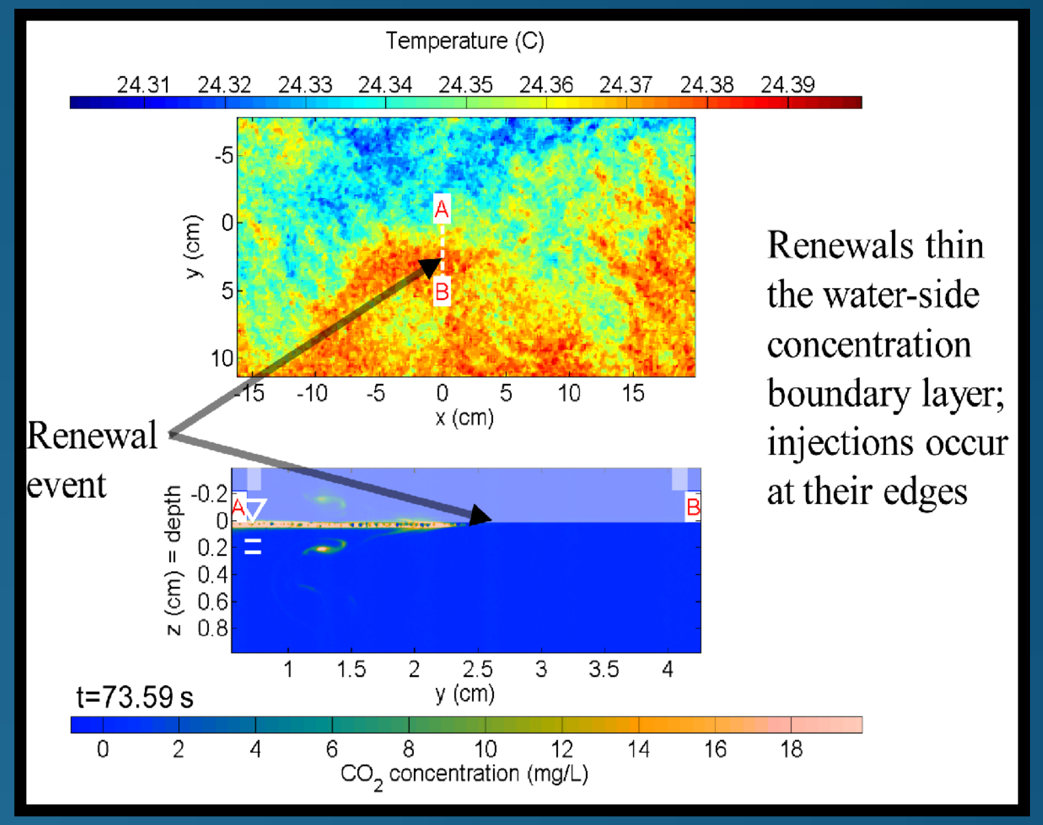
The infrared imager used to measure water surface temperature in this experiment is a CEDIP Jade III LWIR with a 25mm lens. Operating in the Long Wave Infrared (8µm – 9.3µm) region, the CEDIP imager uses an advanced focal plane array technology of the MCT detector type operating in snap shot mode. Able to analyze target temperatures between 20 C to 1500 C, the imager has both RS170 analog output and 14-bit RS422 digital output. For this experiment the sampling frame rate was 100 fps. (2)



For subsurface measurements, two important techniques were used: Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF). In PIV, special tracer particles are employed , which can be traced with the aid of argon lasers and thus reveal important information regarding the velocity fields and motion of the water below the surface of the tank. From this technique we are able to study the water's vector field at any given instant of time in both plains perpendicular to the surface and each other. The other technique, LIF, involves a PH sensitive dye, which fluoresces in the presence of low PH values. This method relies on the assumption that once CO_2 mixes with water, it changes the chemistry of the water making it slightly more acidic (6-6.5 level). Thus calibrating the LIF camera to the brightness of the water (with dye but sans CO_2) we can detect CO_2 injection sites via the difference in brightness that occurs in the slightly more acidic injection area. (3)

Results

Renewal/upwelling events thin the subsurface CO_2 concentration layer, sweeping the CO_2 rich layer into the bulk. However, this process also results in warmer bulk water mixing to the surface and a subsequent heat transfer from the water to the atmosphere. Using the infrared camera we were able to detect where this warmer water broke the surface , thus revealing where and when mixing was strongest.



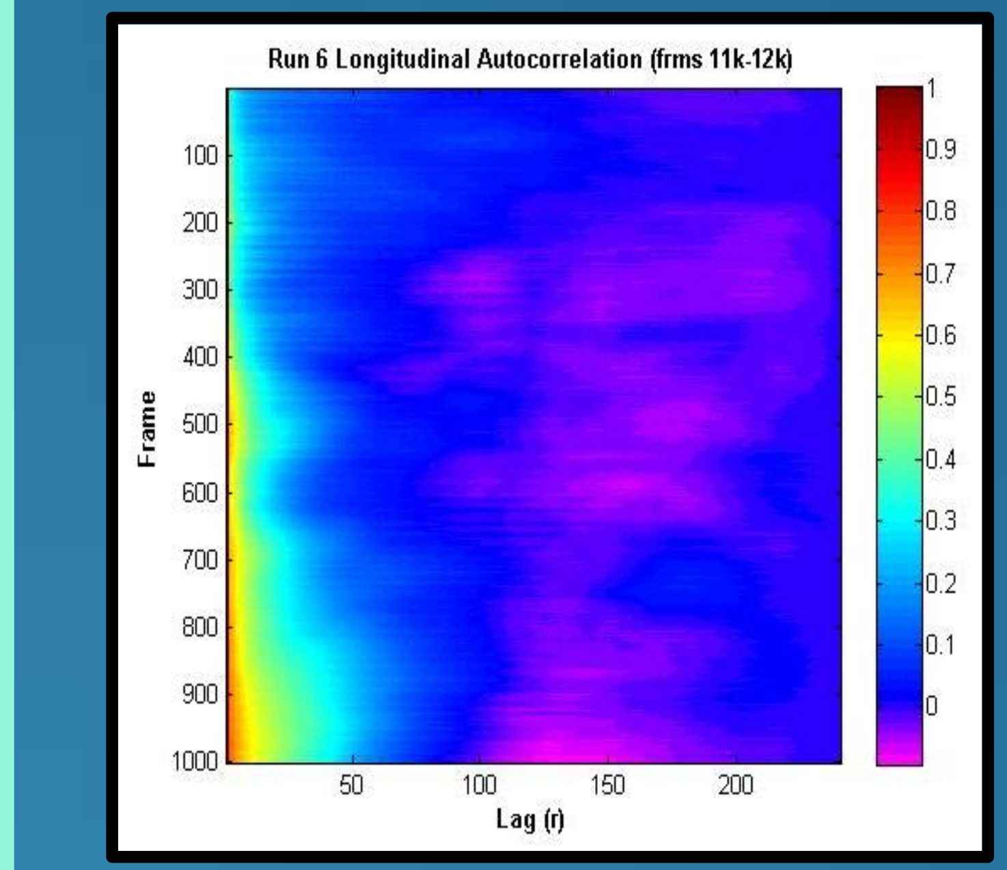


Figure A

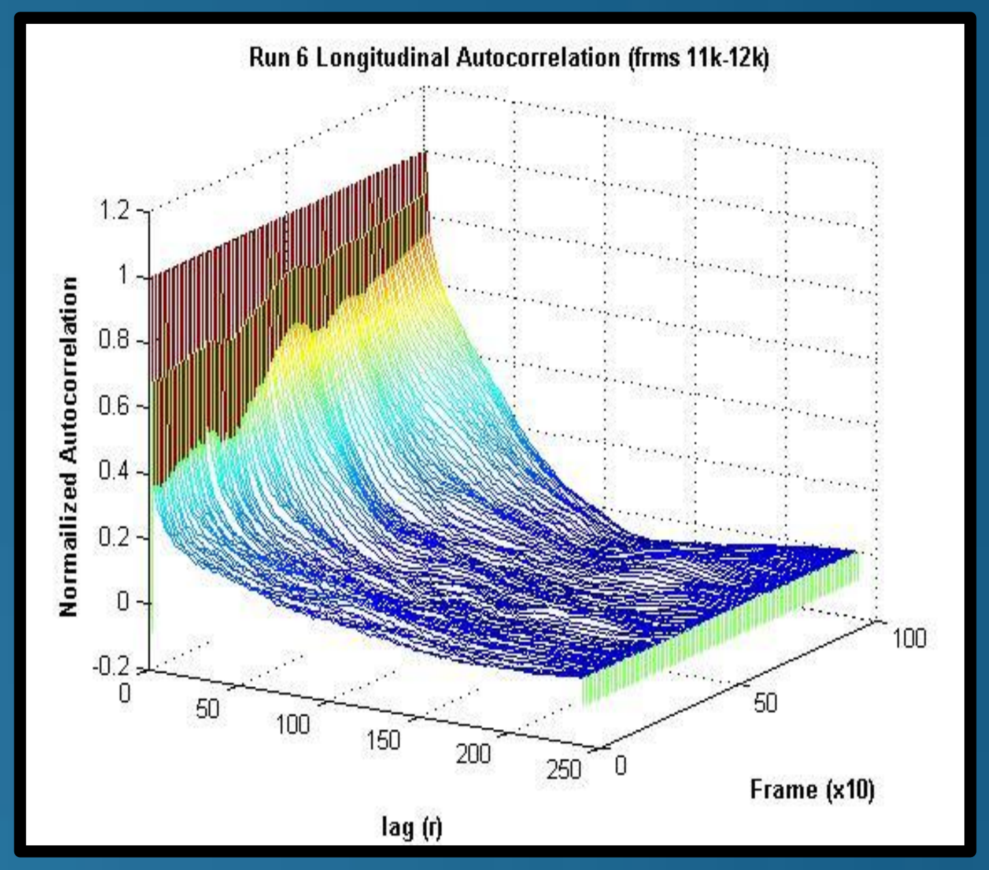


Figure B

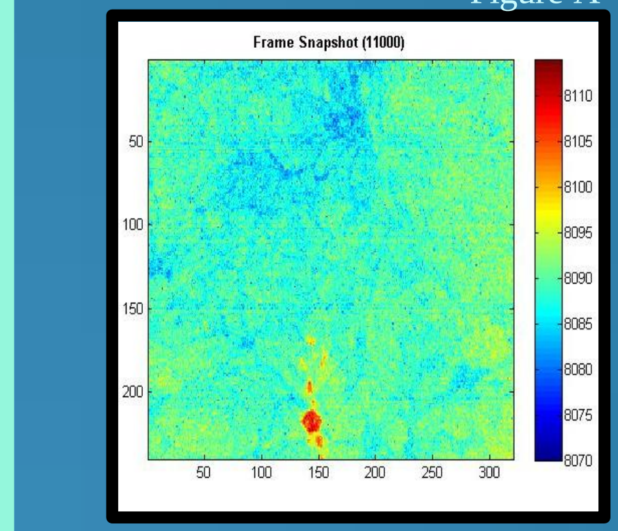


Figure C

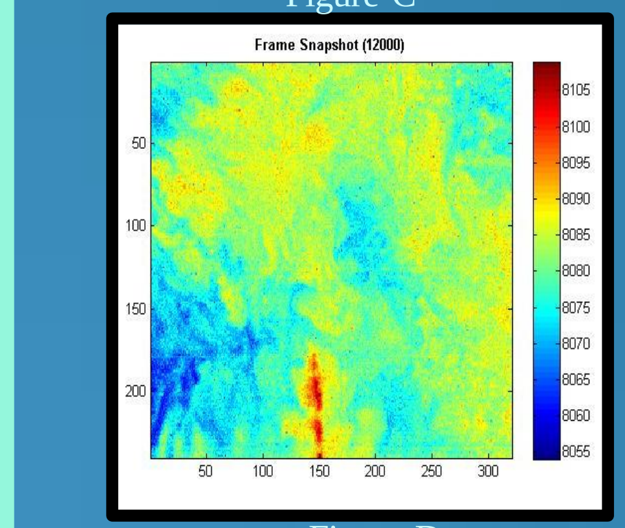


Figure D

Using an autocorrelation function to analyze the infrared images we were able to detect where surface conditions were most variable and , likewise, most homogenous. The figures nearby were all taken from a 1,000 frame sample (10s), in which footage revealed a shift from well-mixed (~0) to more variable (~1000) conditions.

Figures A and B show the longitudinal autocorrelation values for each frame in the sample, with different lag values (when lag is 0, rows completely overlap and correlation is equal to 1, there are 240 pixels in the horizontal direction).

Figures C and D show surface temperature conditions corresponding to individual frames at each end of the sample. Figure C shows well mixed homogenous surface conditions, while figure D reveals more stable, and thus variable, surface conditions.

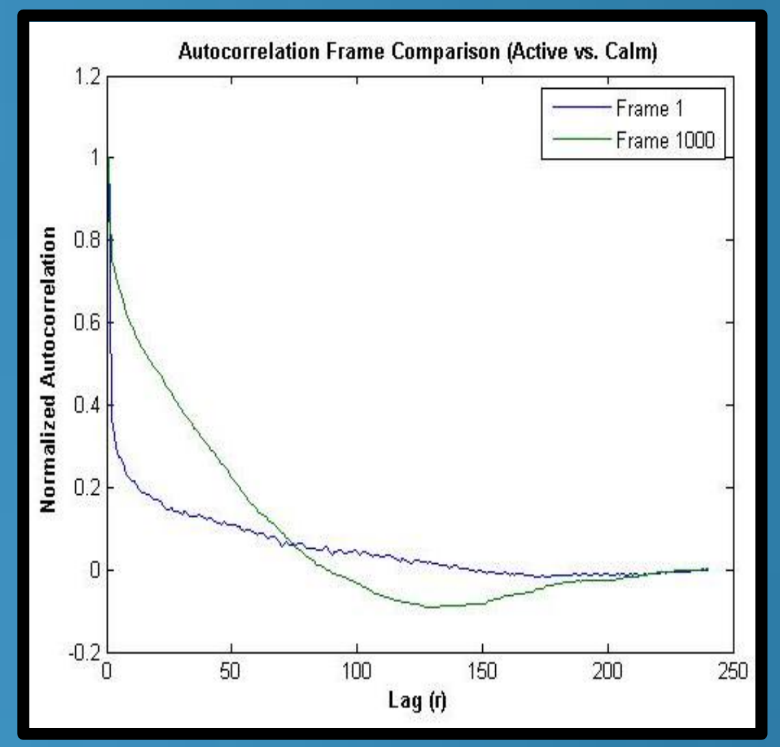


Figure E

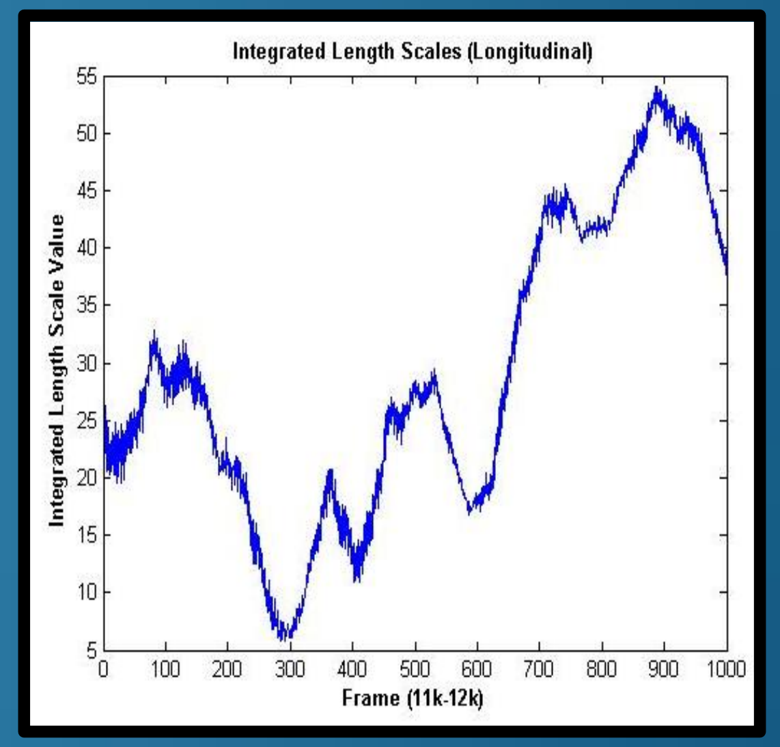


Figure F

Figure E shows the individual longitudinal autocorrelation curves for frames 1 and 1,000. From the plot the difference in surface conditions the two frames represent becomes clear. Figure F shows the integral length scales of each autocorrelation curve in the sample. The values were found by integrating underneath each curve. It reveals the characteristic size (scale) of temperature fluctuations or "events". The average integral length scale of the sample was found to be 29.0575 pixels (2.2645 cm), which is the same value obtained by integrating the average of the autocorrelation curves.