Revealing the role of missing scales in boundary layer observations in gravity wave propagation using the Flying Fiber Optic eXperiment (FlyFOX)

K. Lapo[1], A. Fritz[1], A. Freundorfer[1], B., Schilperoort[2], S. K. Muppa[1], C. K. Thomas[1]
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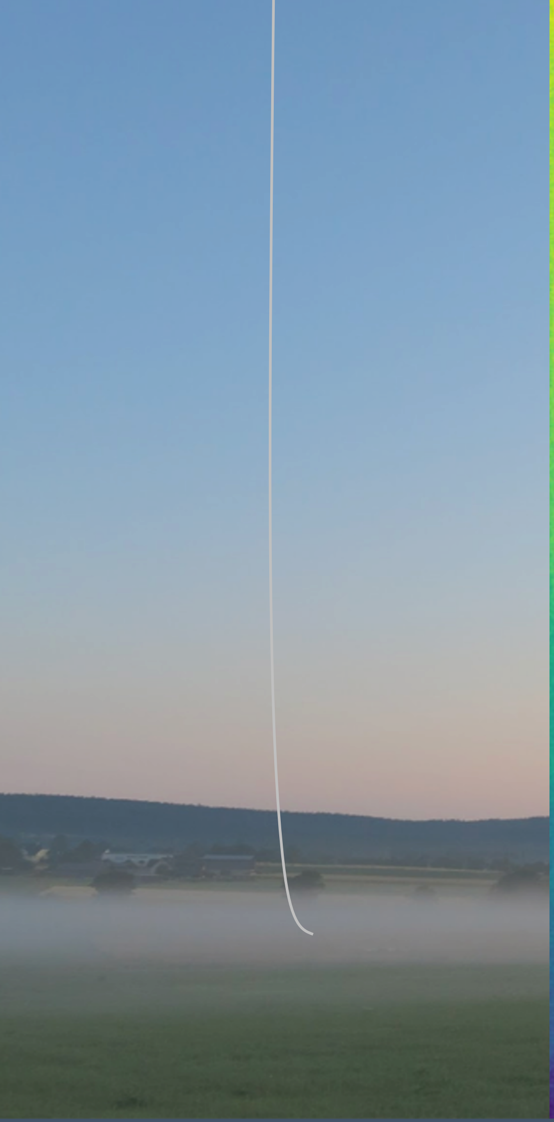

European Research Council
Established by the European Commission

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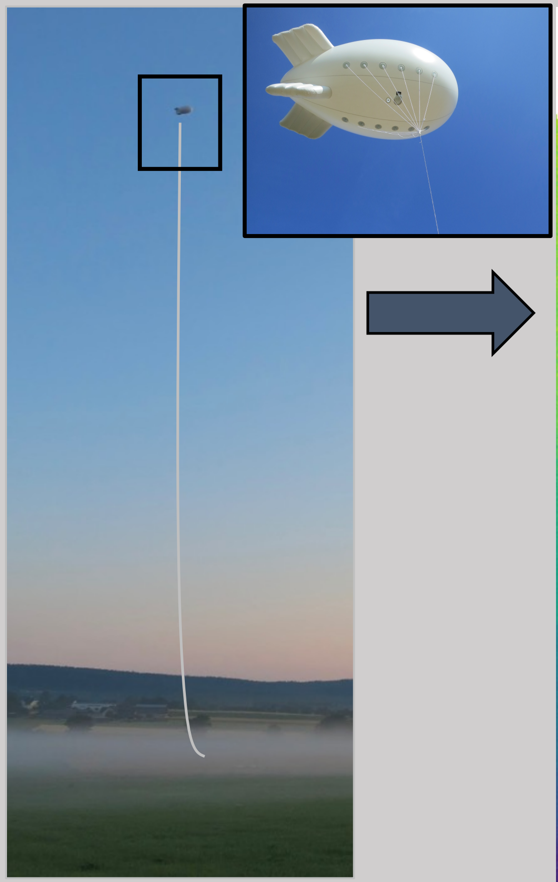
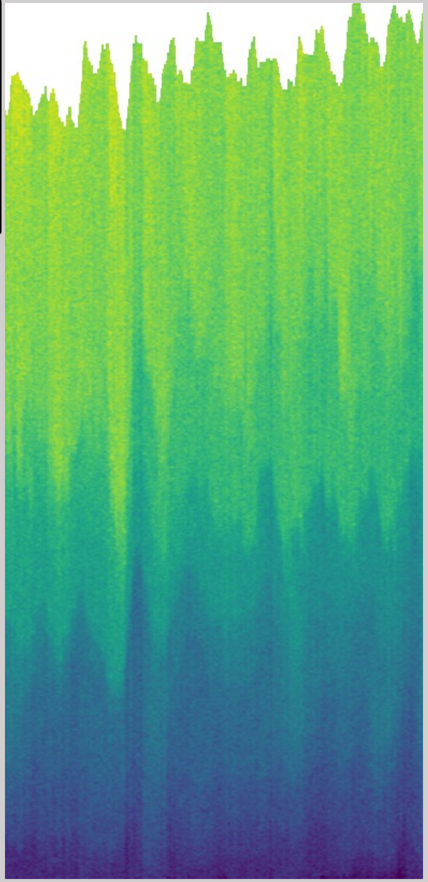
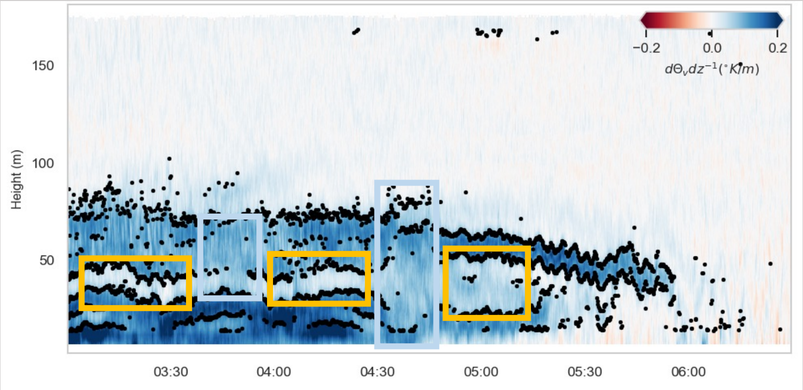
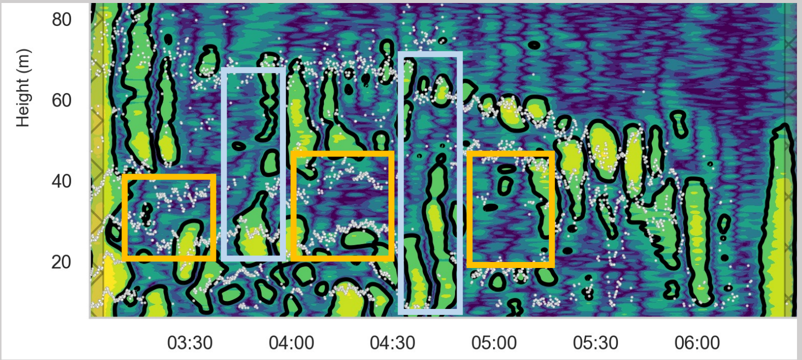
(1) Distributed Temperature Sensing (DTS) with fiber optic cables along a tethered balloon





(2) Reveals for the first time structures, like thermal sublayers, which are not observable with other techniques…

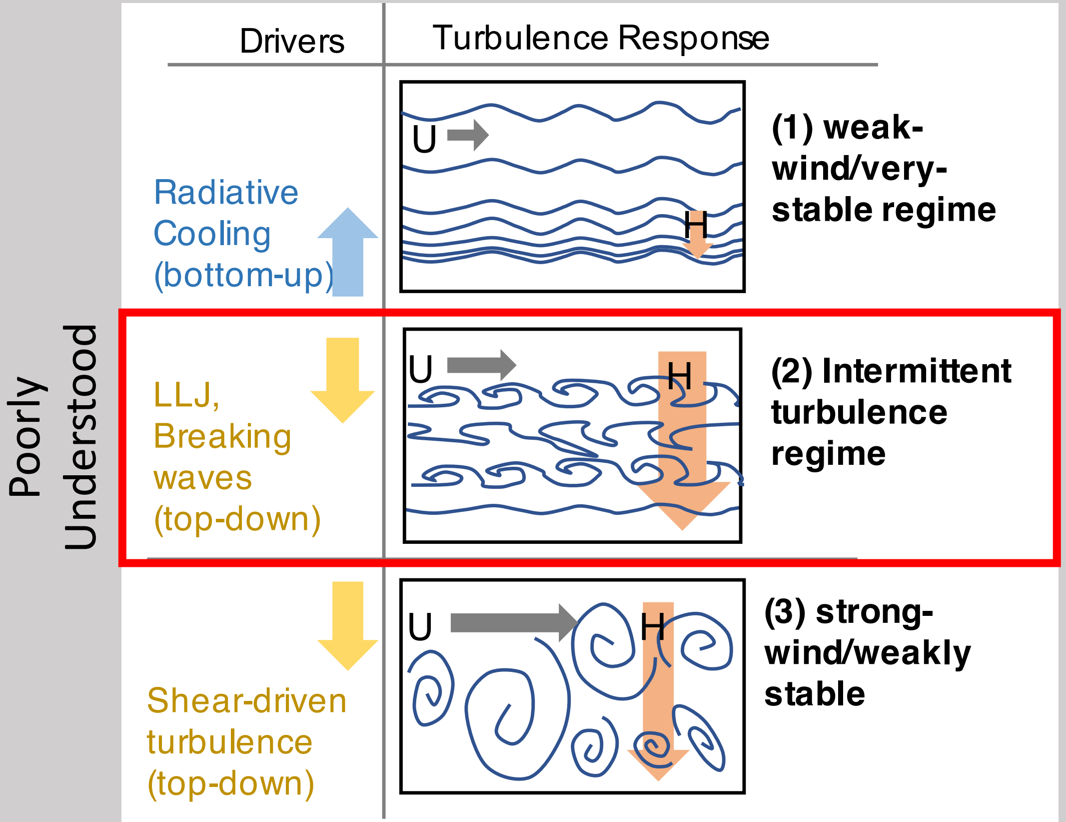




(3) … these structures dictate wave properties and vertical coupling

(4) Tethered DTS fills a critical gap in our observational capabilities for studying wave-turbulence interaction in the boundary layer

Motivation



Wave–turbulence interactions in the stable, weak–wind boundary layer

- Intermittent turbulence drives a large fraction of the heat exchange in the stable, weak–wind boundary layer
- Breaking waves are suspected to be one of the drivers of intermittent turbulence in these conditions
- But their specific relationship to intermittent turbulence is not well understood.
- We suspect this lack of understanding is in part a result of the <u>missing scales</u> of boundary layer observations that Distributed Temperature Sensing can fill.

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Distributed Temperature Sensing (DTS) and the Flying Fiber Optic eXperiment (FlyFOX)

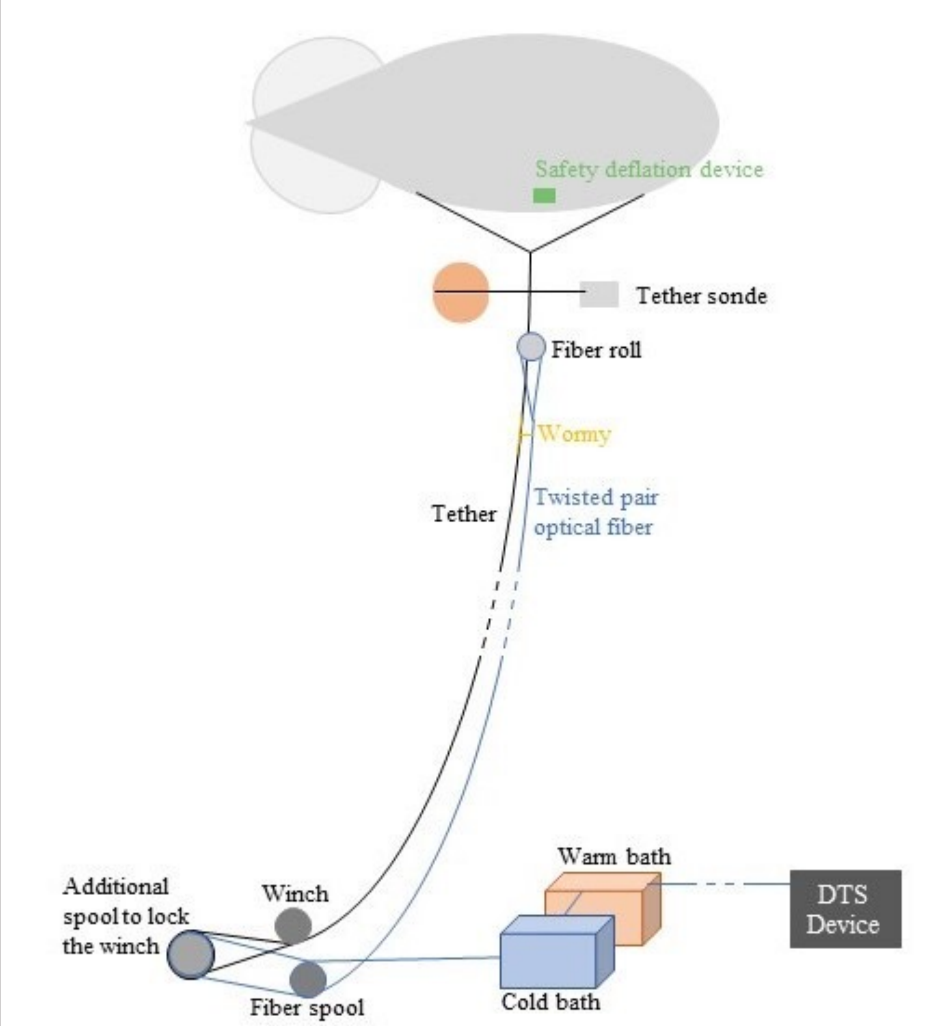
DTS Observational Principle

A near-infrared pulse of laser light is sent down an optical fiber, of which a small fraction undergoes non-elastic Raman backscattering. This backscatter contains two frequency-shifted (red/blue) bands, the ratio of the intensities of which can be used as a thermometer. Distance along the fiber is derived from range-gating.

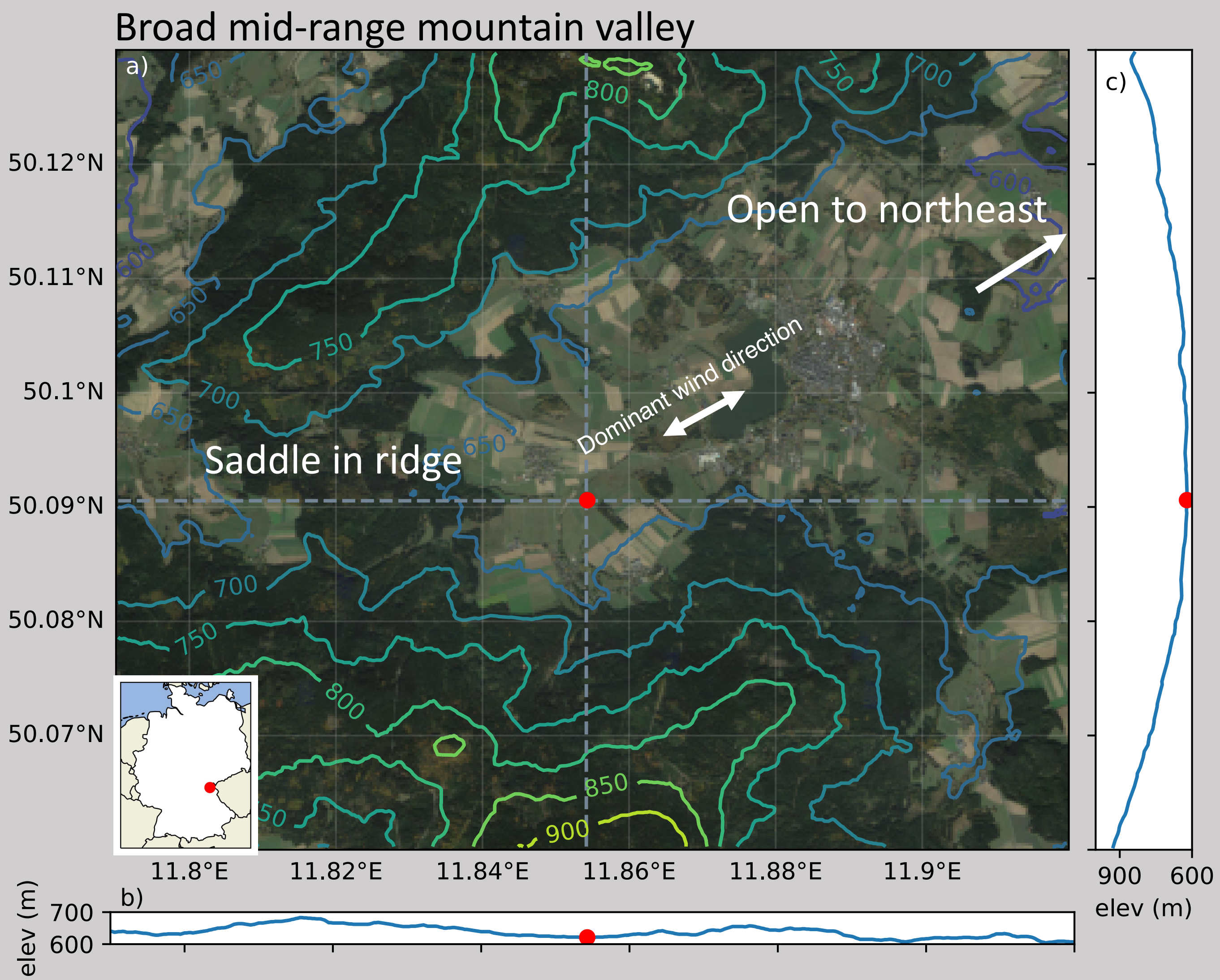
$$T \propto \frac{Intensity_{blue}}{Intensity_{red}}$$

(Backscatter intensities were calibrated following Hausner et al., 2011)

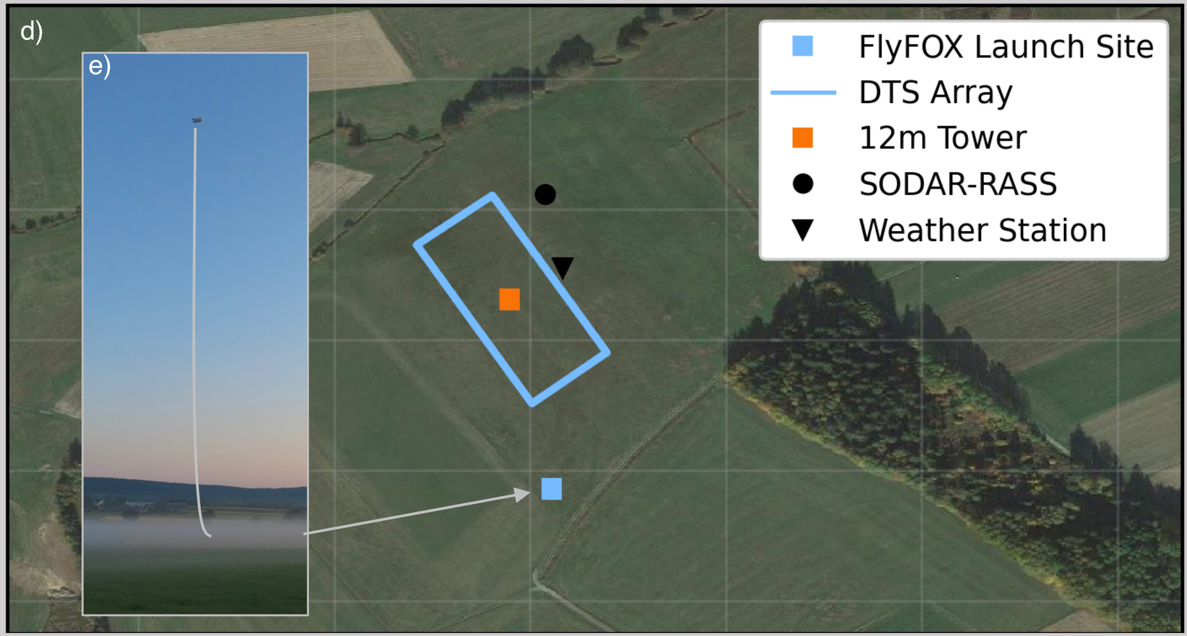
Deployed using a tethered balloon



Large-eddy Observatory, Voitsumra Experiment 2019 (LOVE19)

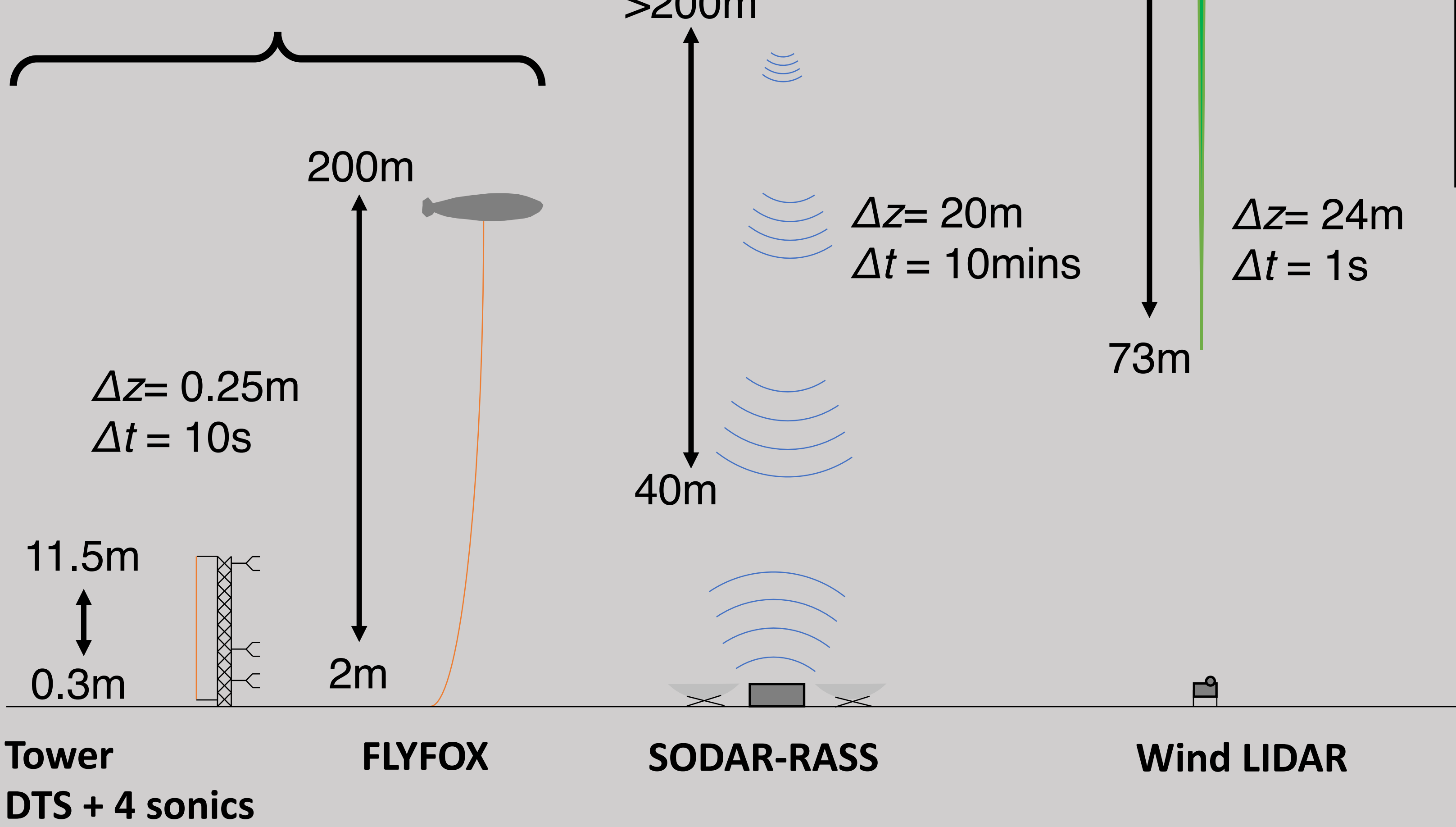


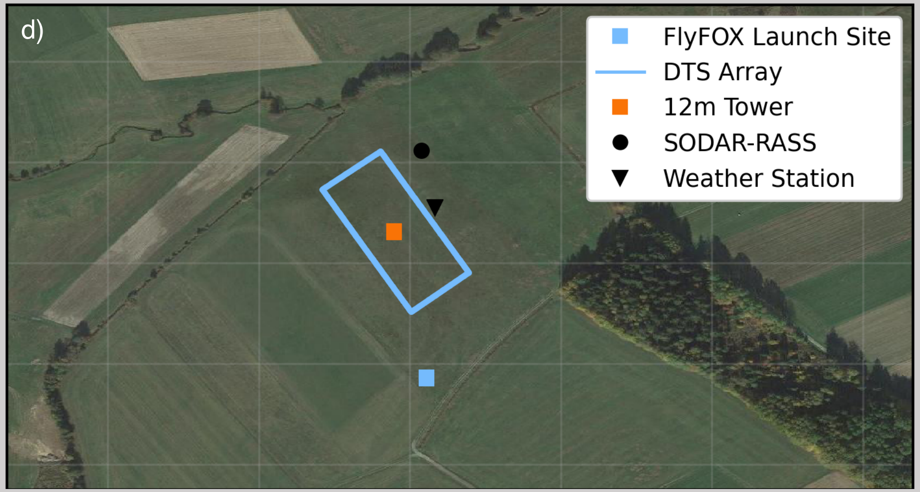
- FlyFOX deployed as part of larger DTS experiment
- Shallow, broad valley in a mid-mountain range. Flow is predominantly channeled within the valley in the lowest 200m.
- Intense cold air pooling, exceptionally deep stable boundary layers, frequent meandering and submeso motions observed



LOVE19 Column

Filling the observational gap between the surface and upper boundary layer using Distributed Temperature Sensing





Flyfox "column"

- 4 CSATS (0.5m, 1m, 4m, and 12m)
- Vertical DTS array on a 12m tower with air temperature and horizontal wind speed
- Fiber optic DTS tethered to a balloon
- SODAR–RASS (horizontal speed, direction, and potential temperatures)
- LIDAR (vertical wind, aggregated to 83s)
- All within 200m of each other

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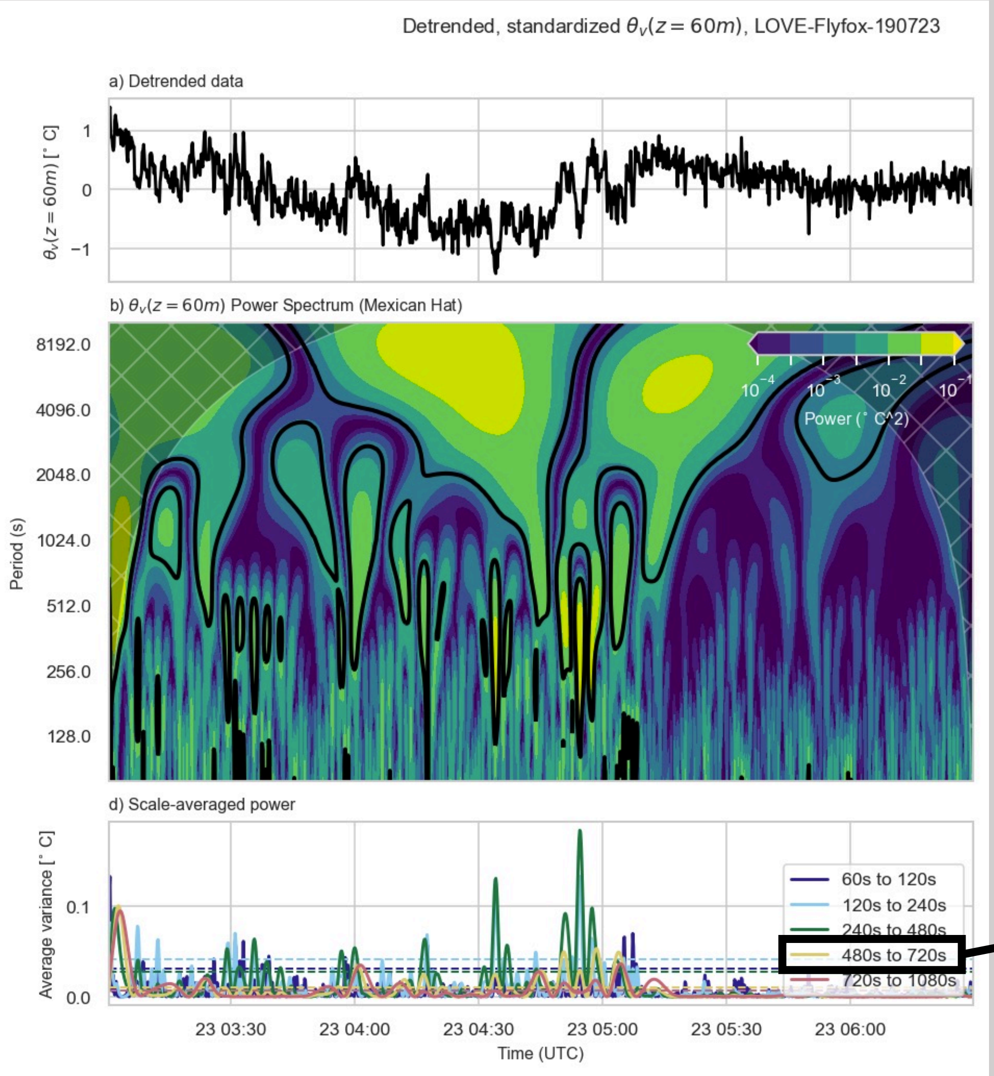
Continuous Wavelet Transform



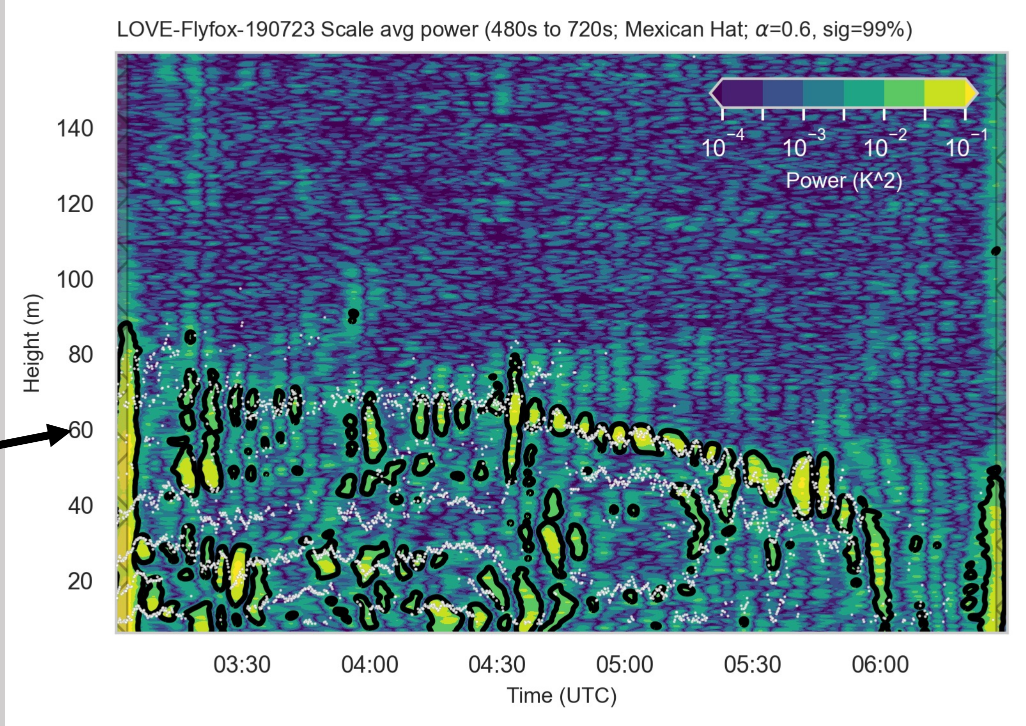
Continuous Wavelet:
Shows how much power is contained at a given time and scale in a time series, becoming a function of time and period.

Black lines show significant frequencies and times.

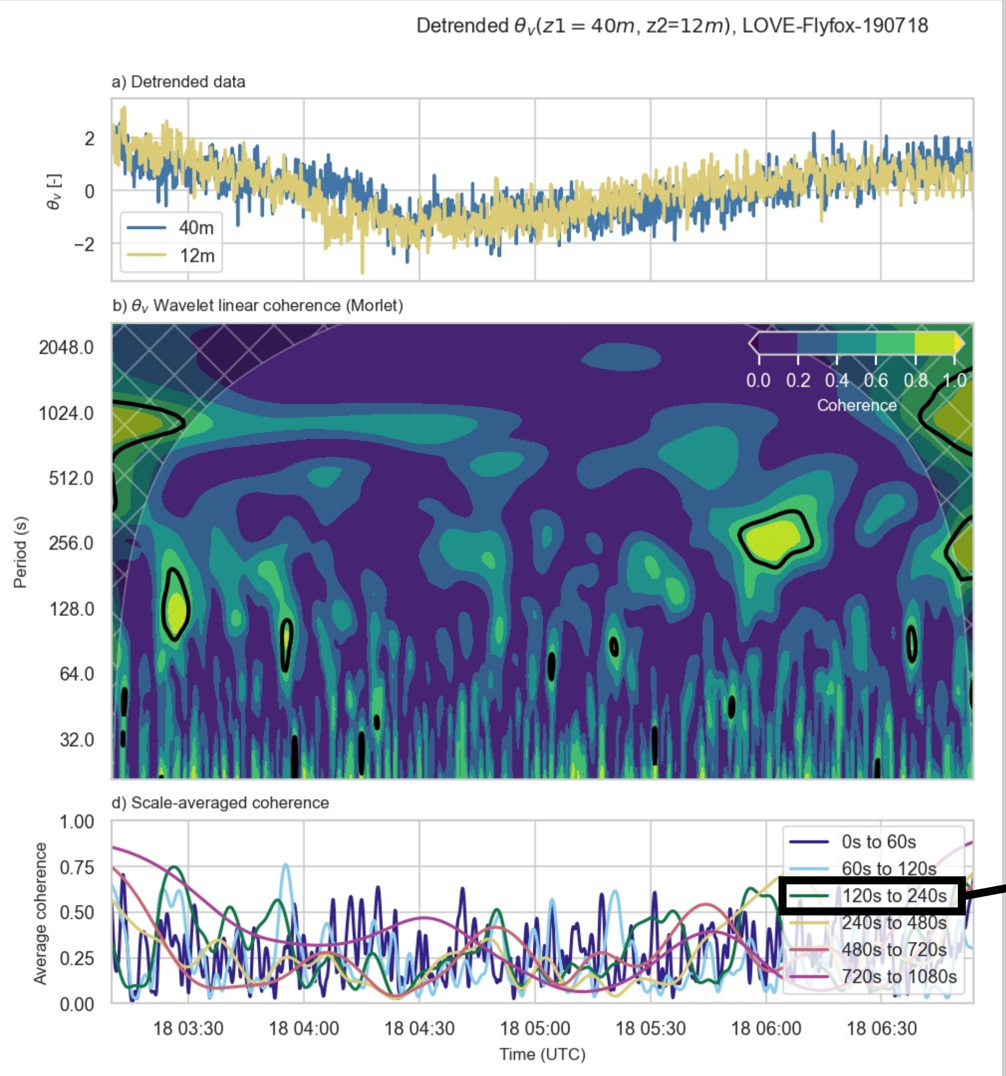
DTS gives thousands of time series, so we use the…

…Scale averaged power
Mean wavelet power between two scales

Scale averaged power Hovmöller Diagram:
Shows the scale averaged power, which is a function of time, across a spatial dimension. Black contours indicate significant power at the given scale (indicated in title).



Wavelet Linear Coherence



Wavelet Linear Coherence

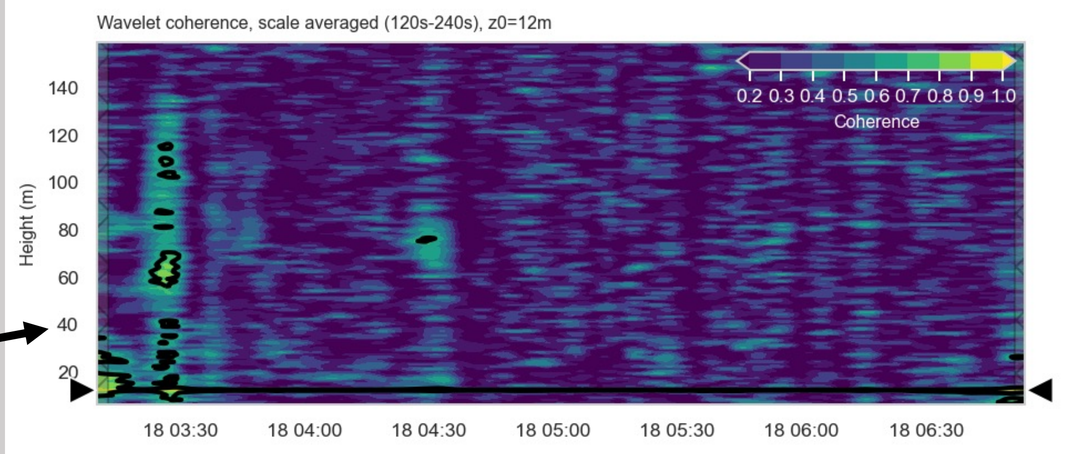
Shows how much two time series covary at a given time and scale.

Time scales with little power in either signal can still strongly covary

DTS gives thousands of time series, so we use the…

Scale averaged coherence Hovmöller Diagram:

Shows the how all heights covary at a given scale relative to the temperature at the reference height. Black contours show significant coherence between height and the reference height (black triangles) at the given scale (title).



…Scale averaged coherence

Mean coherence between two scales

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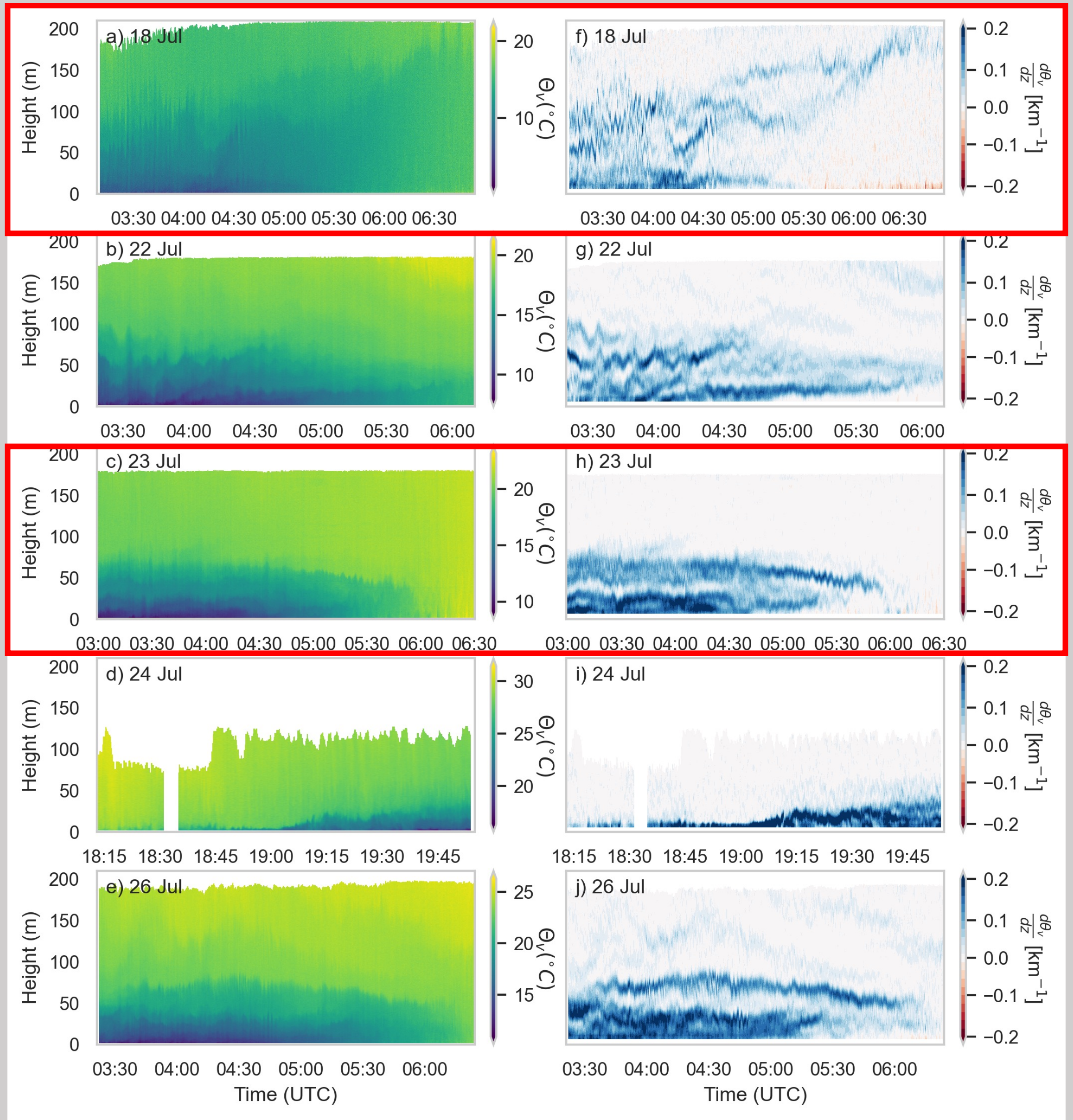
Overview of all FlyFOX flights



<u>18 July</u>

- Higher resolution DTS device with much higher noise floor.
- Fog event near surface
- Less stable conditions

<u>22-26 July</u>

- Lower resolution DTS device with much lower noise floor.
- Generally, more stable conditions

<u>23 July</u>

- Long lived thermal sublayers

Thermal Sublayers

<u>24 July</u>

- Windier conditions = lower flight height of tethered balloon

<u>26 July</u>

- Long lived thermal sublayers

Summary

- Flights limited to low wind speeds (< 5m/s), day light hours, and 200m height
- 4 morning transitions (July 18, 22, 23, 26) and 1 evening transition (July 24)
- DTS temperature converted to virtual potential temperature and length along fiber converted to height above surface using a linear model
- Gradients found using a 10m running block differencing
- 18 and 23 July flights are presented in detail

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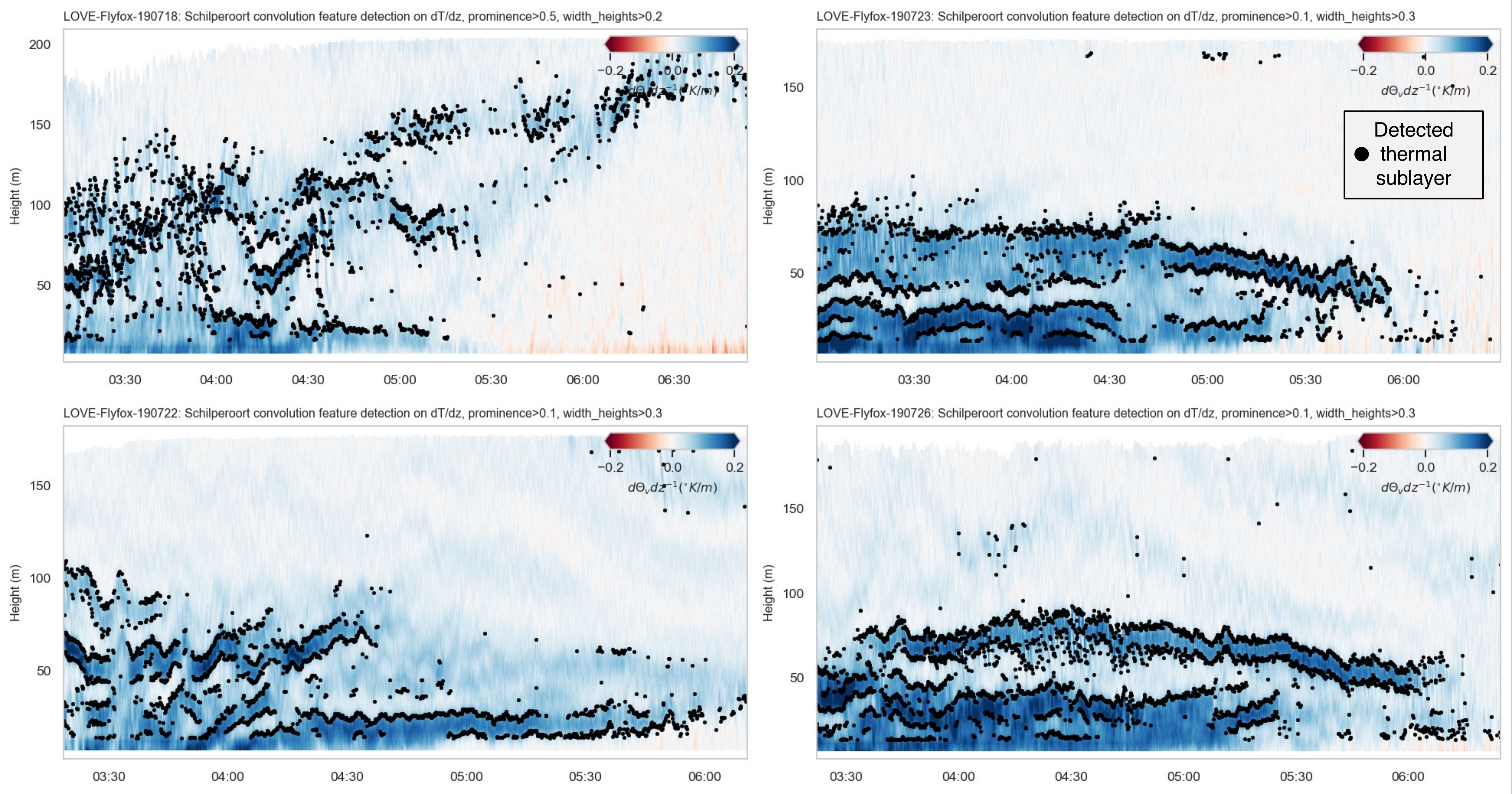
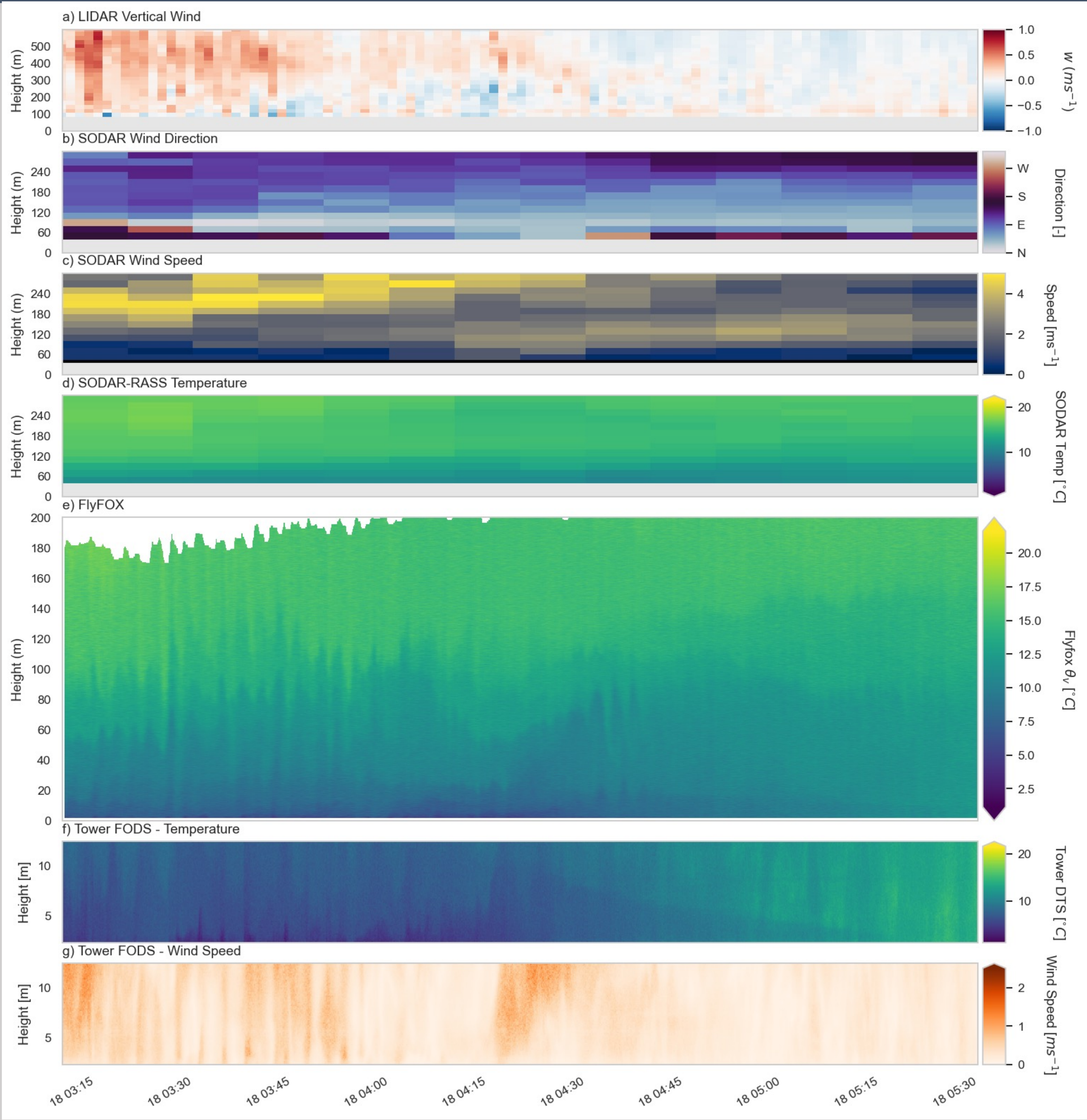
Thermal Sublayers in the Stable Boundary Layer



- FlyFOX reveals the presence of thermal sublayers for the first time
- Detected using a kernel convolution approach
- 10m-20m thick with sharp boundaries over several meters
- Vary between persistent (> 1h) and ephemeral (< 10min)
- 18 July was the least stable and had the fewest and shortest-lived thermal sublayers

High frequency gravity waves



Some directional shear across top of SBL

Low wind speeds, some elevated shear at start of flight

Less stable conditions than other flights.

Less well defined SBL than other flights

Waves can be seen in the potential temperature

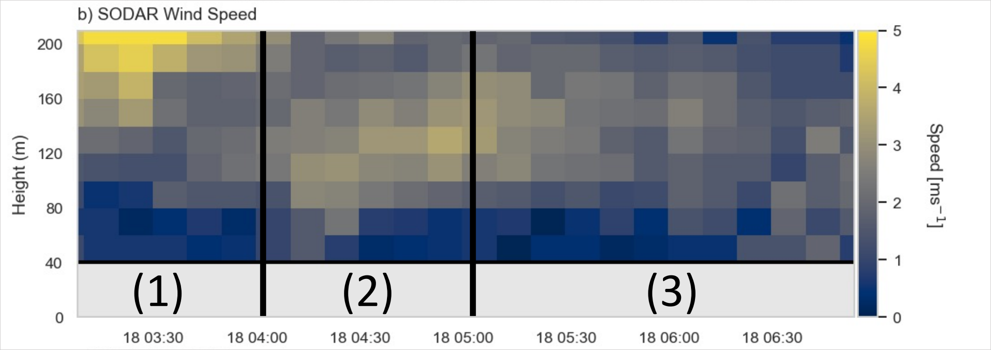
Low wind speeds in surface layer

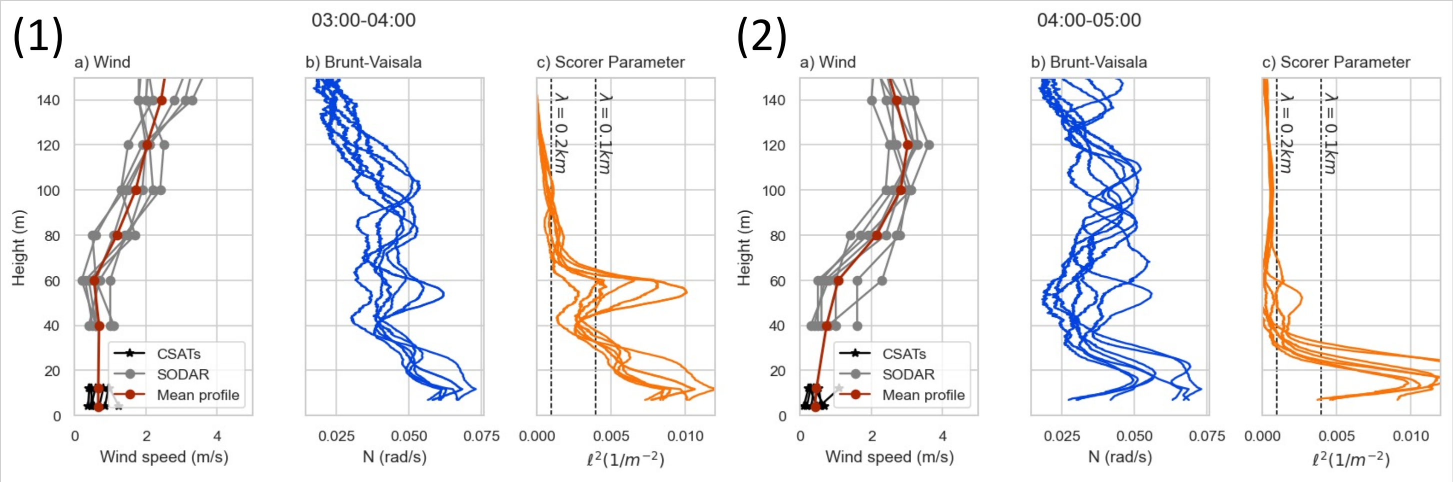
Flight Overview

- During the 18 July flight high frequency gravity waves were observed by FlyFOX (see next slides)
- This flight had the least stable conditions with low laying fog likely contributing

High frequency gravity waves

Wave parameters



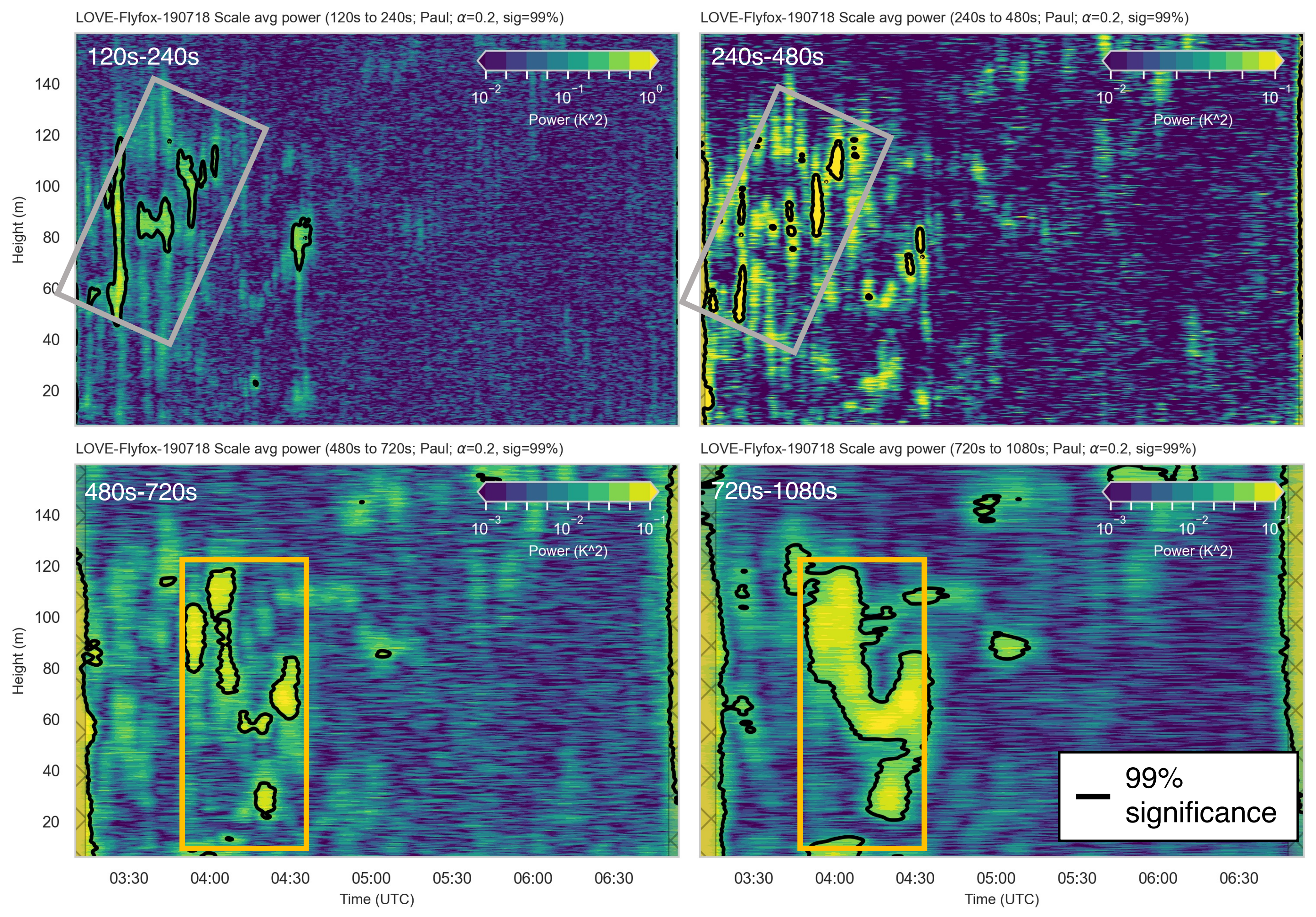


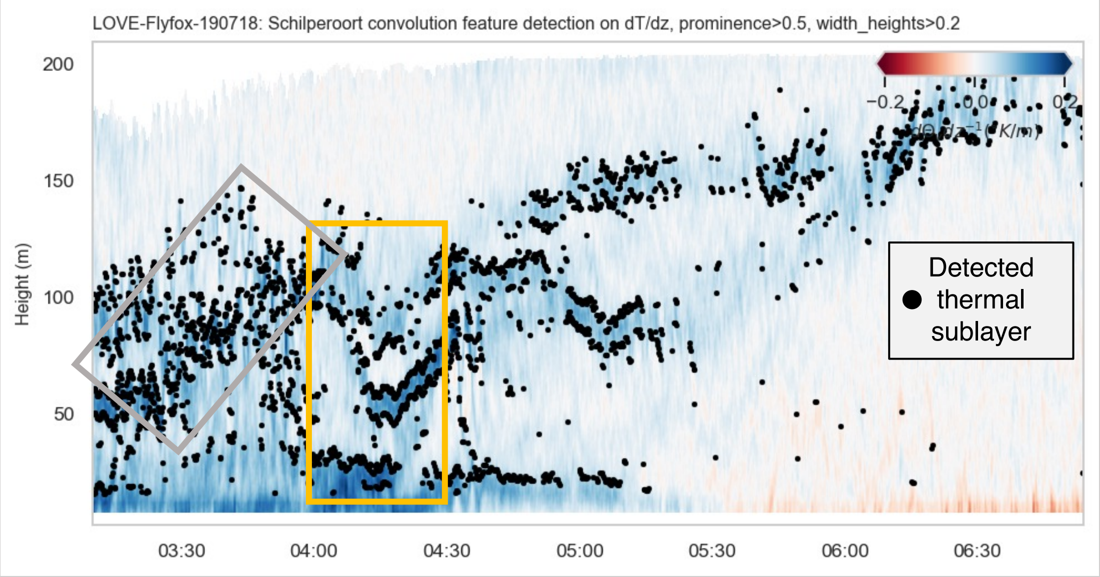
10min avg. profiles of (a) horizontal wind, (b) Brunt–Väisälä Frequency, and (c) Scorer parameter, ℓ^2, for the indicated periods. ℓ^2 calculated with curvature term and time-averaged U(z) profile. Wavelengths, λ, provided for guiding interpretation of ℓ^2.

- Three phases:
  1) 0300–0400: Two regions with high ℓ^2: 45–65m and near surface
  2) 0400–0500: ℓ^2 only elevated near surface
  3) 0500–end of flight: Unfavorable conditions for wave generation.
- Sharp discontinuity in ℓ^2 in (1) may indicate interfacial wave generation
- When is ℓ^2 greater than the wavelength, waves may be evanescent.

High frequency gravity waves

Scale averaged CWT power





Scattered higher frequency waves 0300–0400, especially further aloft, when thermal sublayers are weak.

Power significantly varies at 0330 across a wide range of heights (next slide).

The emergence of thermal sublayers coincides with the occurrence of longer time scale oscillations.

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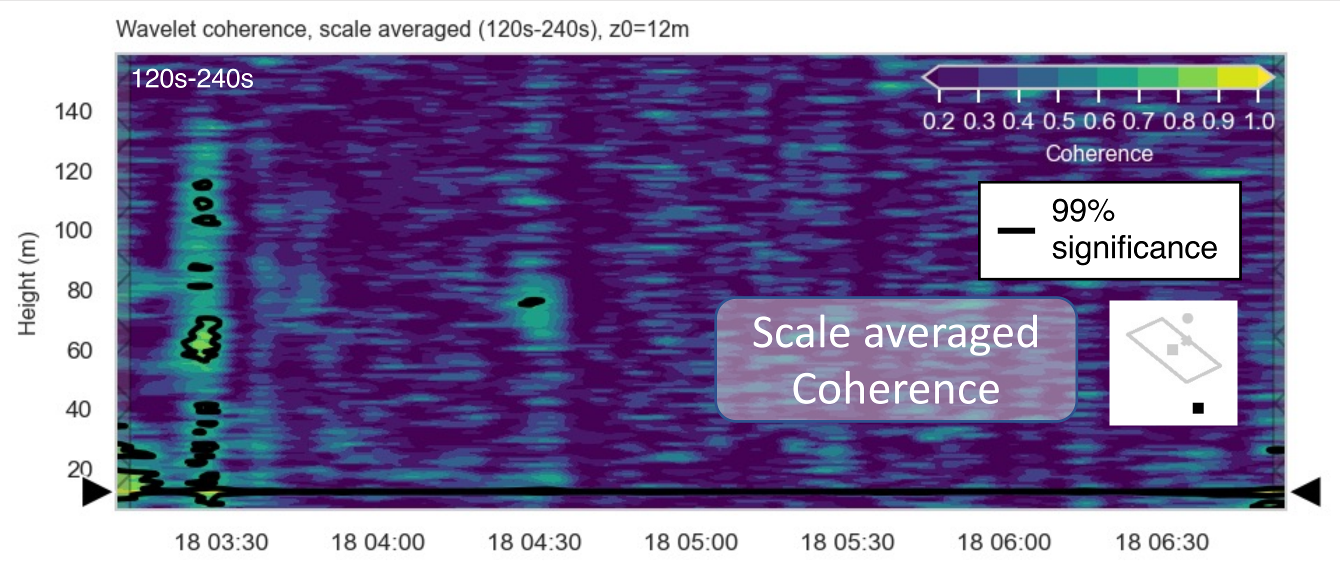
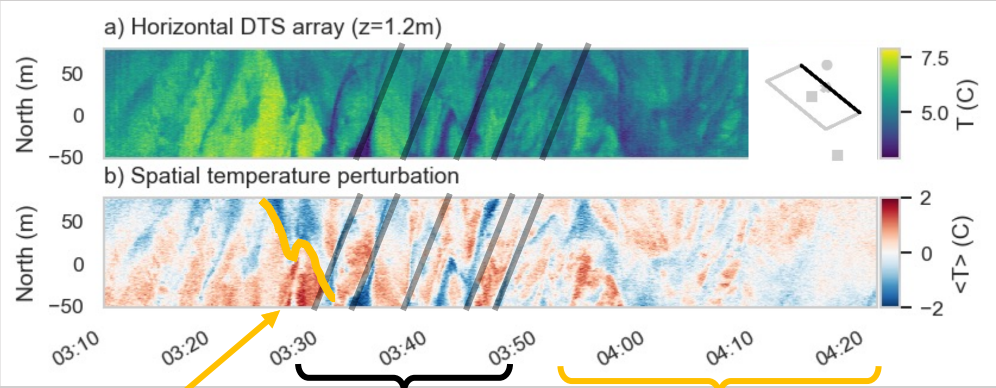
High frequency gravity waves



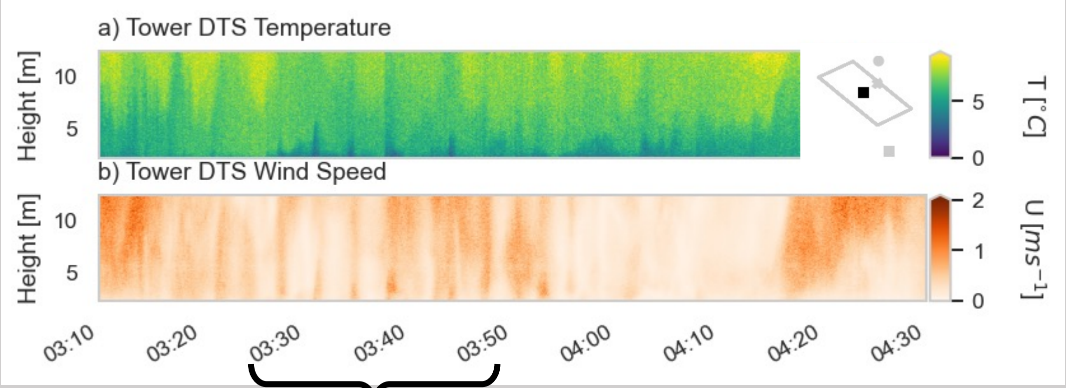
- Wave action is evident across the entire depth of the boundary layer at 03:30 (see coherence)
- These oscillations are present at the surface for approximately 20 minutes but are less prevalent aloft, suggesting an upwards propagating feature
- **DTS uniquely observes these features**



Interaction with submeso modes at the surface

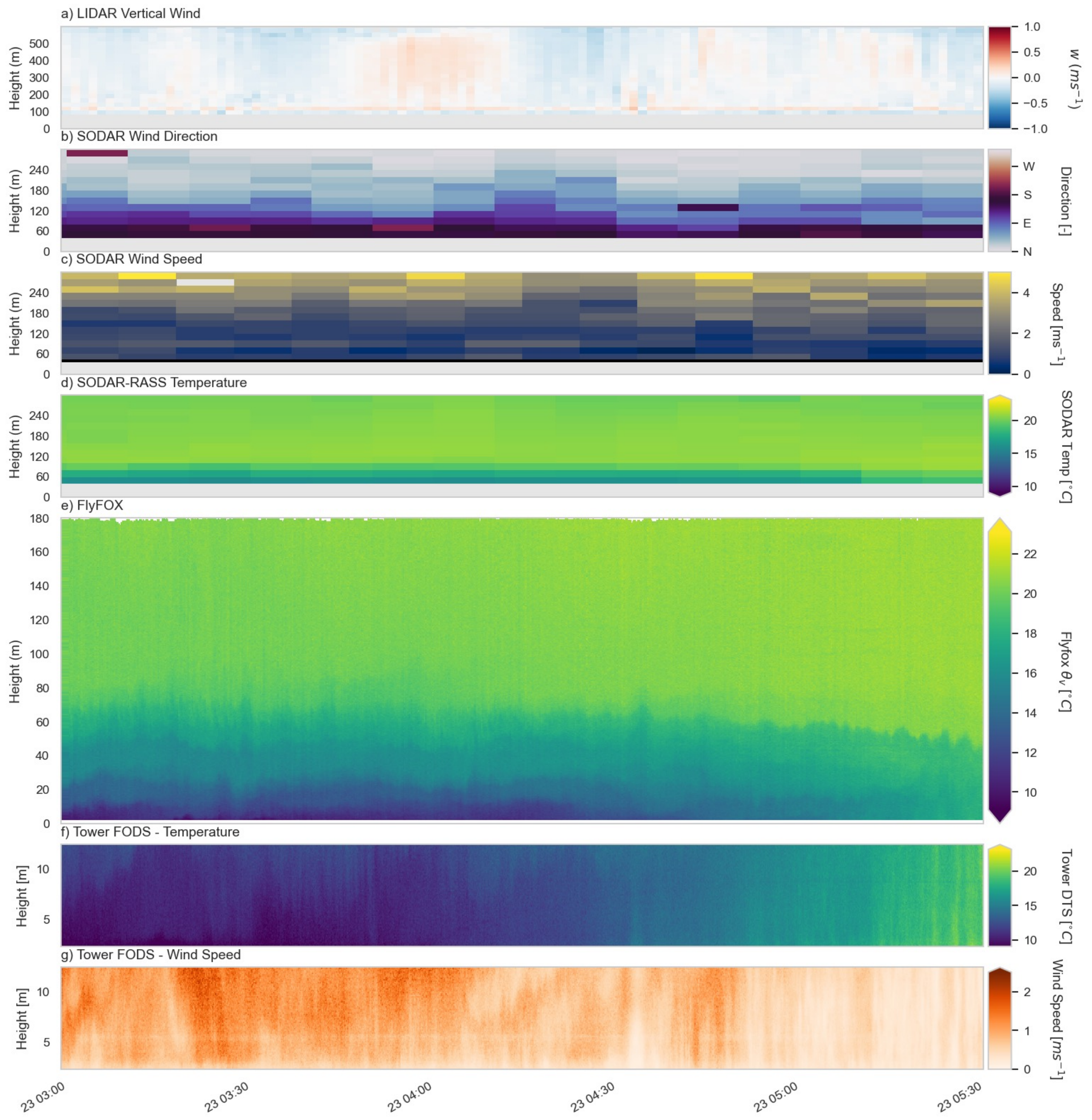
Waves are apparent at the surface with a time scale of ~4minutes

Return to submeso modes after vertical decoupling



Upwards sweeps of waves near surface associated with wind increase and upward sweep of cold air

Thermal sublayers decouple vertical interactions



Little vertical wind

Gradual wind direction shear across top of SBL

Effectively no wind speed shear

Well defined SBL

Presence of thermal sublayers

Sublayers even present in surface layer in both horizontal wind and temperature

Flight Overview

- 23 July flight had long-lived (~2.5h) thermal sublayers at a persistent height
- Very stable conditions and weak winds throughout the morning transition
- These sublayers dictate wave generation and propagation (see next slides)

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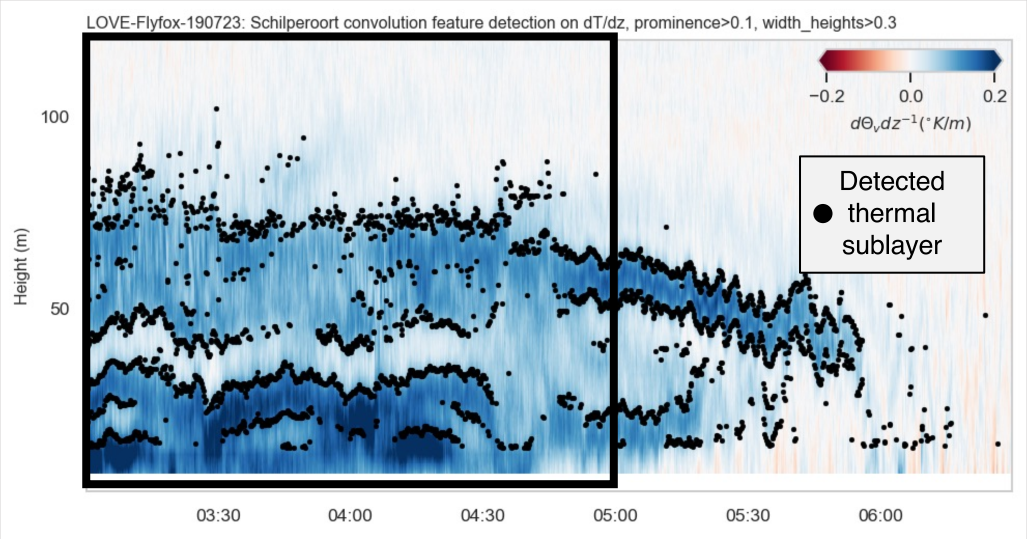
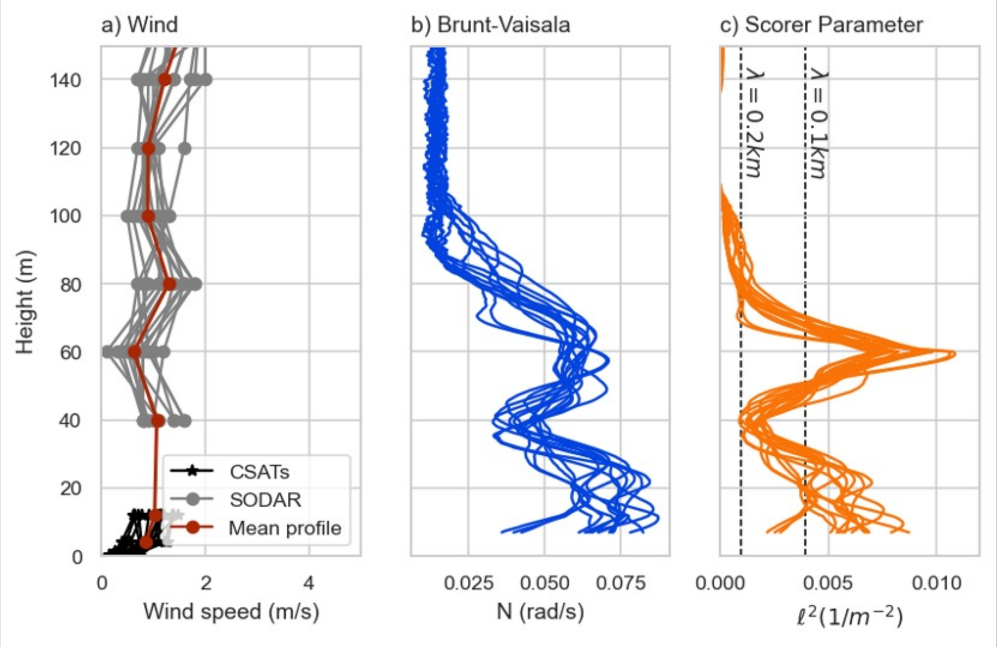
Thermal sublayers decouple vertical interactions



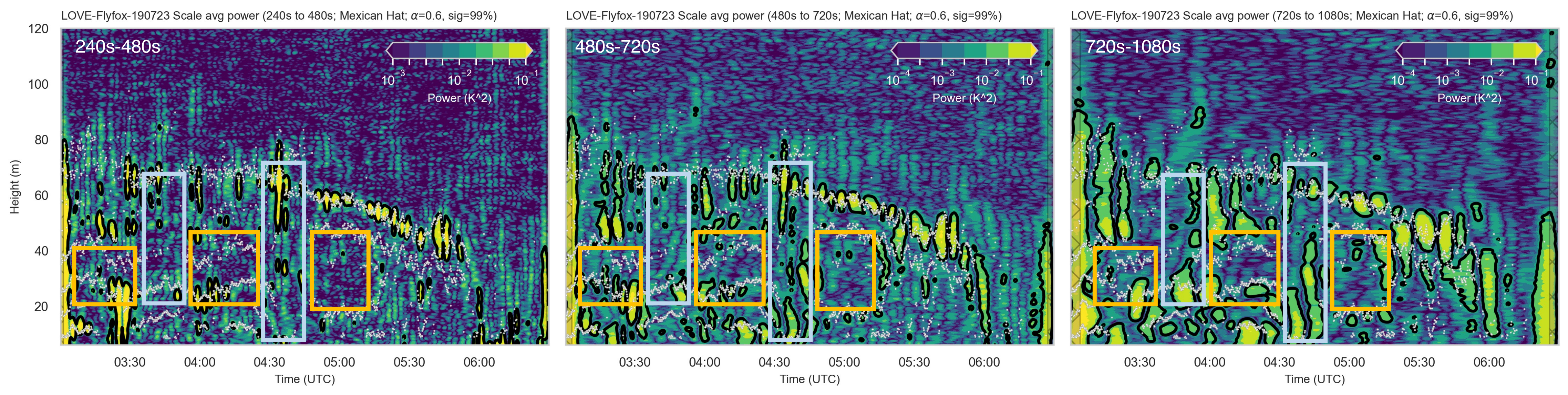
- Persistent sublayers lead to persistent wave properties
- Sharp discontinuity in ℓ^2 in (1) may indicate interfacial wave generation, consistent with wavelet analysis on next slide
- When is ℓ^2 greater than the wavelength, waves may be evanescent (i.e., above the SBL and in the low stability thermal sublayer)



10min avg. profiles of (a) horizontal wind, (b) Brunt-Väisälä Frequency, and (c) Scorer Parameter between 0300-0500. ℓ^2 calculated with curvature term and time-averaged U(z) profile. Wavelengths, λ, provided for guiding interpretation of ℓ^2.

Thermal sublayers decouple vertical interactions

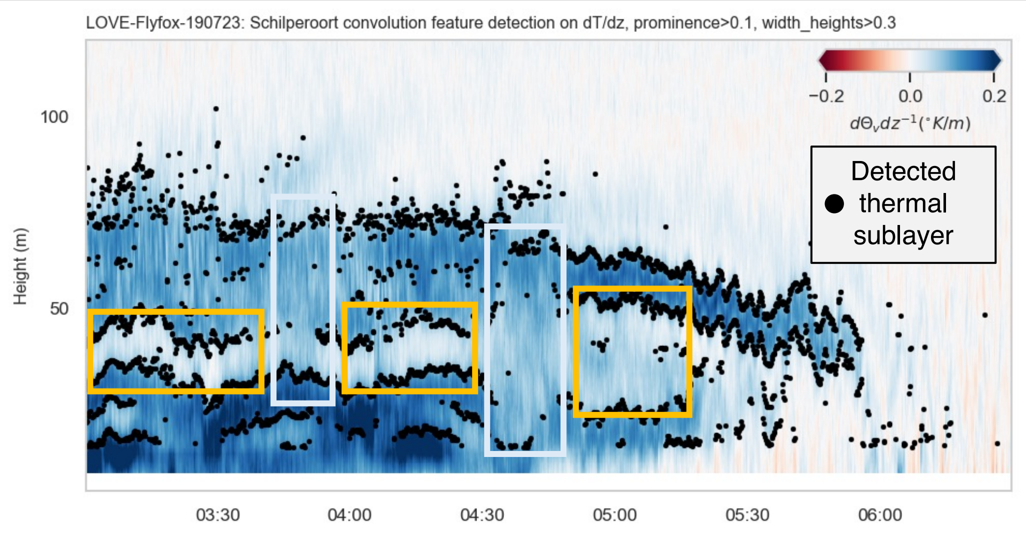
Scale-averaged power from continuous wavelet transform



Detected sublayer

99% significance

Scale averaged CWT power



Vertical interactions occur in periods in which the thermal sublayers weaken (scale avg. power extends vertically)

Otherwise, the vertical extent of wave activity is limited by the presence of less stable thermal sublayers

FlyFOX uniquely observes these features

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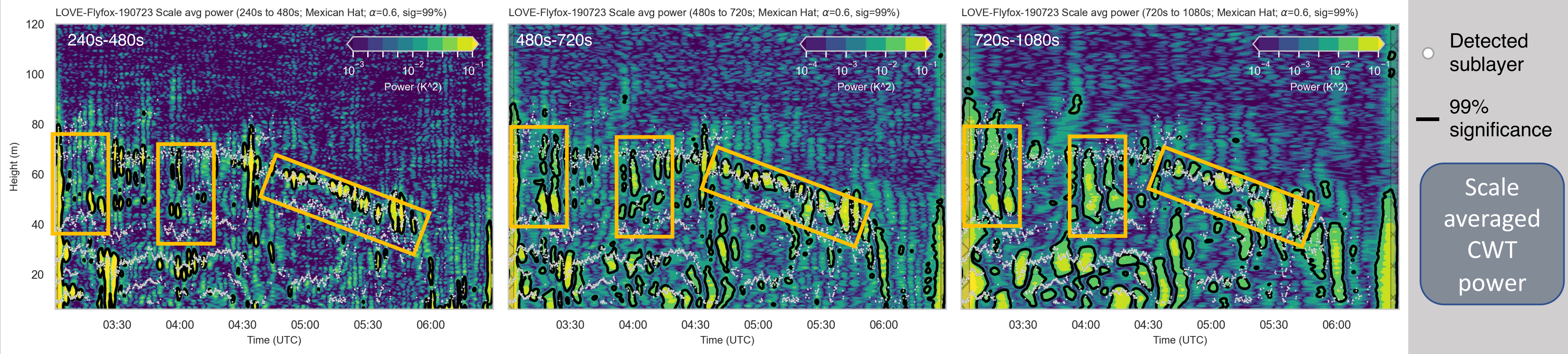
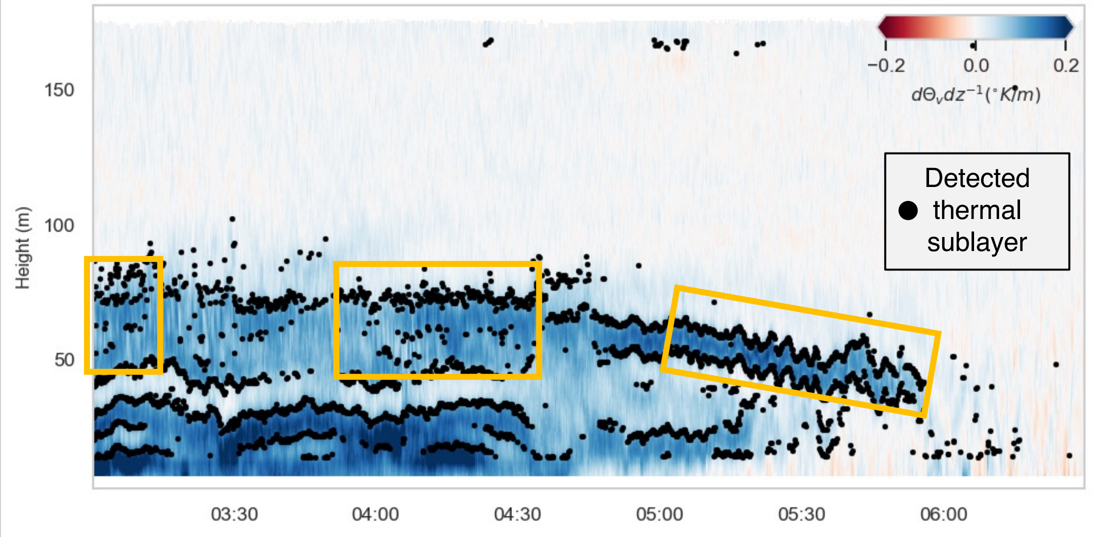
Thermal sublayers decouple vertical interactions

Scale-averaged power from continuous wavelet transform





Waves embed in the stable thermal sublayer

These wave motions have a vertical extent of 5m-40m and time scales between 240s to 1080s.

Smaller vertical extent corresponds with shorter time scale waves

FlyFOX uniquely observes these features

Conclusions and DTS references

1) Distributed Temperature Sensing using fiber optic cables attached to a tethered balloon provide unprecedented view of boundary layer waves (Δt = 1s-10s, Δz=0.127m-0.254m) filling a critical gap in our observational capabilities of the boundary layer. **DTS is a fundamental observational breakthrough.**

2) Filling this observational gap reveals largely unknown structures such as long-lived thermal sublayers. These features have also been found in other environments such as the Arctic and over forests (not shown).

3) These previously unresolved structures dictate wave behavior within the stable boundary layer, especially playing a role in the vertical coupling.
   - Thermal sublayers decouple the surface from the upper stable boundary layer
   - When the sublayers are not present or weaken, vertical interactions may take place.

Further reading on fiber-optic Distributed Temperature Sensing

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Pfister, L., Lapo, K., Mahrt, L., and Thomas, C.K., *in press*. Thermal Submeso Motions in the Nocturnal Stable Boundary Layer - Part 1: Detection & Mean Statistics, *Boundary-Layer Meteorology.*

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