Aircraft measurements of a low-level, three-layer structure offshore of Pt. Buchon, CA and the possible role of Kelvin-Helmholtz instability

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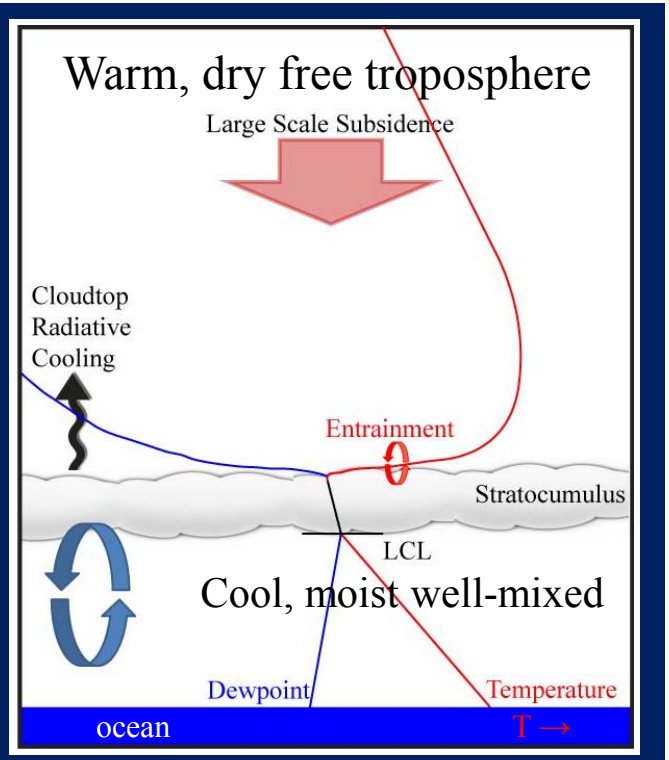
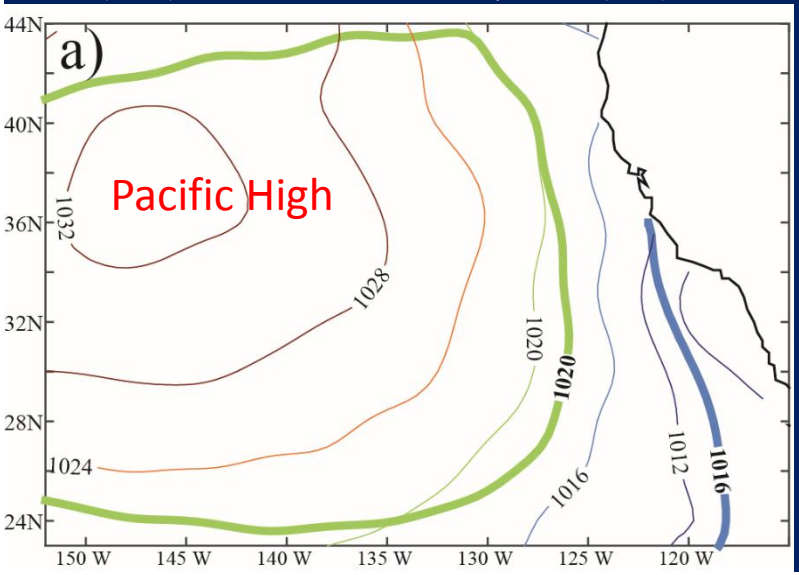
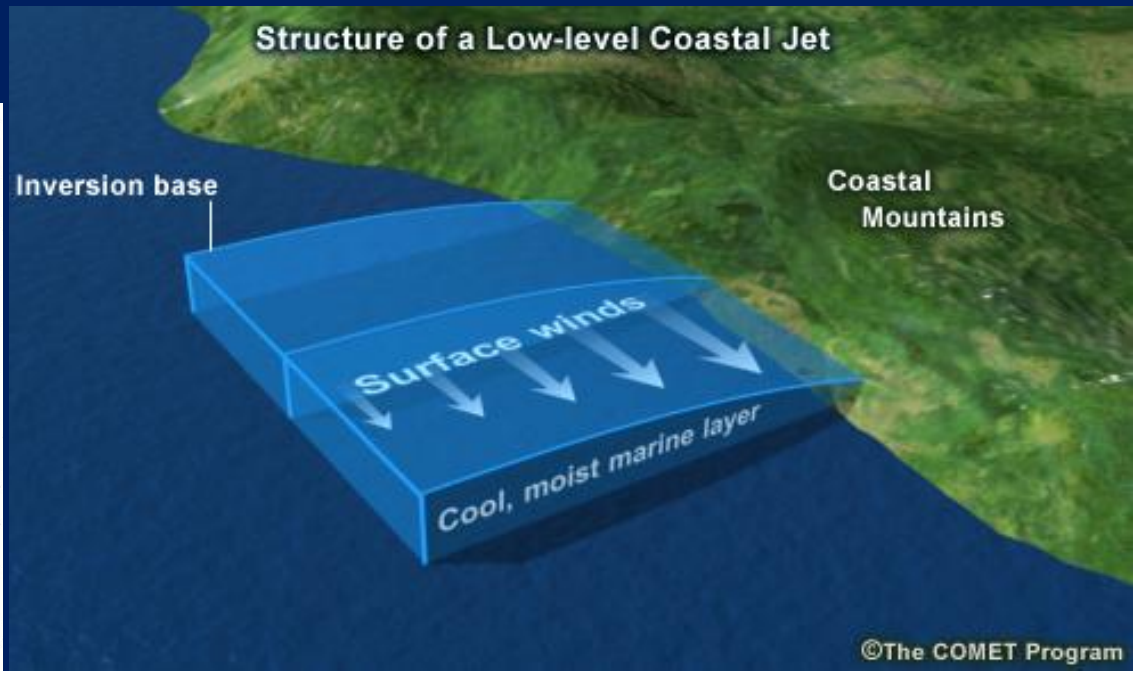
Fluid System

- Sharp temperature inversion separates MBL from free troposphere.
- Two-layer fluid system is bounded laterally by coastal topography.



Average sea level pressure from CFSR for May 1979-2014 (bold) and 1200 UTC 24 May 2012 (thin).





Hydraulic Features along the Coast

- Mechanical fluid flow
  - Hydraulic jumps / expansion fans may be present if Froude number is favorable.

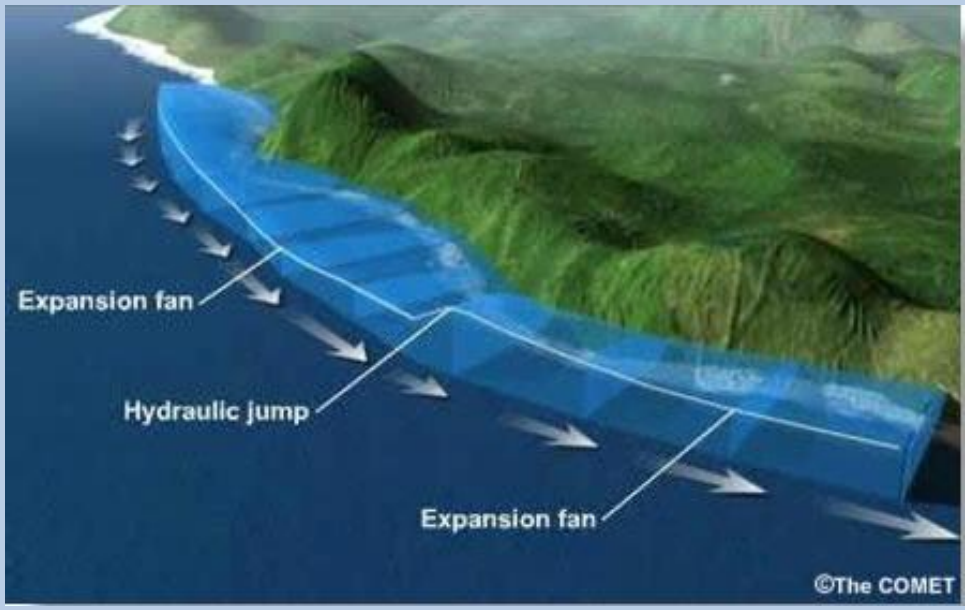
$$Fr = \frac{U}{c} = \frac{U}{\sqrt{g'H}}$$

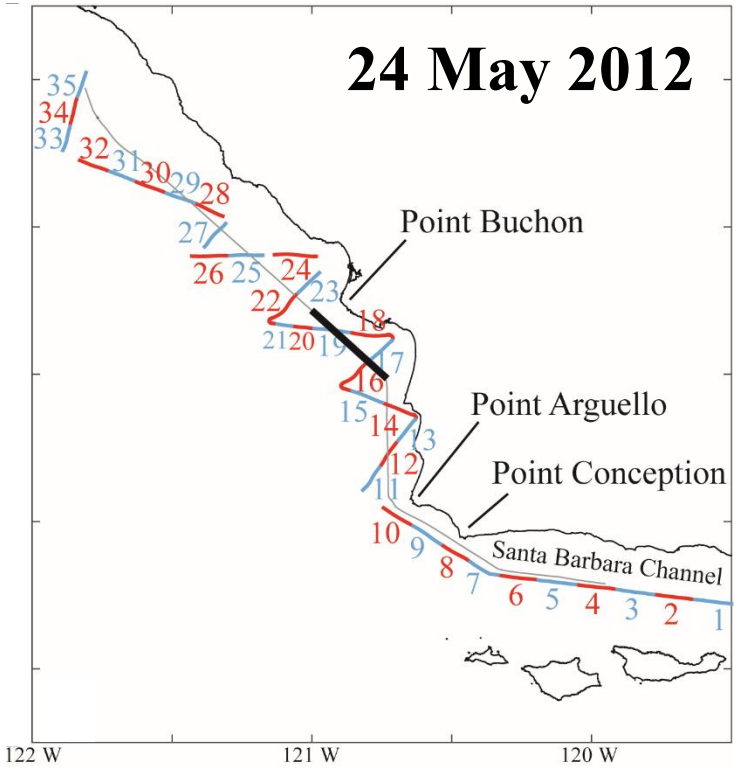
$$g' = \frac{\theta_{inversion\_top} - \theta_{MBL}}{\theta_{MBL}}$$

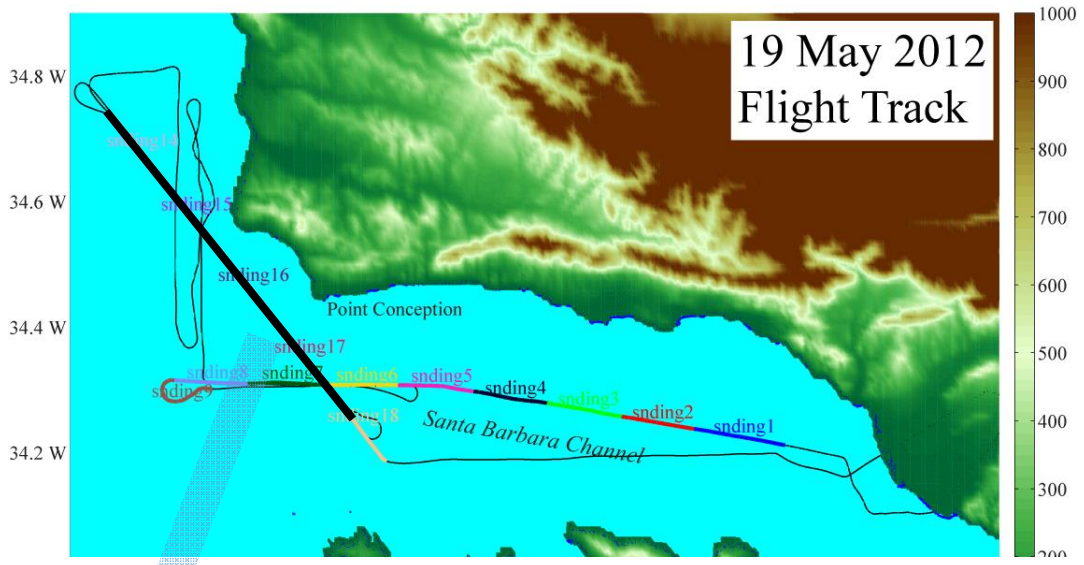
U: Characteristic wind speed
c: Maximum gravity wave speed

H: MBL height
g': Reduced gravity
θ: Potential Temperature

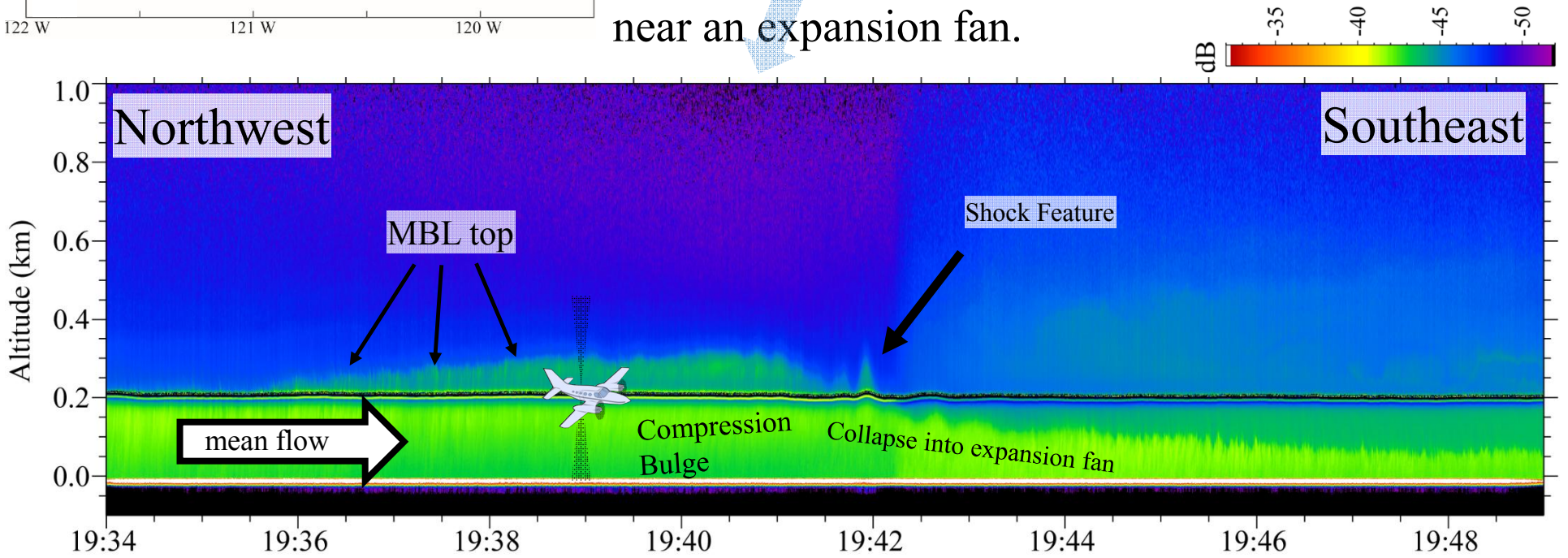
- Fr < 1: Subcritical
  - Gravity waves can freely redistribute mass and momentum towards a geostrophic balance
- Fr > 1: Supercritical
  - Gravity waves cannot move upstream and can support hydraulic features (compression bulge/expansion fan)







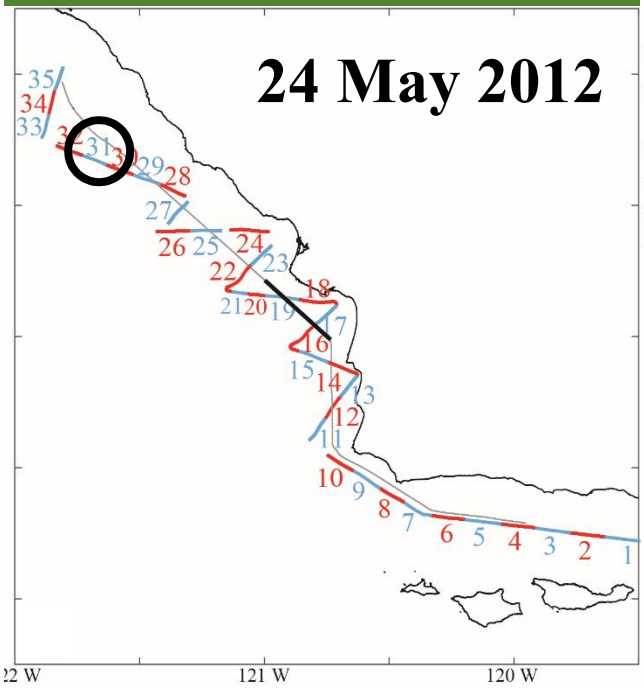
Example from the Wyoming Cloud Lidar (WCL) showing uncalibrated attenuated backscatter (dB) near an expansion fan.

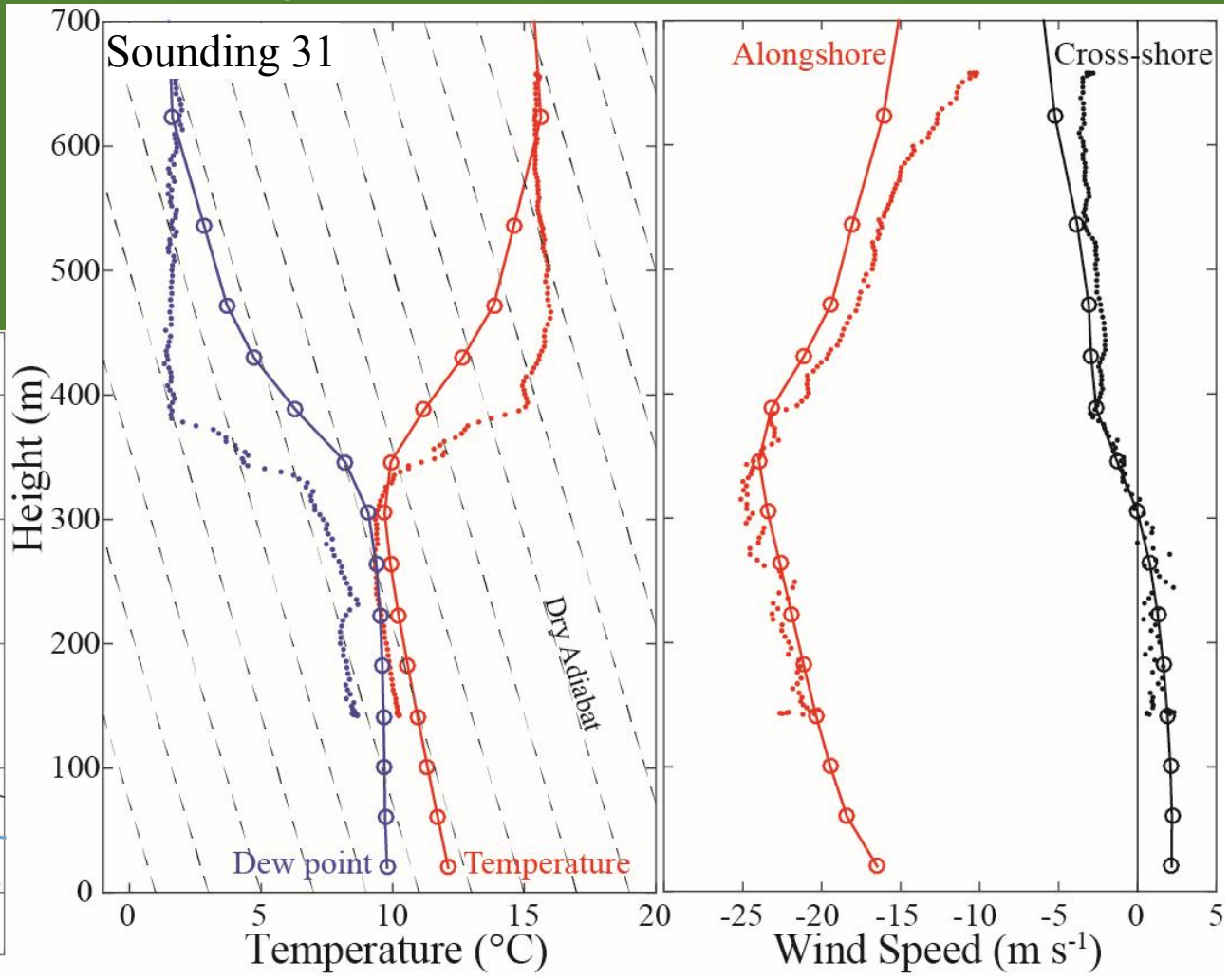


Upstream conditions

- Typical profile of temperature and wind.

Observations are small dots. Modeled values are solid lines with open circles indicating the model levels.

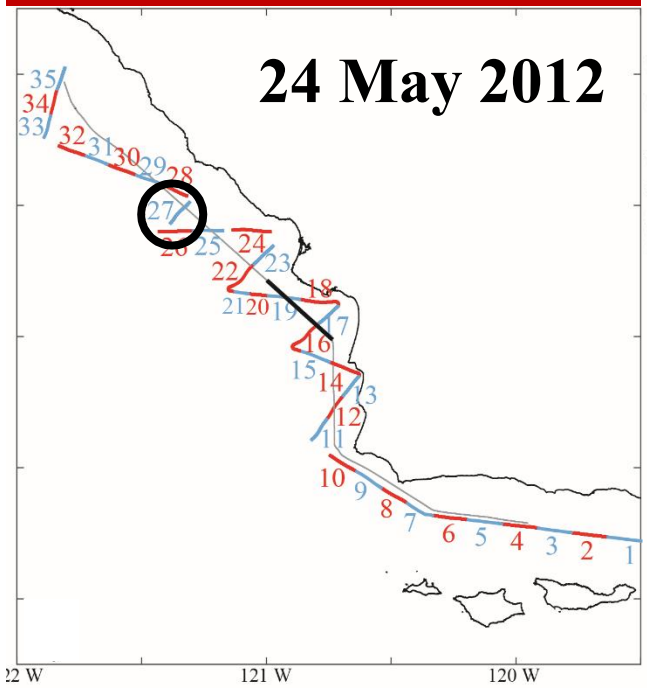


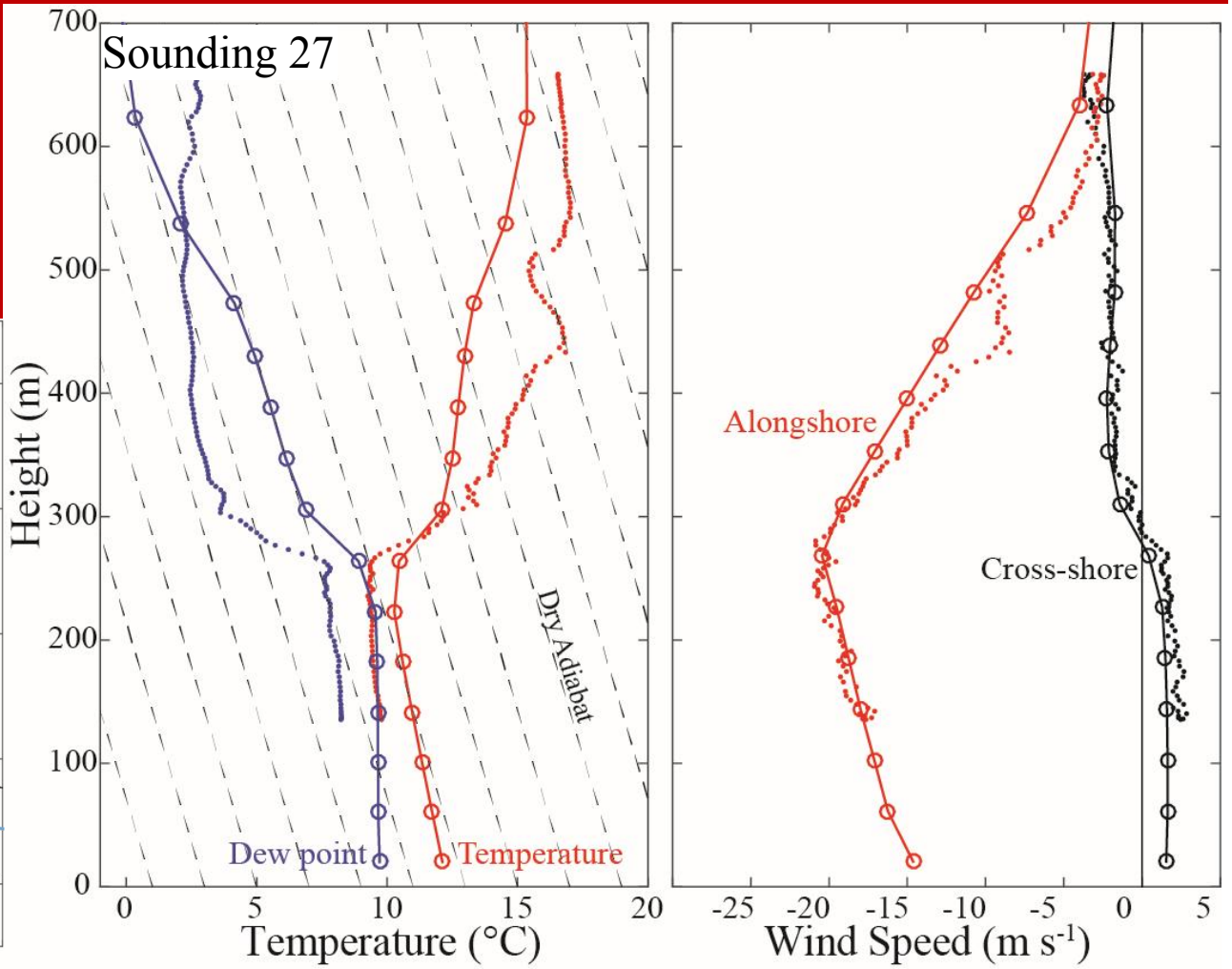


Upstream conditions

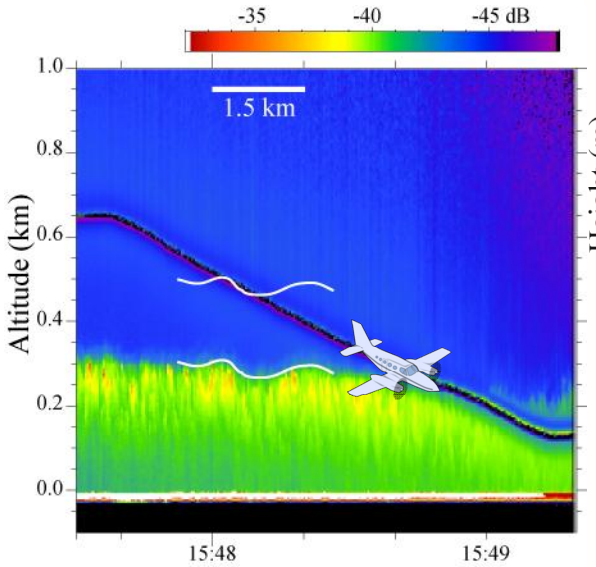
Observations are small dots. Modeled values are solid lines with open circles indicating the model levels.

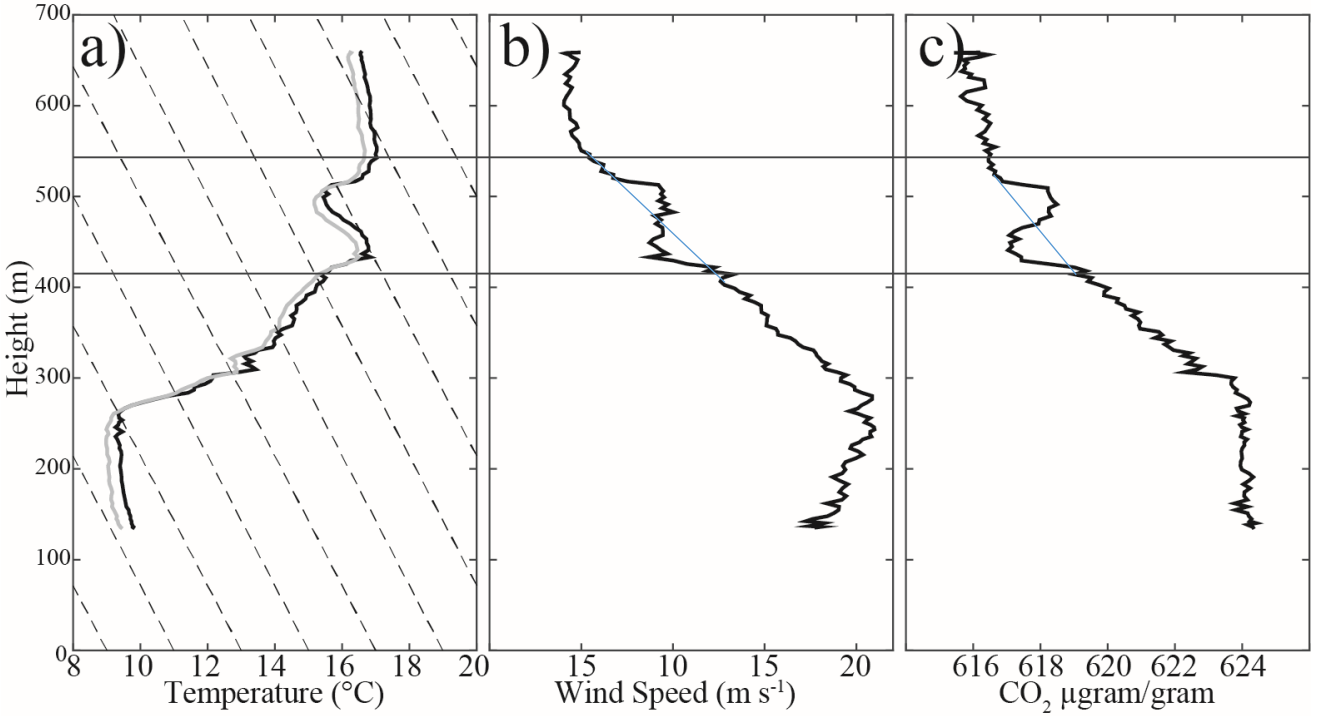
- Similar sounding, but there is a peculiar layer around 500 m.

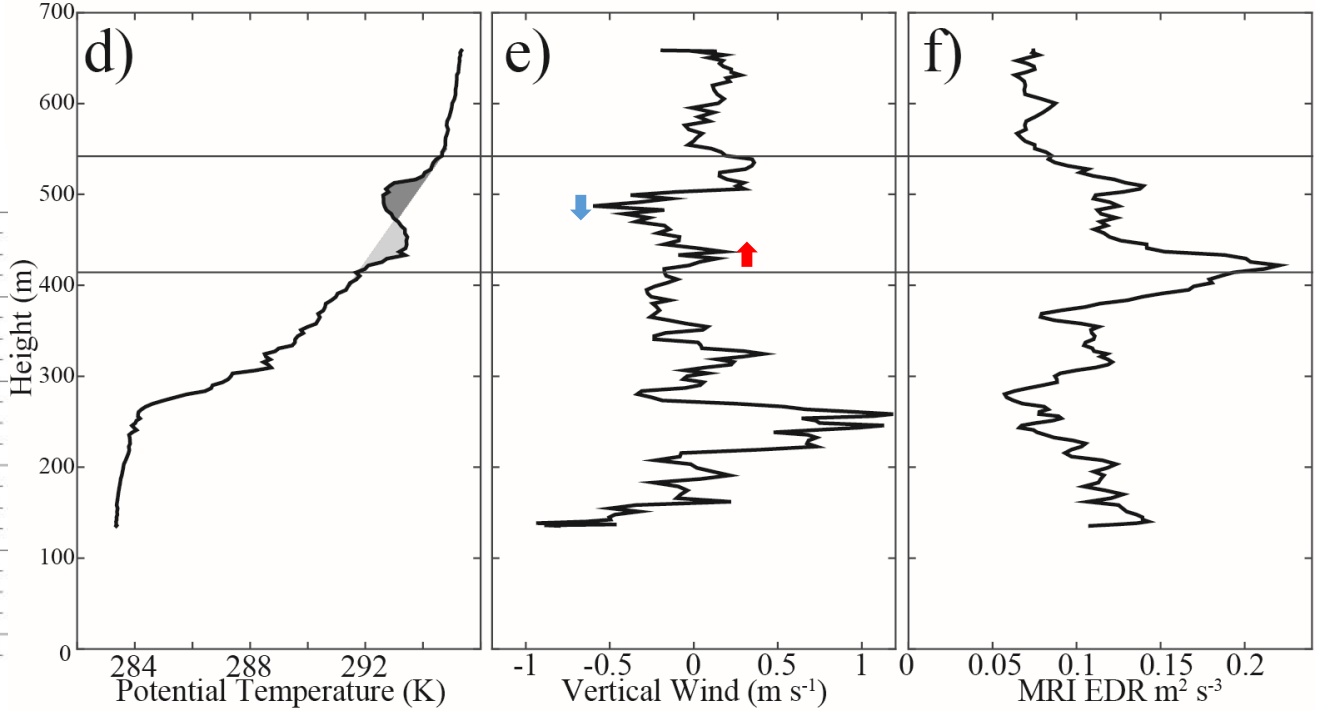




- Momentum, CO_2, θ, seem to be "swapped" in the layer
- Wind shear about constant ~250-550 m, but stability decreases with height in that layer.
- **Overturning or passing through a wave?**







Kelvin-Helmholtz Instability

$$Ri = \frac{Stability}{Shear} = \frac{N^2}{\left(\frac{\partial \bar{u}}{\partial z}\right)^2}$$

$$Ri_b = \frac{g}{\bar{\theta}_v}\frac{\Delta\theta_v \Delta z}{(\Delta U)^2}$$

$$\lambda = \frac{\pi\bar{\theta}_v}{g}\frac{(\Delta U)^2}{\Delta\theta_v} \qquad D = \frac{\lambda}{7.5}$$

- For the 150 m layer, ΔU is 8.6 m s^{-1}, $\Delta\theta_v$ is 3.3 K, and $\bar{\theta}_v$ is 294 K, which yields a Richardson number (Ri) of 0.22.
  - Ri < 0.25 instability possible
  - Ri > 0.25 stable
- Maximum unstable wavelength for the above values is 2 km.
  - Observed wavelength is ~1.5 km.
  - Corresponding depth ~ 200 m

Browning and Watkins (1970), Nature

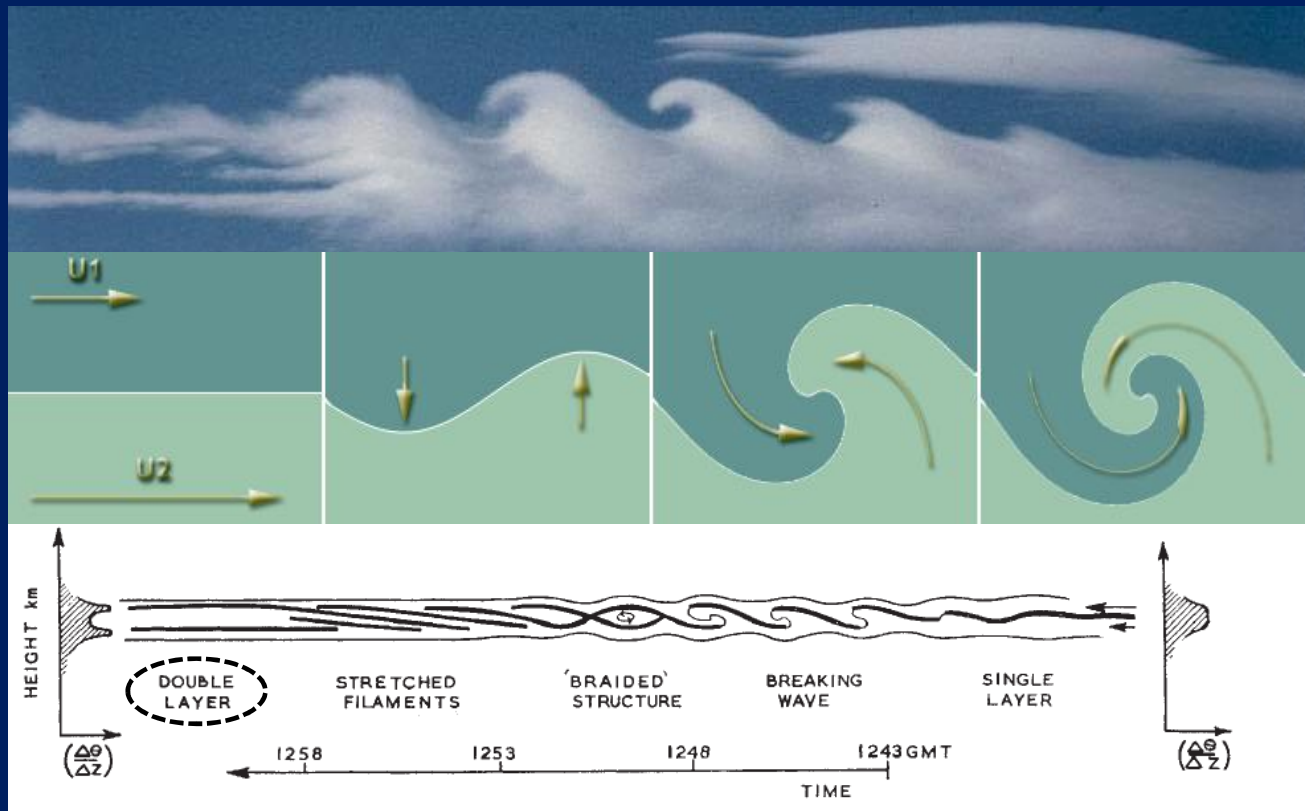
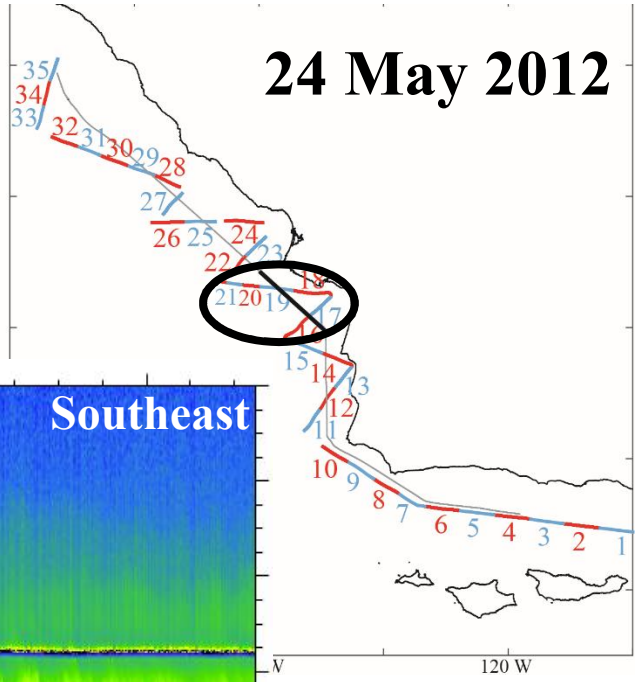
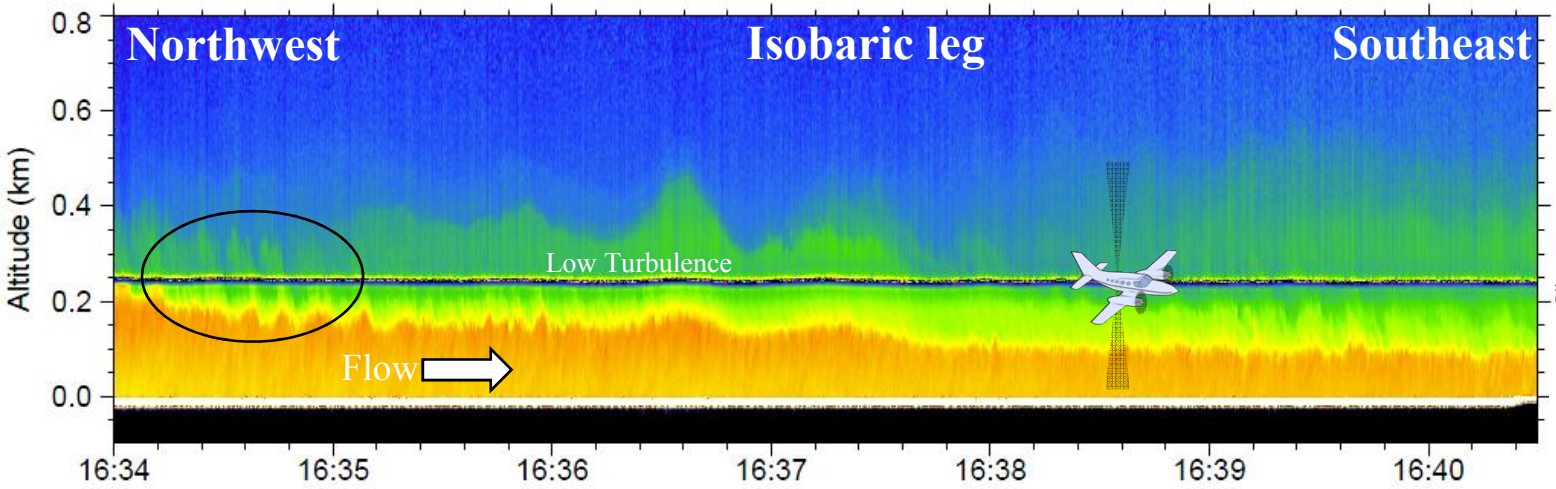
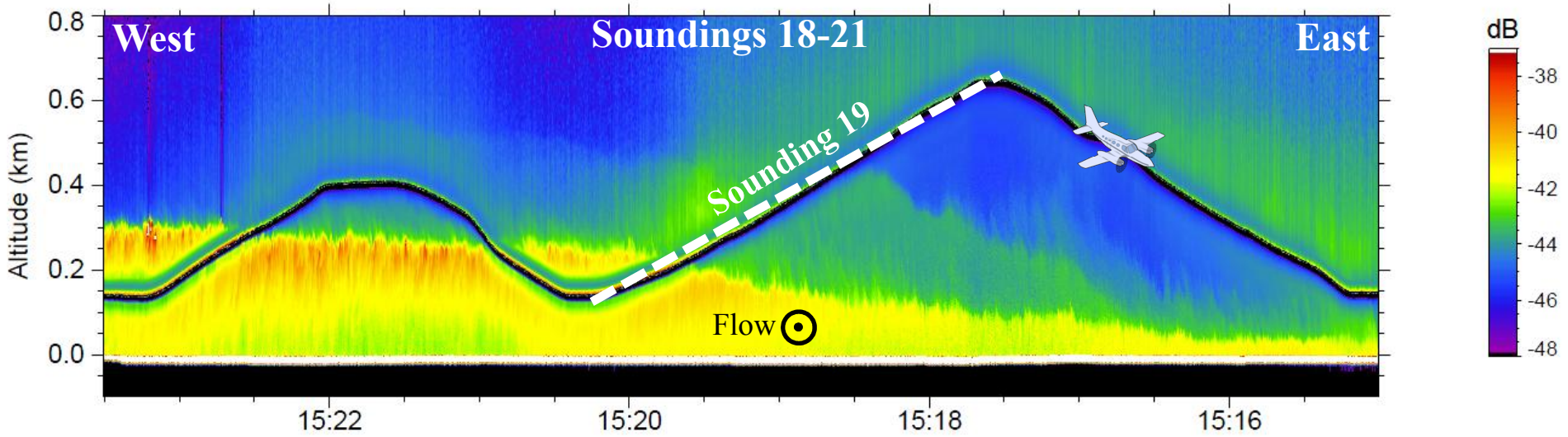


Fig. 4. Schematic representation of the life cycle of an individual Kelvin–Helmholtz billow based on the data in the earlier figures. Time progresses from right to left. Thick lines correspond to the detectable clear air radar echo, which started as a single layer at 1243 and finished as a double layer at 1258 GMT. Schematic vertical profiles of $(\Delta\theta/\Delta z)$ are indicated before and after the occurrence of Kelvin–Helmholtz instability.

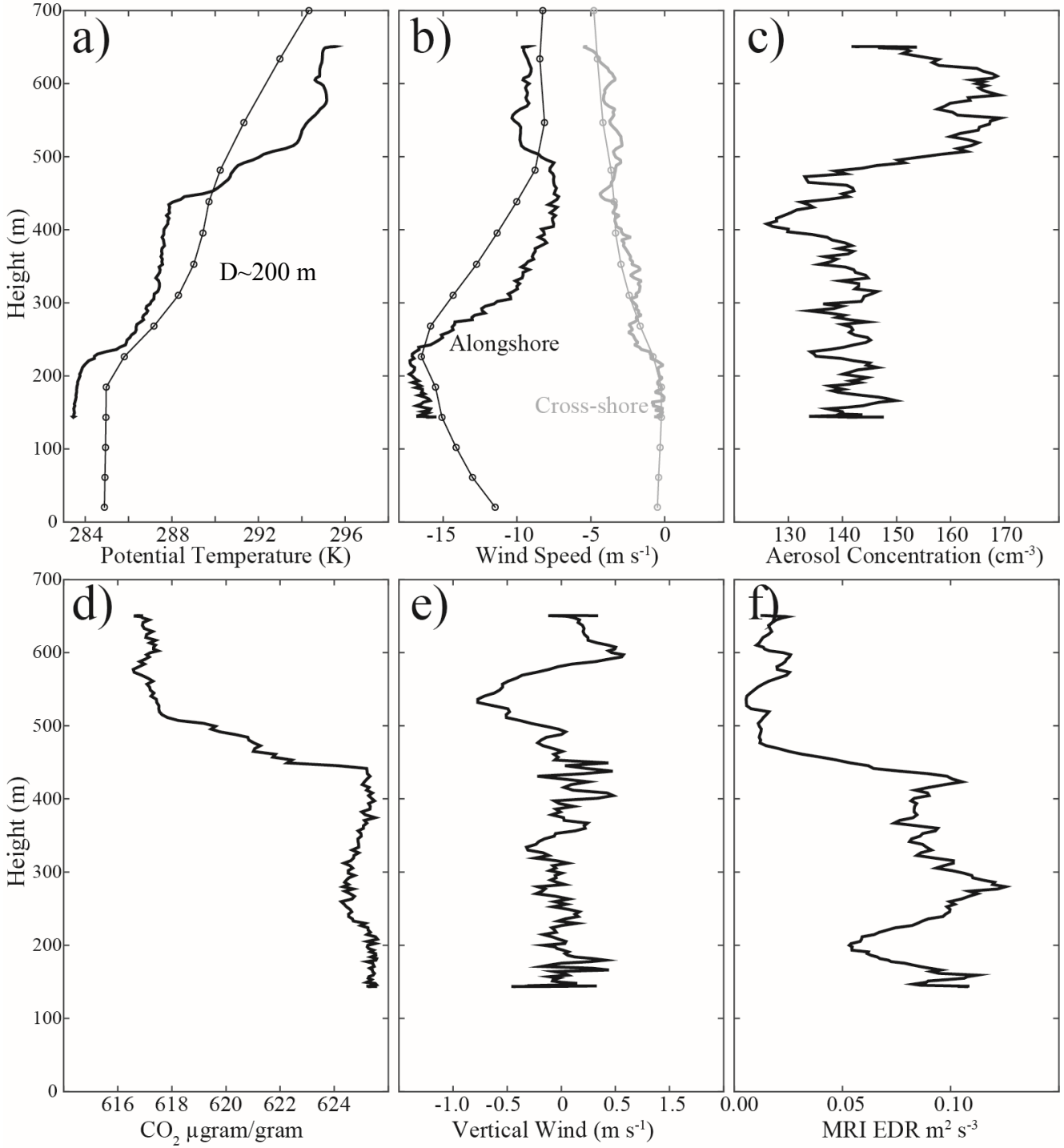
- Lidar data suggests that near Pt. Buchon, there are 3 distinct layers.
  - Note lidar images about an hour apart





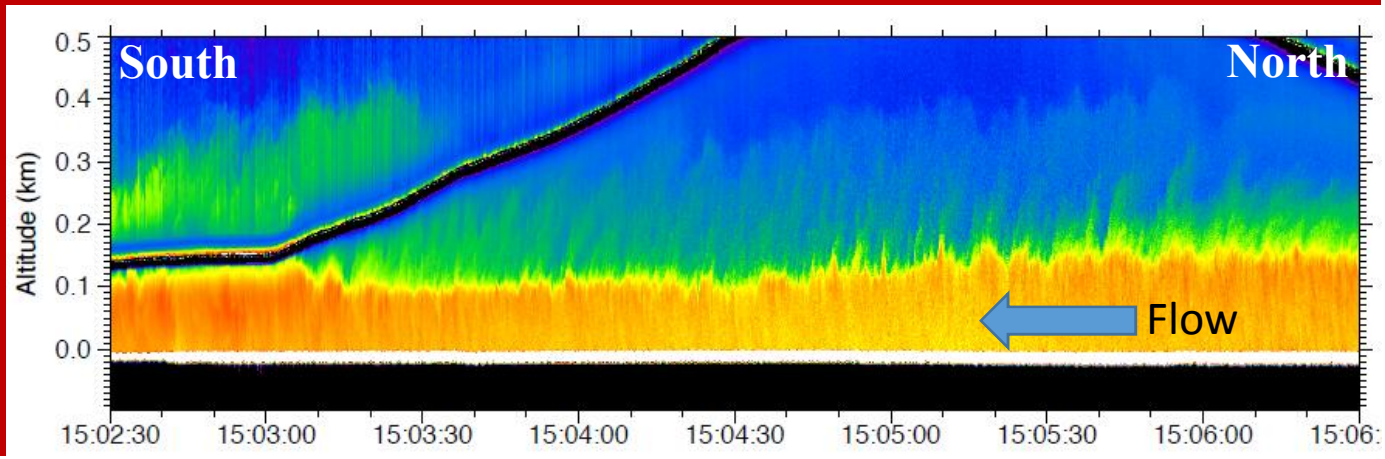


- Two inversion layers separate two relatively well-mixed layers
  - MBL
  - Middle layer
- Mixing between lower and middle layer
- Little cross-shore wind.



Summary/Conclusions

- There is observational evidence of Kelvin-Helmholtz instability impacting the low-level thermal and kinematic structure.
- So what?
  - Hydraulic features still dominate, but it is not a simple two-layer interpretation as in other case studies (analogy breaks down).
  - Entrainment rates will be modified.
  - Model difficultly representing the fine structure
    - Impact on surface wind stress/upwelling?
    - Great test for LES models
- How often does it occur?
- Cross the Ri_c diurnally?




Thank you!