

Deviations of atmospheric coastal flow from the open-channel hydraulics analogy

Dave Rahn

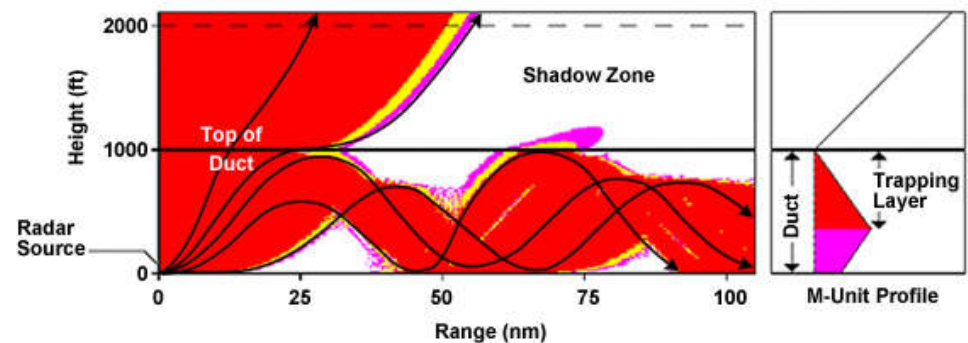
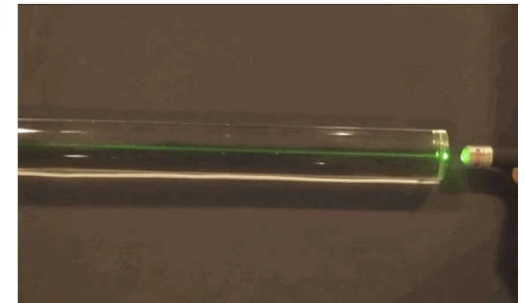
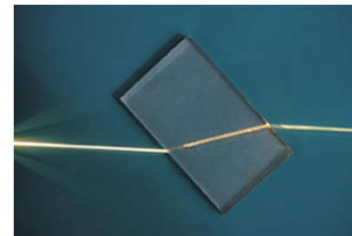
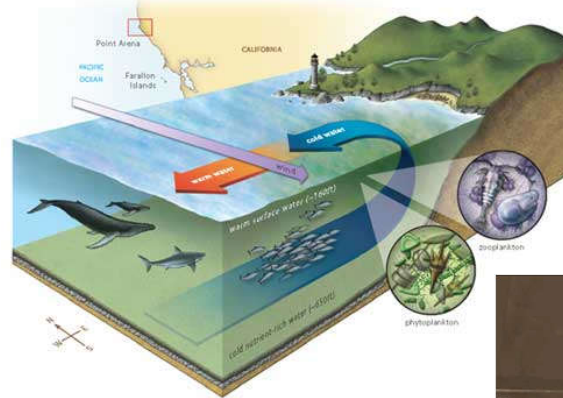
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Who cares?

- Wind energy
- Ocean upwelling is induced by wind stress
 - Ekman transport / Ekman pumping
- Profile of temperature and humidity determines the refractivity profile and electromagnetic wave propagation
 - Radio communication
 - Radar detection



Synoptic Conditions

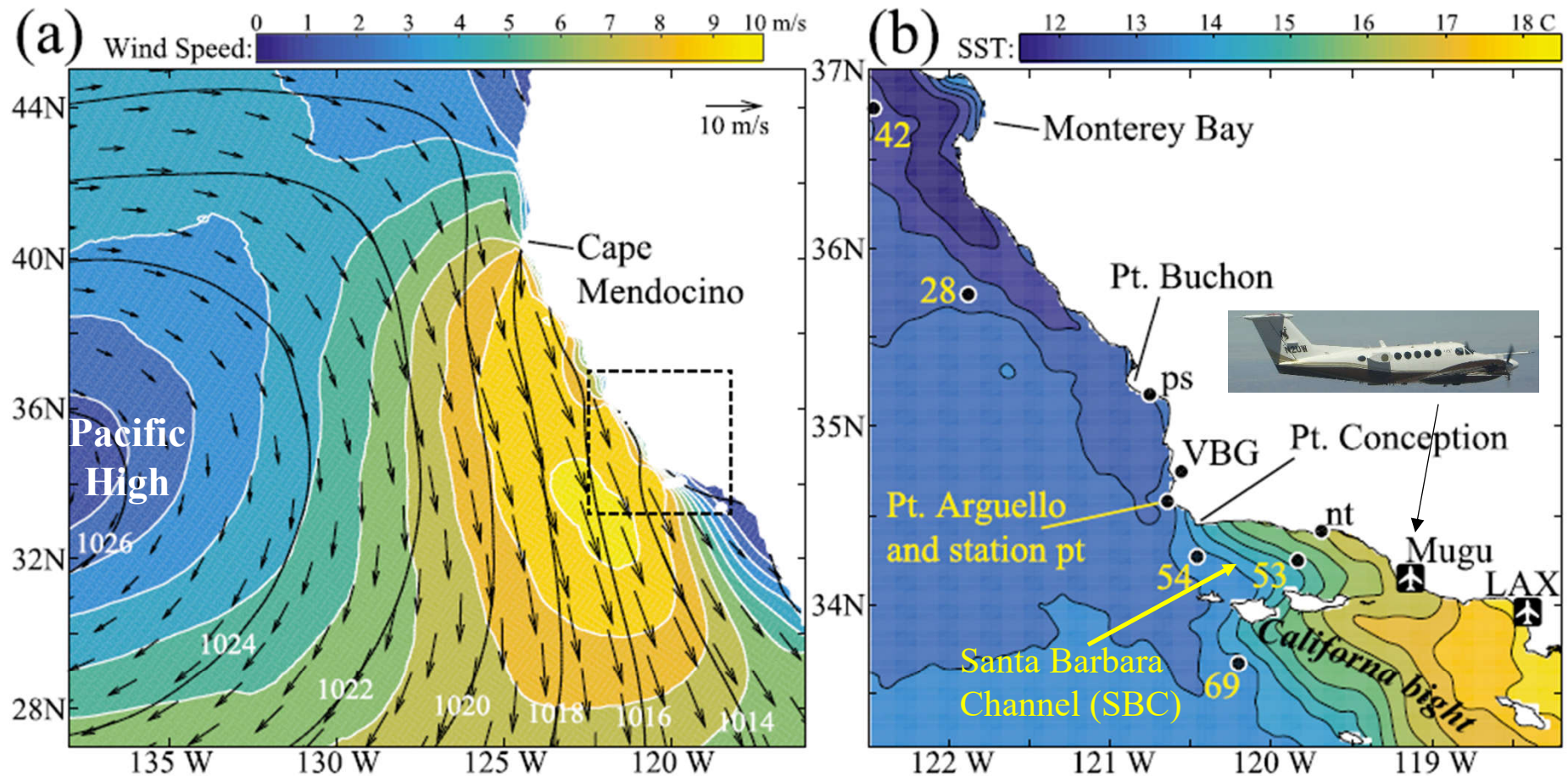


FIG. 1. (a) Average mean sea level pressure (hPa, contours) and daily 10-m wind vectors (m s⁻¹) during PreAMBLE (16 May–16 Jun 2012) obtained from the NAM 218-grid analysis. (b) Average SST (color and contoured every 0.5°C) from the Global 1-km Sea Surface Temperature (G1SST) product (Chao et al. 2009, <http://ocean.jpl.nasa.gov/SST>). The dots indicate locations of buoy and surface station observations. Pertinent geographic locations identified. The domain of (b) is indicated by the dashed box in (a).

Fluid System Framework

Froude Number

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

$$g' = \frac{\theta_{inversion_top} - \theta_{MBL}}{\theta_{MBL}}$$

U: Flow speed

H: Layer depth (MBL)

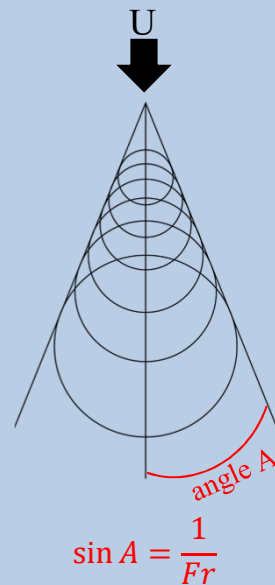
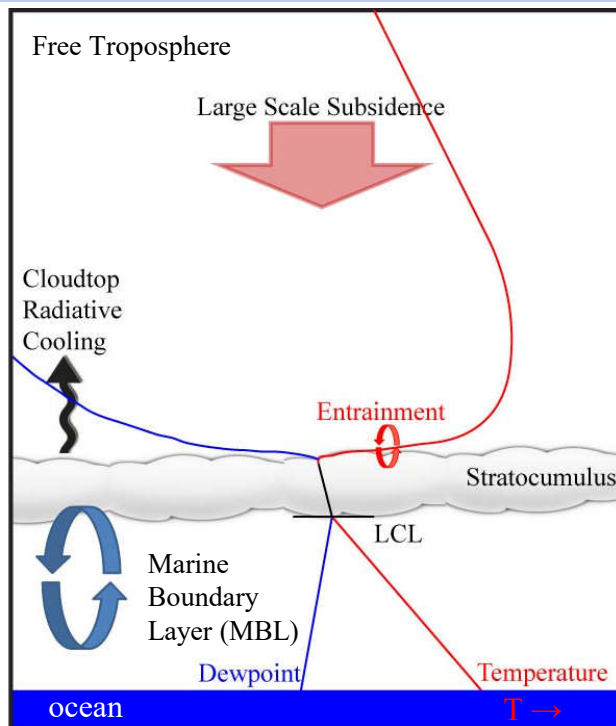
g': Reduced gravity

θ : Potential temperature

c: speed of gravity wave

$Fr > 1$: Supercritical

Flow faster than speed of gravity wave
No upstream impact of perturbations



Shallow water system with a lateral boundary



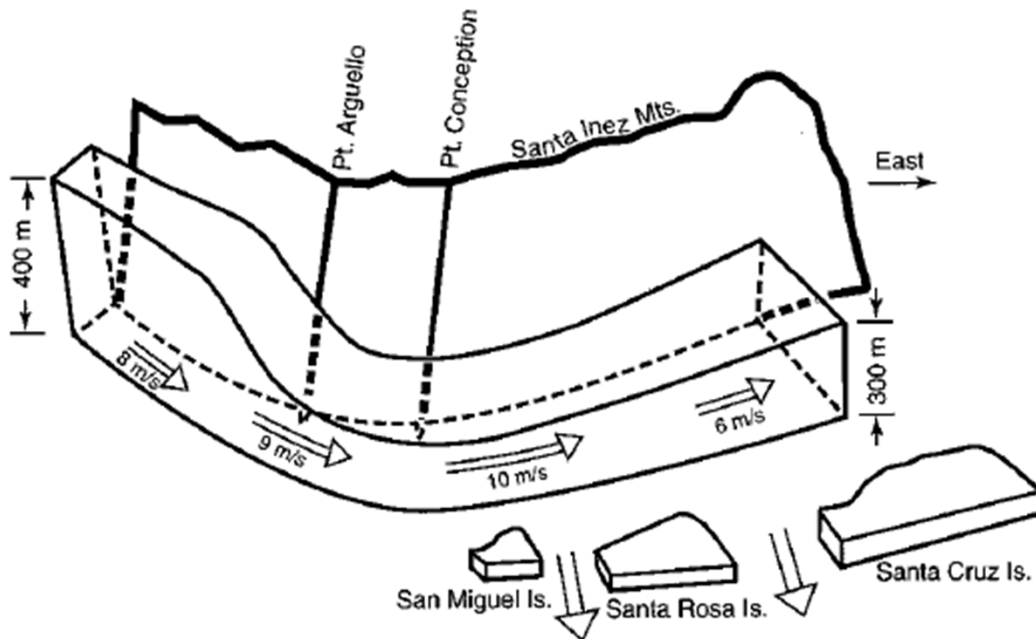
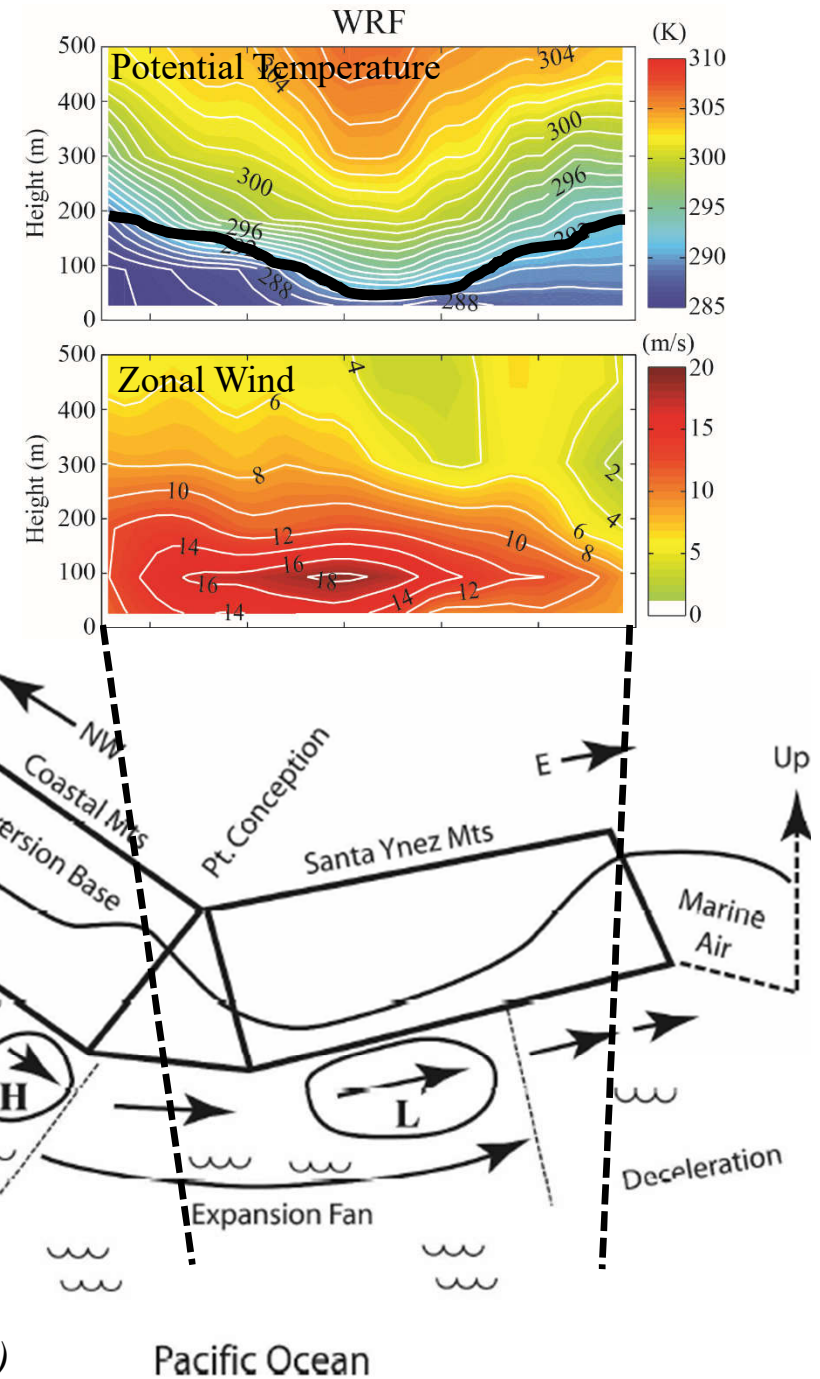


FIG. 21. Schematic model of the marine-layer structure turning into the Santa Barbara Channel. The marine air thins, expands, and accelerates as it turns the corner into the Santa Barbara Channel, causing the fastest winds to be at the western mouth.

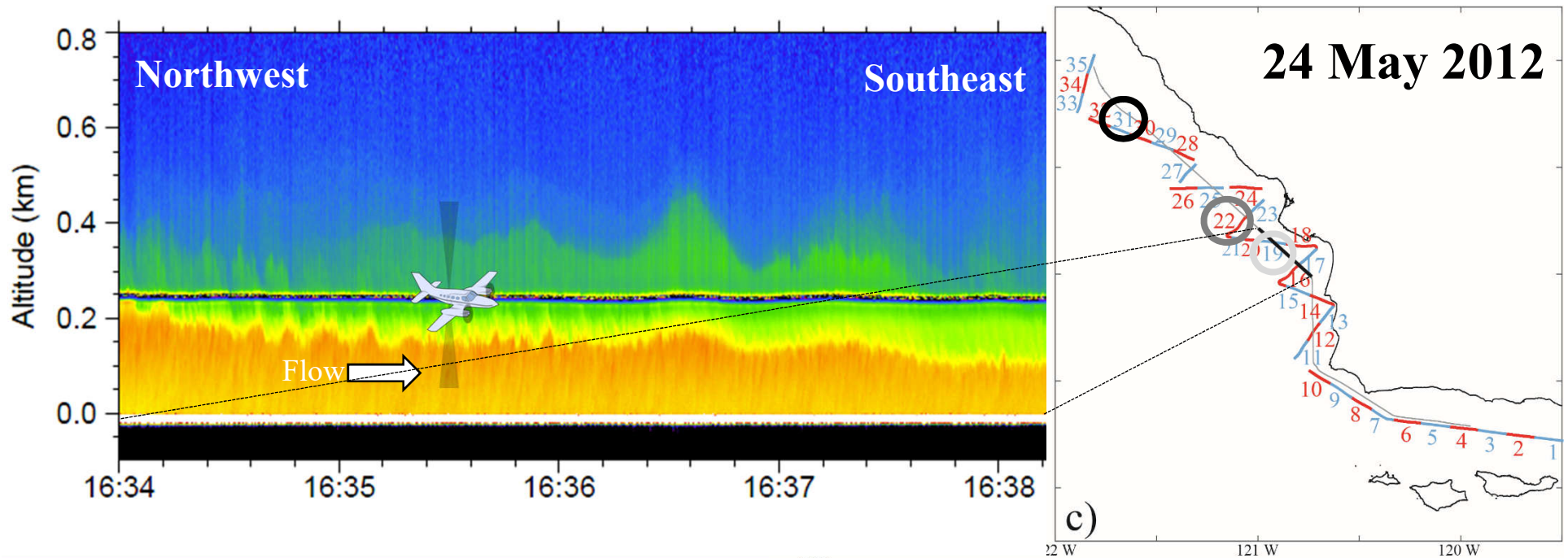
Dorman and Winant (2000)

The open-channel flow analogy has been used to explain features seen in Southern California.



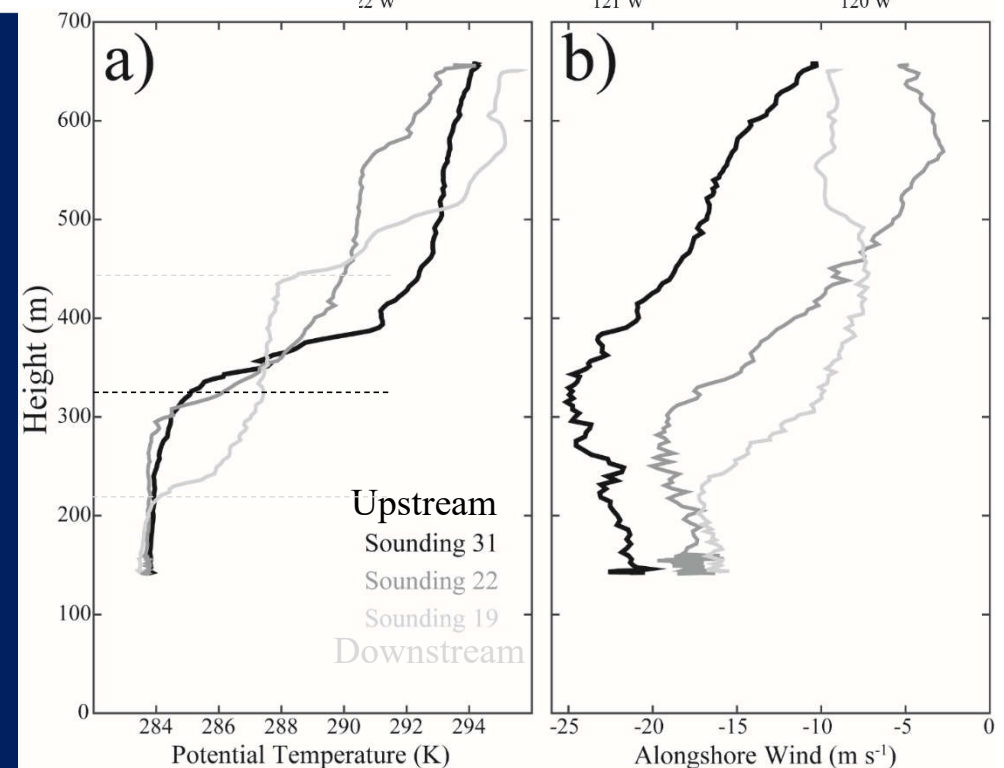
Dorman and Koraćin (2008)

FIG. 7. Diagram of marine layer hydraulic response to Point Conception.



Deviation #1

- Instead of just a MBL and free troposphere, an intermediate layer can form.
- Develops due to Kelvin-Helmholtz instability.



Kelvin-Helmholtz Instability

$$Ri = \frac{\text{Stability}}{\text{Shear}}$$

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

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

- 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 $\sim 1.5 \text{ km}$.
 - Corresponding depth $\sim 200 \text{ m}$

*Browning and Watkins
(1970), Nature*

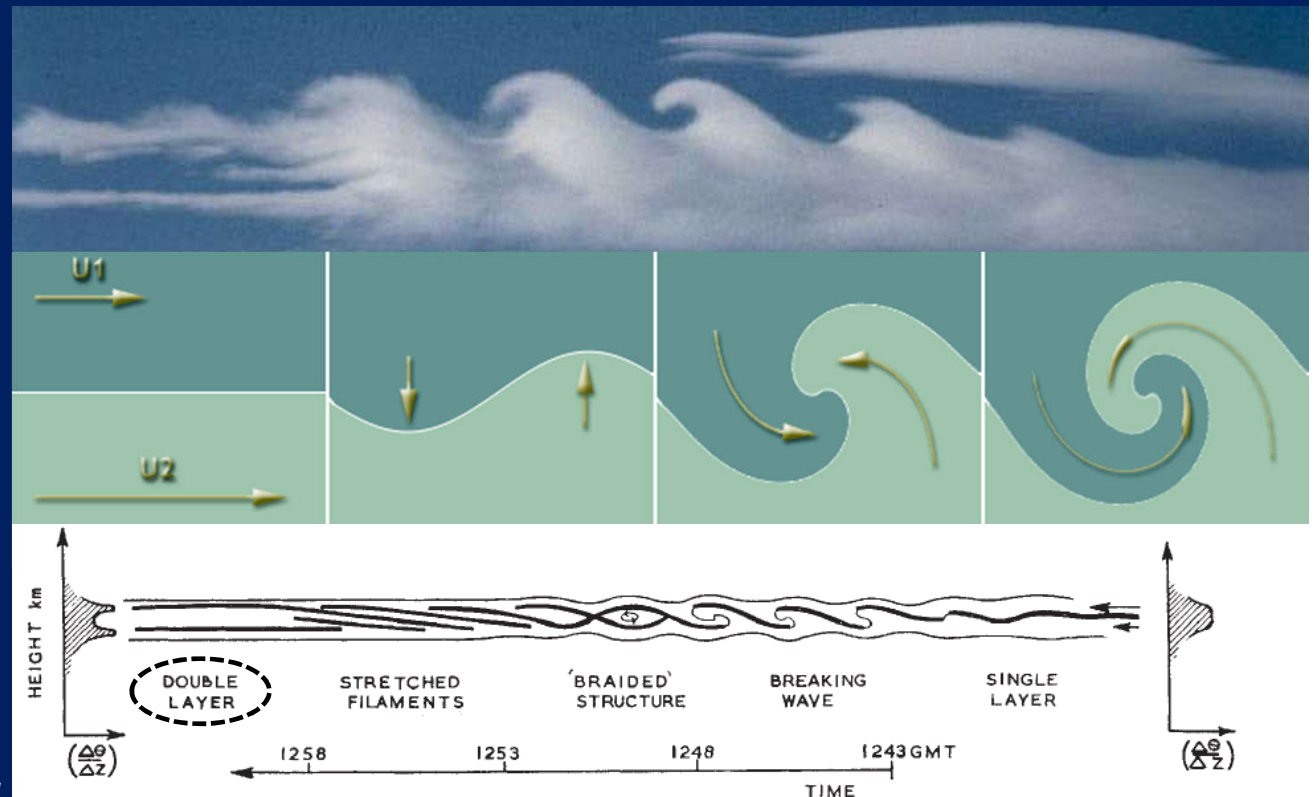
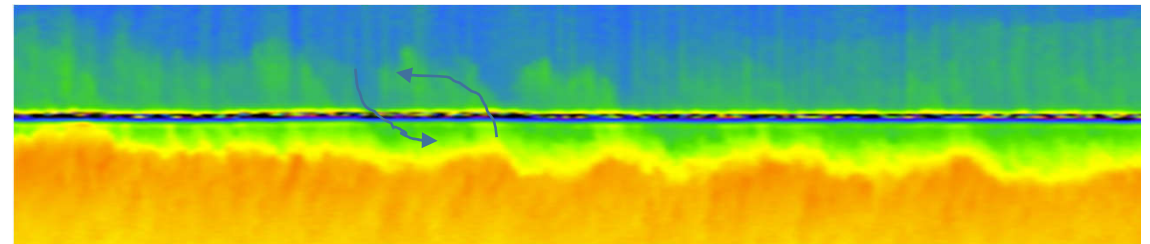
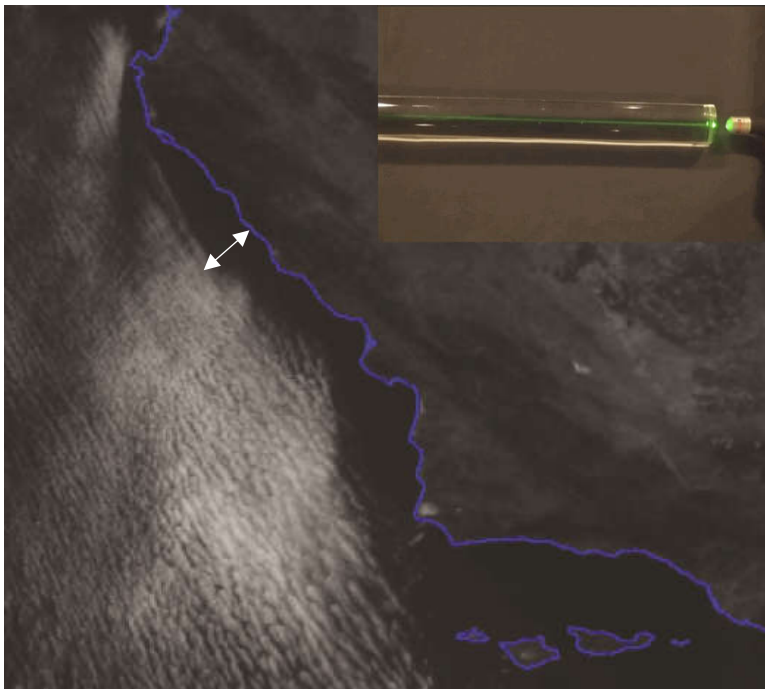
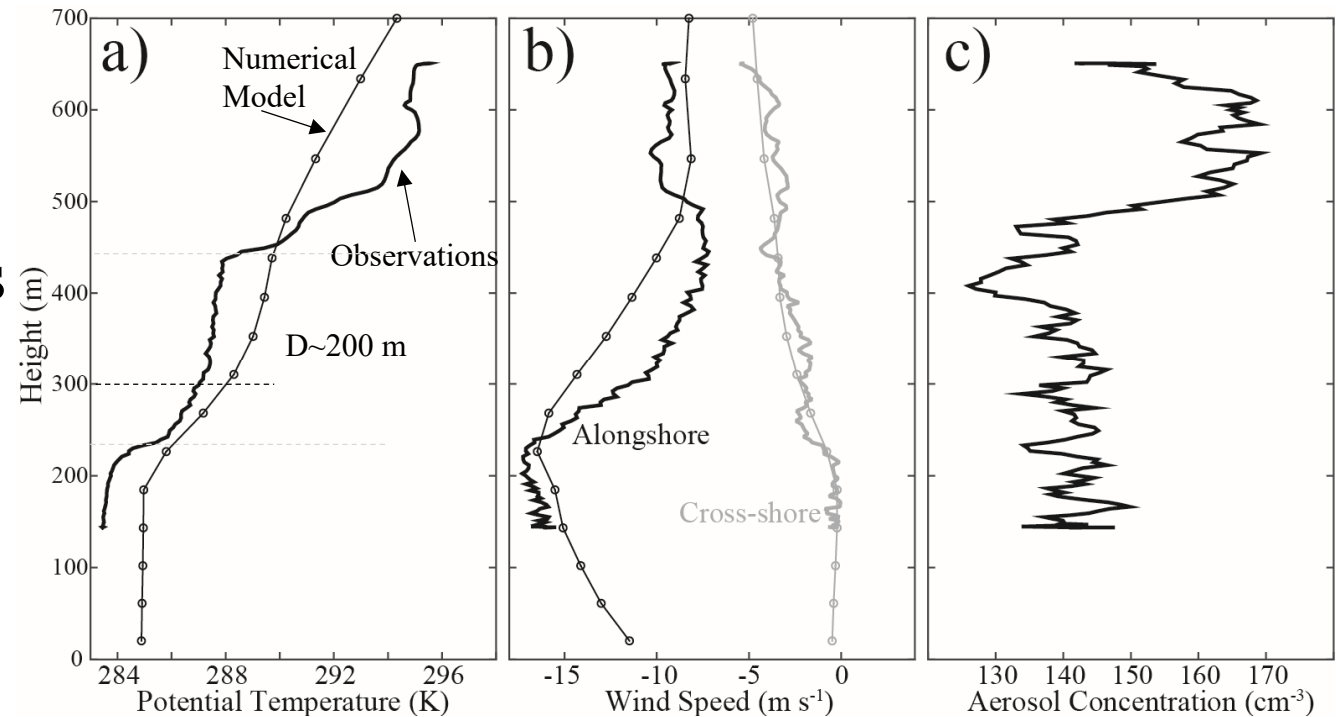


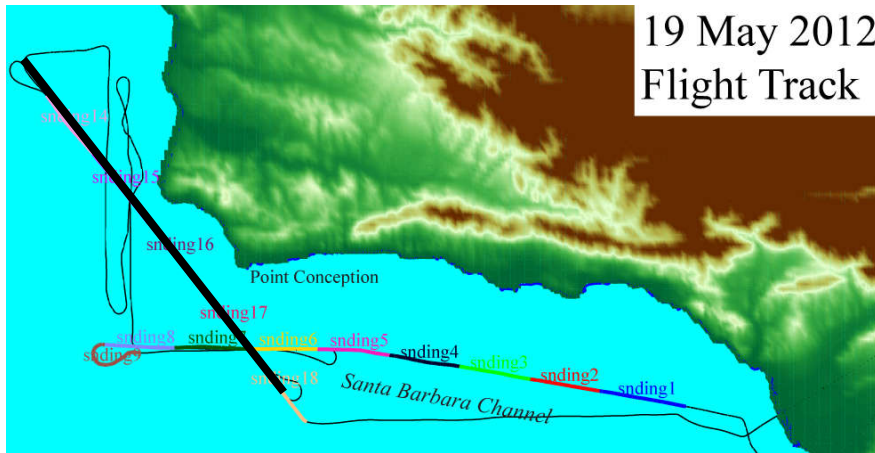
Fig. 4. Schematic representation of the life cycle of an individual Kelvin-Helmholtz billow based on the data in the earlier figures. Time progresses from right to left. Thick lines correspond to the detectable clear air radar echo, which started as a single layer at 1243 and finished as a double layer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

- Two inversion layers separate two relatively well-mixed layers
 - MBL
 - Middle layer
- Mixing between lower and middle layer

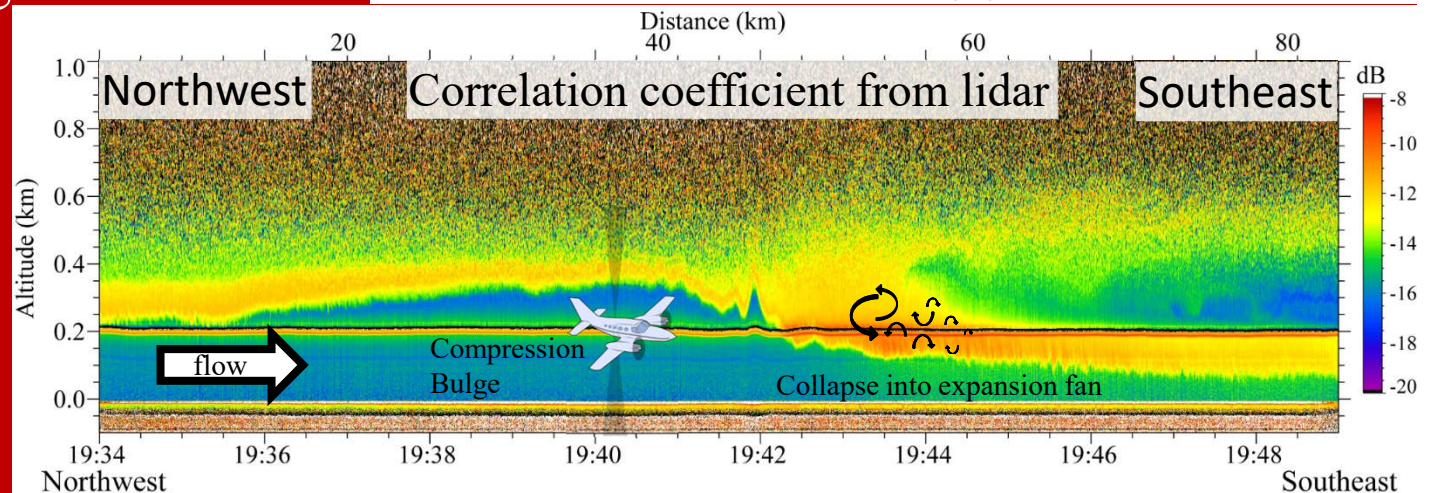
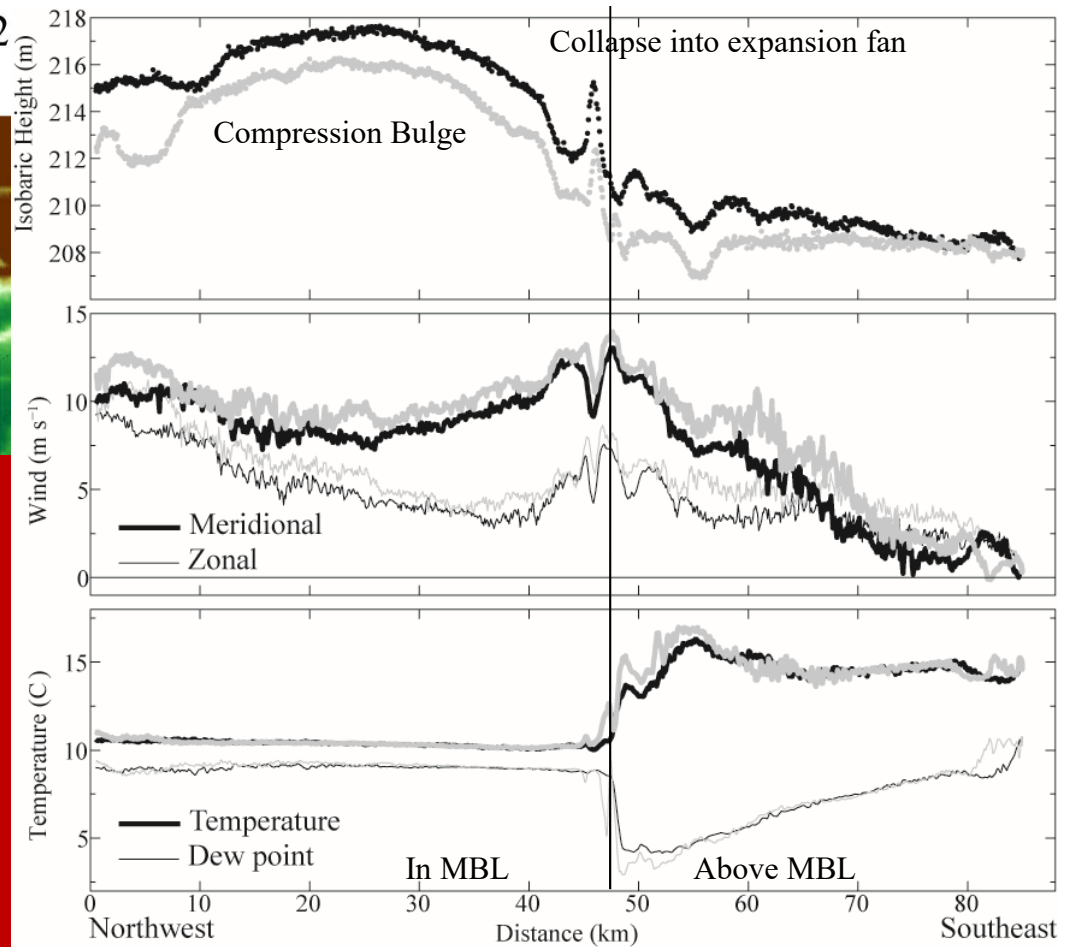


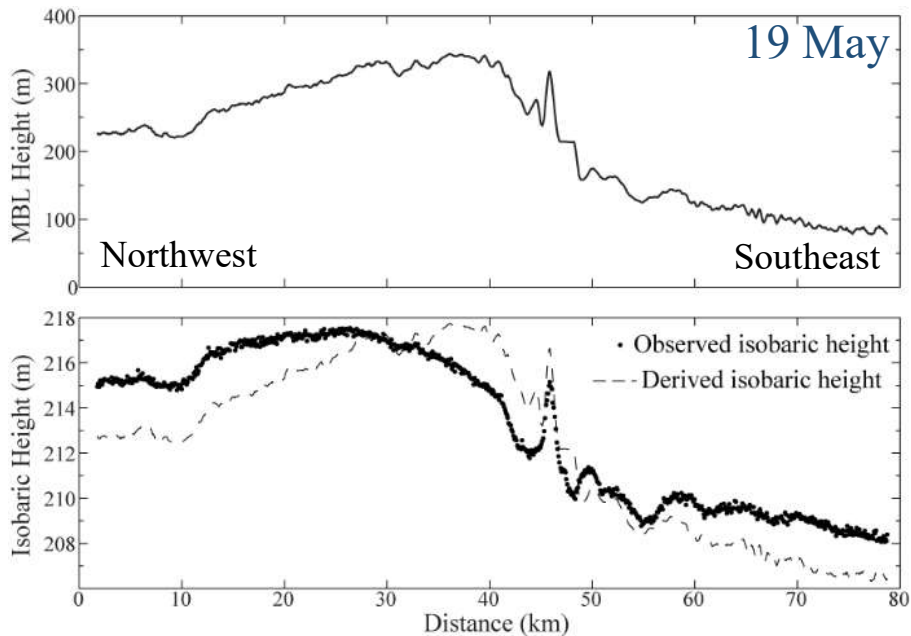
Photograph from different flight with clouds.





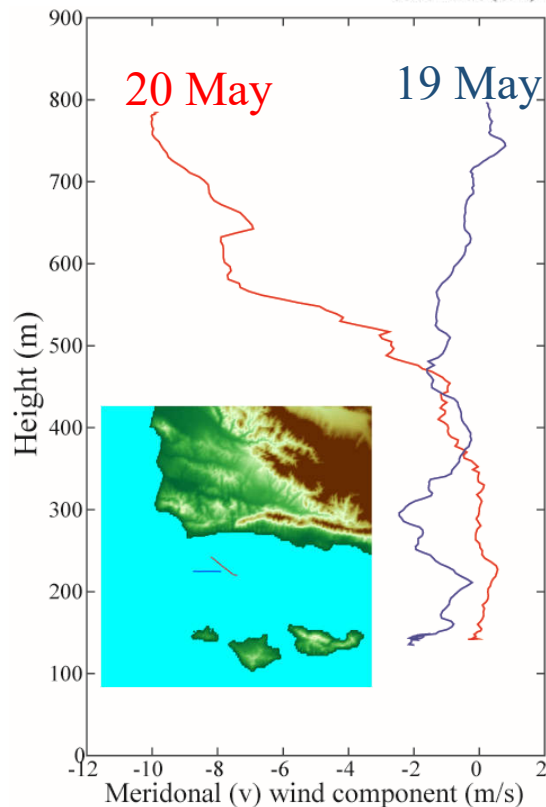
- Features detected near Point Conception:
 - Compression bulge
 - Collapse into expansion fan
 - Stationary waves in the transition region
 - Inverse relationship between wind and height.



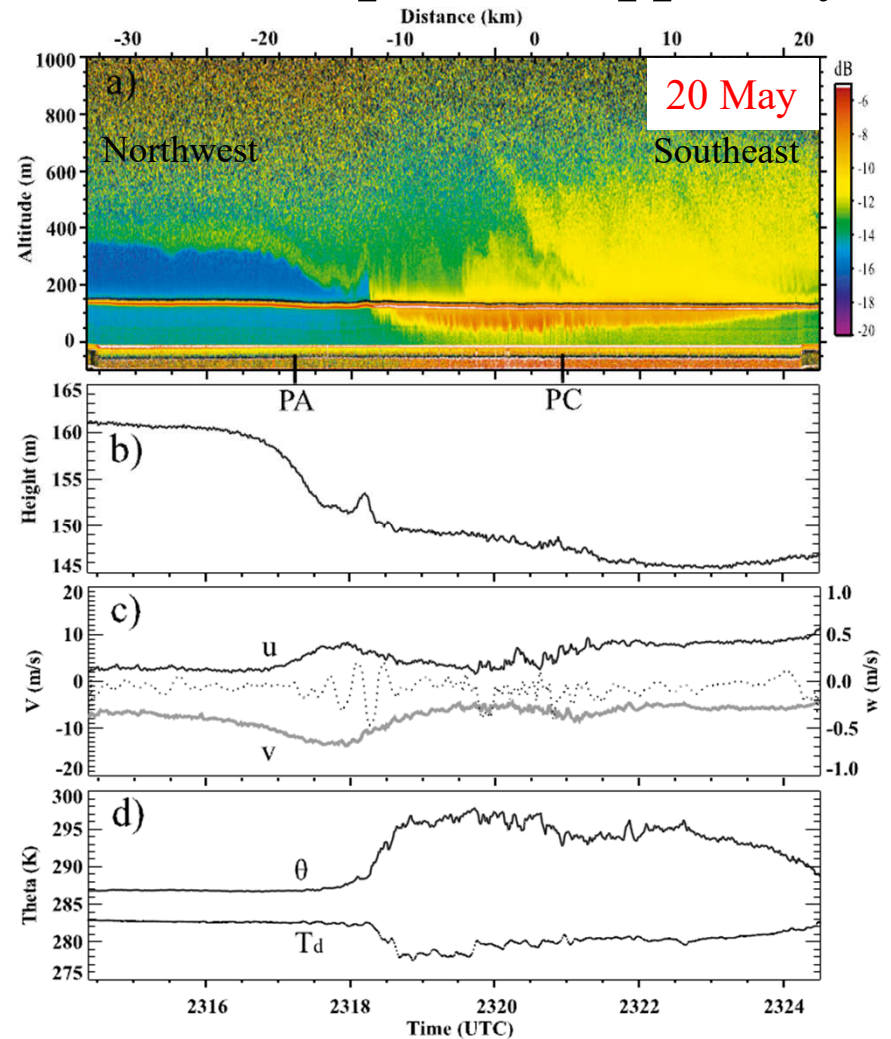


Deviation #2

- Processes *above* the MBL cannot be neglected.
- Not purely a hydraulic response that *assumes passive upper layer*.

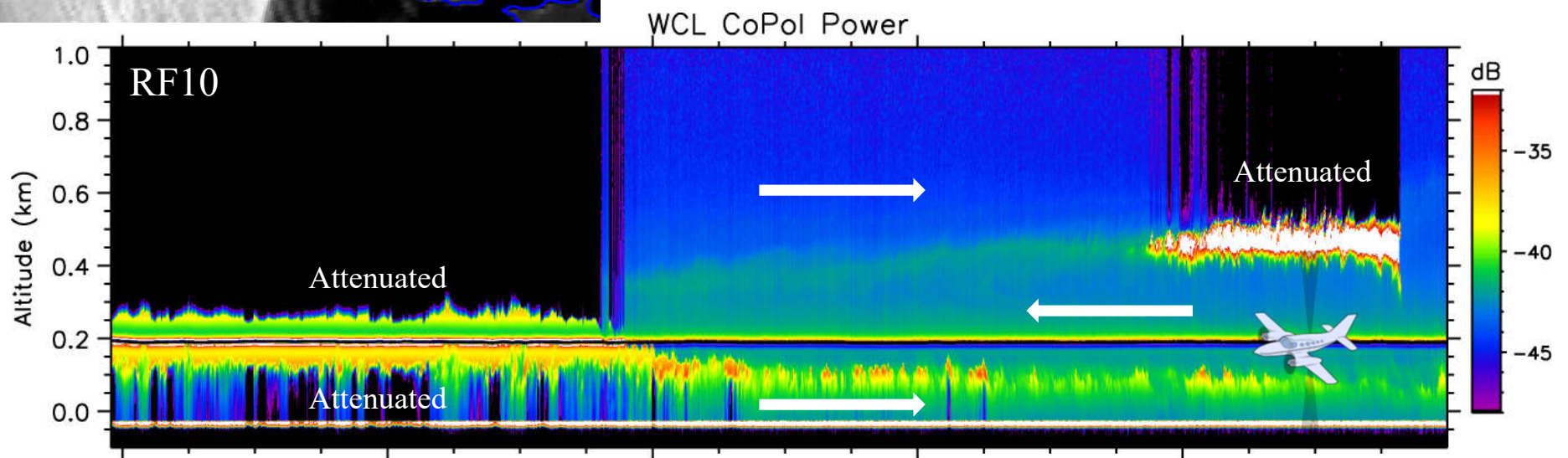
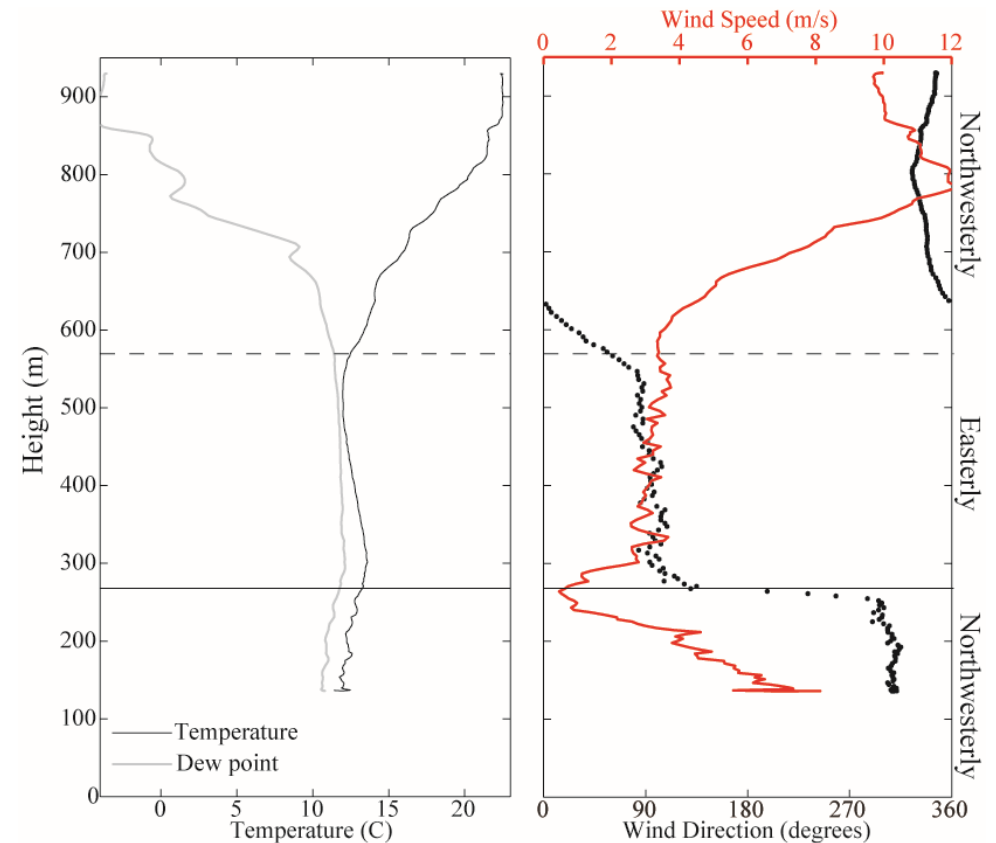
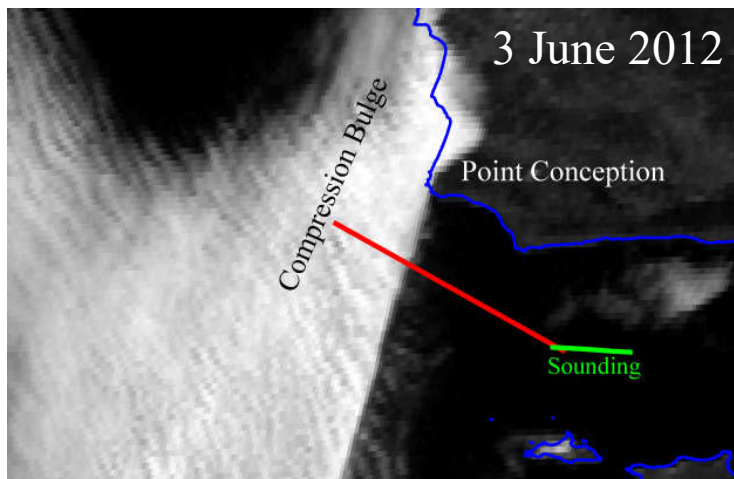


- Topographic waves can also occur in the lee of the coastal ranges, especially for northeast flow.

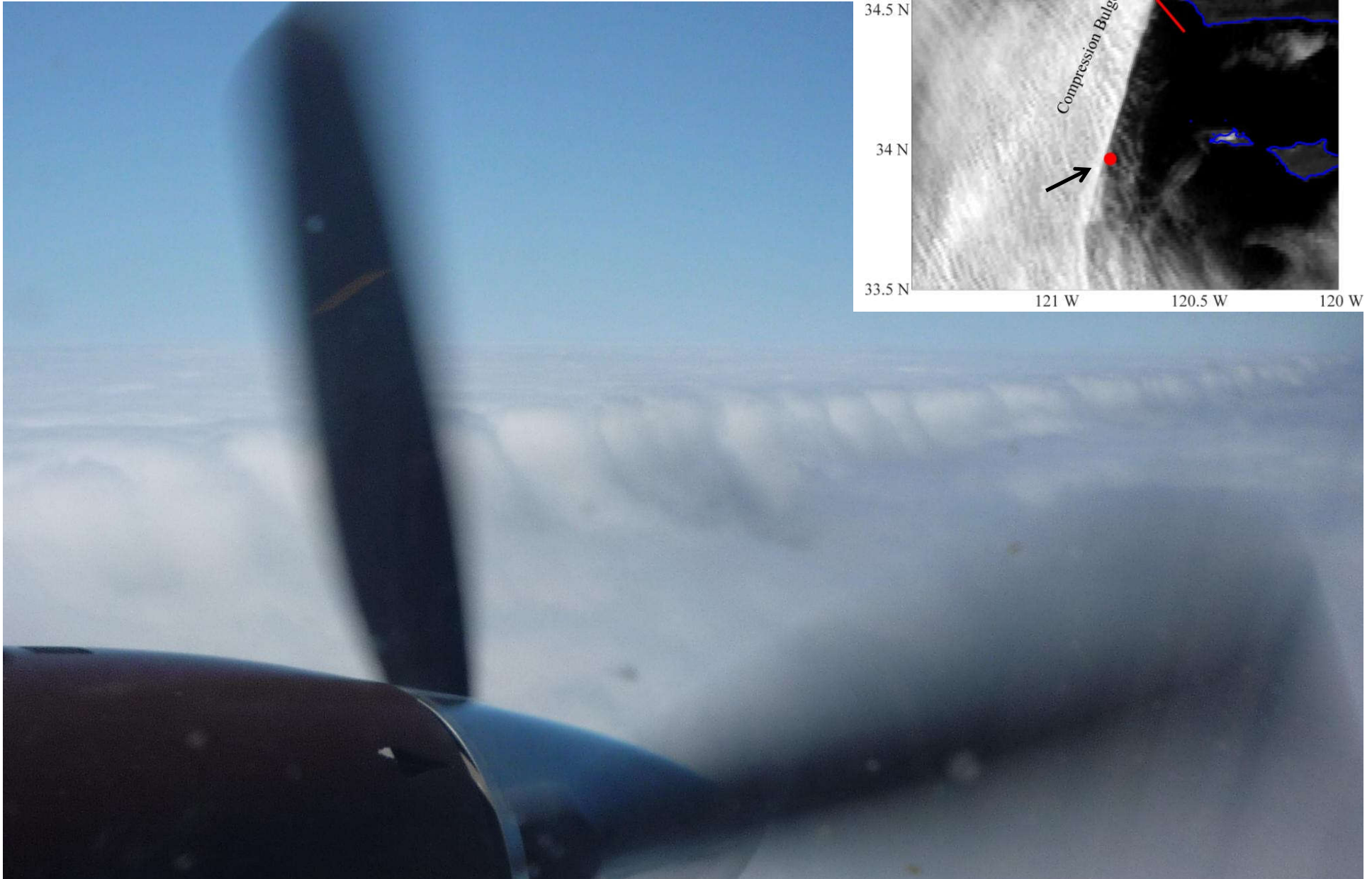


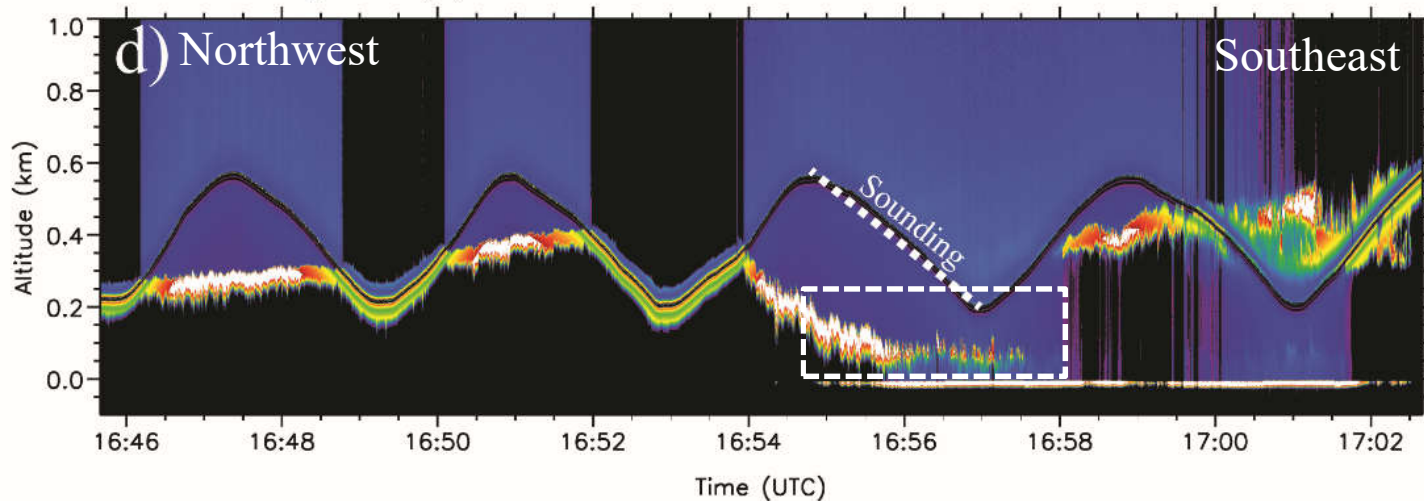
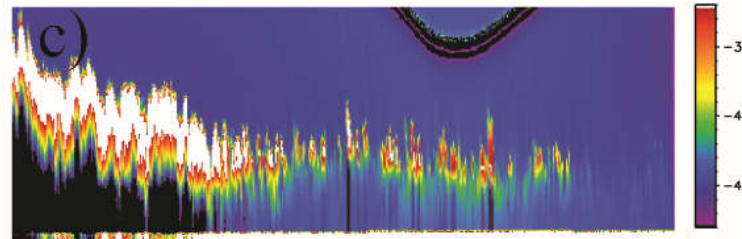
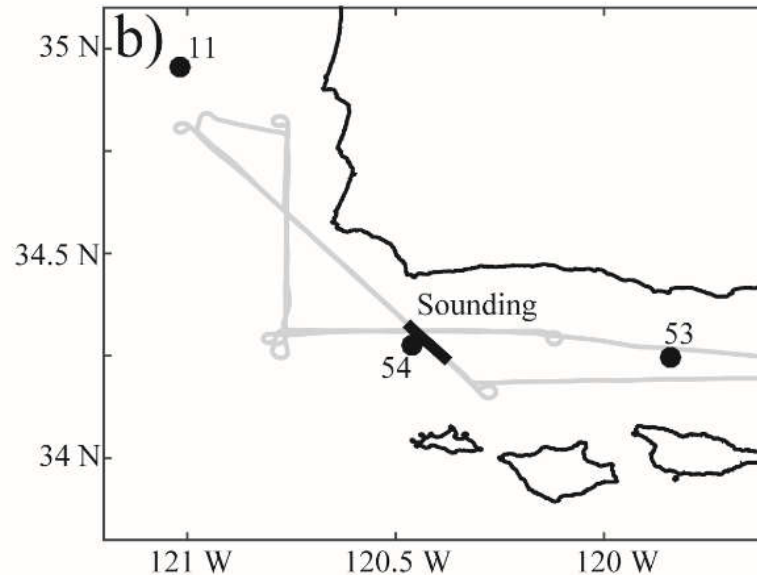
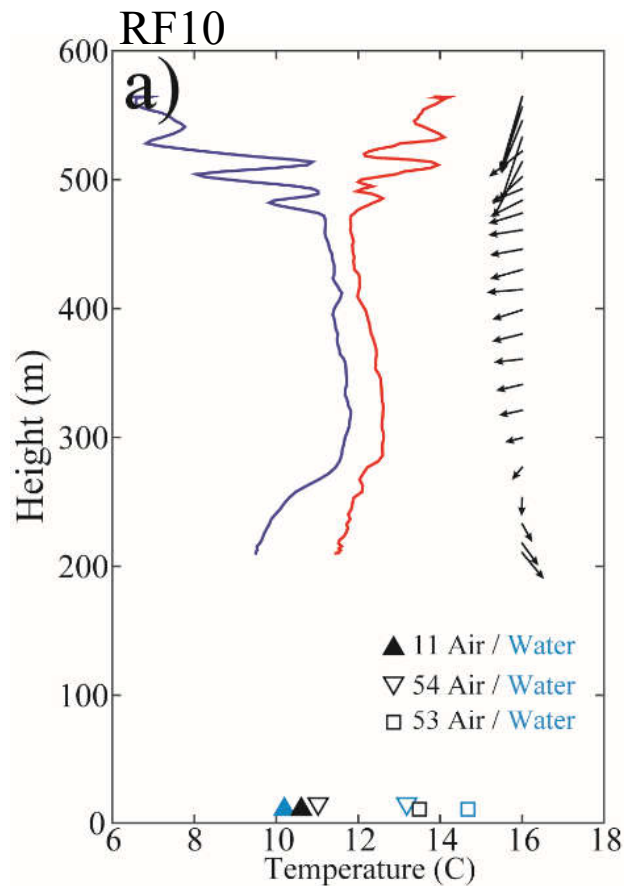
Deviation #3

- The Santa Barbara Channel is not passive.
 - Easterly low-level flow is often present, especially through the morning.



Sharp Cloud Edge!





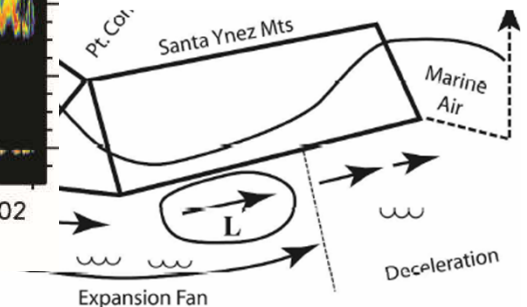
Deviation #4

The lower layer typically loses its identity as it moves over warmer water.

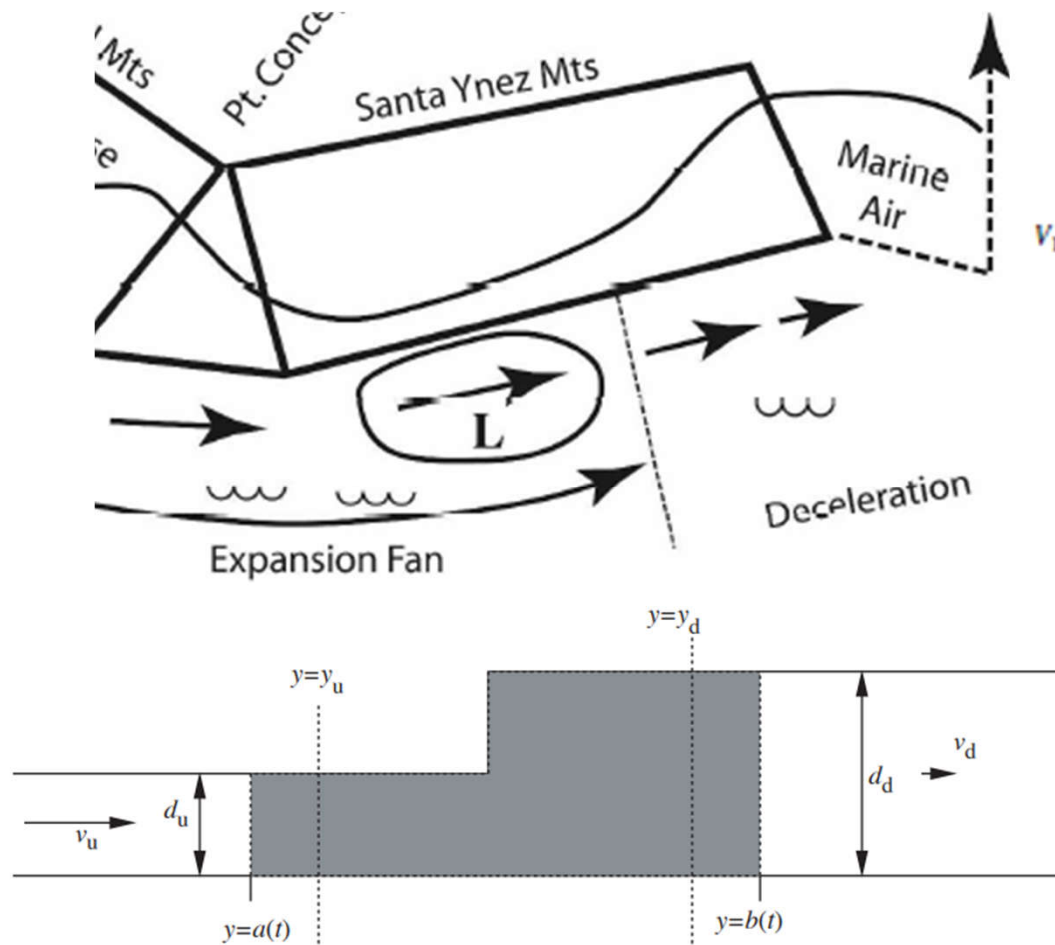
Near b-54:

Water at 1 m depth is 2.2°C warmer than the 4-m air temperature.

Mixing near the surface erodes the lower layer.

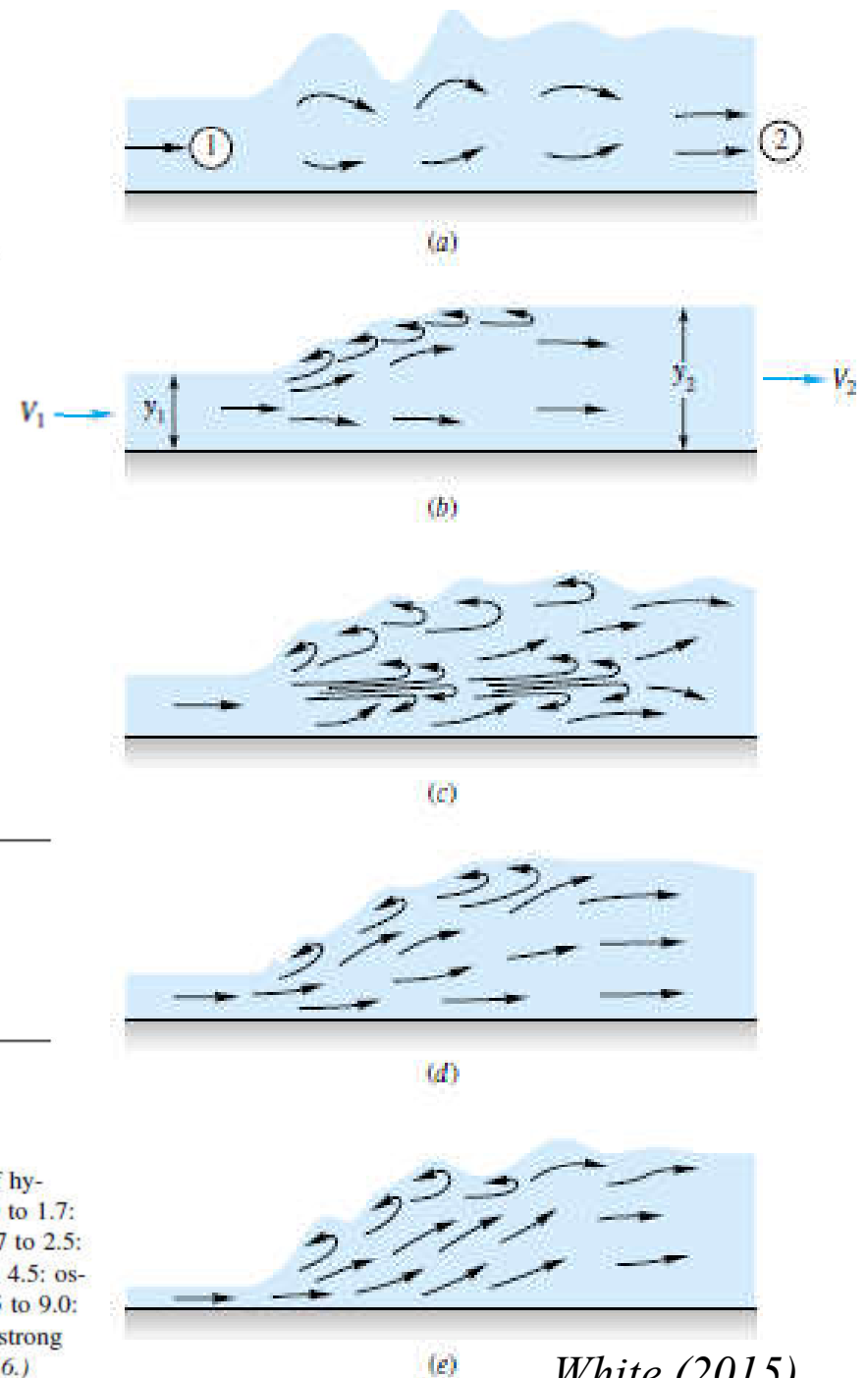


Hydraulic Jump

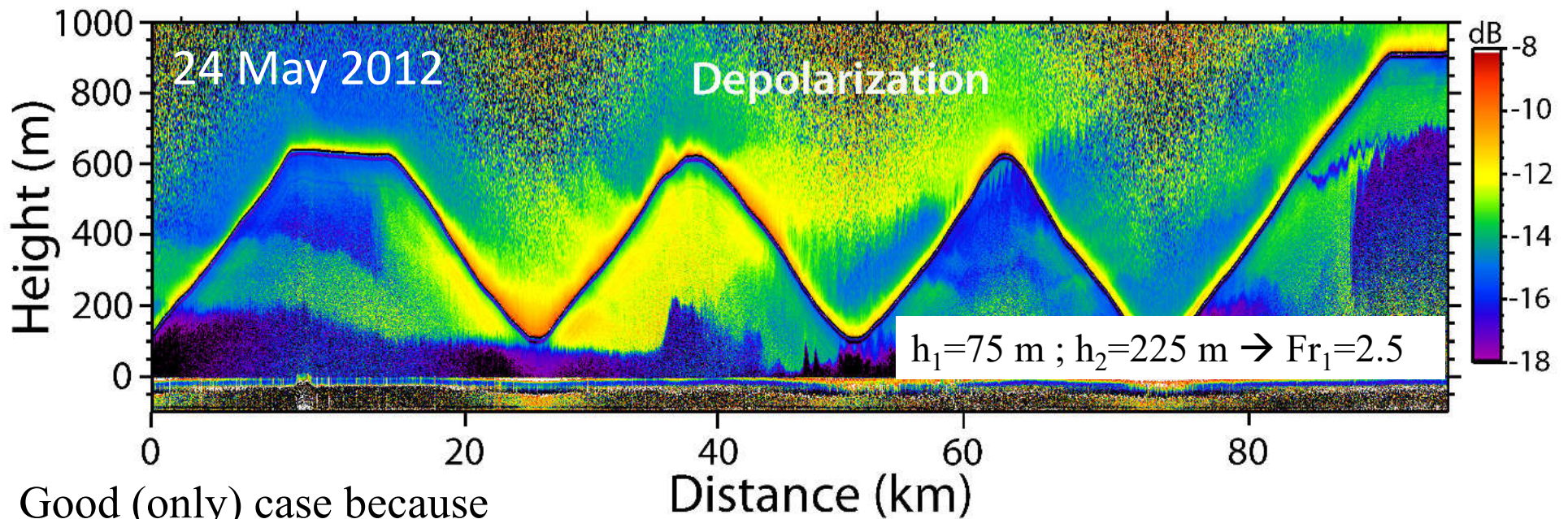


$$\frac{h_2}{h_1} = \frac{1}{2} \left(\sqrt{1 + 8Fr_1^2} - 1 \right)$$

Fig. 10.12 Classification of hydraulic jumps: (a) $Fr = 1.0$ to 1.7 : undular jumps; (b) $Fr = 1.7$ to 2.5 : weak jump; (c) $Fr = 2.5$ to 4.5 : oscillating jump; (d) $Fr = 4.5$ to 9.0 : steady jump; (e) $Fr > 9.0$: strong jump. (Adapted from Ref. 16.)

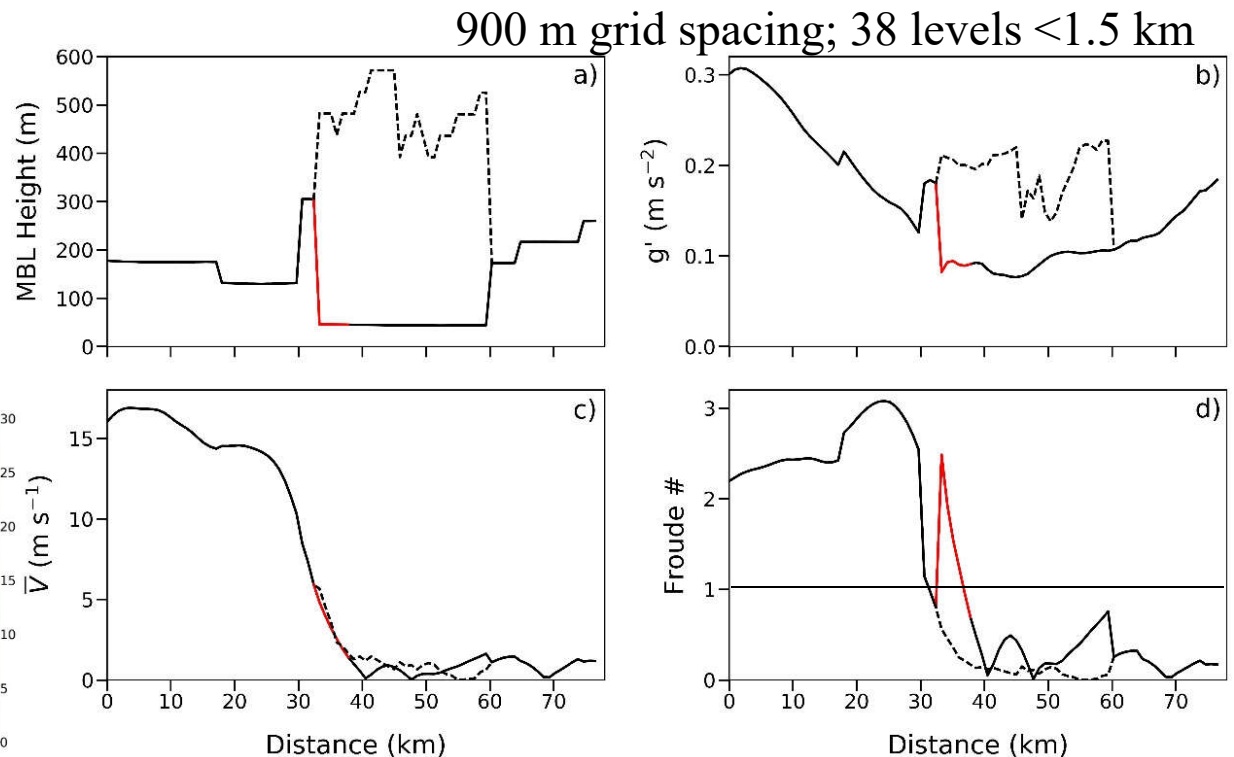
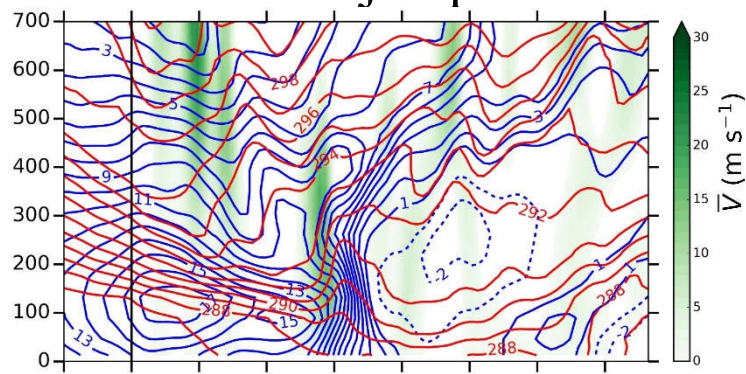


White (2015)



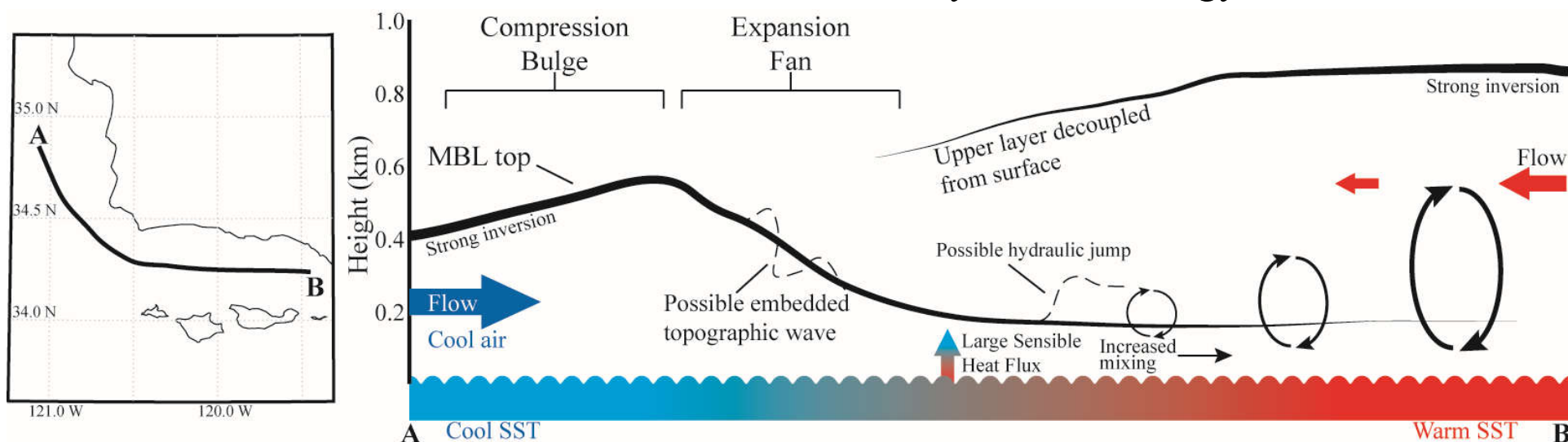
Good (only) case because
of the **high stability of
incoming flow**.

High resolution modeling
was able to capture similar
features of the jump.



Modified Conceptual Model

- Compression bulge and expansion fan still primary features, but lower atmosphere can exhibit substantial deviations from the basic hydraulic analogy.



Deviation #1

Instead of just a MBL and free troposphere, an intermediate layer can form upstream given a low Richardson number.

Deviation #2

Processes *above* the MBL cannot be neglected. Not purely a hydraulic response that *assumes passive upper layer*.

Deviation #3

The Santa Barbara Channel is not passive either and usually has opposing (easterly) flow.

Deviation #4

The lower layer often loses its identity as it moves over warmer water and precludes development of a hydraulic jump.

A photograph of a sunset or sunrise over a vast expanse of dark, textured clouds. The sun is a bright, glowing orb on the horizon, with several long, thin rays of light extending downwards through the clouds. The sky above the horizon is a pale, hazy yellow. The word "Questions?" is written in a large, white, serif font across the middle of the image, centered horizontally and slightly below the horizon line.

Questions?