Abrupt marine boundary layer changes revealed by airborne in situ and lidar measurements

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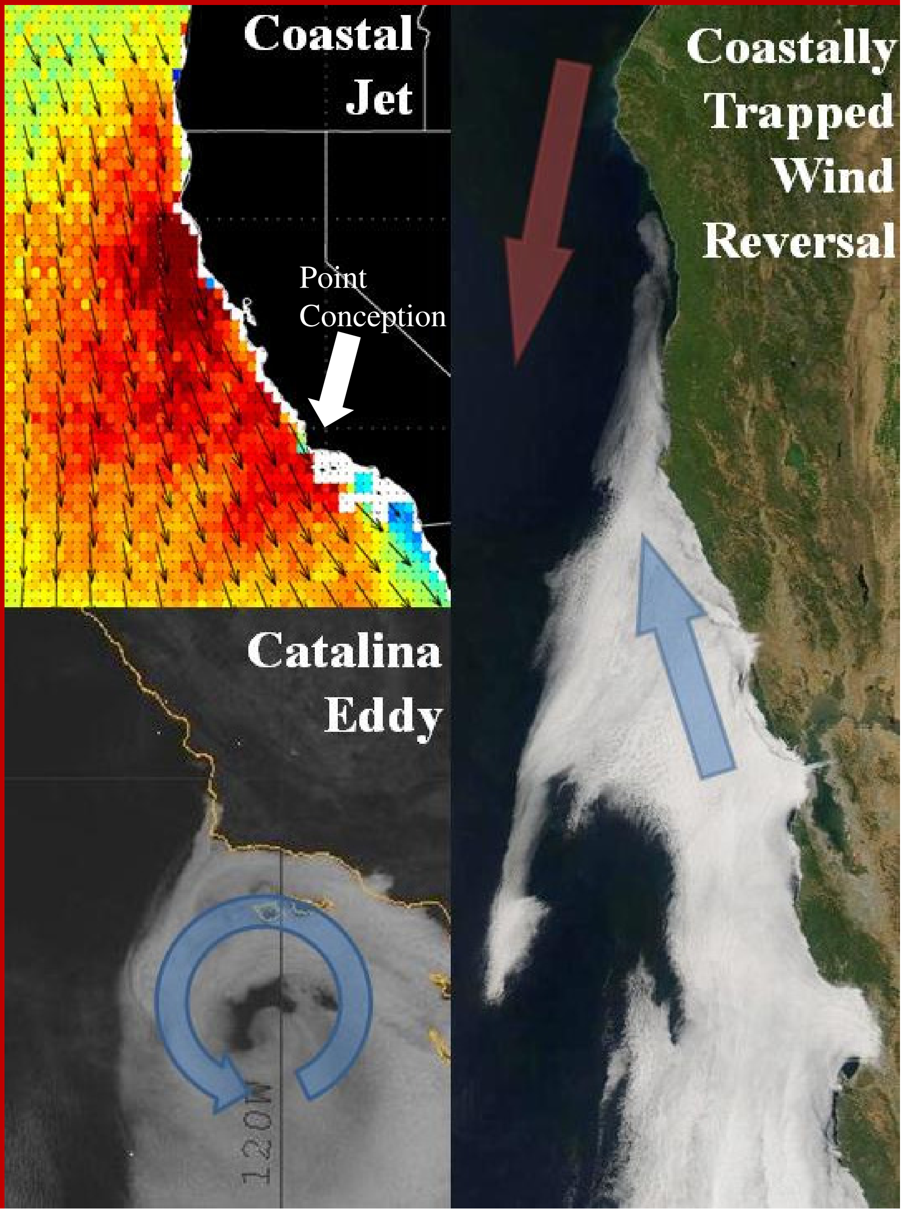
PreAMBLE

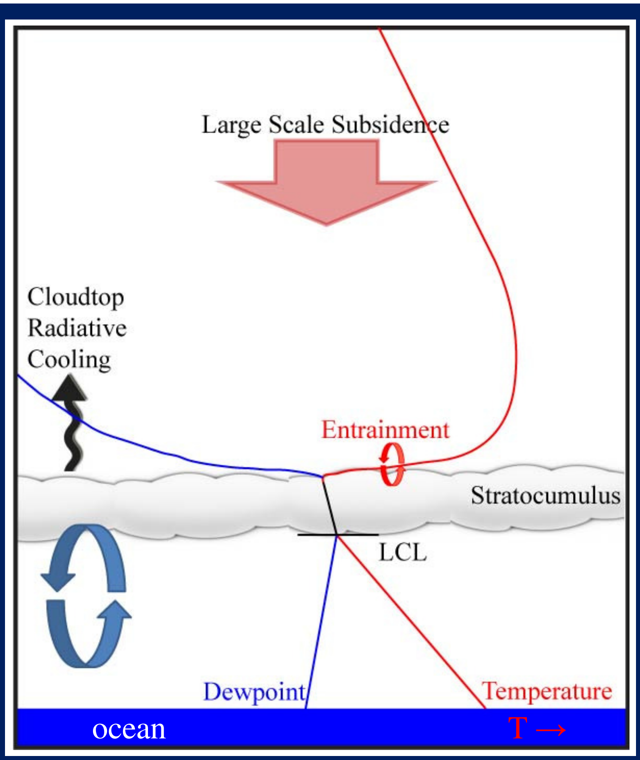
17 May – 17 June 2012

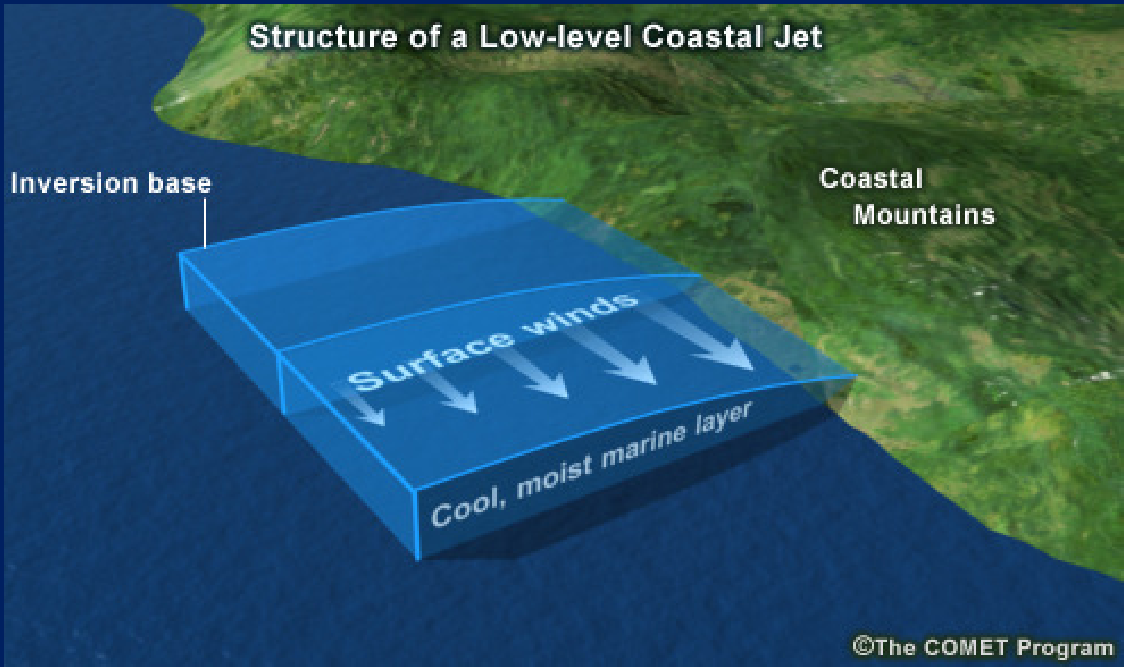
- Precision Atmospheric Marine Boundary Layer Experiment (PreAMBLE) goals:
  - Directly measure the forcing of the coastal jet within the marine boundary layer (MBL) near Point Conception, CA using the University of Wyoming King Air.
    - Map isobaric surface to obtain the horizontal pressure gradient field.
    - Quantify components in the equation of motion.
    - Compare with hydraulic flow theory (compression bulge/expansion fan).
  - Secondary: Assess the dynamics associated with a Catalina Eddy and/or initiation of coastally-trapped wind reversal (CTWR).



Fluid System

- Large scale subsidence creates a warm, stably stratified layer aloft (free troposphere).
- Cool, well-mixed layer near surface (MBL).
- Sharp temperature inversion separates the two layers.
- Result: MBL next to coastal mountains is represented by a two layer fluid system with a lateral boundary.
- Supports:
  - Coastal Jet
  - Trapped density currents
  - Topographically trapped ageostrophic response
  - Kelvin waves





California Expansion Fan

- Mechanical fluid flow
  - *Not* thermally driven (locally)
  - Hydraulic features (jump/expansion fan) may be present depending on the conditions
    - Determined by Froude number

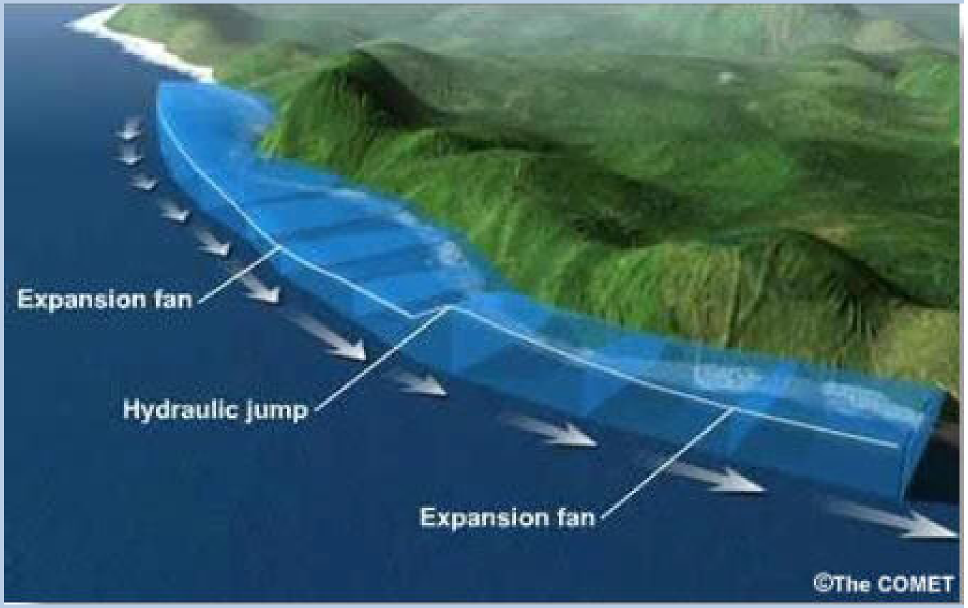
$$Fr = \frac{U}{c} = \frac{U}{\sqrt{g'H}}$$

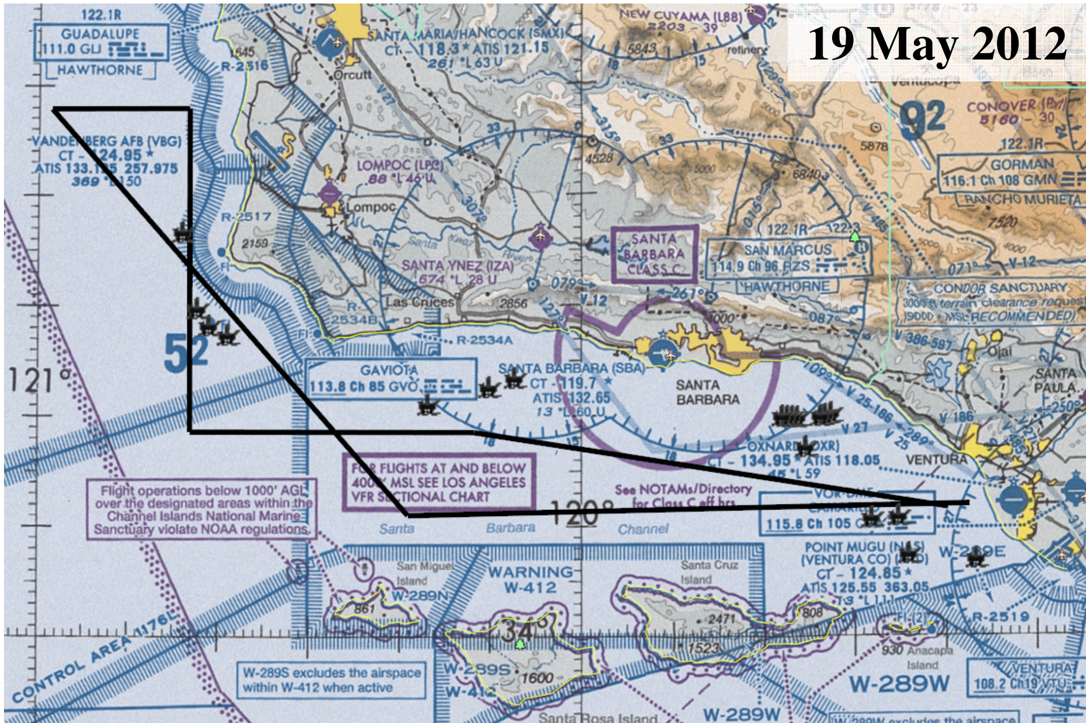
$$g' = \frac{\theta_{inversion\_top} - \theta_{MBL}}{\theta_{MBL}}$$

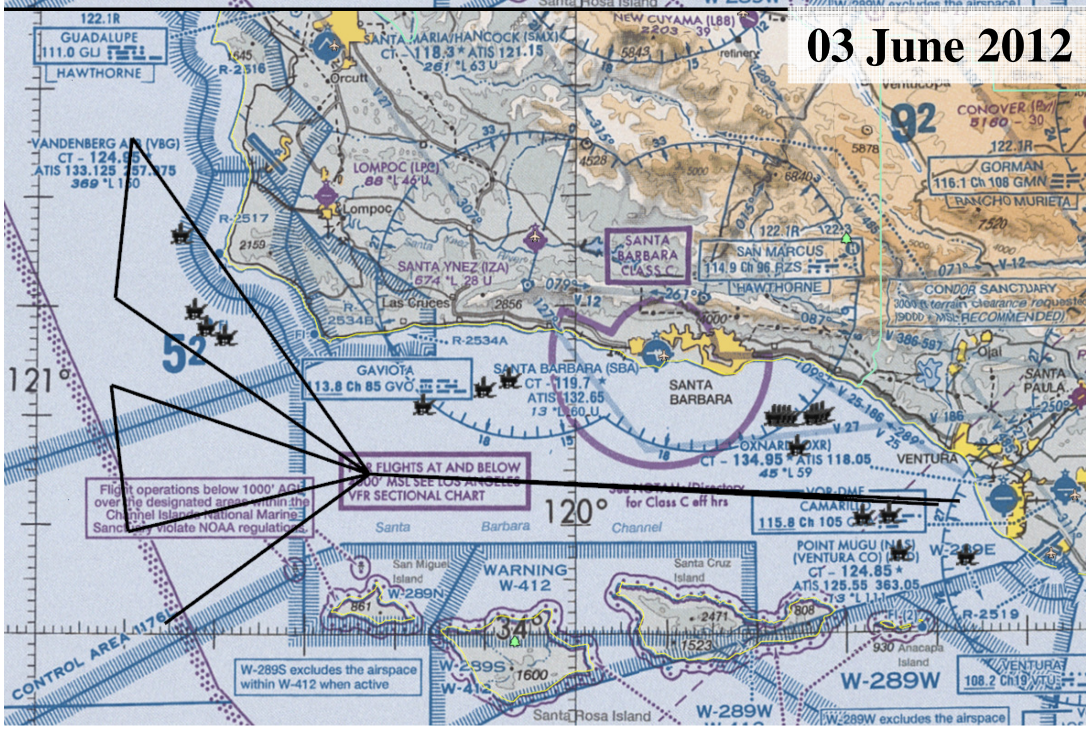
U: Characteristic wind speed
c: Maximum gravity wave speed

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)





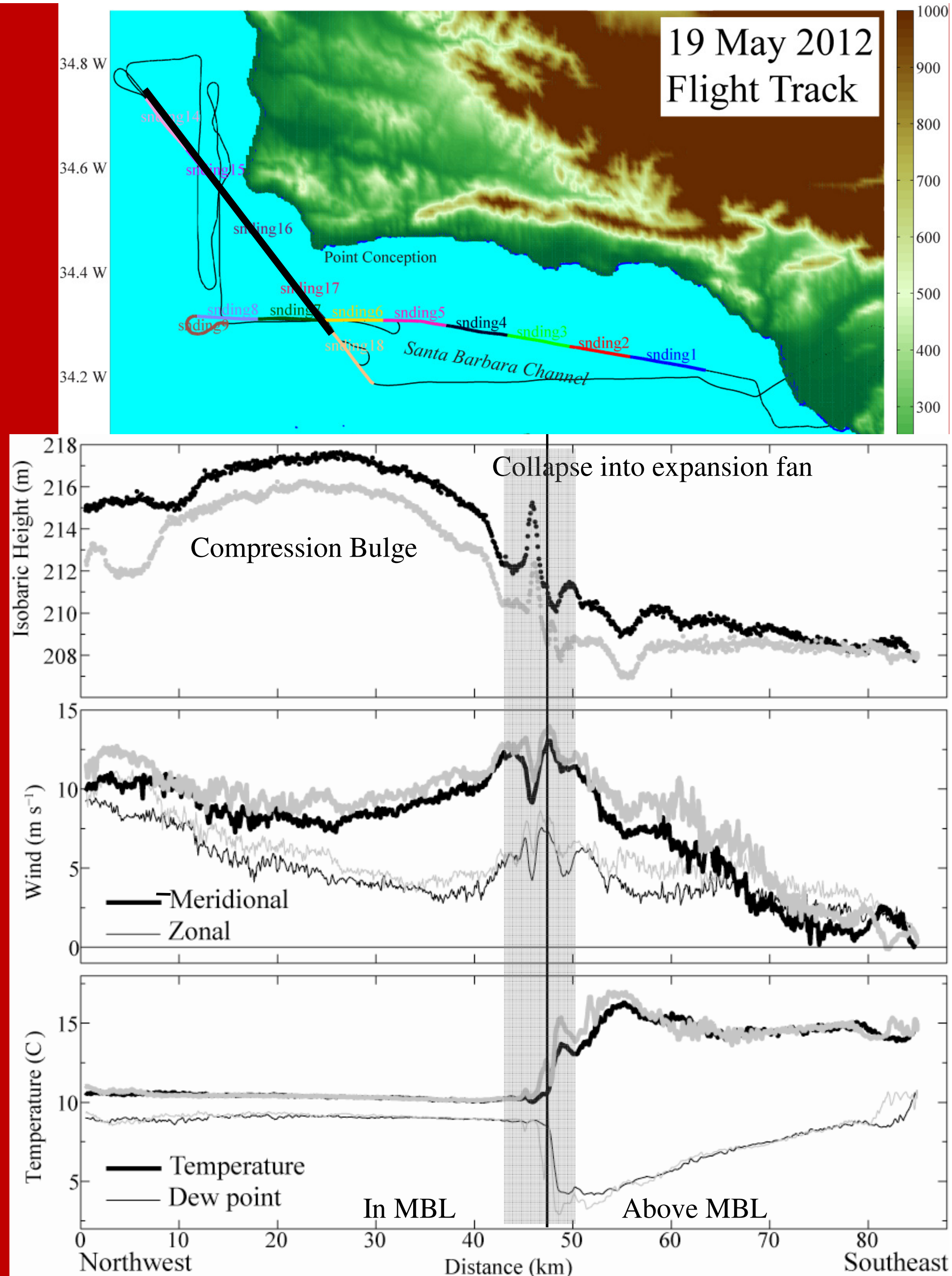


Selected Flights

- Both supercritical
  - Fr > 0.8
- 19 May 2012
  - Clear sky
  - Relatively calm in the Santa Barbara Channel
- 03 June 2012
  - Cloud band extending southwest from Pt. Conception
  - Opposing wind in the Santa Barbara Channel

NW-SE Track

- Flying on an isobaric surface to obtain pressure changes along the flow.
  - Need precise measurements!
- Fairly level flight and steep MBL slope, so aircraft exits MBL to the east.
- Features detected:
  - Compression bulge
  - Collapse into expansion fan
  - Stationary waves in the transition region
  - Note inverse correlation between wind and height.



Wind and Height Perturbations

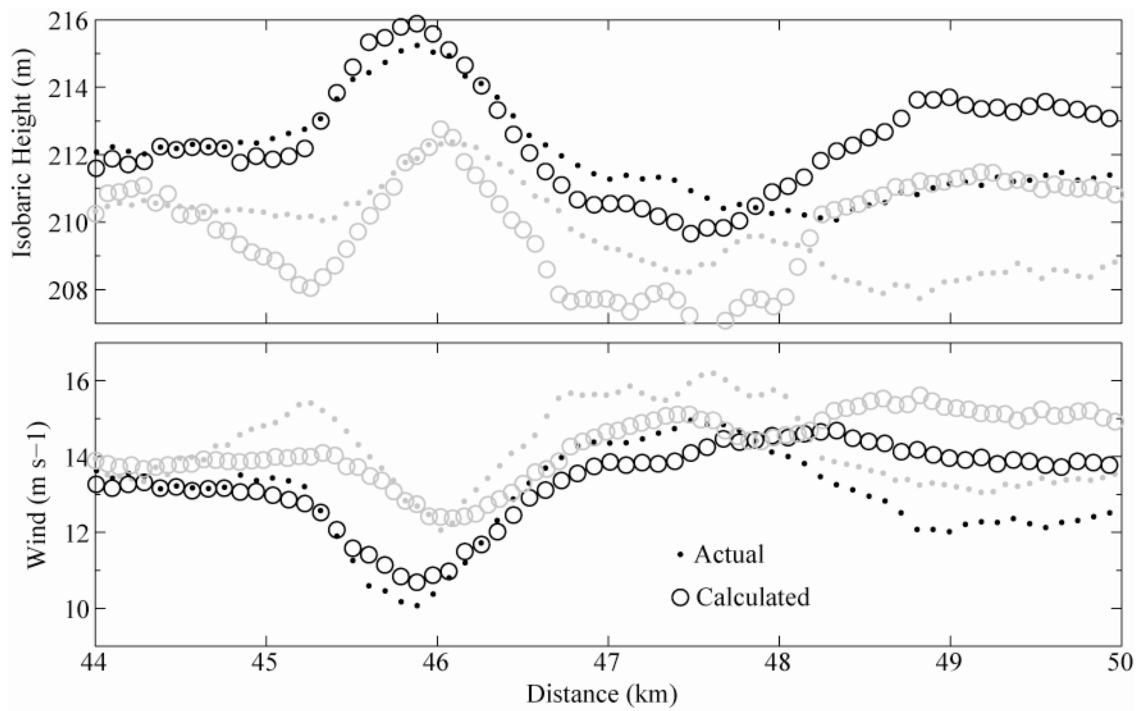
- From inviscid momentum equation for motion in isobaric coordinates
  - Define x being along the flight track
  - Assume
    - Steady state
    - Coriolis is small over the scale of the perturbation
    - Advection of cross-leg wind is small
    - Vertical advection is small

$$\frac{\partial u}{\partial t}^{0} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}^{0} + \omega\frac{\partial u}{\partial p}^{0} = -g\frac{\partial z}{\partial x} + fv^{0}$$

$$u\frac{\partial u}{\partial x} = -g\frac{\partial z}{\partial x}$$

$$\frac{u^2}{2} + gz = C_o$$

- Integrate remaining terms, it reduces to the Bernoulli Equation.
- This simple equation relates measurements near the anomalies.
  - Out of the MBL the assumptions break down and so does relationship.

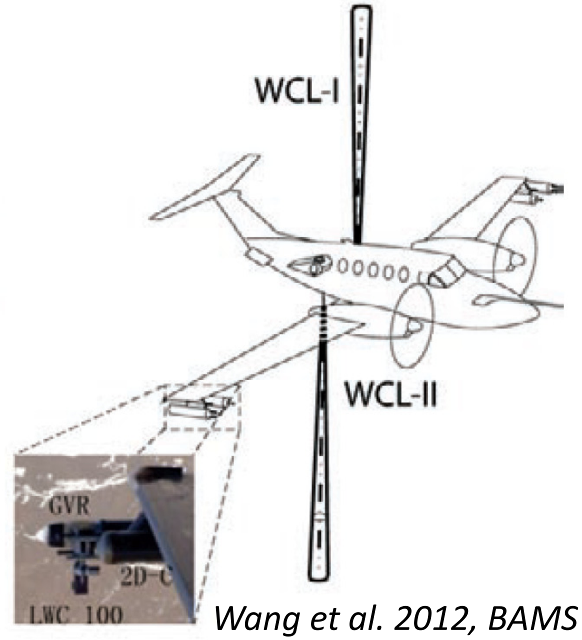


From 1D to 2D

- Since the MBL height likely varies greatly above and below the aircraft, remotely sensing is desirable.
  – In clear skies a lidar is ideal to detect the MBL above and below the aircraft
  – If stratus is present at the top of the MBL, the aircraft must fly above the MBL to detect changes of the MBL height.

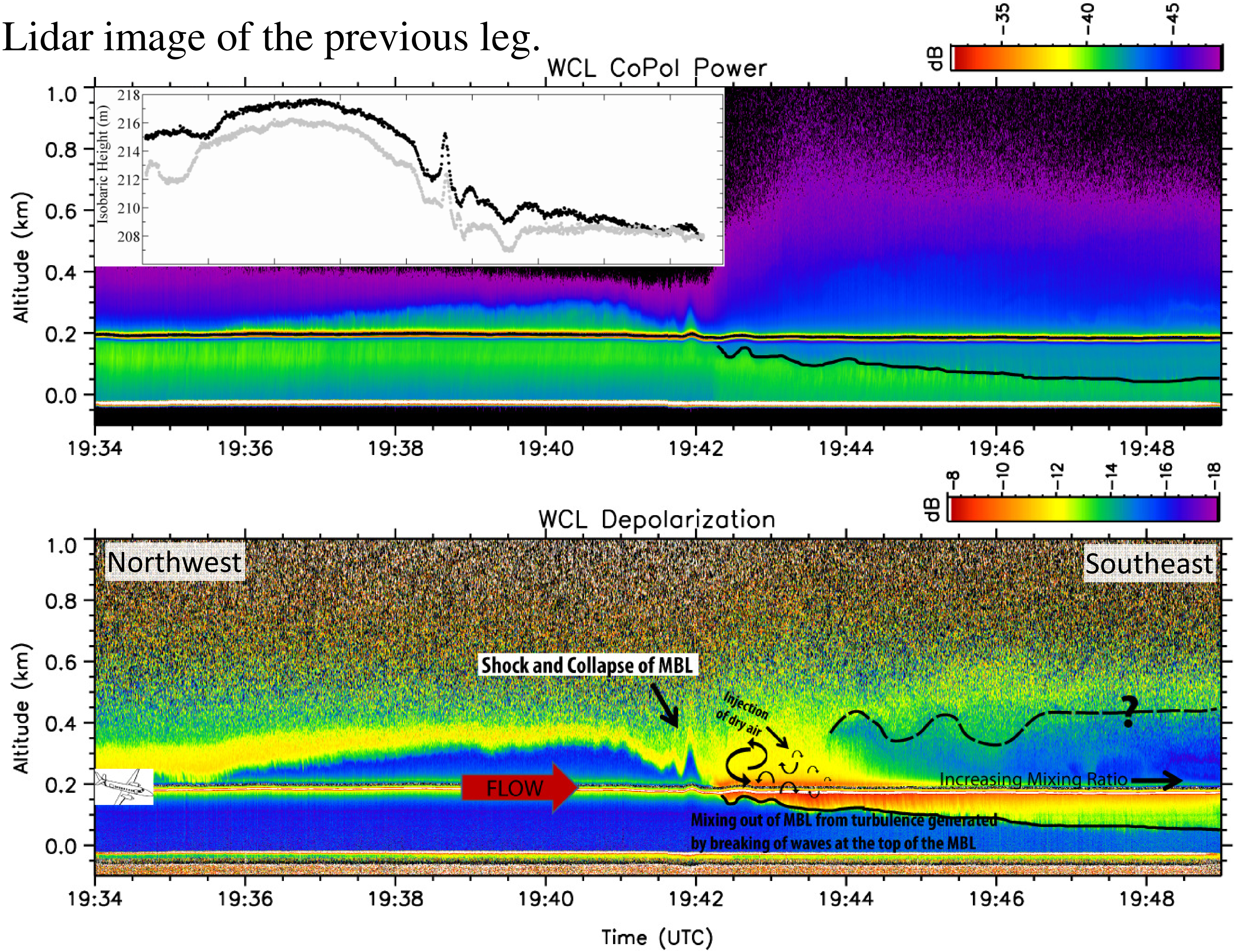
- Wyoming Cloud Lidar (WCL, 355 nm) was configured with upward and downward pointing beams.

- Lidar data is combined with INS/GPS data to produce time-height images of the (uncalibrated) attenuated backscatter and depolarization.



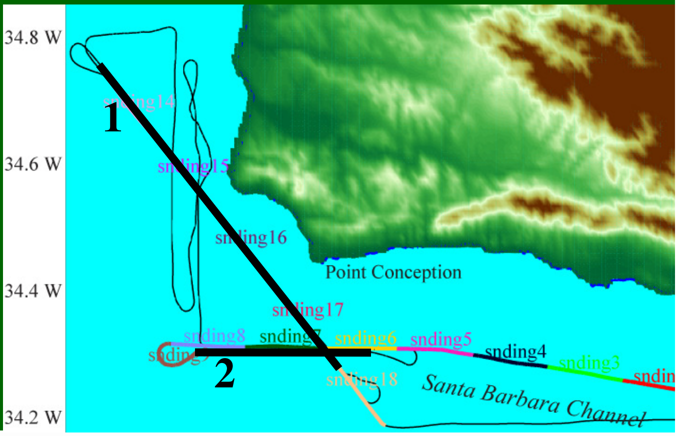
Wang et al. 2012, BAMS

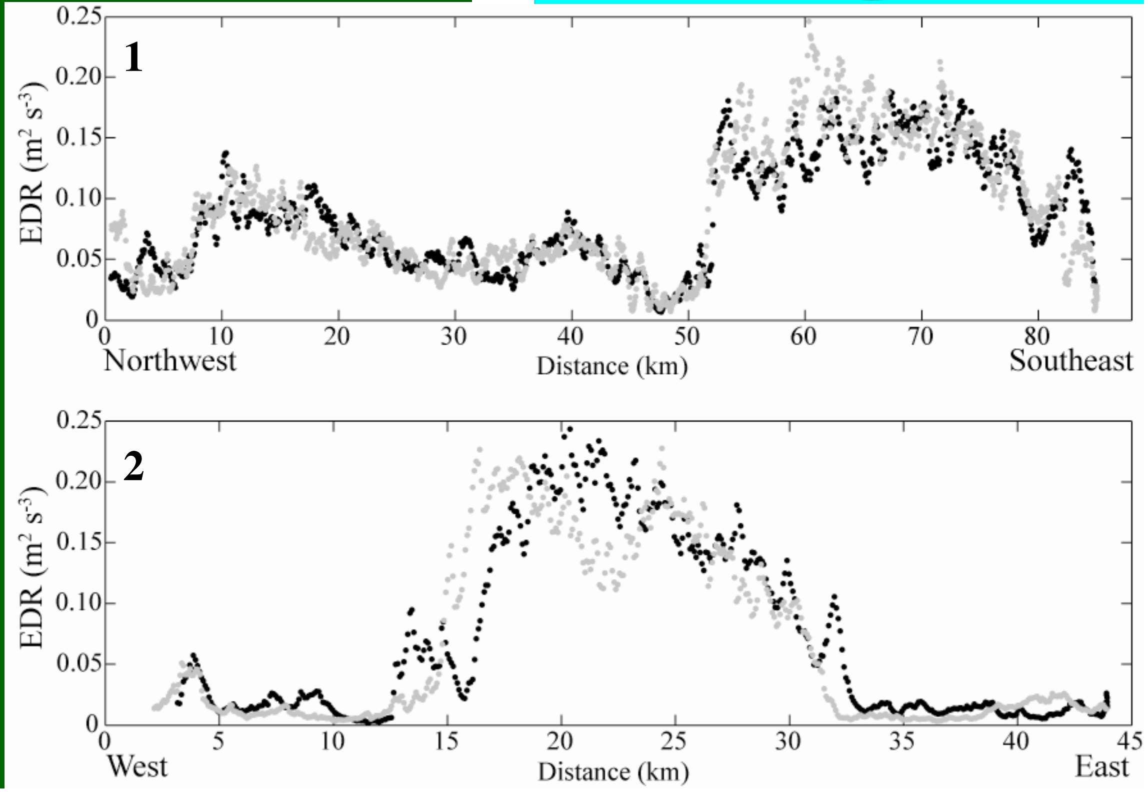
Lidar image of the previous leg.



Turbulence Measurements

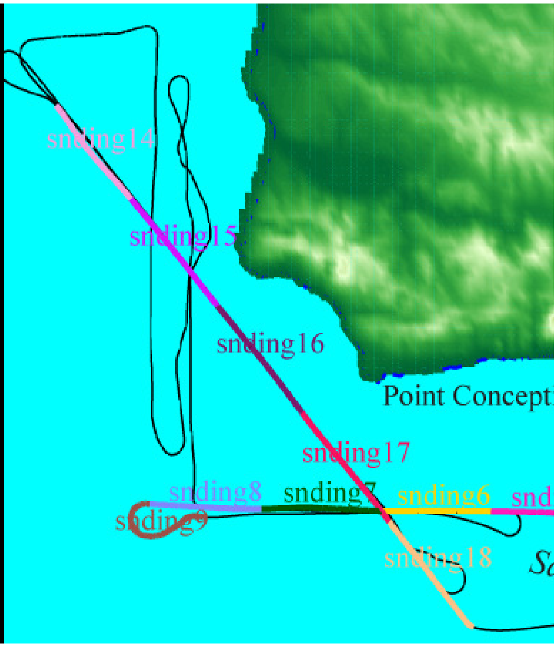
- Eddy dissipation rate (EDR) obtained from the MRI probe.
- Maximum of turbulence downwind of the jump, which decreases eastward.
- This confirms the interpretation of strong turbulence and mixing just after the MBL collapse.
  - Aerosols mixed out of the MBL and dry air mixed down.
- Implications for two-layer model?

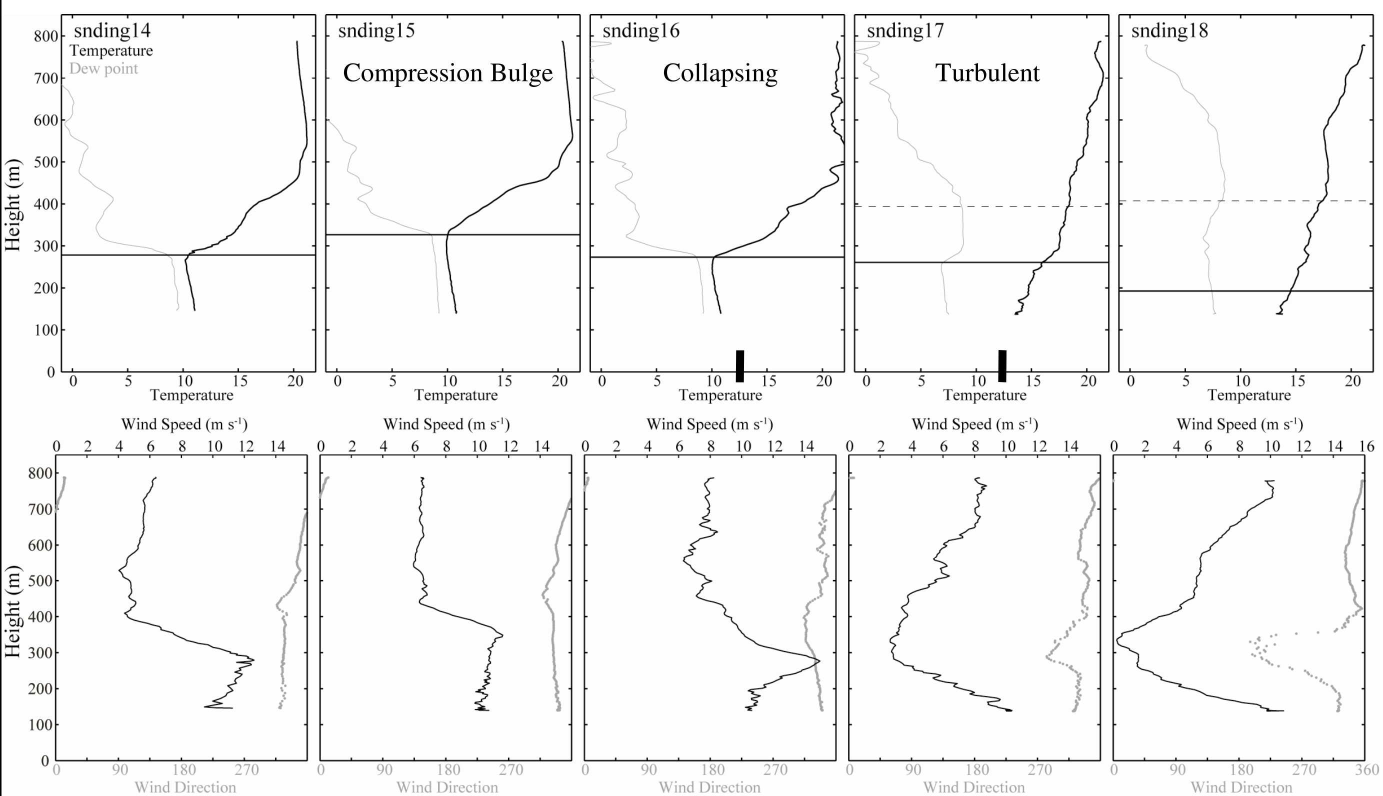




Soundings

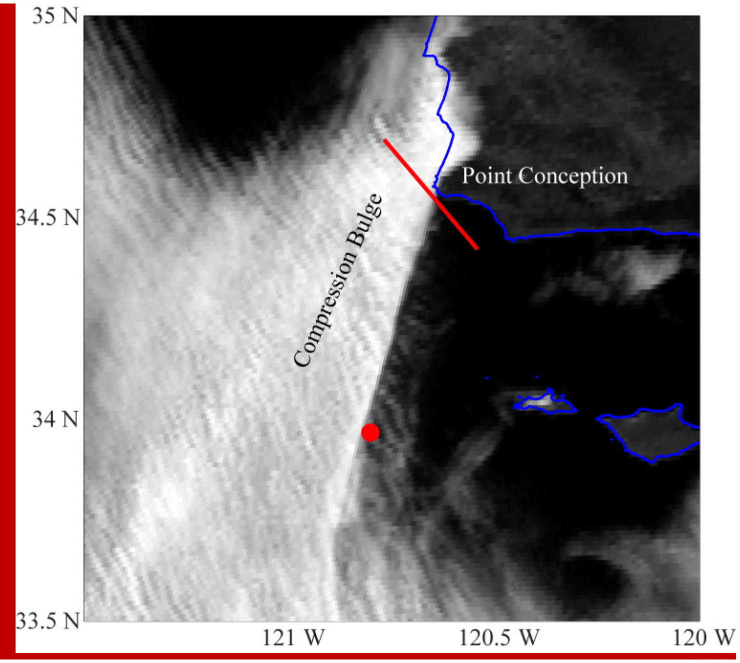
- Soundings depict the compression bulge and collapse of the MBL along with the strengthening of the wind near the collapse.
- After the collapse, the concentrated capping temperature inversion becomes a deep inversion.
- Dew point suggests layers, but not clear.
- Northwest wind still strong near the surface.
- Are there still two layers after the collapse?



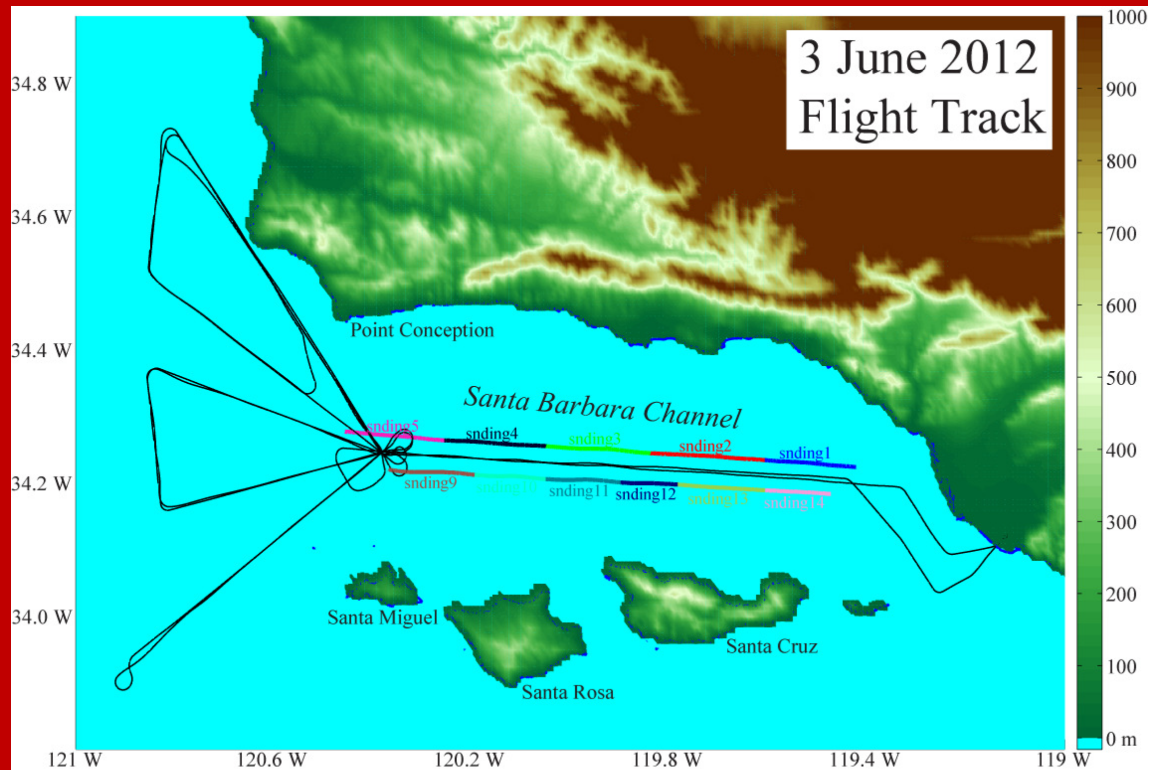


3 June 2012

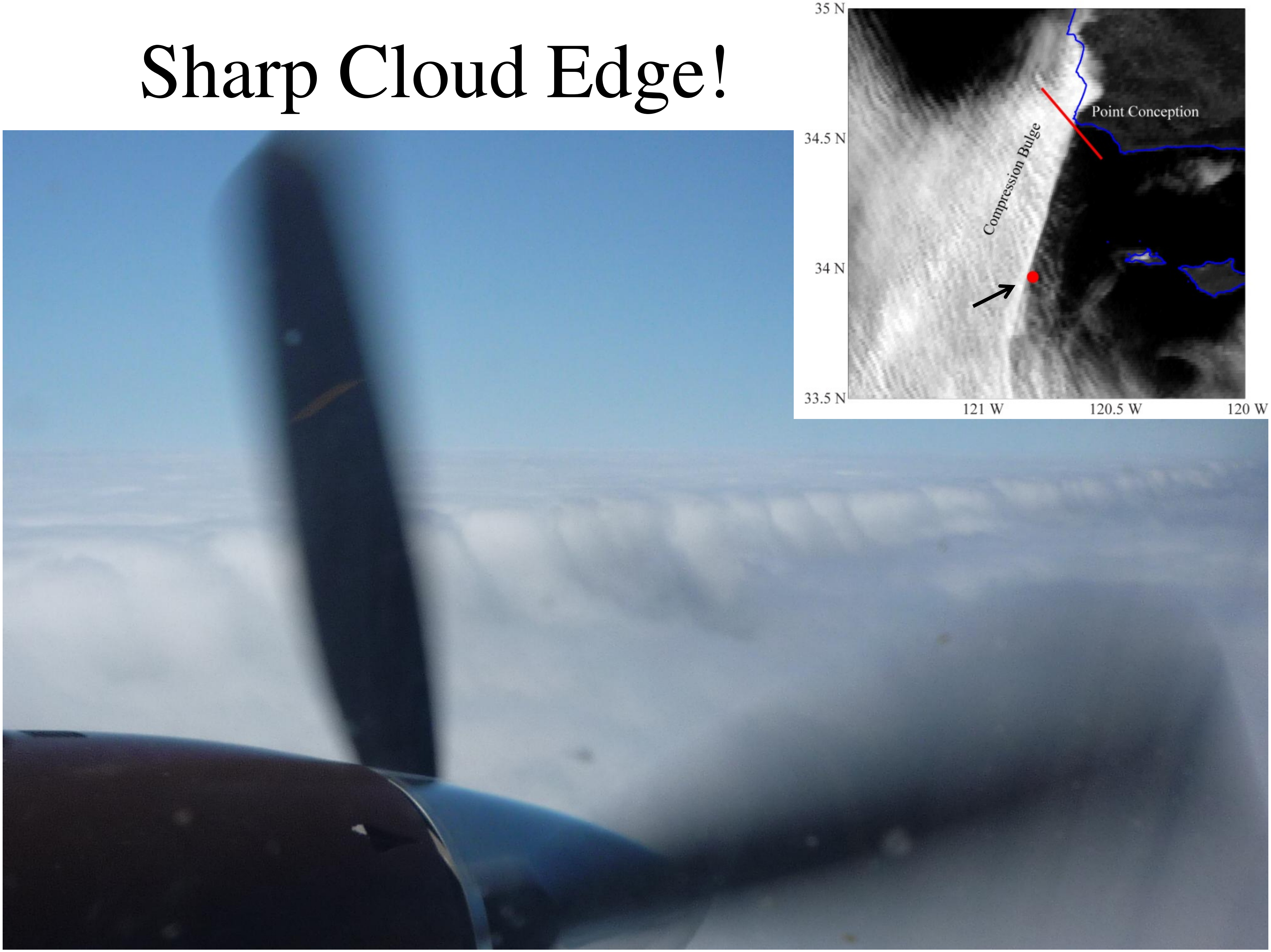
- A sharp cloud edge can manifest during strong northwesterly flow.
  - The compression bulge deepens the MBL enough to reach the LCL.
  - The cloud edge is associated with the collapse into the expansion fan.



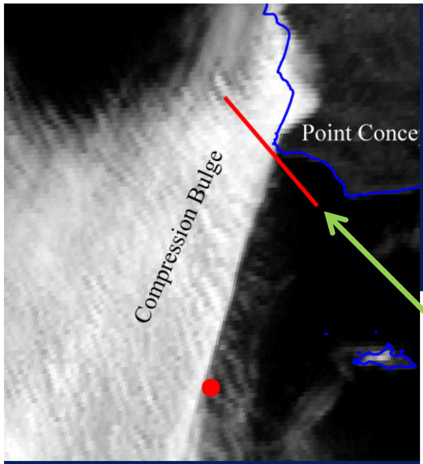
- A “spoke pattern” was flown to capture the variations along the cloud edge.
- Soundings were taken on the ferry out and back.



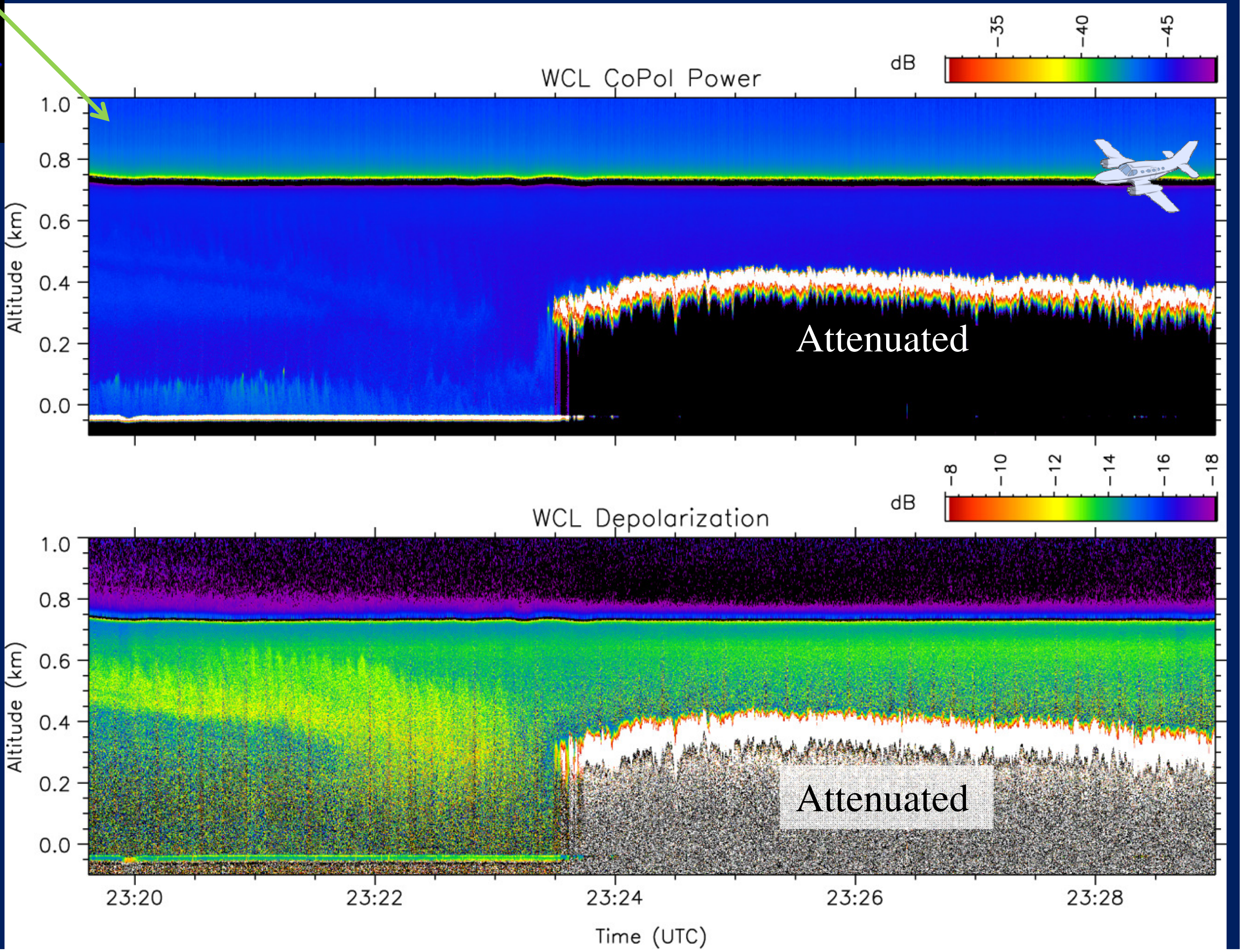
Sharp Cloud Edge!



MBL Collapse

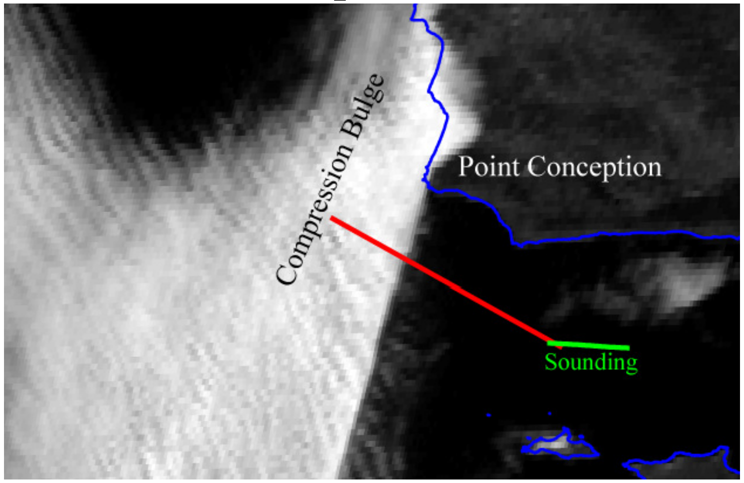


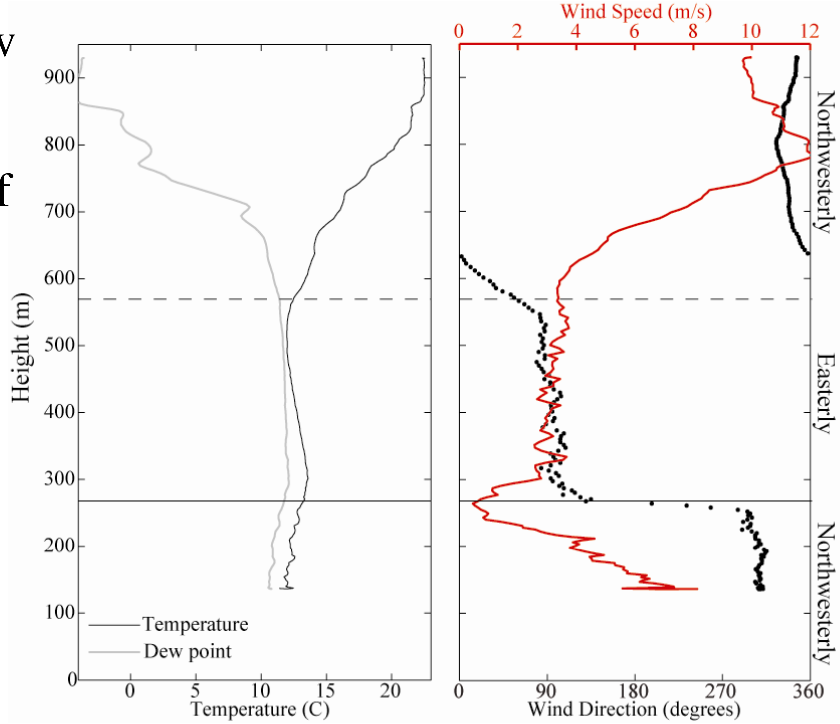
- Nearly vertical drop at cloud edge.
  - 400 m to 100 m
- Another MBL layer to the southeast (?).
- High depolarization seen again downwind of the collapse.

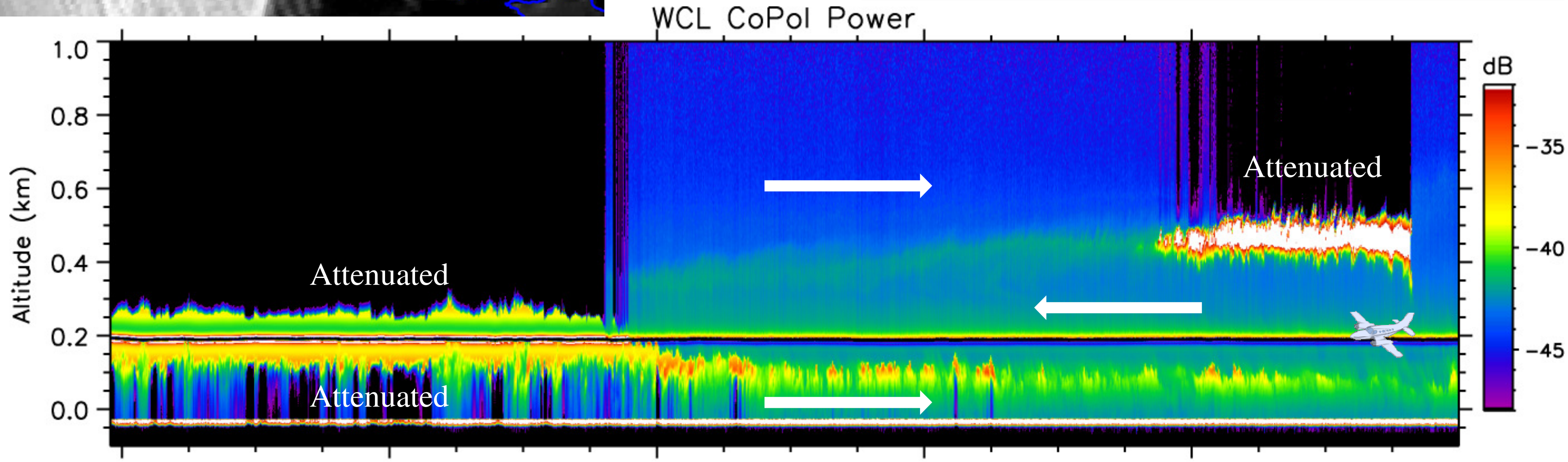


3-Layer System

- Three distinct layers
  - Warm and dry free troposphere with north-northwest flow
  - Cool and moist marine layer with easterly flow originating from the channel
  - Cooler and moist marine layer with northwesterly flow originating from upwind of Pt. Conception.





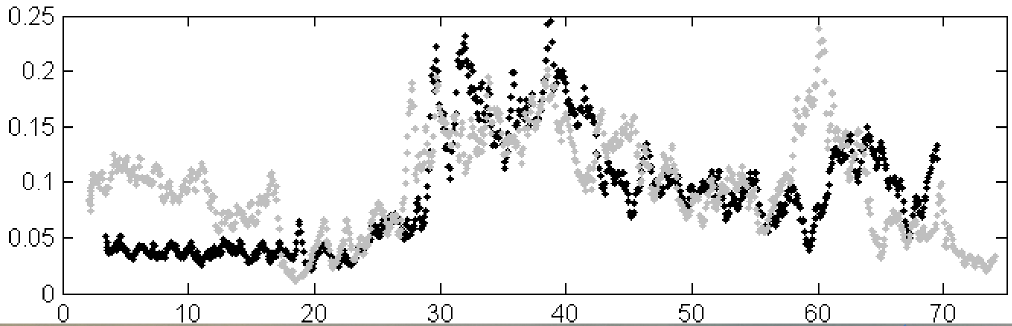


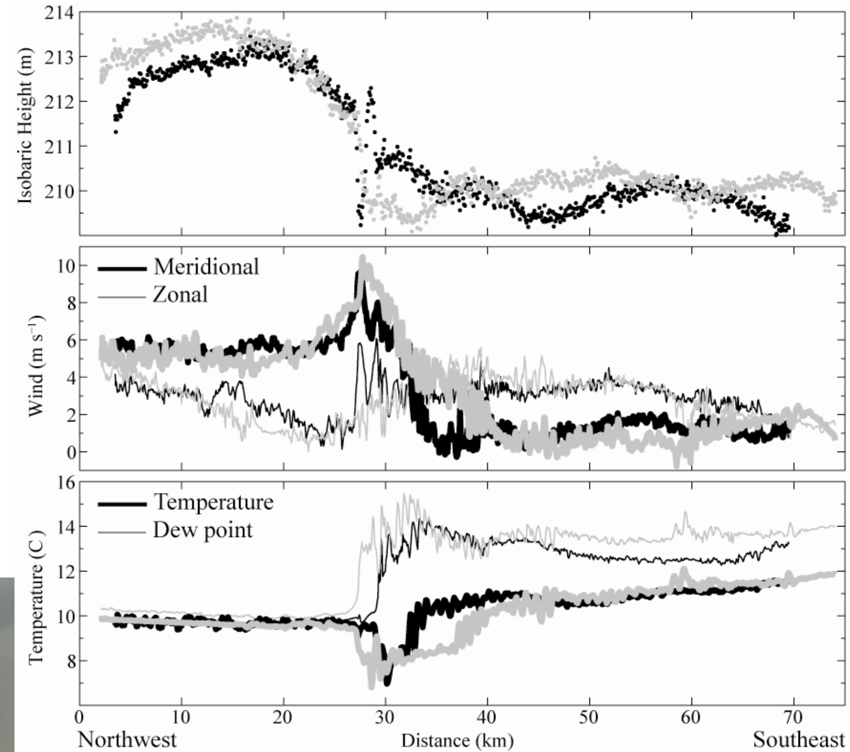
Summary

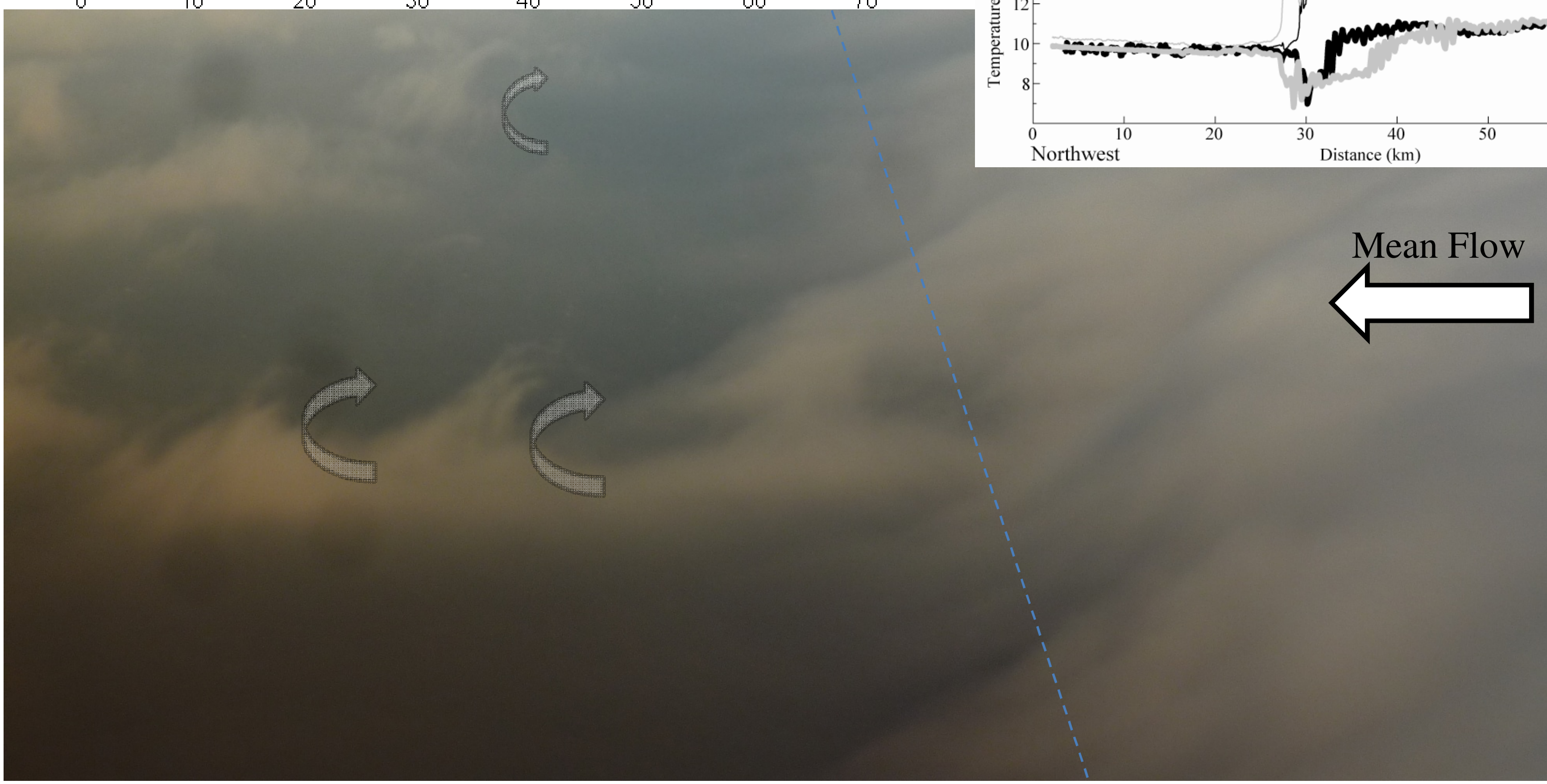
- Two-layer shallow water system with a lateral boundary
- Consistencies with the theory:
  - In situ and lidar measurements clearly show the compression bulge and collapse into the expansion fan.
  - Data applied to simple Bernoulli’s Equation to relate wind and height measurements.
- As the flow transitions around Pt. Conception there are departures from the ideal:
  - Enhanced mixing after the MBL collapses dilutes the sharp inversion separating the two layers.
  - Collapse of the MBL can be reinforced by opposing flow from the Santa Barbara Channel leading to an extremely sharp cloud edge.
    - If cyclonic circulation is common in the bight, this is likely why such sharp boundaries are often seen here, more than just a collapse into the expansion fan.

- Must consider the interaction of a three-layer system.
- Challenging to simulate such a fine scale feature!

Visual Evidence of Turbulence







Santa Barbara Channel

- Soundings indicate deep marine layer in the channel and possibly several layers.
- Light southerly wind component in the east.