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

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• **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
      \[
      Fr = \frac{U}{c} = \frac{U}{\sqrt{g' H}}
      \]
      \[
      g' = \frac{\theta_{\text{inversion \_ top}} - \theta_{\text{MBL}}}{\theta_{\text{MBL}}}
      \]
      
      - 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

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \omega \frac{\partial u}{\partial p} = -g \frac{\partial z}{\partial x} + f v
\]

- 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.
Lidar image of the previous leg.

Northwest

Southeast

Shock and Collapse of MBL

Injecting of dry air

Increasing Mixing Ratio

Mixing out of MBL from turbulence generated by breaking of waves at the top of the MBL

Flow
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!
• 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.
• 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

Mean Flow
Santa Barbara Channel

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