Characterization of the Afternoon to Evening Transition (AET) of the Planetary Boundary Layer over N AL and Implications for Convective Maintenance, Enhancement, and Initiation

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Outline & Motivation

• Background:
  – Diurnal BL, AET
  – CBZs, Cl

• N Alabama AET characterization
  – Data & methods
  – Results & summary

• Case studies: CBZs during AET
  – Data & methods
  – Results & summary

• Simulation exercise

• Conclusions

  • Extend relatively limited previous observational work characterizing AET
    – **H1**: During transition, surface wind speeds decrease while winds above surface layer increase

  • Evaluate CBZ structure & kinematic changes to assess AET effects that may encourage maintenance, CE, or Cl
    – **H2**: In AET, existing CBZs display an increase, or at a minimum a lack of or delay in a decrease, in horizontal wind convergence above the surface layer
    – **H3**: Decay of BL eddies renders CBZs more slabular
Diurnal BL Structure

- **Distinct regimes**
  - Wangara (Clarke et al. 1971), Flatland (Angevine et al. 1998), CASES-99 (Poulos et al. 2002)

- **Daytime CBL:**
  - Thermal plumes, eddies
  - Well mixed variables
  - Nearly continuous turbulence

- **Nighttime NBL:**
  - Stably stratified, LLJ
  - Some variability
  - Turbulence bursts or very little at all

- **Surface Layer:**
  - Sharpest gradients
  - Traditionally lowest 10%

- All driven by the surface heat flux → rise, set of the sun

TKE budget:

\[
\frac{\partial e}{\partial t} + \frac{\partial e}{\partial x_j} = +\delta_{i3} \frac{g}{\theta_v} (u_i' \theta_v') - u_i' u_j' \frac{\partial u_i}{\partial x_j} - \frac{\partial (u_j' e)}{\partial x_j} - \frac{1}{\rho} \frac{\partial (u_i' P')}{\partial x_i} - \varepsilon
\]

Only ways to get turbulence on non-local scales

Daytime CBL

- **Buoyant** TKE production dominates in ML
- Some mechanical TKE production in surface layer
- Scaling linked to values representative of thermals

\[
w^* = \left[ \frac{g z_i (w' \theta_v')_{sfc}}{\theta_v} \right]^{1/3}
\]

\[
t^* = z_i / w^*
\]

Nighttime NBL

- **Mechanical** TKE production
- Buoyancy becomes a loss term upon inversion formation
- More structural variability
- Scaling linked to vertical turbulent momentum fluxes

\[
u^* = \left[ \frac{u' w'_{sfc}^2 + v' w'_{sfc}^2}{2} \right]^{1/4}
\]

Afternoon – Evening Transition (AET)

- So, when is the AET?
  - Multiple definitions: Reversal of sign sfc heat flux (or a proxy of) most common
  - Best AETs: clear sky, light winds, homogeneous areas
- Early modeling studies struggled to reproduce Wangara observations
  - AET ≠ instantaneous collapse
- Tethersonde, 915 MHz profilers:
  - Turbulent fluxes in top half of CBL decrease w/ sfc heat flux, BL depth decreases \( \rightarrow \) eddies, upward turbulent transport diminish
  - ↓ magnitude & variability of 915 return aloft, can begin several h before SS

Less mixing \( \rightarrow \) less sfc WV sink \( \rightarrow \) humidity jump

“Decay of Convective Turbulence”
(Nieuwstadt & Brost 1986, Sorbjan 1997)
- Vertical components decay first, faster
- As \( t^* \) increases, TKE decreases

Afternoon – Evening Transition (AET)

- Consistent pattern through 30 UAH AETs (Busse 2010, Busse & Knupp 2012):
  - Sodar backscatter minimum, w/in 30 min have:
    - Decrease: $U^2$, T, $T_2 - T_{10}$
    - Increase: $r_v$, stratified structure
    - Warmer days $\rightarrow$ longer AET

- AET challenge for models
  - SCM: T profile curvature
  - LES: surface wind speeds
  - Faster decay in vertical turbulent components
  - $w^*$, $t^*$ “inappropriate” in AET

- “afternoon” & “early evening” (Nadeau et al. 2011)
  - ~const., then accelerating TKE decay rate
  - Vertical turbulent components decrease faster

Example of CBL demise with minimum in Sodar return power from Busse & Knupp (2012)

**H1 & H2:** expect an increase in wind speeds above the surface layer

Why do we expect waning surface heat flux and decaying BL turbulence to result in an increase in winds above surface layer?

Mean wind:

\[
\begin{align*}
\frac{\partial \bar{u}_i}{\partial t} + u_j \frac{\partial \bar{u}_i}{\partial x_j} &= -\delta_{i3}g + f_c \varepsilon_{ij3} u_j - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} - \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial u_i}{\partial x_j} \frac{u_i'}{u_j'} \\
\end{align*}
\]

Turbulent momentum flux:

\[
\begin{align*}
\frac{\partial u_i u_k'}{\partial t} + u_j \frac{\partial u_i u_k'}{\partial x_j} &= -u_i u_j' \frac{\partial u_k'}{\partial x_j} - u_k u_j' \frac{\partial u_i'}{\partial x_j} - \frac{\partial u_i}{\partial x_j} \frac{u_i'}{u_j'} + \frac{g}{\theta_v} \left[ \delta_{k3} u_i \theta_v' + \delta_{i3} u_k \theta_v' \right] \\
&+ \frac{p'}{\rho} \left( \frac{\partial u_i'}{\partial x_k} + \frac{\partial u_k'}{\partial x_i} \right) - 2 \varepsilon_{u_{ik}}
\end{align*}
\]

Vertical momentum variance:

\[
\begin{align*}
\frac{\partial \bar{w}^2}{\partial t} + u_j \frac{\partial \bar{w}^2}{\partial x_j} &= 2g \frac{\bar{w} \theta_v'}{\theta_v} - 2\bar{w}' u_j \frac{\partial \bar{w}}{\partial x_j} - \frac{\partial \bar{w} u_j'}{\partial x_j} - \frac{2 \partial \bar{w} p'}{\rho} - \frac{2 p' \partial \bar{w}}{\rho} - 2 \nu \left( \frac{\partial \bar{w}}{\partial x_j} \right)^2
\end{align*}
\]

When thermals dominate:
-- Vertical turbulent components large
-- Buoyancy terms as source

As sfc heat flux decreases: (assume little other forcing & initially unif. wind profile)
-- Decreasing vertical fluxes contribute to decrease in mean wind
  \( \rightarrow \) at sfc first, fastest bc sfc fluxes experience most abrupt change
  \( \rightarrow \) buoyancy becomes a loss term

Communicated through BL:
-- initially on \( t^* \) scale, but increases when & where sfc heat flux decreases
  \( \rightarrow \) sfc begins to decouple

Develop sheared wind profile:
-- Increases mechanical source aloft for turbulent momentum fluxes
-- Flux terms then support an increase in mean wind above surface layer

\[
\begin{align*}
\text{Communicated through BL:} & \quad w^* = \left[ \frac{g z_s (\bar{w} \theta_v')_{sfc}}{\theta_v} \right]^{1/3}
\end{align*}
\]
CBZs & CI: Early Work

- **Prominence along boundaries**: within ~15 km (Byers & Braham 1949, Purdom & Marcus 1982, Wilson & Schrieber 1986)
- **Boundary Collisions**: often promote CI, but not always
- **Significance of low level moisture ($r_v$), convergence**
  - Modest variations (1-2 g/kg, 1-2 m/s) along parent CBZ affect resulting cells’ vertical extent or Cu formation (Lee et al. 1991; Weckwerth et al. 1996, 1997)
  - Vertical T & $r_v$ gradients, horizontal flow & stability above CBZ influence depth of lifting (Crook 1996, Crook & Klemp 2000)
  - Soil moisture variability, mesoscale solenoid → N AL MCS (Knupp et al. 1998)
- **CBZ motion direction** & ambient shear-induced vorticity
CBZs & CI: Early Work


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- **CBZ motion direction & ambient shear-induced vorticity**
CBZs & CI: IHOP

- **IHOP**: (Weckwerth et al. 2004, Weckerth & Parsons 2006)
  - CBZs contain enhanced low level $r_v$ & vertical motion (e.g. Karan & Knupp 2006, Knupp 2006, Weckwerth et al. 2008)
  - Misocyclones: (e.g. Arnott et al. 2006, Marquis et al. 2007, Buban et al. 2007)
    - Intersection of CBZ w/ large CBL eddies; ~0.5-4 km diameter
    - Prominence decreases with time…
  - “Slabularity” (Stonitsch & Markowski 2007)
    - Fraction of CBZ containing updraft; CBZ vs convective forcing
    - CBZs w/ weakening misocyclones become more slabular, more 2-D
  - **H3**: Decreasing sfc heat flux in AET $\rightarrow$ shuts down CBL eddies $\rightarrow$ expect existing CBZs less 3-D with time
CBZs & CI: IHOP


- IHOP: (Weckwerth et al. 2004, Weckwerth & Parsons 2006)


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**H3:** Decreasing sfc heat flux in AET $\Rightarrow$ shuts down CBL eddies $\Rightarrow$ expect existing CBZs less 3-D with time
CBZs & CI: IHOP & beyond

• **Local forcing**: (Markowski et al. 2006, Xue & Martin 2006, Weckwerth et al. 2008)
  – Dryline & outflow intersection – *Cu but no Cb due to lack of “persistent, spatially continuous corridor of mesoscale ascent”*
  – CBZ made CI more likely, local circulations (BL rolls) force CI

• **CBZ Collisions**:
  – CI best correlated w/ balanced horizontal circulations (Wakimoto & Murphey 2010)
  – Parent/daughter CBZs sfc-based, evolve to wave features (Karan and Knupp 2009)
  – CI more likely with smaller (<~80°) collision angle, higher Z in initial finelines, pre-existing Cu field (Harrison et al. 2009)

• **DC-B-SW continuum**
  – Avenue through which “active convective systems can survive after sunset, and can even intensify”

• **Vertical displacements destabilize NBL**:
  – Gust front evolution to bore (N 0.011 s⁻¹), solitary wave (N 0.018 s⁻¹) (Knupp 2006)
  – Bore as destabilization, CI mechanism (Koch et al. 2008, Marsham et al. 2011)
  – “the waves lowered the LFC and also made it easier for a parcel to reach it” (Coleman & Knupp 2011)
Present Study: Objectives & Hypotheses

• Extend relatively limited previous observational work characterizing AET
  – **H1**: During transition, *surface wind speeds decrease while winds above surface layer increase*

• Evaluate CBZ structure & kinematic changes to assess AET effects that may encourage maintenance, CE, or CI
  – **H2**: In AET, existing CBZs display an *increase, or at a minimum a lack of or delay in a decrease*, in horizontal wind convergence above the surface layer
  – **H3**: Decay of BL eddies renders *CBZs more slabular*
Observation Network

- **Surface measurements**
  - NSSTC Berm
  - Mobile meteorological measurements vehicle (M3V)
  - [KHSV ASOS]
- **MIPS:**
  - 915 MHz wind profiler (915)
  - Microwave profiling radiometer (MPR)
  - 3.17 cm X-band profiling radar (XPR)
  - 0.905 μm Lidar ceilometer
  - Soundings
- **1.5 μm Doppler wind lidar (DWL)**
- **Scanning radars:**
  - ARMOR (C-band)
  - MAX (X-band)
    - ARMOR back up site 3 km to west
  - RSA (S-band)
  - [KHTX (S-band)]
  - Dual-Doppler baselines:
    - MAX-ARMOR: 18 km
    - RSA-ARMOR: 14 km

Observational domain includes surface heterogeneities
(USGS NLCD, Fry et al. 2006)
CA AET Characterization: Methodology

• “Clear air” case criteria:
  – Minimal sky cover (< ~25%)
  – Light mean winds (< 5 m/s)
  – Minimal large scale forcing
    • Generally similar on synoptic scale, H over N AL & SE US
• Mar – Nov 2012, 2013 → 143 days
  – Not every platform available everyday
  – DWL: limited availability starting spring 2013 (only 30 cases)
  – SS -3/+2 h as generic AET interval (Busse 2010, Busse & Knupp 2012)

• Surface Data:
  – Variances (15 min): $T_2$, $T_{10}$, $U_{10}$
  – $T_2 - T_{10}$ difference
  – Mean $r_v$ (from MPR), difference from value at SS-3 h

• 915:
  – NIMA (Cornman et al. 1998, Morse et al. 2002) 10 min cns horiz wind magnitudes
  – Composite mean $w_{915}$ profiles
    • Interpolated to coarsest gate spacing used (106 m)
  – Variance of $w_{915}$ (at 200 m)

• DWL:
  – Composite mean $w_{DWL}$ profiles
  – Variance of $w_{DWL}$ (at 195 m)

• ARMOR EVAD-derived horizontal wind convergence (Srivastava et al. 1986, Matejka & Srivastava 1991)
  – ~60% area within 20 km

• Quartile analysis in 20 min bins relative to sunset time
EVAD Process

- Editing – SoloII
- EVAD processing completed via RadX software (Dixon 2010)
- Extended Velocity-Azimuth Display technique (Srivastava et al. 1986, Matejka & Srivastava 1991)
  - Linear flow assumption
  - 10 km radius used to compute meso-γ-scale convergence

\[ V_r(\phi) = (u \sin(\phi) + v \cos(\phi)) \cos(\theta) + w \sin(\theta) \]  
\[ V_r = \frac{1}{2} a_0 + \sum_{n=i}^{\infty} (a_n \cos(n\phi) + b_n \sin(n\phi)) \]

\[ a_0 = \frac{r}{2} \cos(\theta) (\nabla V_h) + w \sin(\theta) \]
\[ a_1 = u_0 \cos(\theta) \]
\[ b_1 = v_0 \cos(\theta) \]
\[ a_2 = \frac{r}{2} \cos(\theta) \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) \]
\[ b_2 = \frac{r}{2} \cos(\theta) \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \]
\[ \nabla V_h = \frac{-a_1^2 + b_2^2}{\cos(\theta)} \]  
\[ \delta = \frac{\pi}{2} - \tan^{-1} \left( \frac{a_1}{b_1} \right) \] for \( b_1 < 0 \)
\[ \delta = \frac{3\pi}{2} - \tan^{-1} \left( \frac{a_1}{b_1} \right) \] for \( b_1 > 0 \)

Errors: mainly if non-linear flow, not steady-state, also random sampling errors, beam propagation effects

Figures from Doviak & Zrnic (1993)
CA AET Characterization: Data Availability

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<th></th>
<th>Total cases</th>
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<tr>
<td>2013 Summer</td>
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<td>2013 Autumn</td>
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<td>2012–2013 Spring</td>
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<tr>
<td>2012–2013 Summer</td>
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<td>2012–2013 Autumn</td>
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<tr>
<td>2012–2013 Mar-Nov</td>
<td>143</td>
<td>140</td>
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</table>
Results: CA AET Characterization

• TKE analog \( \tau = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \)
• Accelerated decay \( \sim 100 \) min before sunset, slightly later in spring/fall
  – Minimum by 20 min post-SS
• End of AET vs. start: \( \sim \)order less
• Nadeau et al. (2011)
  – Afternoon: decreasing surface heat flux
  – Early evening: negative surface heat flux
CA AET

- Surface $r_v$: 12% (1 g/kg) increase across AET, begins ~80 min pre-SS
  - Short-term jumps
  - Earlier start in spring
  - Summer: largest change, smallest range of values
- Continued evaporation with decreased vertical mixing → build up of $r_v$ (increase continues after SS)
- Previous observations:
  - Jumps near time of $T$ inflection; surface heterogeneity impacts
    - Fitzjarrald & Lala (1989), Acevedo & Fitzjarrald (2001)
  - Range (±2 h) of “jump”
    - Busse (2010), Busse & Knupp (2012)
Results: CA AET Characterization

- 2 m & 10 m T difference as surface heat flux proxy
- Initial inversion by ~20 min before sunset
  - Steadies by ~1h post-SS
  - Weakest in summer (0.2°C vs 0.4°C), not on all days*

- T variance at 10 m initially greater than at 2 m
- 10 m variance declines faster
  - Decreased vertical mixing
  - Ahead of accelerated vertical, horizontal wind fluctuation decay
  - Sodar minimum*
- Minima by 20 min pre-SS
- Very modest increase after SS (spring T_{10})

*Busse(2010), Busse & Knupp (2012)
• $w_{915}^2$: rapid decline, minimum IQR at SS bin, increase after ~40 min post-SS (spring, fall)

• $w_{DWL}^2$: initial increase, then < 0.01 m² s⁻² by SS

• 915 sensitive to particulate scatterers: 33 cm vs 1.5 μm

• Vertical wind fluctuations decay faster than horizontal (e.g. Nieuwstadt & Brost 1986, Pino et al. 2006)
• Tower in composite mean $w_{DWL}$ at AET start
• CBL thermals (deeper in summer, consistent with increased variance at -160 min bin)
• Final implication of thermals: 1 h pre-SS
• Persistent up, down layers below 400 m
  – Manifestations of local effects
mean $w_{915}$
black: 0 m/s
grey: 0.5 m/s

- Tower of composite mean $w_{915} > 0$: ~35 min post-SS
  - Strongest in spring, above 600 m
  - Summer: $w_{915} < 0$ again after 60 min post-SS

- “Tale of two platforms”
  - 915 includes Bragg, particulate scattering effects
  - DWL represents true air motion

• 10 min consensus horiz. wind magnitudes
  – Steady increase at 300 m (~1.5-2 m/s)
  – ~20 min post-SS: $|U_{915}| > 5$ m/s at 300 m
  – spring cases: stronger, more depth
  • Enhanced PBL shear, may help account for late AET variability increase near sfc ($T_{10}$)
• Meso-γ scale convergence at 300 m
  – Subtle, but steady, increase
  – Not all cases, broad ranges at all time bins
• Effective mean increase through AET: $0.3 \times 10^{-3}$ m s$^{-1}$ h$^{-1}$
  – Statistically significant at $p=0.01$ ($t=4.63$, df=202, $p<0.01$)
  – Case selection: H pressure over AL/SEUS

mean $|U_{915}|$
black: 5 m/s
• \( T_{10}, T_2 \) variances: sharpened decline
• Vertical velocity fluctuations decay faster, at faster rate than in horiz.
• Accelerated horizontal decay
  – Reduced thermals inhibit vertical mixing \( \rightarrow \) buoyancy becomes loss term in \( \overline{w'^2} \) budget
  – \( \overline{u'^2} \) decreases with less vertical, turbulent transport, slower rate bc still have mechanical source
• Achieve minimum \( \overline{w'^2}, \overline{u'^2} \) by \(~20\) min after sunset \( \rightarrow \) higher \(|U|\)
• Subtle, steady convergence increase

\[ \text{Summary: CA AET} \]

Overall Average Sunset Relative Time of Occurrence

\[
\begin{align*}
100 \text{ min before SS:} & \quad \text{Fastest } U'^2 \text{ decline rate begins} \\
80 \text{ min before SS:} & \quad \text{increase in mean } r_0 \text{ begins (up to 1 hr earlier in spring)} \\
20 \text{ min before SS:} & \quad \text{variance of } T_{10m} \text{ reaches minimum} \\
20 \text{ min before SS:} & \quad \text{range of 915 vertical motion variance reaches minimum} \\
60 \text{ min before SS:} & \quad \text{layer upward DWL vertical velocity forms & persists} \\
60 \text{ min before SS:} & \quad \text{last coherent positive DWL vertical motion through 300 m AGL} \\
35 \text{ min after SS:} & \quad \text{300 m AGL horizontal winds exceed 5 m s}^{-1} \\
\text{Throughout Entire Time Period:} & \quad \text{steady increase in low level meso-\( \gamma \) scale convergence & 300 m AGL horizontal wind speed}
\end{align*}
\]

• More heterogeneity = more complicated AET pattern, e.g. Brazel et al. (2005)

\( \rightarrow \) Implications for pre-existing convergent boundaries? … \( H2, H3 \ldots \)
CBZs in AET: Methodology

• Evaluate CBZ kinematic changes during AET:
  – H2: increase, or at a minimum lack or delay in decrease, in horizontal wind convergence above the surface layer
  – H3: CBZs should become more slabular, less 3-D

• Case studies of boundaries in ABIDE network during AET

<table>
<thead>
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<th>Case Date</th>
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CBZs in AET: Methodology

• Kinematic & thermodynamic characteristics pre-, post-, & CBZ structure
  – Time series & profiler measurements
    • 10 min MPR averages: LCL, LFC, CAPE, CIN (RAOB), 1 min MPR: LCL, Brunt-Vaisala
  • Estimate CBZ motion from Z fineline [Vr gradient]
• Single-Doppler:
  – EVADs (as in CA study, Srivastava et al. 1996, Matejka & Srivastava 1991)
  – 2-D vertical plane analysis (e.g. Knupp 2006, Karan & Knupp 2009)
• Dual-Doppler: (e.g. Armijo 1969, Miller & Stauch 1974, Ray et al. 1980, Testud & Chong 1983…)
  – 3-D wind field, horizontal convergence, vorticity
    • 0.25 x 0.25 x 0.20 km spacing, variational integration (BC: 0.5*Δz*conv)
  – Spatial means along each CBZ
  – SD v DD comparisons
• Visual observations: Photographs & field notes of cloud field character
• H2: increase, or lack of decrease, in convergence above sfc layer along CBZ leading edge
• H3: more slabular, less 3-D, with time
Dual-Doppler Process

- Editing, gridding – SoloII, REORDER (Oye et al. 1995)
  - Spacing: 0.25 x 0.25 x 0.20 km, origin at ARMOR [or MAX]
  - Dimensions vary by case, radar pair

  - Independent measurements of same flow
  - Vertical integration of continuity to get w
    - Variational approach
    - BC: 0.5*Δz*conv at top & bottom
  - Kinematic computations from 3-D winds
  - Spatial means (~24 km², moving box) along CBZ
  - Baseline distance, beam width: coverage, resolution

\[
A(\beta) = 2(d \csc(\beta))^2 (\pi - 2\beta + \sin(2\beta))
\]

\[
s = R\Delta \frac{\pi}{180}
\]

\[
\begin{align*}
V_{r1}(x, y, z) &= \frac{1}{r_1} [xu + yv + z(w + V_r)] \\
V_{r2}(x, y, z) &= \frac{1}{r_2} [(x - x_2)u + yv + z(w + V_r)]
\end{align*}
\]

assumed Z-V relation, 2 eqns, 3 unknowns underdetermined system

\[
\begin{align*}
u &= \frac{1}{x_2} (r_1 V_{r1} - r_2 V_{r2}) \\
v &= \frac{1}{yx_2} [(x - x_2) r_1 V_{r1} + x r_2 V_{r2}] + \frac{z}{y} (w + V_r)
\end{align*}
\]

mass continuity eqn

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \left( - \frac{\partial \ln(p)}{\partial z} \right) w
\]
30-31 August 2013

- 2 CBZs in network during AET
  - CBZ1: density current
    - Stalls, dissolves ~2300-2330
  - CBZ2: develops wave-like characteristics later in AET
- ARMOR, MAX, RSA
  - 2 sets of DD lobes
- MIPS: at NSSTC berm
  - Including XPR
- DWL from NSSTC - RAPCD lab
- M3V operations
- Sunset: 0015 (7:15 pm)
- -3/+2 h interval: 2115-0215
30-31 August:

CBZ1: 2113
CBZ2: 2330
SS: 0015

- Late CBL: mixed to 1.5 km, thermals 2 m/s
- CBZ1: cleaner, cloud, $w_{DWL}$ 8+ m/s

rise starts before wind shift

5°C

2.3°C

wind speed inc.
over 6 m/s

shift to NEly
30-31 August:

- CBZ1: 2113
- CBZ2: 2330
- SS: 0015

- CBZ2: more subtle at surface, sustained modest upward $w_{DWL}$ (< 1 m/s)
30-31 August:

CBZ1: 2113
CBZ2: 2330
SS: 0015

accumulation of scatterers implies rotor late CBL E compnt to 700 m, then ~300 m

max: 8.6 m/s

max: 4.6 m/s

max: 3.9 m/s
30-31 August:

**CBZ1**: 2113

**CBZ2**: 2330

**SS**: 0015

- subtle surface indicators
- shallow in MIPS 915 wind profiles

- 915 SNR, XPR Z consistent with lack of prominent fineline
- Sustained, modest upward motion (~25 min, < 1 m/s)

**late CBL**

more easterly below 500 m
30-31 August:

CBZ1: 2113
CBZ2: 2330
SS: 0015

- **CBZ1**: $T$, $r_v$, $\theta$, $\theta_v$ changes begin same time as upward $w$ (2105)
- 2113: more cooling, $\uparrow r_v$ depth, min $\theta_v$ (depth consistent w/ $w_{DWL}$ rotor, 1.4 km), $\downarrow$ sfc LCL
- 700 m lift along 302 K isentrope
30-31 August:

CBZ1: 2113
CBZ2: 2330
SS: 0015

• CBZ2: lacks prominent $\theta_v$ gradient

• Above surface layer:
  – Isentropes rise ~200 m; $r_v \downarrow \uparrow$ $\downarrow$
  – After broad, upward w (0055):
    – cooling, drying above; sfc $r_v \uparrow$ 2 g/kg (sfc $T_d$ rise)
30-31 August:

CBZ1: 2113
CBZ2: 2330
SS: 0015

- CBZ1: T, r, θ, θ_v changes begin same time as upward w (2105)
- 2113: more cooling, ↑r_v depth, min θ_v (depth consistent w/ w_DWL rotor, 1.4 km), ↓sfc LCL
- 700 m lift along 302 K isentrope

ML parcel (lowest 100 mb)

- CBZ1:
  - Rapid cooling, moistening lowers LCL, LFC
  - Attendant cloud (ceilom, DWL, 915, XPR, MPR integrated liquid ~6 mm)
- CBZ2:
  - Slight increase in 0-3 km CAPE, lower LFC mainly due to changes in moisture profile
30-31 August sunset

- RSA-ARMOR northern DD lobe: 2057-2139
- Plan views at 200 m grid level
- Pockets of higher values → moderate slabularity
  - Consistent with other results in this domain
- Box area (24 km$^2$) for spatial means
30-31 August  
sunset  
CBZ1  
0015  
CBZ2

- CBZ-normal vertical planes
  - Convergence (grey): $1 \times 10^{-3}$ s$^{-1}$ interval
  - $w_{DV}$ (black): 0.4 m/s interval
- Vertical updraft, feeder flow, rotor
  - Density current features (SD, too)
30-31 August sunset 0015 CBZ1 CBZ2

- CBZ-normal vertical planes
  - Convergence
  - $w_{DV}$ (black)
- Vertical updraft, feeder flow, rotor

- Spatial means of convergence & vert. motion
- No increasing trend
  - Relatively young gust front, early in AET
30-31 August sunset CBZ1
0015 CBZ2

- RSA-ARMOR southern DD lobe: 2145-2322
- Initially very smooth, narrow; fields broaden, weaken (in magnitude, definition) with time
  - T drop: 2113: 5°C (MIPS), 2215: 1.5°C (KHSV)
  - Progression of Z fineline slows down
30-31 August sunset CBZ1

- Remnant vertical circulation
- Updraft less vertical with time, mainly in CBZ-relative context
- Ground-relative flow: maintains direction toward CBZ motion
30-31 August sunset 0015 CBZ1 CBZ2

- Remnant vertical circulation
- Updraft less vertical with time, mainly in CBZ-relative context
- Ground-relative flow: maintains direction toward CBZ motion

- No trend supportive of H2
  - Early in AET: 2115-0215
- Fields generally more slabular even as Z fineline begins to slow down, weaken
30-31 August sunset CBZ1 0015 CBZ2

- MAX-ARMOR northern lobe: 2221-2345
- CBZ fineline stalls, fades 2300-2330
  - Updraft gradually less vertically aligned
  - Lack of flow in direction of CBZ motion, in CBZ- & ground-relative perspectives
30-31 August sunset CBZ1 0015 CBZ2

- MAX-ARMOR northern lobe: 2221-2345
- CBZ fineline stalls, fades 2300-2330
  - Updraft gradually less vertically aligned
  - Lack of flow in direction of CBZ motion, in CBZ- & ground-relative perspectives
30-31 August sunset 0015 CBZ1 CBZ2

- MAX-ARMOR northern lobe: 2221-234
- CBZ fineline stalls, fades 2300-2330

Updraft gradually less vertically aligned
Lack of flow in direction of CBZ motion, in CBZ- & ground-

- No clear increase, but decrease is less severe:
  - RSA N & S lobes: $\sim 1 \times 10^{-5} \text{ s}^{-1} \text{ min}^{-1}$
  - MAX N lobe: $0.3 \times 10^{-5} \text{ s}^{-1} \text{ min}^{-1}$
30-31 August sunset CBZ1 0015 CBZ2

- RSA-ARMOR southern DD lobe: 2340-0015
  - Broad but coherent, widest $w_{DV} > 0$ sig. ~10 km across
- Vertical planes across low level conv, $w_{DV}$ sigs
  - Lack rotor or other density current characteristics (SD)
  - Generally upright updraft
  - Width refines slightly with time
30-31 August sunset CBZ1 CBZ2

- RSA-ARMOR southern DD lobe: 2340-0015
  - Broad but coherent, widest w DV sigs ~10 km across
  - Vertical planes normal to conv, w DV sigs
  - Lack rotor or other density current characteristics (SD)
  - Generally upright updraft
  - Widths refine slightly with time

- No increase trend, convergence decreases at rate 
  \( \sim 0.4 \times 10^{-5} \text{ s}^{-1} \text{ min}^{-1} \)
  - Less than half earlier, sharpest decrease rates
30-31 August  
0015  
sunset  
CBZ1  
CBZ2  

- Kinematics suggest more “propagative”
  - Sustained up, modest $p^\uparrow$ at MIPS, wave shape in $r_v, \theta$
  - $T$ trends: $\downarrow$ at MIPS, $-$ at KHSV, $\uparrow$ at M3V (yellow dot)
- Less wind shift; mags stronger (weaker) ahead (behind)
- Conv, vert. motion refine with time
  - modest $w (< 1 \text{ m/s within lowest } 1 \text{ km})$
30-31 August sunset 0015 CBZ1 CBZ2

- **S of baseline**: slight decrease (0.47 x 10^-5 s^-1 min^-1)
- **N of baseline**: clear increase (2.4 x 10^-5 s^-1 min^-1)
  - Nearly 5x rate of mean mesoscale increase in CA

**CBZ1**: early in AET
- Density current
- Less convergence decrease with time in AET
- H3: modest qualitative support

**CBZ2**: heart of AET
- Broad, subtle; wave-like
- H2: generally supported, but other process, too – complex
- H3: good qualitative support
9-10 July 2013

- Typical summer convection develops in afternoon
  - Outflow from storms to W moves through ABIDE during AET
  - CI along CBZ, ~11 km SSW of MAX
  - Late AET Cu development
- MAX, ARMOR (RSA not archived)

- MIPS: at Belle Mina site
  - XPR once at field location
  - 2 soundings
- DWL not available
- M3V operations
- Sunset: 0102 (8:02 pm)
- -3/+2 h interval: 2202-0302
9-10 July

CBZ@MIPS: 2349
SS: 0102

- W CBL flow backs to S

After CBZ, cell, \( w_{915} \), \( w_{XPR} \) suggest gravity waves

Late AET \( w_{915} \) enhanced \( \rightarrow \) supports Cu development
After CBZ, cell, $w_{915}$, $w_{XPR}$ suggest gravity waves

Late AET $w_{915}$ enhanced ➜ supports Cu development
9-10 July

CBZ@MIPS: 2349
SS: 0102

- Early in AET: low level $r_v$ ↑ as in CA cases
- MIPS sonde prior to CBZ arrival:
  - Ceilometer cloud base heights along CBZ agree w/ ML LCL  (Craven et al. 2002)
- Isentropes imply lifting at CBZ
- $\theta$ ($\theta_v$ similar): minimum 10 min post-CBZ
  - Precip not CBZ structure (no rotor)
- Decreasing stability ~1 km, after sunset

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LCL: 1050 m
LFC: 1244 m
0-3km CAPE: 68 J/kg
CIN: -8 J/kg

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9-10 July

- Peak conv, vert. motion in pockets at earlier times
- Cross-CBZ feature appears in vicinity of where cell initiates along the boundary, new cell at intersection
  - Base ARMOR: 30 dBZ by 2335
  - Base KHTX (85+ km away): 50 dBZ by 2343
- Kinematic fields generally more slabular with time
9-10 July

- CBZ-relative vectors
  - Lacks clear rotor, feeder flow
- $2 \times 10^{-3}$ s$^{-1}$ at least 2 km width
- Updraft vertically aligned
- Near new cell, multiple $w_{DV}$ maxima aloft

Conv (grey) at $1 \times 10^{-3}$ s$^{-1}$

$w_{DV}$ (black) at 0.4 m/s
9-10 July
CBZ@MIPS: 2349
SS: 0102

- 2345: photo from MIPS (looking as red arrow) as CBZ nears
  - ARMOR base Z ~45 dBZ
  - Cloud line noted as fairly linear

- Spatial means enhanced prior to CI
  - Convergence increase, clearer in vertical motion → may imply enhanced conv through deeper layer

- Interaction with cross-CBZ entity apparently aided CBZ
  - AET effects may support CBZ as a favorable CI location, but other local forcing required (Weckwerth et al. 2008, Xue & Martin 2006)
9-10 July

- MAX-ARMOR northern DD lobe: generally less along-line kinematic variability
  - [also better SD v DD comparisons]
  - Supported by visual observations/photos
- Persistent lack of rotor, feeder flow

Photo looking to NE from MIPS after CBZ & CI cell have passed

Highly slabular Cu line extends from the cell
9-10 July

- MAX-ARMOR northern DD lobe: generally less along-line
  - [also better SD v DD comparisons]
  - Supported by visual observations/photos
- Persistent lack of rotor, typical DC features

• Spatial mean convergence **fairly steady** through northern DD lobe
  - Within 1 h after sunset
  - Lack of prominent decrease supports minimum criteria for H2
Late AET Visual Convective Signal
- After SS: Sc \(\rightarrow\) castellanus \(\rightarrow\) Cu mediocris (photo) \(\rightarrow\) congestus
  - Ceilometer, \(w_{915}\), MPR
- DD, stationary avg box (10 km\(^2\))
  - Abrupt initial increase, but steady convergence & \(w_{DV}\) during Cu obs
Late AET Visual Convective Signal

- After SS: Sc → castellanus → Cu mediocris (photo) → congestus
  - Ceilometer, $w_{915}$, MPR
- DD, stationary avg box (10 km$^2$)
  - Abrupt initial increase, but steady convergence & $w_{DV}$ during Cu obs
9-10 July

Late AET Visual Convective Signal

- After SS: Sc → castellanus → Cu mediocris (photo) → congestus
  - Ceilometer, $w_{915}$, MPR
- DD, stationary avg box (10 km$^2$)
  - Abrupt initial increase, but steady convergence & $w_{DV}$ during Cu obs
- MIPS 0130 sounding:
  - Cooling 850-700 mb
  - saturated layer
  - destabilization (MPR-derived N)

↓ LCL by 840 m
↓ LFC by 270 m
↑ 0-3CAPE by 123 J/kg

obs. cloud base ~2 km → elevated, entrainment
Late AET Convective Signal:
- Spatial DD means (stationary box) are steady, MIPS profiles suggest enhanced upward motion
- Thermodynamics (MPR, sonde) indicate destabilizing late AET BL

CI Along Outflow ~1.5 h Before Sunset:
- Convergence increase along CBZ immediately before echo achieves 30 dBZ
- Apparent local, cross-CBZ feature
  - Weckwerth et al. (2008), Xue & Martin (2006)
- DD-derived convergence & vertical motion through southern & northern lobes:
  - Spatial means along boundary lack prominent decrease
  - Generally more coherence with time (consistent with visual Cu line character)
19-20 July 2013

- Hampton cove storm: 11pm +
- MIPS: at NSSTC
  - XPR started 2115
  - 0 Z sounding
- DWL not available
- Sunset: 0058 (7:58 pm)
- -3/+2 h interval: 2158-0258

KHTX 0312
• Late summer afternoon CBL
• Early AET resembles CA cases:
  – T variability, difference; |U| fluctuations, Td
• Clouds arrive ahead of CBZ, then deepen

• CBZ at KHSV ASOS (0115):
  – modest p rise, warming
• CBZ at MIPS/NSSTC (0145):
  – winds ↑ through 1.5km, most to ~600 m
  – Initially steady T, then decrease
19-20 July

SS: 0058  CBZ: 0145

- Cloud (base ~1.5 km) & likely biota targets
- Wave-like above ~1 km, after sfc sigs
- Sustained, modest up through 1.5 km: ~0.6 m/s ~8.5 min

'late CBL

early AET

CBZ

thermals to ±2 m/s

late CBL

early AET

CBZ

thermals to ±2 m/s

thermals to ±2 m/s
19-20 July

SS: 0058
CBZ: 0145

- MIPS/NSSTC sonde launched at 0000 UTC
  - Modest lingering instability ~1 h before sunset, albeit with some CIN
- With CBZ:
  - Slight T decrease, prominent $r_v$ increase (2+km)
  - Vertical isentrope, $r_v$ excursions ~1 km
19-20 July

SS: 0058
CBZ: 0145

With CBZ:
- Slight T decrease, prominent $r_v$ increase (2+km)
- Vertical isentrope, $r_v$ excursions ~1 km

ML (lowest 100 mb) parcel:
- LCL, LFC, |CIN| reduced; 0-3 km CAPE 200+ J/kg
19-20 July

SS: 0058  CBZ: 0145

- CI to S of MAX: 20+ dBZ by 0056
  - More coherence along CBZ at other times
  - Apparent cross-CBZ feature near new cell
  - Persistent upward $w_{DV}$ across CBZ
19-20 July

SS: 0058
CBZ: 0145

- CI to S of MAX:
  - More coherence along CBZ at other times
  - Apparent cross-CBZ feature near new cell
  - Persistent upward $w_{DV}$ across CBZ

- Temporary enhancements in spatial means, but no overall increase – or decrease – along the CBZ
  - Supports minimum H2 criteria
- Visually, modest coherence in clouds, kinematics
  - Little prominent change

MAX
20 dBZ at 1.7°
(cell S of MAX)
19-20 July
SS: 0058
CBZ: 0145

- CBZ resolved as coherent convergence, upward $w_{DV}$
- Upright updraft; (modest) peak $w_{DV}$ aligned w/ max low level convergence
  - Consistently no rotor or feeder flow
19-20 July
SS: 0058
CBZ: 0145

- CBZ resolved as coherent convergence, upward $w_DV$
- Upright updraft; (modest) peak $w_DV$ aligned w/ max low level convergence
  - Consistently no rotor or feeder flow

- No increase, but general lack of prominent decrease as the Hampton Cove cell initiates and intensifies to East along wave-like CBZ
- Values in similar range as for S lobe
Summary: CBZ Case Studies

• 30-31 August:
  – Decreasing convergence along density current, but rate of decrease is halved later in AET
  – Likely bore shows nearly 5x the CA rate of increase

• 9-10 July:
  – Steady convergence appeared to support CI ~1.5 h before sunset, local feature also a factor
  – Late AET visual convective signal – not on radar

• 19-20 July:
  – 2 CI events along likely solitary wave, in & E of DD
  – Steady convergence through AET

• Overall, visual obs, character of kinematic results, SD vs. DD comparisons → modest slabularity trend

• Not only is BL transitioning…Transitioning CBZs!
  – Need to simplify to better assess H2…
Simulation Experiment

- WRF ARW v3.6
- Default simulation: Idealized gravity current
  - 15 K from mean $\theta$
  - Const. $\theta$, dry, no wind
  - 65 vert. lvls, top=6409 m
  - $\Delta x = 100$ m, $\Delta t = 1$ s
  - BCs: periodic in x & y
  - All physics turned off

- To test H2:
  - Idealized GC sim, with real CA case soundings through the AET period
  - 100 x 6 km domain, run for 40 min of sim time

- input_sounding files:
  - 10 min MIPS 915, MPR
  - 2 h interval relative to SS

- 2 CA days chosen:
  - Meet all CA criteria
  - Varied mean flow
  - Ample obs; SS times

Skamarock et al. (2008), Straka et al. (1993)
• Increases 22 – 00 – 02 UTC (20 min +)
  – 02 UTC: steadier values through simulation time
  • Lack of decrease along the evolving GC
  – 00 UTC: consistently higher w than 22 UTC
• Abrupt, substantial decrease at night (04 UTC)
- Increases through afternoon, then decays
  – Sunset run (00 UTC) character follows afternoon lines
  – More prominent convergence decrease for post-
sunset simulations (02, 04)
- Example of delay in dramatic decline
• Through t~30 min, increase 21 – 23 – 01 – 03 UTC
  – Most prominent at 500 m for 23 vs. 01 UTC sims
• 01 UTC: Steadier convergence, lack of decrease along GC evolving in SS environment
• 03 UTC: nocturnal enhancement?
• Increases with later input: 17 – 19 – 21 – 23 UTC
  – Sunset run (01 UTC): less than 23 UTC simulation, but within range of the afternoon results
• 03 UTC: below noon simulation values (by up to $4 \times 10^{-3} \text{ s}^{-1}$, 1 m/s) through t~30 min
Conclusions

• **H1**: Surface wind speeds decrease while winds above surface layer increase
  - Progression of CBL decay consistent with physical demise of turbulent eddies
    - Surface winds decrease, flow ~300 m increases
    - Modest increase in meso-γ convergence at 300 m

• **H2**: Existing CBZs display an increase, or at a minimum a lack of or delay in a decrease, in horizontal wind convergence above surface layer
  - Case studies overall strongly support minimum criteria
  - Simulation exercise bolsters findings: increase & delayed decrease

• **H3**: CBZs more slabular
  - Case studies provide qualitative support

Key Points:
- CBZ kinematics in AET can be quite complex, involving multiple processes, including formation/intensification of waves/bores
- Visual AET convective signal not always apparent on radar
- Deep convection initiated by CBZs during the AET can persist into overnight hours

→ Altogether, results suggest the AET BL is a favorable habitat for maintenance of existing CBZs & can support enhancement/initiation of a range of convective elements – from clouds to persistent storms
Ongoing & Future Work

• Local observations continue at NSSTC/SWIRLL
  – MIPS, ARMOR, cameras

• Additional locations
  – CBZs in AET during PECAN
  – SGP ARM facility
    • Characterization, regional/surface differences

• Observations can support future development/refinement of PBL parameterizations

• Documenting effects of varied scattering regimes on vertical motion measurements: 915 vs. XPR vs. DWL
  – PECAN observations

AET processes can affect:
  – Fog or frost formation, pollutant concentrations, agricultural concerns, forest management/controlled burns, transportation safety, public health, deep convection…
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