The Link between Coherent Structures and Particle Transport in Canopy Flows

Brian N. Bailey[1], Rob Stoll[1], Eric R. Pardyjak[1]
Walter Mahaffee[2]
bbailey@eng.utah.edu

[1]Department of Mechanical Engineering
University of Utah, Salt Lake City, UT, USA
[2]USDA ARS
Corvallis, OR, USA

May 30, 2012

Canopy Turbulence

General characteristics of turbulence in plant canopies

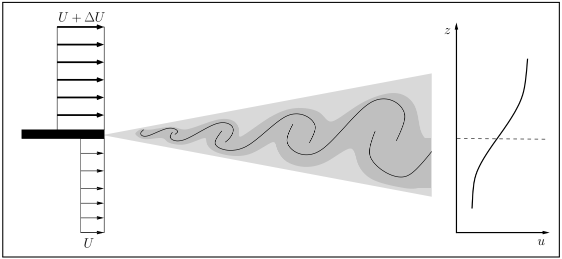
1. Turbulence is highly intermittent
2. Large turbulent intensities
3. **Turbulence seems highly organized**

The Mixing Layer

Hypothesis:

Raupach (1996)

Flow near the canopy is analogous to a plane mixing layer.



Challenges:

For complex, 3-D turbulent flows:

- The definition of a coherent structure itself is vague
  - Need to define a trigger or indicator
- Coherent structures generally occur at random locations and have random strengths
  - Need composite averages
  - May require a (sometimes arbitrary) threshold

Challenges:

For complex, 3-D turbulent flows:

- The definition of a coherent structure itself is vague
  - Need to define a trigger or indicator
- Coherent structures generally occur at random locations and have random strengths
  - Need composite averages
  - May require a (sometimes arbitrary) threshold

Coherent Structure Detection Methods: EOF & POD

- **Gao et al (1989) and others:** Temperature ramps/microfronts
- **Finnigan & Shaw (2000):** Empirical orthogonal function (EOF) analysis
- **Huang et al (2009):** Proper orthogonal decomposition (POD)
- **Finnigan et al (2009):** Conditional averaging based on pressure spikes

Coherent Structure Detection Methods: EOF & POD

- **Gao et al (1989) and others:** Temperature ramps/microfronts
- **Finnigan & Shaw (2000):** Empirical orthogonal function (EOF) analysis
- **Huang et al (2009):** Proper orthogonal decomposition (POD)

Finnigan et al (2009) detection method

The Underlying Hypothesis: “sufficiently large” pressure spikes at the canopy top are an indication of the presence of coherent structures.

Coherent Structure Detection Methods: Composite average based on pressure spikes

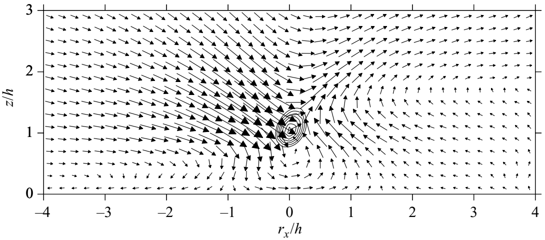
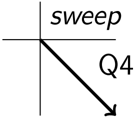
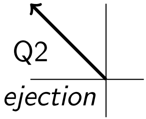


Figure from Finnigan et al (2009; JFM). Vectors of $\overrightarrow{V} = (\tilde{u}', \tilde{w}')$ in the $x - z$ plane.





Coherent Structure Detection Methods: Composite average based on pressure spikes

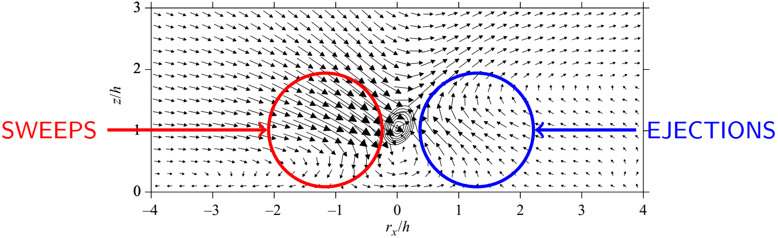
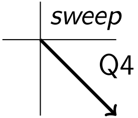
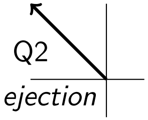


Figure from Finnigan et al (2009; JFM). Vectors of $\overrightarrow{V} = (\tilde{u}', \tilde{w}')$ in the $x - z$ plane.





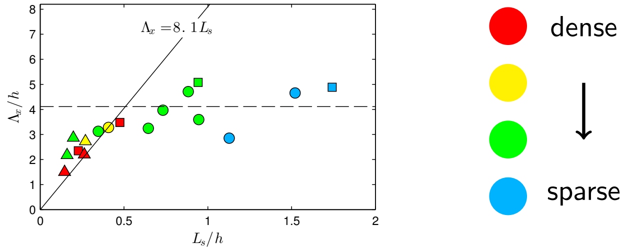
Large-Eddy Simulations

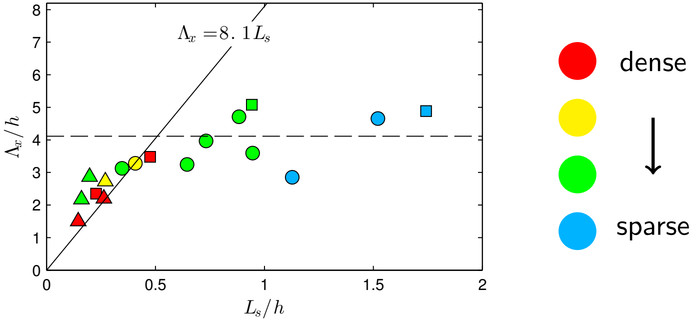
- Horizontally homogeneous canopy (neutral stability)
  - $F_i = C_d\, a\, \tilde{u}_i\, \tilde{V}$
- Wide range of canopy densities: $1.0 > LAI > 0.077$, $C_d = 0.5$
  - 8 different densities
- Numerics
  - horizontally periodic domain
  - pseudospectral differencing in horizontal, 2nd order FDS in vertical
  - $192 \times 192 \times 160$ points, $24h \times 24h \times 8h$ domain
  - dynamic scale-dependent Lagrangian SGS model
- Code details can be found in Stoll and Portè-Agel (2006; WRR)

Indirect Coherent Structure Identification: integral length scales

Integral Length Scales

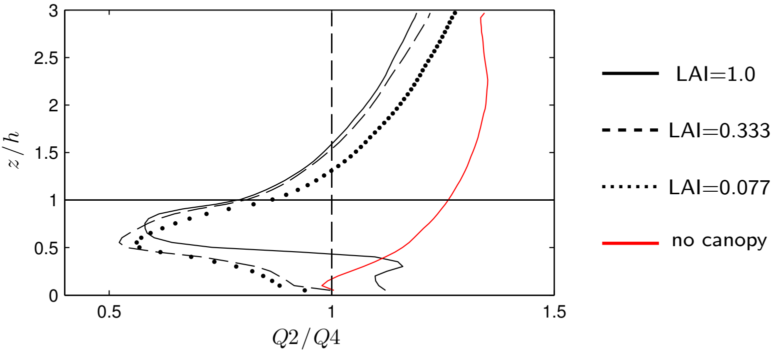
- $\mathbf{L_{\ddot{w}}}$ Integral length scales at h determined by integrating w autocorrelation function $(\Lambda_x = 2\pi L_{\ddot{w}})$
- Comparison with:
  - Dupont and Brunet (2008; AFM) LES [△]
  - Huang et al (2009; BLM) LES [□]
  - Current LES [○]





Turbulent length scale at the canopy top resembles a pure boundary-layer as the canopy becomes sparse

Indirect Coherent Structure Identification: quadrant-hole analysis

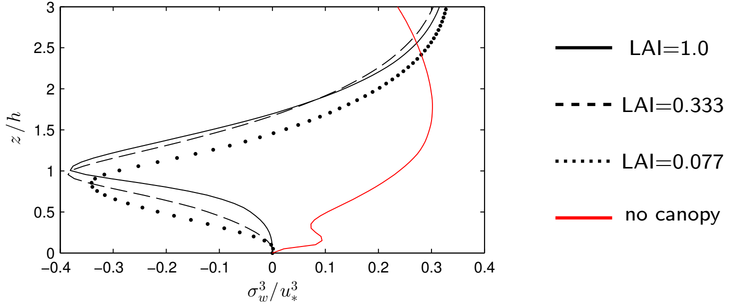


quadrant-hole analysis ($H = 0$)

As the canopy becomes sparse:

- sweeps dominate throughout canopy
- **profiles still resembles that of a canopy (sweeps dominant)**

Indirect Coherent Structure Identification: vertical velocity skewness σ_w^3

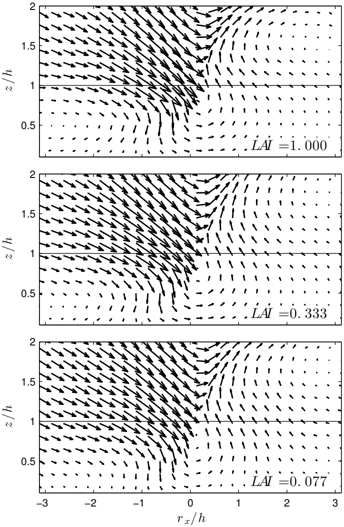


vertical velocity skewness

As the canopy becomes sparse:

- skewness decreases within the canopy
- height of the profile peak decreases
- **skewness profile still resembles that of a canopy**

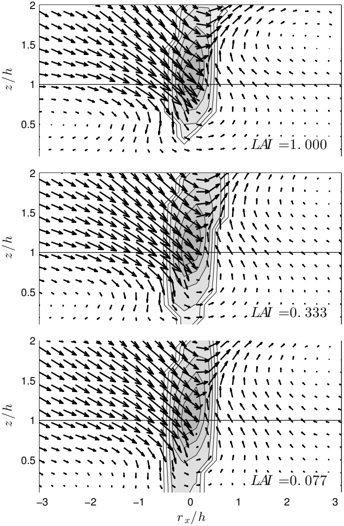
Coherent Structure Detection: pressure perturbation method



Coherent Structures

- similar structures regardless of density
- structures tend to penetrate deeper in the sparser canopies

Coherent Structure Detection: pressure perturbation method



Coherent Structures

- similar structures regardless of density
- structures tend to penetrate deeper in the sparser canopies

Particle-Based Coherent Structure Detection Method

General Methodology

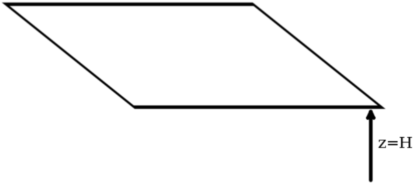
- Use *Lagrangian* particle dispersion information as a criteria for composite averaging *Eulerian* velocity fields.
- Velocity fields and particle trajectories obtained from large-eddy simulation (LES) data.

The Underlying Hypothesis:

- **IF:** Particle transport to/from the canopy is dominated by coherent structures,
- **Particle ejection/re-entry from/to the canopy can be used as an indicator for coherent structures**

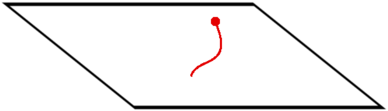
Eulerian/Lagrangian Detection Method

1. Control surface at $z = h$ (canopy top)



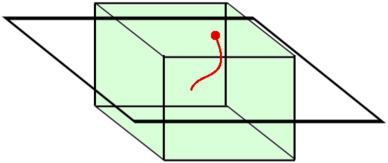
Eulerian/Lagrangian Detection Method

1. Control surface at $z = h$ (canopy top)
2. Trigger when particles cross surface



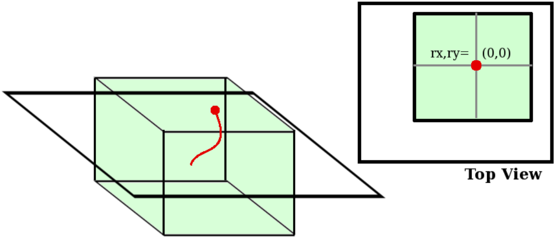
Eulerian/Lagrangian Detection Method

1. Control surface at $z = h$ (canopy top)
2. Trigger when particles cross surface
3. 3-D fields of fluctuating velocity extracted, centered at ejection/re-entry point



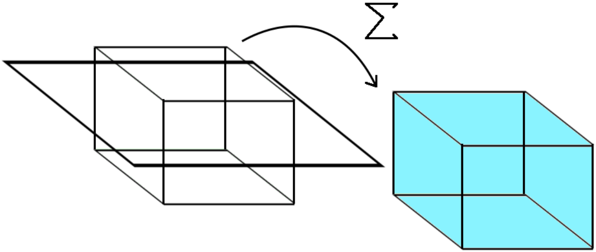
Eulerian/Lagrangian Detection Method

1. Control surface at $z = h$ (canopy top)
2. Trigger when particles cross surface
3. 3-D fields of fluctuating velocity extracted, centered at ejection/re-entry point



Eulerian/Lagrangian Detection Method

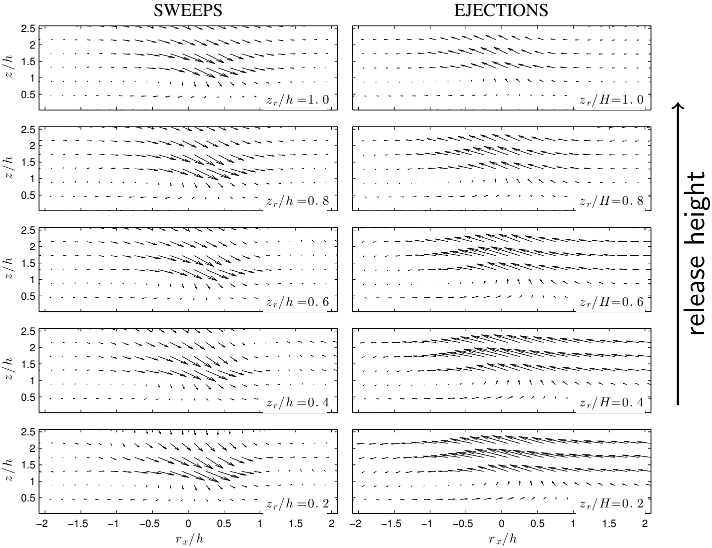
1. Control surface at $z = h$ (canopy top)
2. Trigger when particles cross surface
3. 3-D fields of fluctuating velocity extracted, centered at ejection/re-entry point
4. Extracted 3-D fields composite averaged (ejections and re-entries averaged separately)



Dispersion Simulation Details

- 250,000 particles released continuously from 5 heights within the canopy
  - Passive tracers (i.e., no inertia, no deposition)
- Trajectories tracked in a Lagrangian sense $\mathrm{d}x_i = u_i \mathrm{d}t$
- SGS particle motions modeled following Weil et al (2004; JAS)

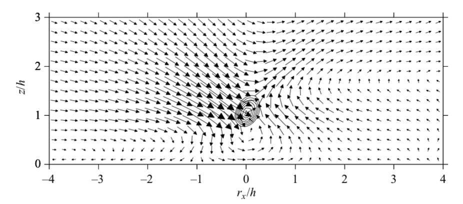
Eulerian/Lagrangian Detection Method



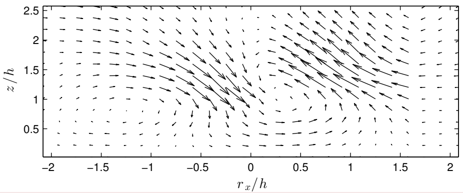
Structure Superposition: Animation

Eulerian/Lagrangian Detection Method

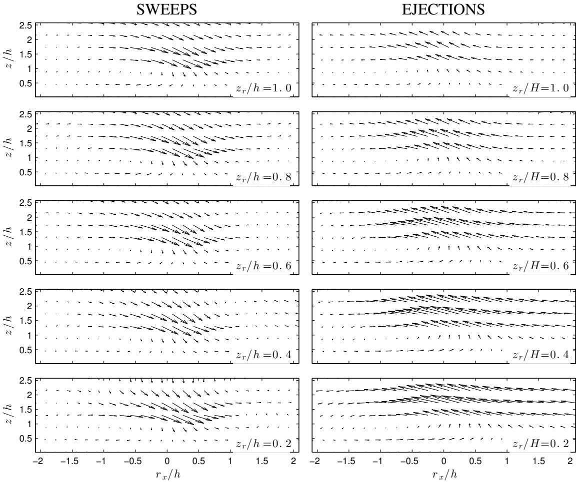
Finnigan et al (2009; JFM) Structures



Particle-Based Detection Method



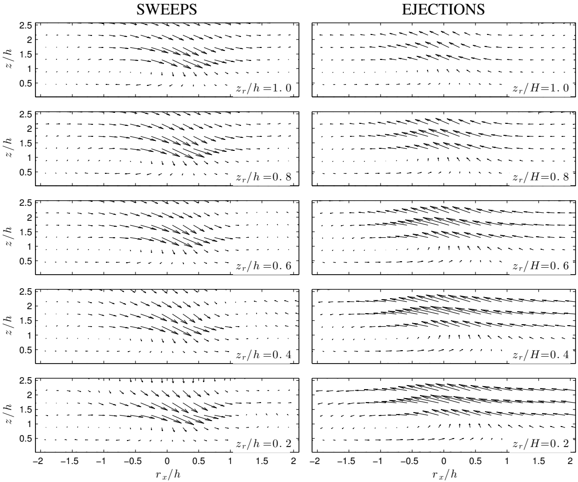
Eulerian/Lagrangian Detection Method



Key Features

Same basic structures at all release heights

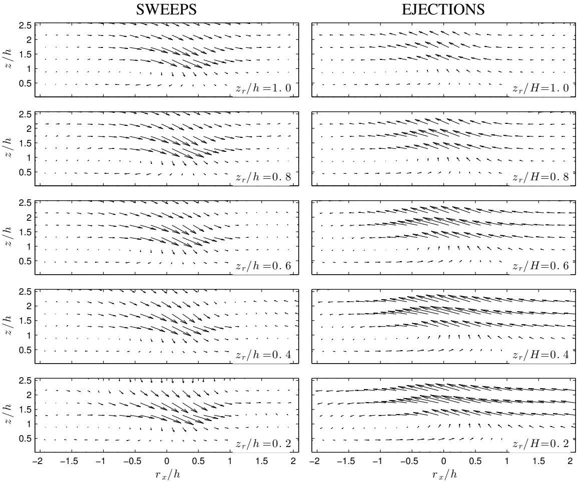
Eulerian/Lagrangian Detection Method



Key Features

Ejection structure strength decreases with height

Eulerian/Lagrangian Detection Method



Key Features

Sweep structure strength constant with height

Conclusions

- Integral length scales (@ $z = h$) are not necessarily indicative of canopy structures
- Other turbulence statistics indicate that relatively sparse canopies still behave like a canopy layer
- Mixing-layer-like structures appear important for particle transport to/from the canopy

Acknowledgments

University of Utah Center for High Performance Computing