The Link between Coherent Structures and Particle Transport in Canopy Flows

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General characteristics of turbulence in plant canopies

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

Raupach (1996)

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

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:

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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
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.

- **Sweep**
- **Ejection**

Q2

Q4
Coherent Structure Detection Methods: Composite average based on pressure spikes

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

Canopy Structures and Particle Transport
Bailey et al
Canopy Turbulence
Structure Detection
LES Results
New Method
Conclusions

SWEEPS

\[ \text{sweep} \]

\[ \text{Q4} \]

ejection

\[ \text{Q2} \]
Large-Eddy Simulations

- Horizontally homogeneous canopy (neutral stability)
  - \( F_i = C_d \alpha \tilde{u}_i \tilde{V} \)
- 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, 2\(^{nd}\) 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

- $L_w$ Integral length scales at $h$ determined by integrating $w$ autocorrelation function ($\Lambda_x = 2\pi L_w$)

- Comparison with:
  - Dupont and Brunet (2008; AFM) LES [$\Delta$]
  - Huang et al (2009; BLM) LES [$\square$]
  - Current LES [$\circ$]

![Graph showing comparison of integral length scales with different symbols representing dense and sparse conditions.](image-url)
Turbulent length scale at the canopy top resembles a pure boundary-layer as the canopy becomes sparse.
Indirect Coherent Structure Identification: quadrant-hole analysis

As the canopy becomes sparse:
- sweeps dominate throughout canopy
- profiles still resembles that of a canopy (sweeps dominant)
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

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- 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**
1. Control surface at $z = h$ (canopy top)
Eulerian/Lagrangian Detection Method

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2. Trigger when particles cross surface
Eulerian/Lagrangian Detection Method

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3. 3-D fields of fluctuating velocity extracted, centered at ejection/re-entry point
Eulerian/Lagrangian Detection Method

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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 $dx_i = u_i dt$
- SGS particle motions modeled following Weil et al (2004; JAS)
Eulerian/Lagrangian Detection Method

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Conclusions

SWEEPS

EJECTIONS

release height

$z/h$ vs $r_x/h$

$z_r/h = 1.0$

$z_r/H = 1.0$

$z_r/h = 0.8$

$z_r/H = 0.8$

$z_r/h = 0.6$

$z_r/H = 0.6$

$z_r/h = 0.4$

$z_r/H = 0.4$

$z_r/h = 0.2$

$z_r/H = 0.2$
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
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Eulerian/Lagrangian Detection Method

Key Features

- Ejection structure strength decreases with height
Eulerian/Lagrangian Detection Method

Sweeps 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

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