In-Canopy Turbulence: How Do Coherent Structures Affect Fluxes In and Out of the Canopy?

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Background

The exchange of heat, momentum, and trace gases between the canopy and the atmosphere is driven by turbulence. Turbulent transport in dense vegetation canopies is known to be dominated by large coherent structures that intermittently move air in and out of the canopy in 'bursts' and 'sweeps', coupling the canopy with the atmosphere above.

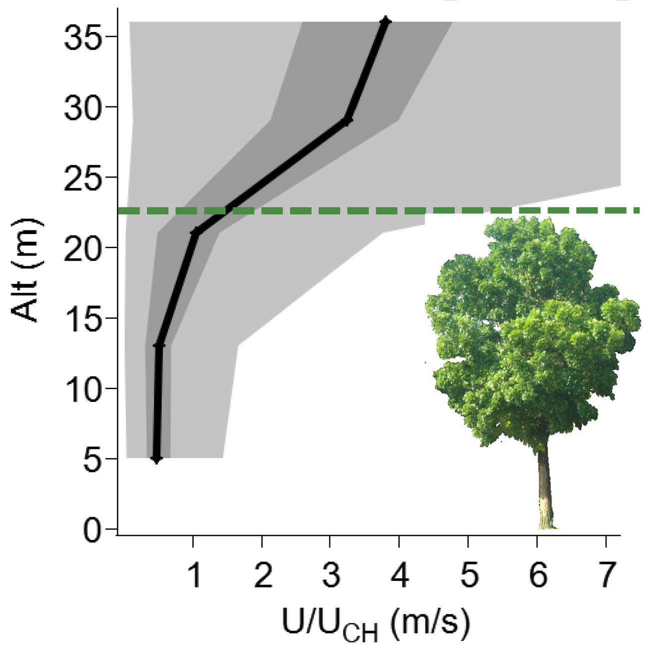

Fig 1. Vertical profile of mean velocity during the PROPHET-AMOS campaign normalized to canopy height velocity. The inflection point at canopy height makes the flow susceptible to Kelvin-Helmholtz instability.

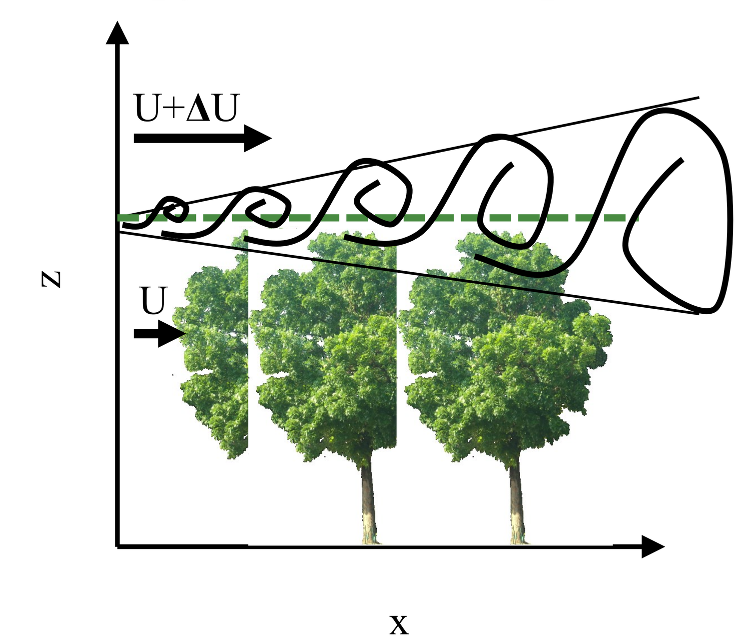

Fig 2. Cartoon schematic showing the formation of large, coherent structures from the instability [Raupach *et al.* 1996].

These bursts and sweeps are responsible for a significant portion of eddy-fluxes in and out of the canopy but they are not represented in the traditional, computationally efficient, K-theory (turbulent diffusion) based approaches used in conventional modelling.

Turbulent Measurements During PROPHET-AMOS

We set up a vertical series of sonic anemometers as part of the PROPHET-AMOS campaign (July 2016 at the University Michigan Biological Station) to identify the presence of coherent turbulent structures and quantify their duration, frequency of occurrence, and fractional contribution to heat and momentum fluxes using conditional sampling and wavelet analysis. Canopy coupling classification was determined by the covariance of kinematic heat fluxes between sonic anemometers [Thomas *and* Foken 2007, Steiner *et al.* 2011].

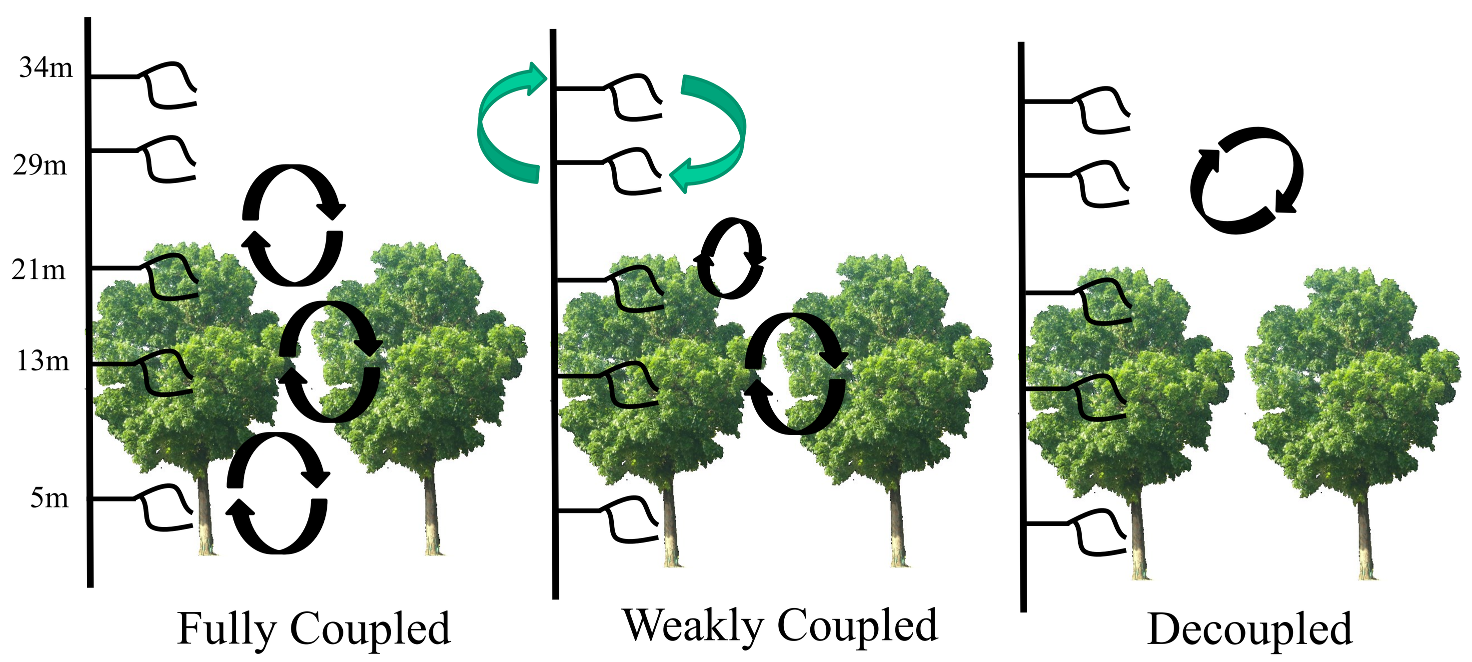

Fig 3. Schematic of canopy coupling classifications. Heat fluxes are well correlated between all heights during fully coupled conditions and uncorrelated during decoupled conditions.

Observations

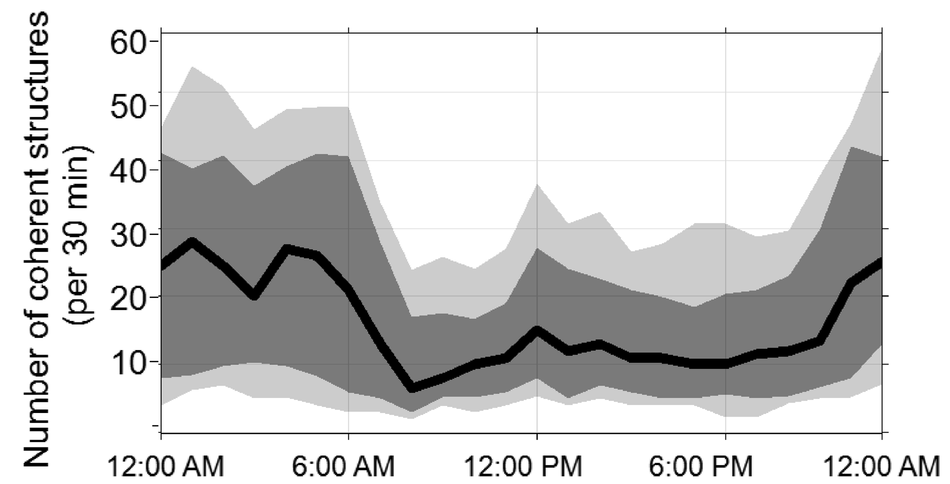

Fig 4. Diel plot of the number of coherent structures per half hour showing campaign median, 25th/75th, and 5th/95th quantiles.

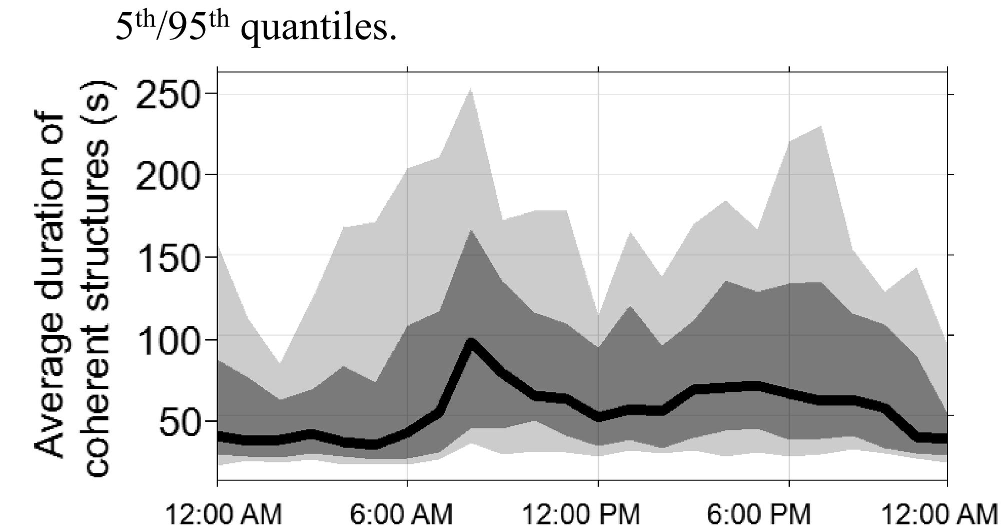

Fig 5. Diel plot of the average duration of coherent (s) showing campaign median, 25th/75th, and 5th/95th quantiles.

The important question is not how many coherent structures occur, but how they affect fluxes in and out of the canopy.

The fractional contribution of coherent structures to the total kinematic flux was calculated for each 30-min time period as per Lu and Fitzjarrald (1994),

$$F_{coh} = \frac{\sum_{i=1}^{n} \left(\overline{w'x'_{coh,i}} \times t_{coh,i} \right)}{\overline{w'x'} \times t}$$

Where $x \in (T, u)$, $\overline{w'x'}$ is the vertical kinematic flux of variable x over time t, $\overline{w'x'_{coh,i}}$ is the vertical kinematic flux of variable x during the ith coherent structure, $t_{coh,i}$ is the duration of the ith coherent structure, and t is the total duration of the analysis window (30 min).

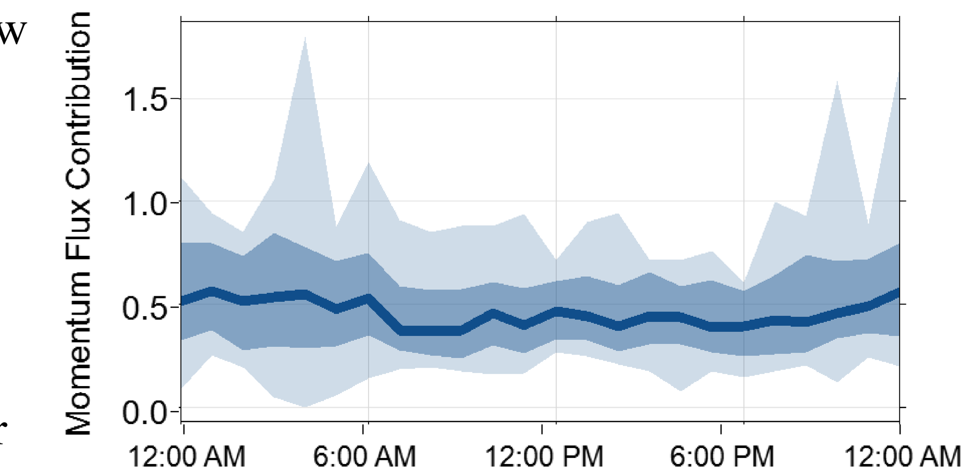

Fig. 6. Diel plot of the fractional contribution of coherent structures to kinematic momentum flux showing campaign median, 25th/75th, and 5th/95th quantiles.

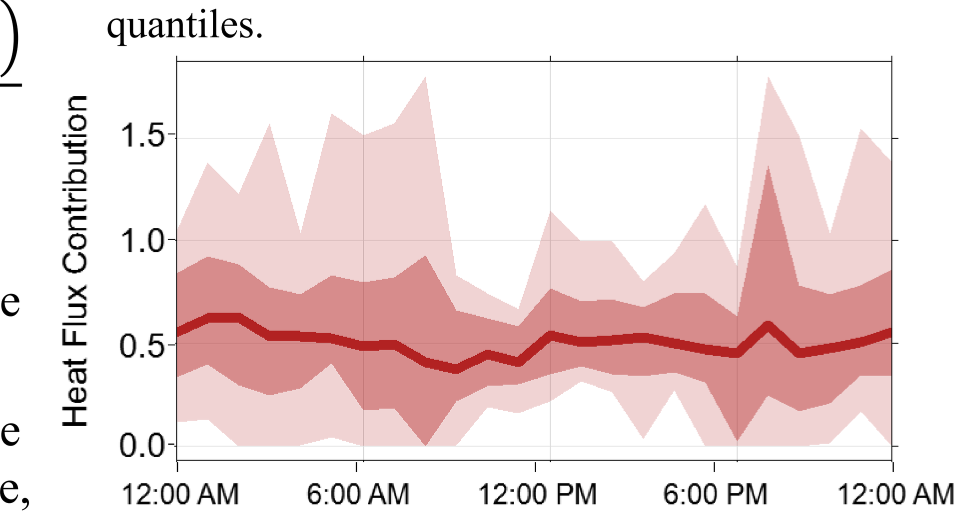

Fig. 7. Diel plot of the fractional contribution of coherent structures to kinematic heat flux showing campaign median, 25th/75th, and 5th/95th quantiles.

We find that coherent exchange is responsible for approximately 50% of both the heat and momentum flux out of the canopy during the PROPHET-AMOS campaign. Coherent structures contribute significantly to kinematic fluxes throughout the day, although their significance is greatest just around sunrise/sunset and during periods of atmospheric stability.

Can We Model Consequences for Ozone Fluxes?

With such a large contribution to the heat and momentum fluxes being attributable to these intermittent, un-K-theory-like, structures, what hope do we have for correctly modelling canopy fluxes of any species with a simple K-theory based approach? The FORCAsT 1-D column model, despite not explicitly representing coherent exchange, predicts heat and momentum fluxes during PROPHET-AMOS with good accuracy thanks to an observationally constrained eddy-diffusivity term [Makar *et al.* 1999, model details in Bryan *et al.* 2012]. By imposing artificial canopy-atmosphere coupling or de-coupling in the model, we can begin to assess the impact of canopy mixing on ozone fluxes.

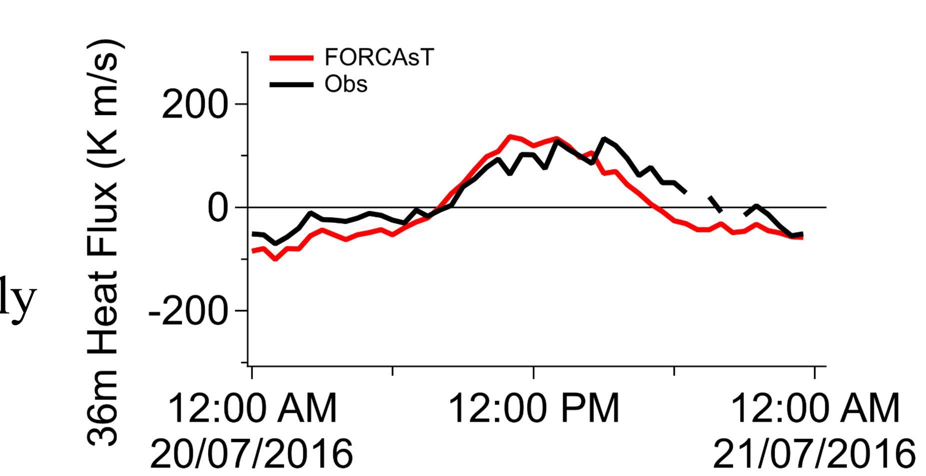

Fig 8. FORCAsT modelled kinematic heat flux and observations during one day of the PROPHET campaign. Good model-measurement agreement can be seen on most rain-free days during the campaign.

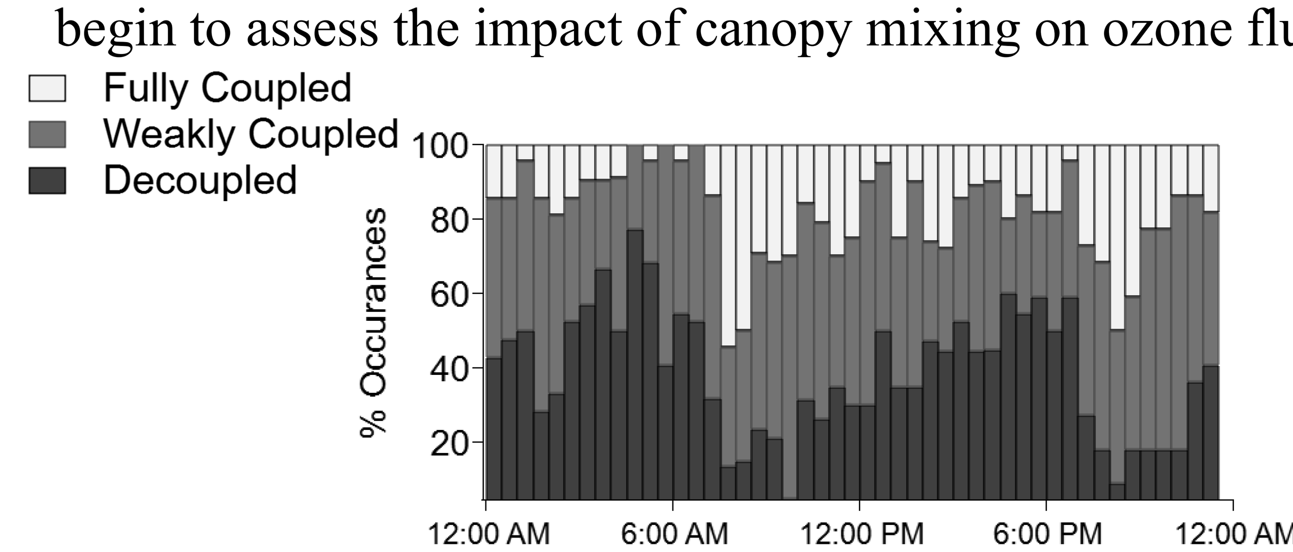

Fig 9. Diel plot of percent occurrence of coupling class (fully coupled, weakly coupled, decoupled) for each 30-min period during PROPHET-AMOS determined from vertical heat flux correlations. While diurnal trends are apparent, the canopy can be fully coupled or de-coupled with the atmosphere above at all times of day.

Decoupling is imposed by inserting a 2m model layer at the top of the canopy where vertical exchange in the layer is reduce to 1% of it's original rate to simulate a stagnant air layer or dense foliage.

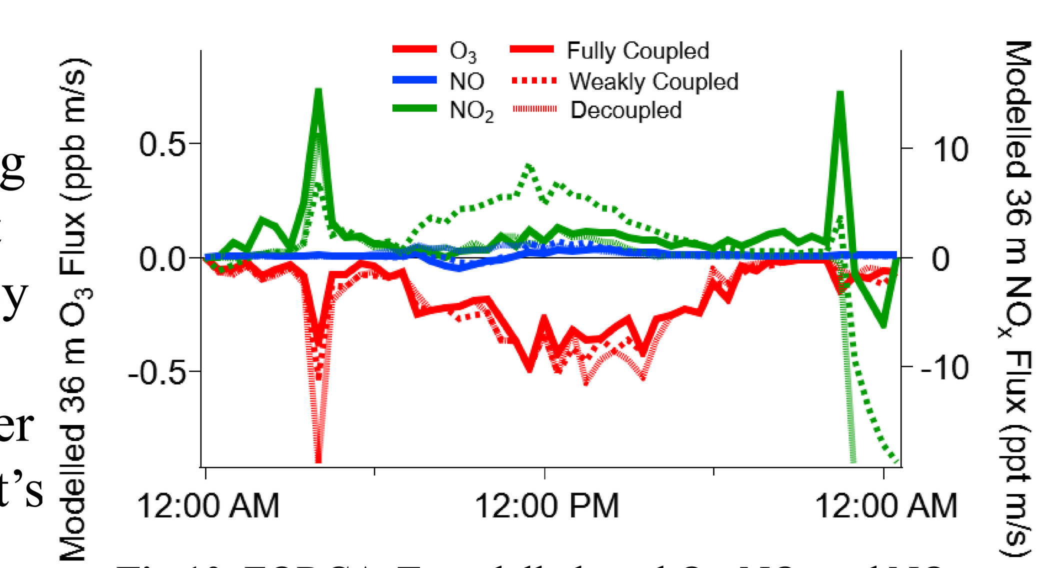

Fig 10. FORCAsT modelled total O_3, NO, and NO_2 fluxes at 36m assuming different coupling conditions are present. Over a 24 hrs, 4.5% more and 6% more ozone is lost to dry deposition in the fully coupled case than in the weakly coupled and decoupled cases.

Assuming our model is suitable for studying a canopy where exchange is significantly controlled by coherent structures, we see relatively small changes in ozone fluxes and dry deposition when changing model coupling. Is this reasonable? We need more flux observations to say one way or the other.

Acknowledgements

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