Efficiency of turbulent transfer over an urban surface in relation to seasonal changes in source area patchiness

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Background

The eddy covariance (EC) method of analyzing in-situ data from flux towers has become the standard tool for monitoring turbulent heat exchange, and the water balance over land surfaces [1]. However, the EC method was developed for horizontally homogenous ecosystems like croplands and forests, where the source area has a uniform distribution of sources and sinks. This is not usually the case for cities, as sources and sinks of sensible heat and water vapour are dissimilar, and vary spatially and temporally.

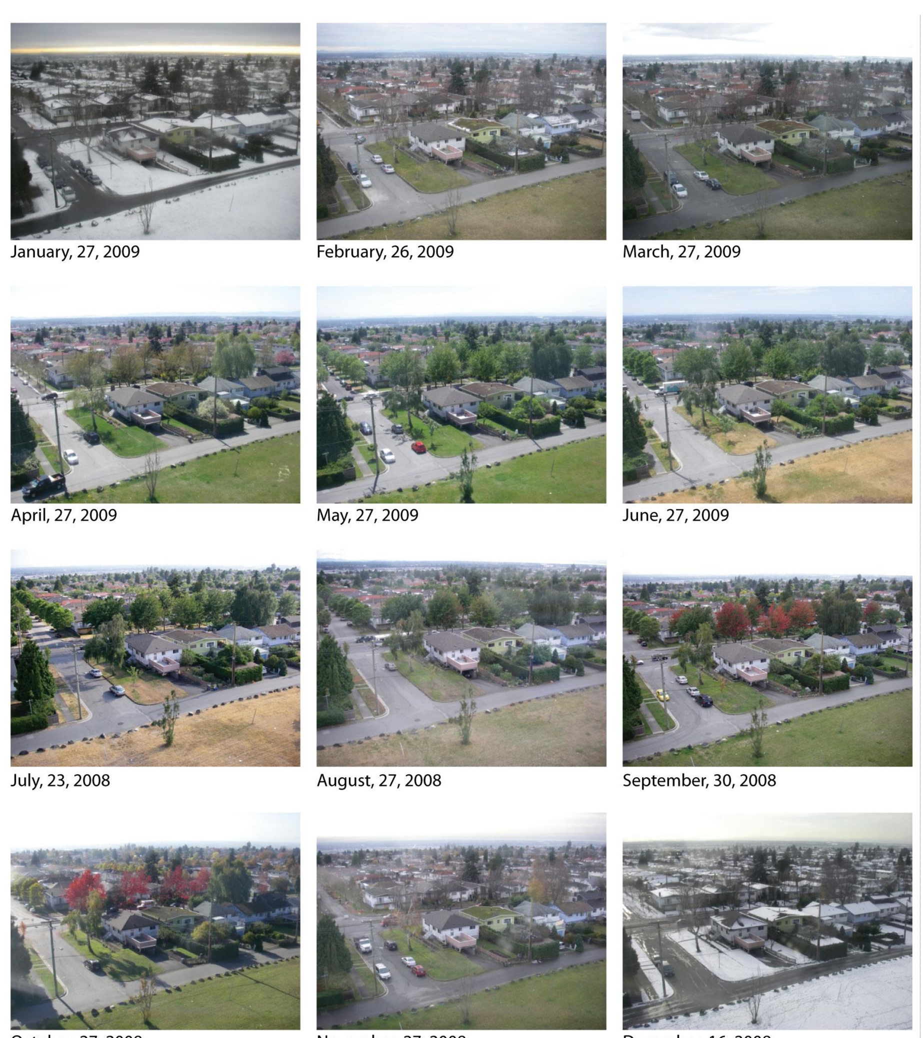
The goal of this research is to establish a link between surface patchiness and the efficiency of turbulent exchanges of different scalars. Specifically, the aim is to:

1) **Characterize the exchange efficiencies of momentum, sensible heat, and water vapour over a heterogeneous urban landscape.**
2) **Relate these exchange efficiencies to remotely-sensed surface patchiness.**
3) **Investigate how exchange efficiencies change seasonally and diurnally.**

Methods

Study Site

Eight years of EC data (May 2008 to April 2016) was collected from a flux tower located in a residential area in the City of Vancouver, BC, Canada (49.2ºN, Fluxnet ID "Ca-VSu"). The source area of this tower is representative of a typical urban setting with a mix of detached single-family homes (average height: 5.3 m), and tree coverage of 17.1 stems / ha (LCZ 6). The EC instrumentation was located at a height of 28.8 m comprising of a sonic anemometer (CSAT-3, Campbell Scientific Inc.), and an open-path infrared-gas analyzer (Li-7500, Licor Inc.).



◀ **SW view from EC tower of an adjacent residential area during each month of the year.** Effects of water availability are readily observable (e.g. broadleaf foliage, droughts, and snow cover).

Correlation coefficients of the turbulent entities of interest were calculated for the full eight years (Equation 1), and specific relationships were established by conditionally sampling from particular wind directions, atmospheric stabilities, and times of year and day.

Attribution of fluxes to seasonally changing surface characteristics was done using the Kormann and Meixner analytical footprint model [2] in combination with remotely sensed data of surface cover and urban morphometry (LIDAR, aerial photos). The footprint model was calculated at a resolution of 25x25 m², for a domain of 2x2 km, centred on the tower location. Footprint-weighted surface properties were determined so that relative exchange efficiencies could be related to the characteristics of the changing turbulent footprints.

What does the correlation coefficient tell us?

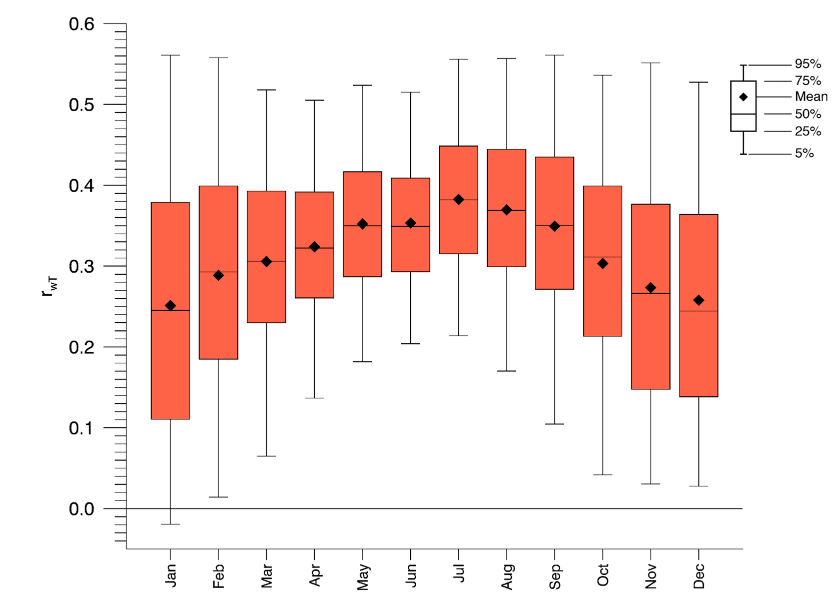
The correlation coefficient is a measure of how efficiently a turbulent entity is being transferred. It ranges from -1 (perfect negative correlation) to 1 (perfect positive correlation). A value of 0 means no correlation.

$$r_{wT} = \overline{w'T'} \,/\, (\sigma_w \sigma_T)$$

◀ **Equation 1.** Correlation coefficient for sensible heat (r_{wT}). $\overline{w'T'}$ is the covariance between vertical wind and temperature fluctuations, and $\sigma_w \sigma_T$ are the standard deviations of vertical wind and temperature, respectively.

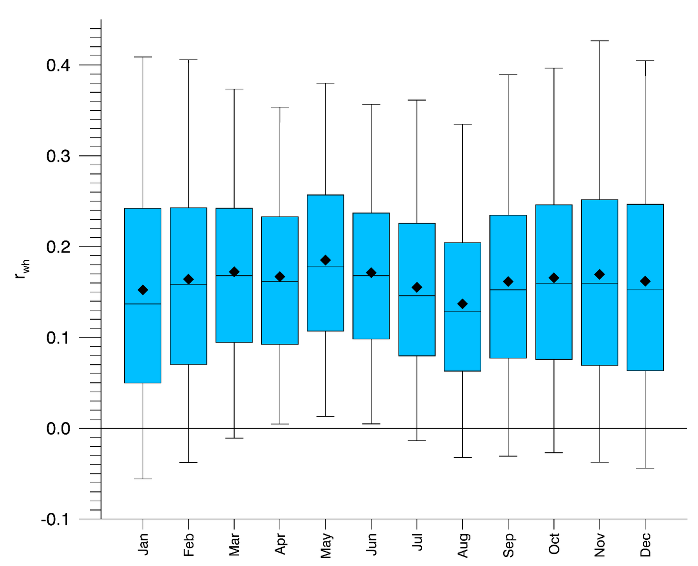
Results

Sensible Heat



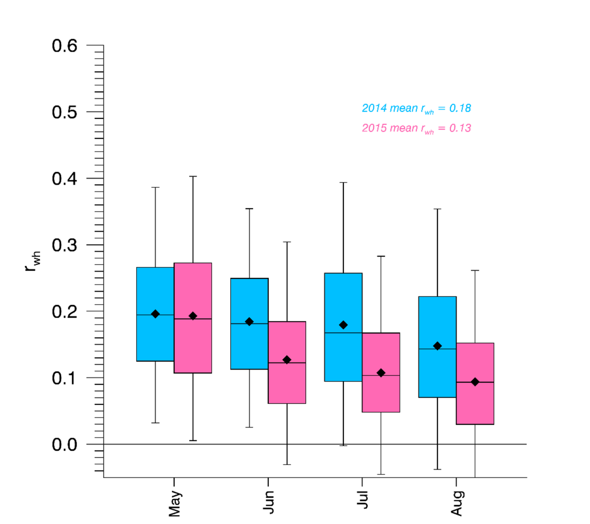
▶ **Seasonal changes in the exchange efficiency of sensible heat for unstable, daytime conditions** during the eight-year study period. Increased exchange of sensible heat (r_{wT}) is observed in summer when the higher solar elevation and the longer days cause more uniform heating across the entire 3D surface. At this time, days are longer and sunlight is the dominant source of heat (as opposed to winter, when days are shorter, lower solar elevation preferentially heats roofs, and patchy home-heating sources cause patchier sources of sensible heat).

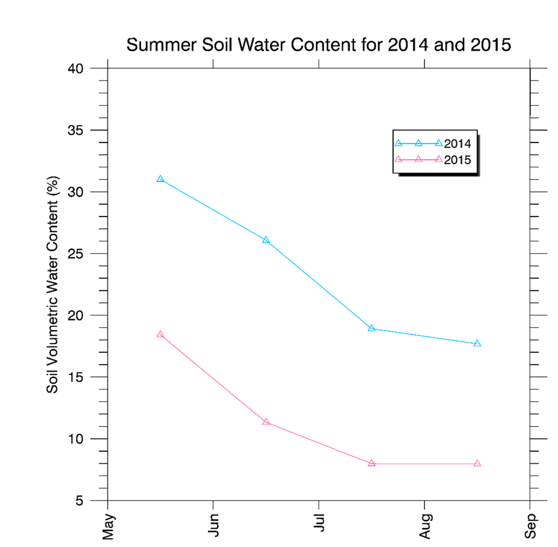
Water Vapour



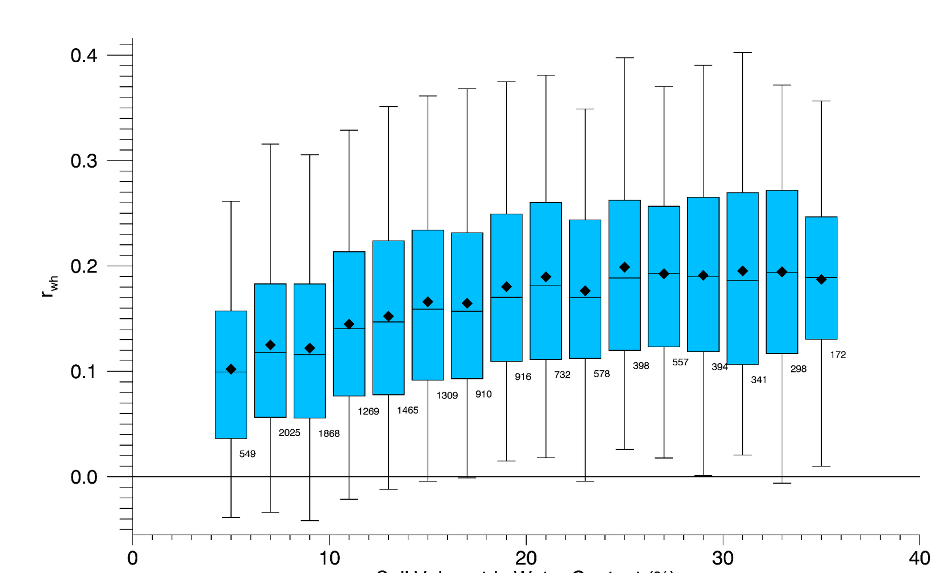
◀ **Seasonal changes in the exchange efficiency of water vapour for unstable, daytime conditions** during the eight-year study period. There is a reduction in the correlation coefficient for water vapour (r_{wh}) over the course of summer with a minimum in late summer (August) (patchier distribution of water – see figure below) compared to winter, when sources of water are distributed more uniformly in the urban environment.

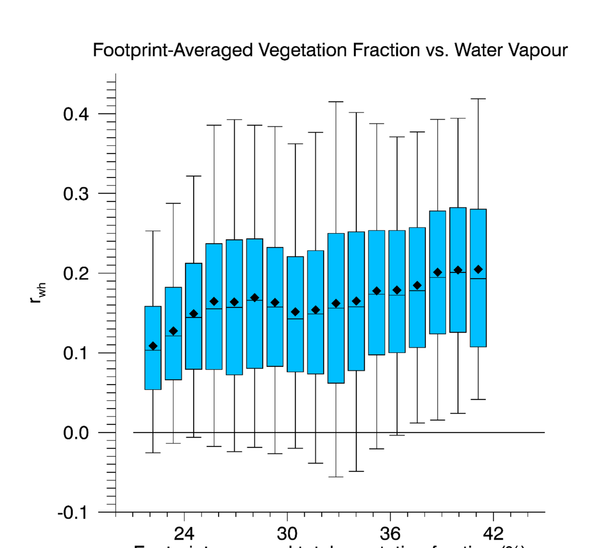
▼ **Water vapour exchange during a dry and a wet summer.** A subset of data from the above figure was used to compare water vapour correlation coefficients for a dry summer (2015) and a wet summer (2014). The mean value given is the average mean value of all three months. Analysis of how wet or dry each summer was is based on the soil volumetric water content for each year (right). In 2015 there was a water ban (severely restricted garden irrigation) in effect, causing an even a patchier distribution of water at the surface.

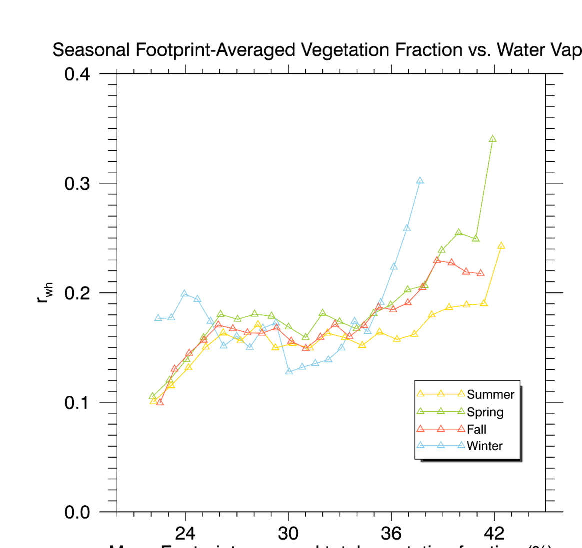




▶ **Relationship between soil volumetric water content (%) and the exchange efficiency of water vapour for unstable, daytime conditions** during the eight summers is shown. Soil volumetric water content was continuously measured in eight representative lawns in the area [3].



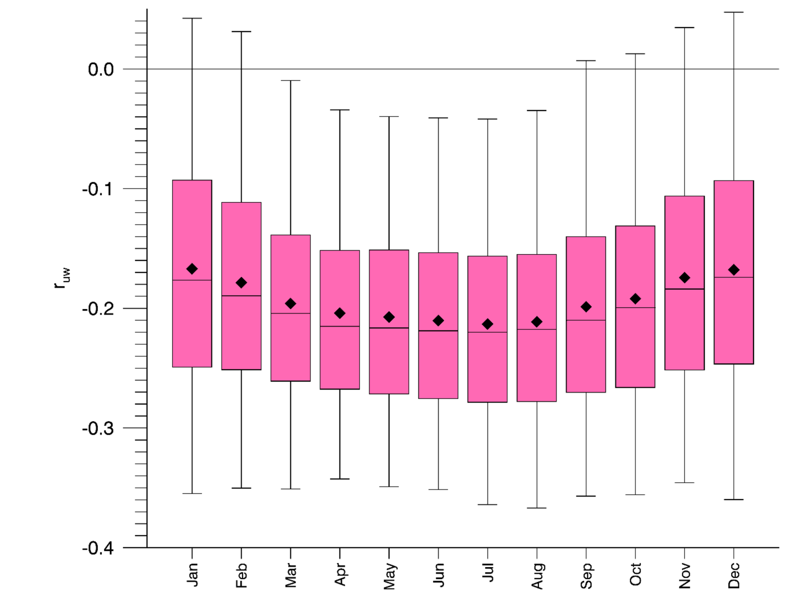


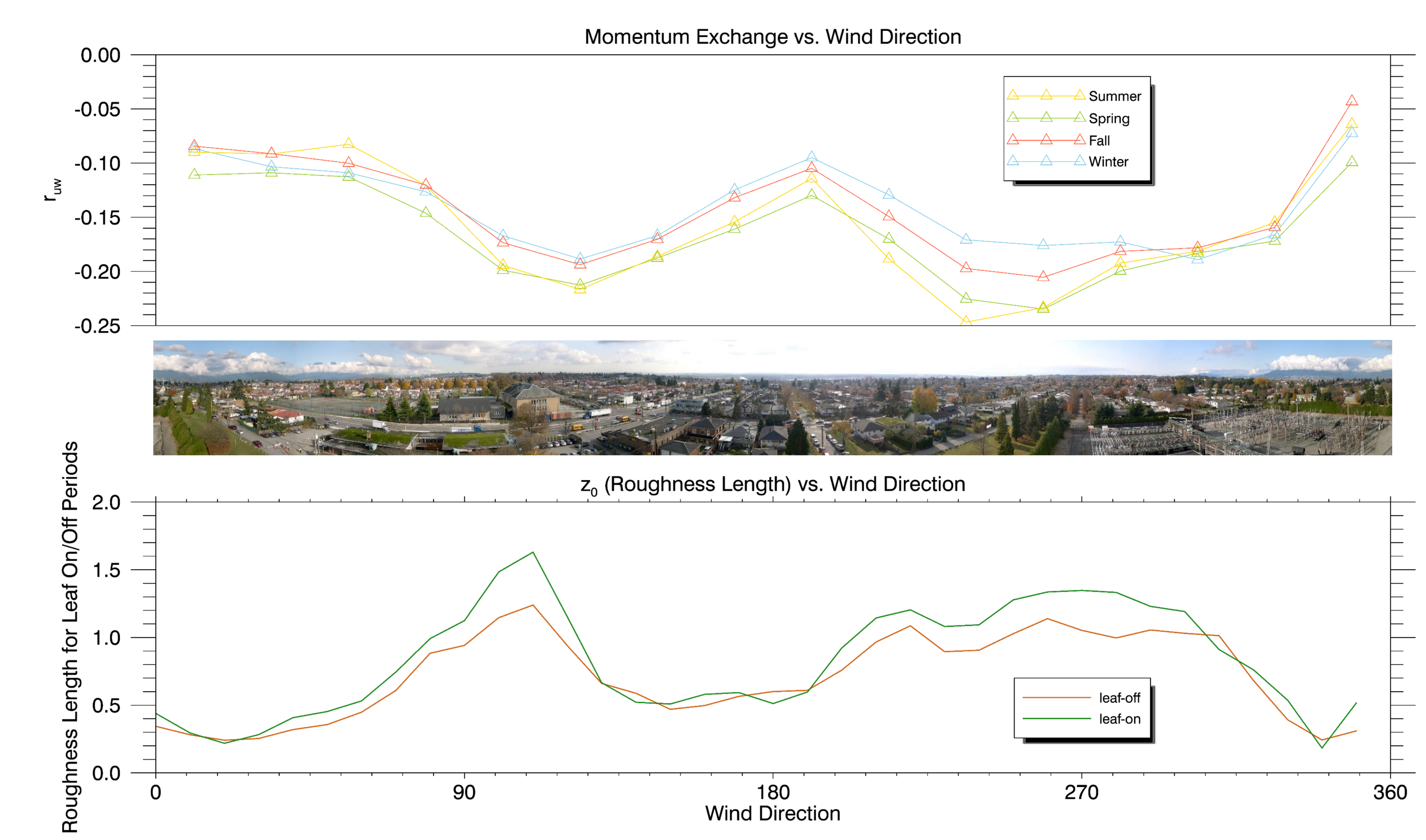


◀ **Exchange efficiency of water vapour for a given footprint-averaged vegetation fraction (with seasonal analysis).** As the footprint-averaged vegetated fraction decreases (becomes sparser and patchier in the footprint), exchange is less efficient.

Momentum

▶ **Seasonal changes in the exchange efficiency of momentum for unstable, daytime conditions** for the eight-year study period. Momentum transfer (r_{uw}) is more efficient during spring and summer when leaves are out (May to September) compared to the leaves-off season (November to March).





▲ **Seasonal changes in the exchange efficiency of momentum in relation to wind direction and (bottom) the roughness length (z_0)**, calculated using the aerodynamic method [4], as a function of wind direction during the leaf-on (May - September) and leaf-off (November - March) seasons. As the surfaces becomes rougher when leaves are out, the efficiency of exchange of momentum increases.

Conclusions

- **Sensible heat is generally more efficiently transferred than water vapour** (under unstable, daytime conditions), which supports earlier findings by Roth and Oke (1995) at the same site [5].
- **As sources of water become patchier, the exchange efficiency of water vapour decreases. For example, exchange efficiency of water vapour is lower throughout summer compared to other seasons** (in dryer summer months, yard irrigation causes a patchier distribution of water which lowers r_{wh}). This is also seen in a clear positive relationship between soil volumetric water content (less than 20%) and r_{wh}. **As the footprint-averaged vegetation fraction increases, efficiency of water vapour exchange increases** (less patchy vegetation means higher r_{wh}).
- **Momentum exchange is more efficient during summer, when leaves are out**, as a result of increased drag by vegetation.

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