Two-point statistics of turbulent flow in the canopy layer

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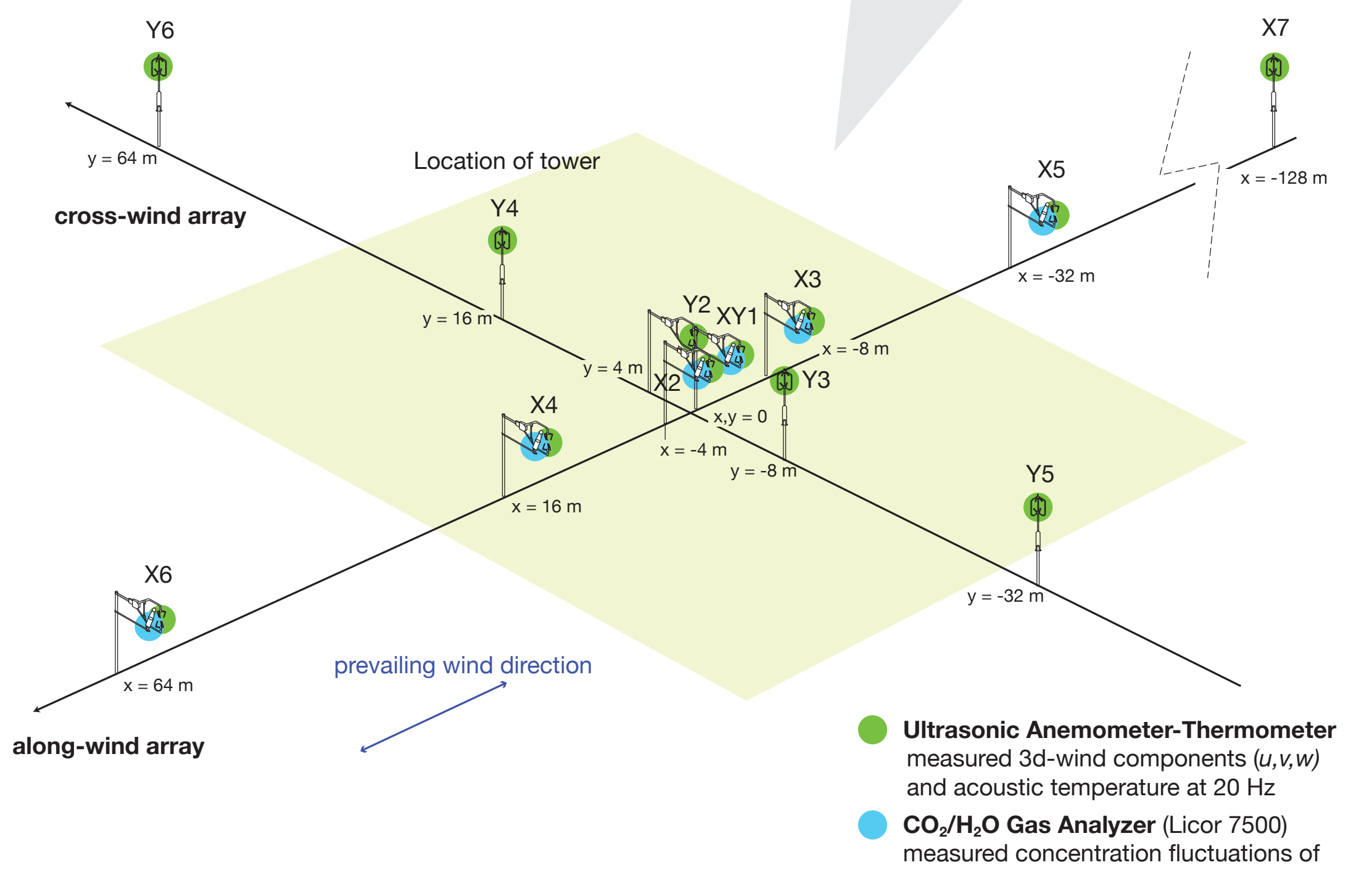
The field experiment HX06 was designed to quantify rarely measured spatial statistics in canopy turbulence. In particular, two-point correlations of velocity fluctuations, temperature, water vapor, and carbon dioxide were experimentally determined in the trunk space of a forest. Further, convection velocity was estimated for selected runs.

Unlike detailed CFD and LES models, which can simulate spatial flow and turbulence fields in forest canopies, experimental studies are not able to capture instantaneously the spatial structure of turbulent fluctuations. Today's preferred turbulence sensors sample time series of turbulent fluctuations at a given location. In many applications, we use a single sensor and implicitly apply Taylor's frozen turbulence hypothesis to 'translate' statistics measured in the time domain back to space. This works reasonably well in the inertial sublayer. However in vegetation canopies, core assumptions of Taylor's hypothesis fail. In this study we explicitly determined 'two-point' statistics. The term 'two-point' refers to the fact that we do not make use of Taylor's frozen turbulence hypothesis but use spatially separated sensors [1].

Experimental set-up

We discuss a data set sampled in the trunk space of a uniform Scots Pine forest at Hartheim Research Station (University of Freiburg, Germany, 47° 56' 04" N, 7° 36' 02" E). The homogeneous forest is located in flat terrain and extends over 10 km in the prevailing wind direction and 1.5 km in the cross-wind direction. The canopy height is $h = 14.5$ m and stand density is 800 trees ha^{-1}.

Turbulence sensor array - Twelve ultrasonic-anemometer-thermometers were installed at $z = 2$ m above ground in the trunk space of the forest ($z/h = 0.14$). Sensors were arrayed in a cross-shaped setup with increasing sensor separation from 4 to 192 m. A first line of sensors (X1 to X7) was aligned into the prevailing wind direction. A second line of sensors (Y1 to Y6) probed at a right angle (cross-wind array). Additionally, six fast CO_2/H_2O analyzers were co-located at X1 to X6. 20 Hz data was sampled from all sensors over 30 days in spring 2006. Digital data from all instruments was logged and synchronized on a single computer.



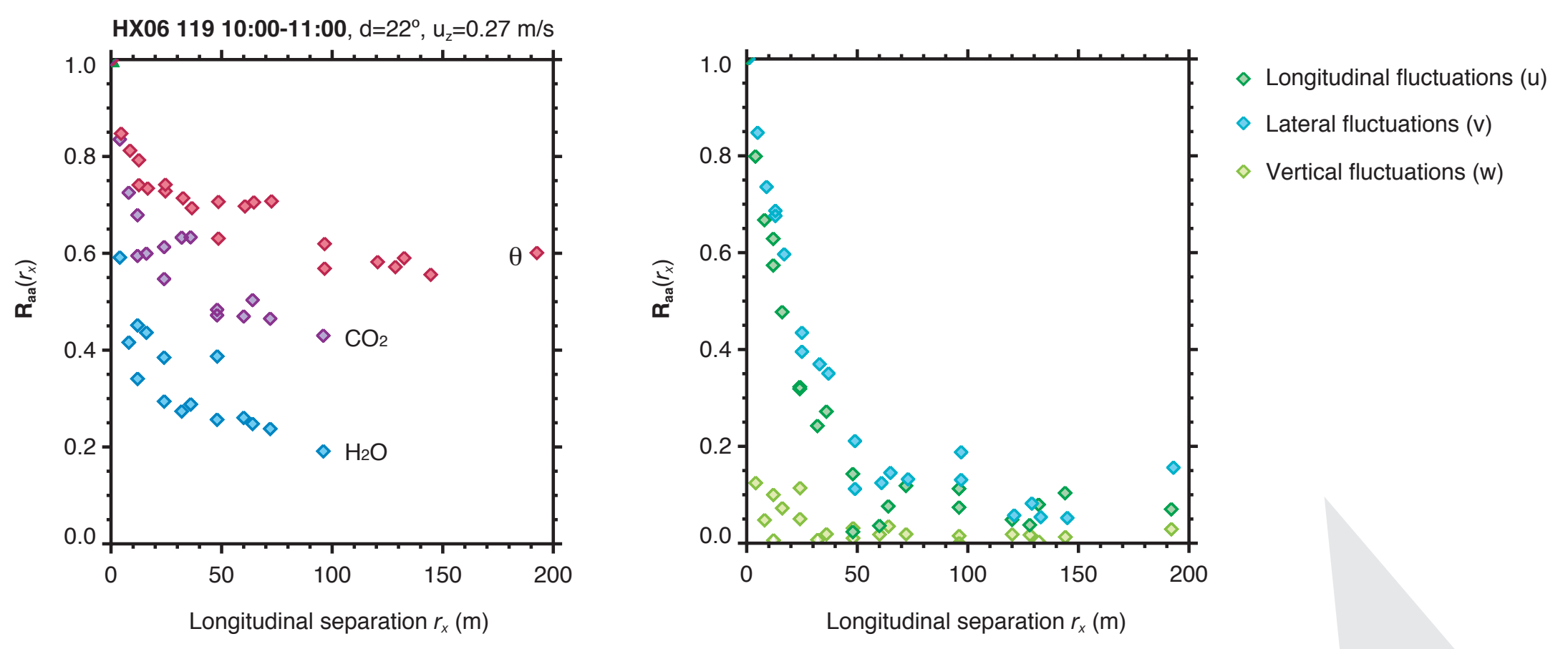
● **Ultrasonic Anemometer-Thermometer** measured 3d-wind components (*u*,*v*,*w*) and acoustic temperature at 20 Hz

● **CO_2/H_2O Gas Analyzer** (Licor 7500) measured concentration fluctuations of carbon dioxide and water vapour at 20 Hz.

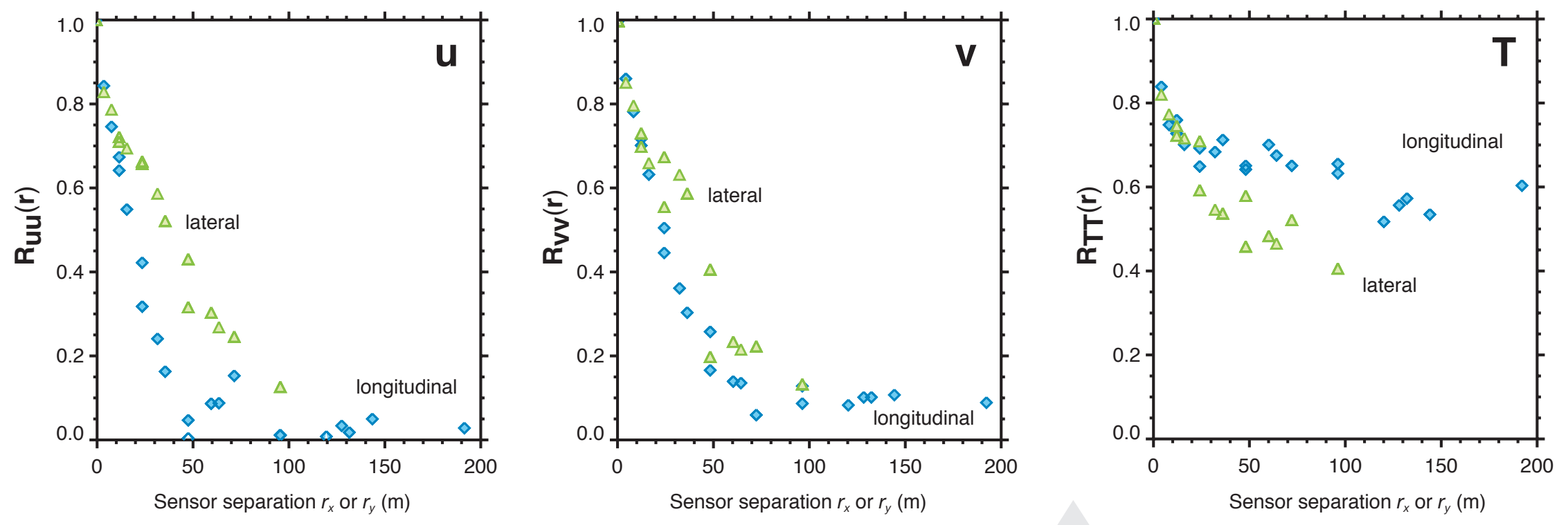
Spatial correlations

From data measured at horizontally separated locations we can determine two-point correlations $\mathbf{R}_{aa}$ of all measured sensor combinations and parameters ($a = u, v, w, T, CO_2, H_2O$). $\mathbf{R}_{aa}$ can be expressed as a function of the horizontal separation vector $\mathbf{r}$ (components r_x and r_y):

$$\mathbf{R}_{aa}(\mathbf{r}) = \frac{\overline{a'(\mathbf{x})a'(\mathbf{x}+\mathbf{r})}}{\sqrt{\overline{a'^2(\mathbf{x})}\;\overline{a'^2(\mathbf{x}+\mathbf{r})}}}$$



Scales - This sample data set shows two-point correlations $\mathbf{R}_{aa}$ for different scalars (left) and wind components (right). The hourly run has a mean flow parallel to the along-wind axis. Data are drawn as a function of longitudinal separation r_x. The energy containing horizontal movements (u,v) and all scalars show a good correlation even at separations greater than several times h. This suggests that large-scale structures dominate these turbulent fluctuations. It is not surprising that vertical movements (w) are more locally determined and nearly uncorrelated at separations larger than h.



Lateral and longitudinal elongation of structures - Again, this data is from a run when observed wind direction was within ±5° of the along-wind axis. Here, we draw correlations along both, the along-wind (longitudinal) and the cross-wind (lateral) axis, i.e. correlations are shown as a function of r_x and r_y sensor separation. Results show that the spatial turbulence field is not isotropic in the horizontal plane. For wind components u and v (left and center), lateral velocity correlations are consistently higher compared to the longitudinal ones. The opposite pattern (elongated structures) is observed in the temperature field (right).

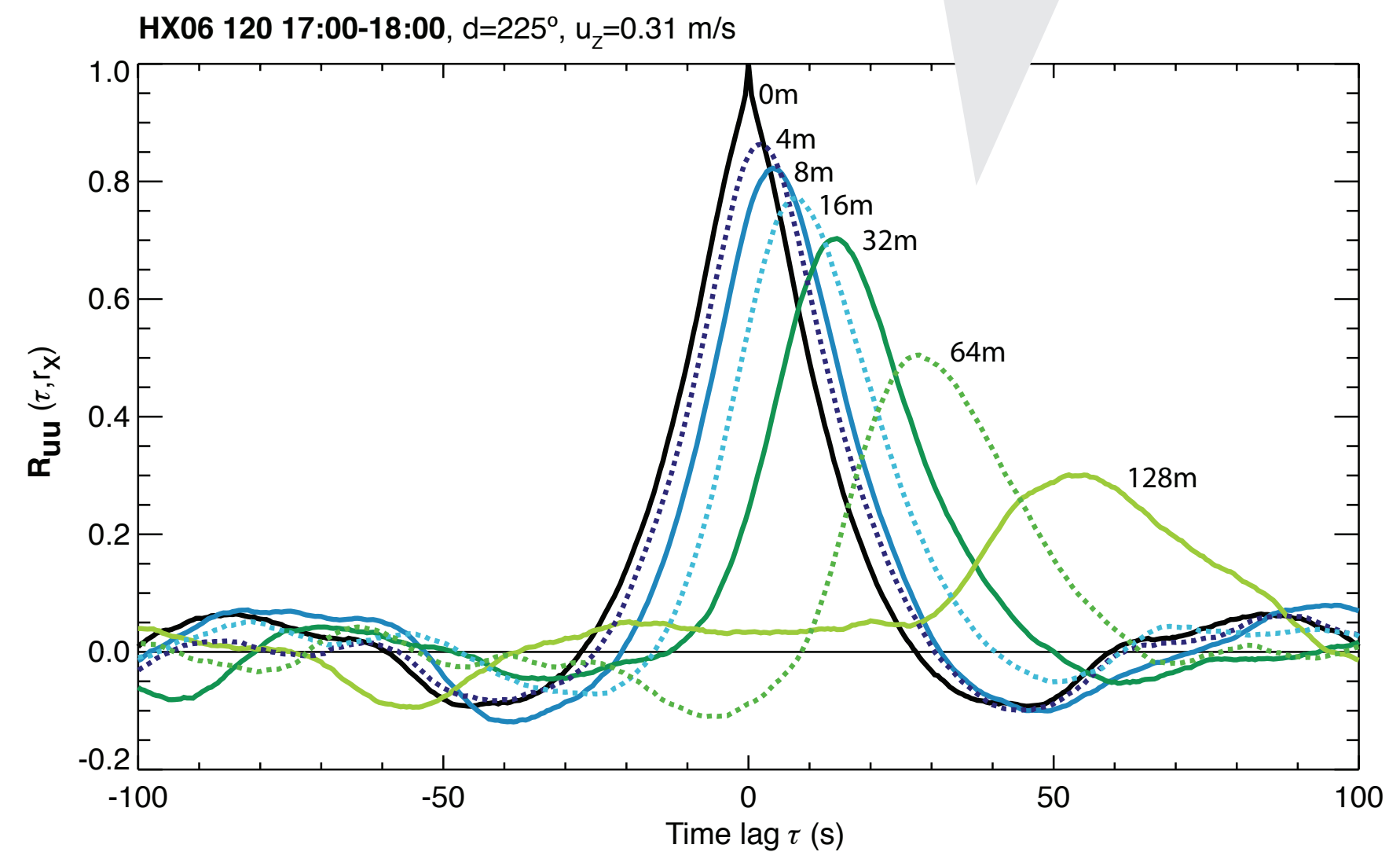
Time lag

In the next step, let us introduce a time lag τ in $\mathbf{R}_{aa}$, i.e. we shift the two time series *by* τ before calculating the correlation:

$$\mathbf{R}_{aa}(\mathbf{r},\tau) = \frac{\overline{a'(\mathbf{x},t)a'(\mathbf{x}+\mathbf{r},t+\tau)}}{\sqrt{\overline{a'^2(\mathbf{x},t)}\;\overline{a'^2(\mathbf{x}+\mathbf{r},t+\tau)}}}$$

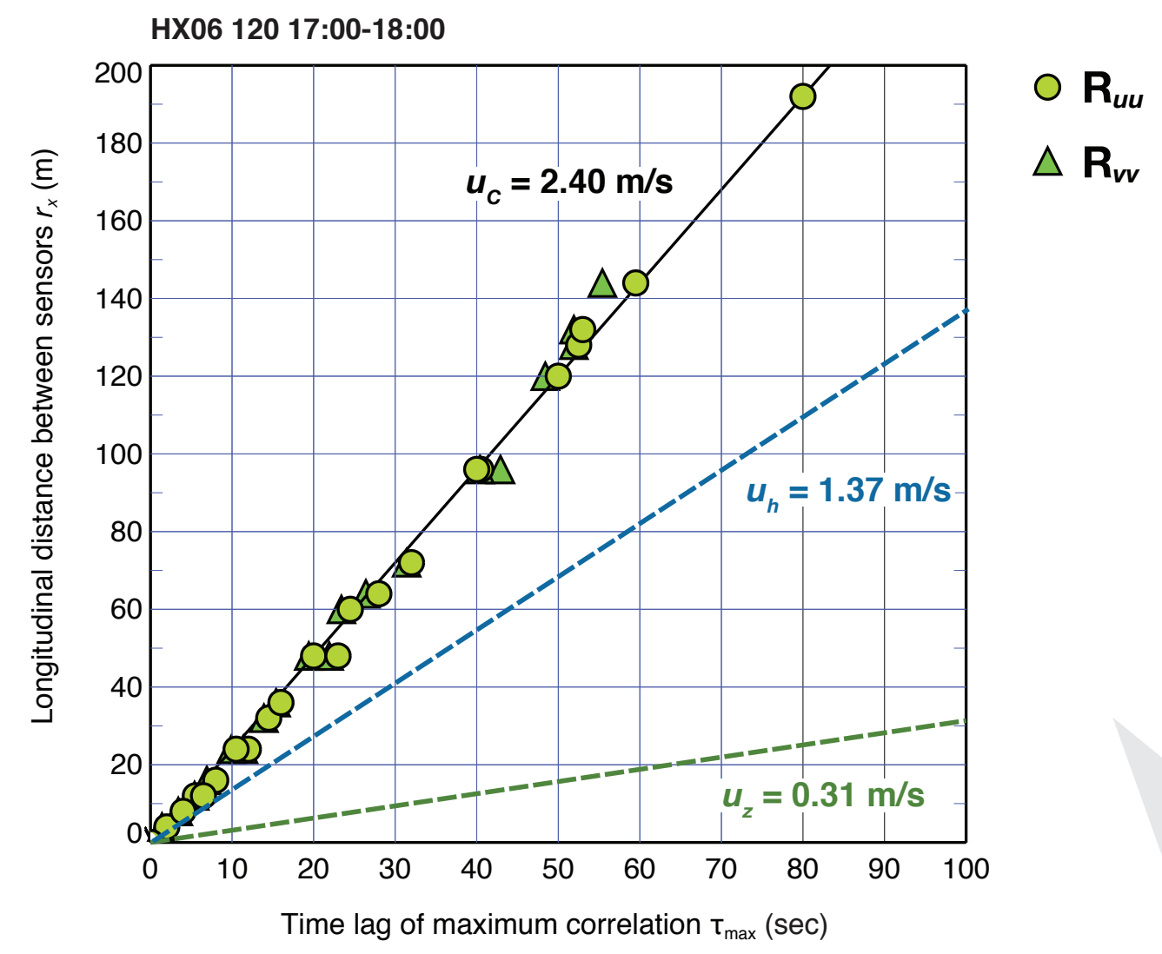
It is not surprising that the highest correlations are not necessarily found at zero time lag. The time lag of maximal correlation τ_{max} is a function of longitudinal separation because large-scale turbulent structures can be advected in the mean flow.

Correlation with time lag - The following example shows the spatial correlation of longitudinal fluctuations as a function of time lag τ for different sensor separations. The black curve is the auto-correlation of instrument X1 (0m). All other curves show the correlations between X1 and sensors in along-wind direction of X1 with increasing separation r_x (X2 to X7, 4m to 128m). The plot illustrates how the timing of τ_{max} is determined by the separation.



Convection velocity

Dominating turbulent structures in the canopy layer are transported much faster than the average Eulerian velocity u_z at 2 m. The velocity of dominating structures is called 'convection velocity' u_c and can be estimated from this data set by $u_c = r_x / \tau_{max}$.



Estimation of u_c - Again, the plot shows data from a hourly run with a mean wind direction within +-5° of the along-wind axis. The cross-correlations of longitudinal and lateral wind components suggest a convection velocity of $u_c = 7.7\ u_z$ (at 2m) = 1.75 u_h (u_h is the wind at canopy top simultaneously measured at a tower located at Y4). The factor 1.75 in the relation $u_c = 1.75\ u_h$ confirms an estimation reported in a previous study from a crop canopy where u_c was found 1.8 times u_h [2].

The fact that the convection velocity is not equal to the Eulerian velocity is observed in many rough wall flows. In forest canopies, the dominating turbulence structures originate from the higher velocity stream above the canopy and penetrate into the porous canopy spacewith increased turbulent kinetic energy (TKE). Hence, dominating TKE and most scalar fluctuations are not locally produced but imported from aloft.

Acknowledgements

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References

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