7.2 Validation of fluxes of an Extra Large Aperture Scintillometer at Cabauw using Sky Arrow aircraft flux measurements

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1. Introduction

Since the summer of 2000 an extra-large aperture scintillometer (XLAS) has been operated for a number of years at Cabauw by KNMI and Wageningen University, Meteorology and Air Quality Group (see Kohsiek et al., 2002). The aim is to obtain the surface flux of heat at a large scale, larger at least than the point measurements that can be obtained by conventional tower measurements with eddy-covariance (EC) equipment.

In 2001 and 2002 a number of field campaigns took place in the framework of RECAB (Regional Assessment and Modelling of the Carbon Balance in Europe), that is part of the CarboEurope projects cluster. Those campaigns encompassed, among other things, observations using the Sky Arrow ERA (Environmental Research Aircraft). More details can be found in Gioli et al. (2004). In this paper the aircraft data gathered at July 27, 2002 (see also de Arellano et al. (2004)) around the Cabauw mast in the Netherlands will be used to verify the sensible heat flux as observed by the XLAS at Cabauw.

2. Data and processing

2.1 *Scintillometer data*

A scintillometer is an instrument that consists of a light source (transmitter part) and a detector (receiver part) that measures intensity fluctuations. Because the measured variance of intensity fluctuations is a measure of the turbulent behaviour of the atmosphere it can indirectly be related to the transport of certain quantities. Depending on the configuration of the scintillometer, e.g. the aperture size, wavelength and the number of receivers the fluxes of heat, water vapour and momentum can be derived. The XLAS at Cabauw operates in the near-infrared part of the optical spectrum and thus, is most sensitive to temperature fluctuations. From the measured quantities the surface sensible heat flux can be derived (for more details see e.g. Meijninger et al. (2002)).

The path of the XLAS is approximately 41 m above the (flat) terrain (taking into account the curvature of the earth's surface). The transmitter is located on the TV-tower at IJsselstein and the receiver on the meteorological tower in Cabauw. The distance between transmitter and receiver (the path length) is 9.8 kilometer. The saturation of the scintillometer signal has been taken into account according to Kohsiek et al. (2006). The statistical error[1] of the in the XLAS-derived sensible heat flux is mainly based on the statistical error in the uncertainties in path length and installation height, the variables used in the calculation of the flux and the uncertainties in the similarity functions. Additional information regarding the processing: similarity functions according to Andreas (1988), roughness length for momentum $z_0 = 0.15m$, wind speed and other addition meteorological parameters from observations at 40 meters at the Cabauw mast. The Bowen ratio, needed for the translation of C_n^2 to C_T^2 (structure parameters of refractive index and temperature, respectively) was determined iteratively from the energy balance using net radiation and soil heat flux determined next to the Cabauw mast.

Apart from the scintillometer fluxes, also the the eddy-covariance fluxes next to the Cabauw mast (measured at 5.4 meter) will be used.

2.2 *Aircraft data*

During the summer campaign of RECAB that took place in the Netherlands (July 2002) a special pattern was flown by the Sky Arrow of IATA-CNR (Italy) to allow for intercomparison of the XLAS fluxes with the aircraft fluxes (and for detailed boundary layer studies, see de Arellano et al. (2004)). The flight path was close to the scintillometer path. These special flights were done on July 27th. An overview of the flights is given in Table 1. Note that the heights mentioned in the table are the nominal heights above the surface. In the calculations the actual mean height above the surface has been used. Note that we refer to a *leg* as a collection of *flights* along the same path, within a limited amount of time (e.g. in Table 1 the 7:44-8:09 leg at 80 meters consists of 7 flights). The flight pattern of all low-level legs, as well as the locations of the transmitter and receiver of the XLAS are shown in Figure 1. The legs do not exactly coincide with the scintillometer path. On of the reasons is that the plane should stay clear from the masts and their guy wires. However, the flight legs have a length (about 8 kilometers) that is comparable to the scintillometer path. And given the heights of XLAS path and the flight leg they both should have comparable footprints. The results will be presented as averages over the different flights, flown in the same time period (making 8 legs, of which 4 legs of low-level flights).

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[1] Here tolerances are used to express the statistical error. The range from observed value minus tolerance to observed value plus tolerance should contain with 95% certainty the real value

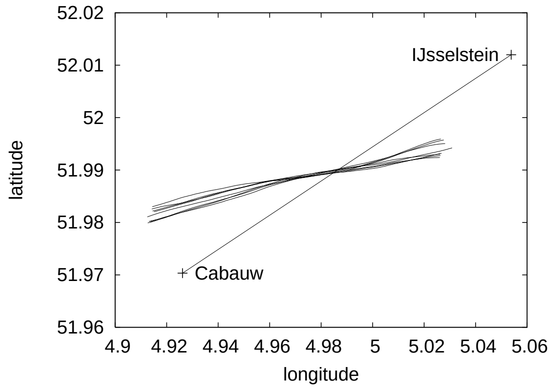

FIG. 1: Location of the low-level flight legs used in this study, relative to the locations of the transmitter (IJsselstein) and receiver (Cabauw) of the XLAS. The path of the scintillometer is indicated as well.

The statistical error in the aircraft fluxes over a leg has been determined in the following way. The error in the fluxes of individual flights has been determined according to Moene and Michels (2002), which is a variant of Lenschow et al. (1994). The resulting error in the flux is averaged over the flights and divided by the square root of the number of flights in a leg.

Apart from the horizontal flights mentioned here, both in the morning and in the afternoon a profile-ascent was made (not used here).

2.3 *Determination of flux divergence below aircraft path*

Since the fluxes measured by the aircraft are not surface fluxes (contrary to the XLAS-derived fluxes, which are based on similarity relationships in which the surface fluxes are used), the aircraft fluxes need to be translated downward. To do this, the vertical flux divergence needs to be estimated. This has been done, based on the budget equation for temperature. The tendency of the temperature has been estimated using the temperature data from the Cabauw mast (yielding $\left(\frac{\partial T}{\partial t}\right)_{obs}$). For the horizontal advection the estimate of de Arellano et al. (2004), based on a high-resolution mesoscale model simulation (valid for midday) has been used: $\overline{u}_i \left(\frac{\partial T}{\partial x_i}\right)_{model}$ =-0.36 K/hr. Horizontal flux-divergence has been assumed to be negligible. Then the surface flux can be derived from the flux at the the flight level z_a with:

$$H_0 = H_{z_a} + \int_0^{z_a} \left[\left(\frac{\partial T}{\partial t}\right)_{obs} + \left(\overline{u}_i \frac{\partial T}{\partial x_i}\right)_{model} \right] dz \quad (1)$$

The vertical integral was replaced by a vertical sum over four height intervals for which the temperature tendency could be derived from the temperature observations on the Cabauw mast (at heights 2, 10, 20 and 40 meters). The temperature tendency was evaluated at the mean time of the aircraft flights. The tendency due to horizontal advection was kept fixed to the value from de Arellano et al. (2004).

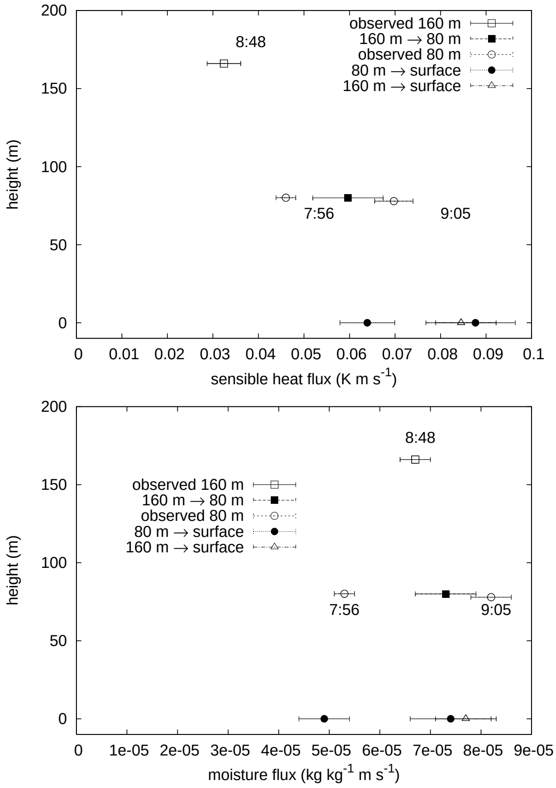

FIG. 2: Comparison of observed fluxes and fluxes translated to different height through flux divergence estimate. Top: heat flux, bottom: water vapour flux.

In order to test the skill of this method, it has been applied to the morning flights where two flight levels fell within the vertical extent of the Cabauw tower. In that case the flux at the upper flight level (160 m) could be translated to the lowest level (80 m). This was done both for heat and for water vapour, where in both cases the horizontal advection has been taken into account (though the contribution in the water vapour tendency was negligible according to de Arellano et al. (2004)). The results for the heat flux and the water vapour flux are shown in Figure 2. The method appears to work very well for both fluxes, also taking into account the differences in time of observation). Given the fact that -for temperature- the horizontal advection term is of the same order of magnitude as the flux divergence, this good result also supports the value used for the tendency due to horizontal advection.

3. Analysis

3.1 *Comparison between XLAS, and eddy-covariance fluxes from aircraft*

Figures 3 and 4 show the flux profiles of the sensible heat flux for the morning and afternoon flights, respectively.

Table 1: Overview of the legs flown on July 27th, 2002 between the Cabauw tower and the TV-tower at IJsselstein. The heights mentioned are the approximate mean heights above the surface.

	morning			afternoon		
level	time (GMT)	height (m)	# flights	time (GMT)	height (m)	# flights
low	7:44-8:09	80	7	12:33-12:42	80	4
low	9:00-9:10	80	4	13:37-13:48	80	4
middle	8:41-8:56	160	4	13:22-13:33	260	4
high	8:27-8:38	250	4	13:09-13:16	600	3

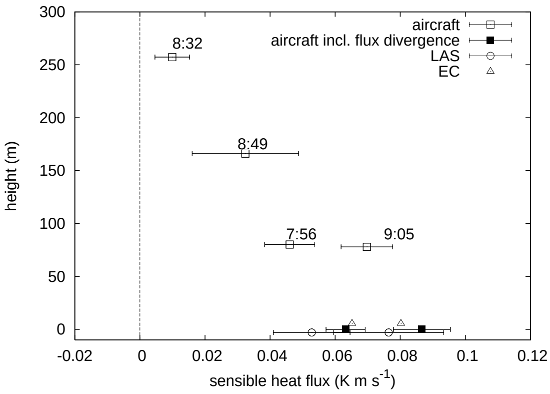

FIG. 3: Morning flights: comparison of the flux profile of aircraft sensible heat flux, with XLAS surface sensible heat flux and eddy-covariance fluxes measured at 5.4 meters. Aircraft surface flux has been derived as described in section 2.3. For XLAS-flux and EC-flux two symbols are shown, corresponding to the two times of the low-level legs. Mean time of the aircraft observations is indicated next to the symbols (note that in the graph, the lowest observations have been displaced vertically to separate them).

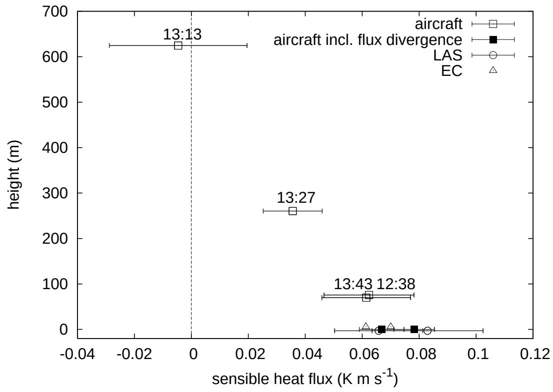

FIG. 4: As figure 3 but for the afternoon flights.

They include the aircraft flux translated toward the surface (according to section 2.3), the XLAS-derived flux and the eddy-covariance flux near the tower. It appears that both for the morning and the afternoon flights the XLAS flux is in good correspondence with the aircraft-derived flux and both fluxes agree within their measurement errors. Furthermore, assuming a linear flux profile, the surface fluxes from the XLAS nicely match the *entire* flux profile from the aircraft. For the morning flight the aircraft-derived fluxes are higher than the scintillometer-derived fluxes. Since Figures 3 and 4 only show snapshots in time, the diurnal cycle of the sensible heat flux is given as well, in Figure 5. The additional information is that the scintillometer gives a much smoother variation in time than the eddy-covariance fluxes. The values of the scintillometer flux and the local eddy-covariance measurements correspond quite well.

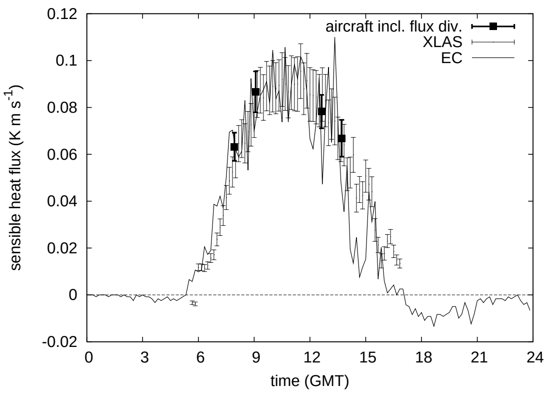

FIG. 5: Diurnal variation of sensible heat flux: aircraft flux at 70 m translated to the surface (see section 2.3), and fluxes derived from XLAS and eddy-covariance.

3.2 *Spatial heterogeneity of aircraft fluxes*

One of the interesting applications of scintillometry is that it can yield the area-averaged sensible heat flux on the

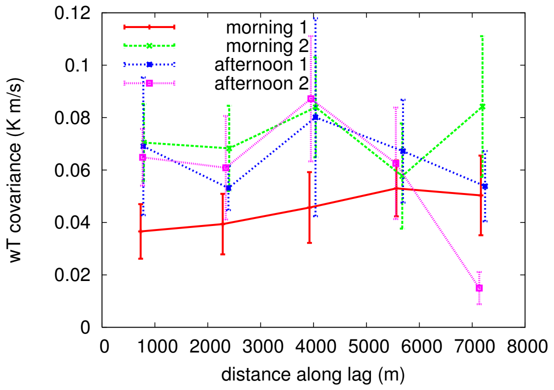

FIG. 6: Spatial variation of heat flux along the flight legs averaged over the group of seven and four morning flights (morning 1 and 2), and the two groups of four afternoon flights (afternoon 1 and 2). The fluxes relate to the fluxes at flight level, *not* ground level.

scale of 1 to 10 kilometers over moderately heterogeneous terrain. In order to investigate to what extent the terrain around Cabauw is heterogeneous, the flight legs have been divided into five sublegs and the subleg fluxes have been determined. To make the sublegs comparable, the individual legs were first truncated to cover the same line (by defining a common east-west extent of the flights). Then the legs were subdivided into five equal sublegs. The resulting fluxes are shown in Figure 6. Except for the first morning flight, the other flights show a clear maximum flux in the middle of the flight leg. However, this maximum does not exceed the error bars. In order to investigate the various sources of the variation of the sensible heat flux (in time and space), a variance decomposition according to Mahrt et al. (1994) is made[2] (see Table 2). Here the temporal variance indicates variations in fluxes between the individual entire flights making up the composite leg (possibly due to the diurnal cycle; see Table 1 for the number of flights per leg). The spatial variance relates to the variance between the mean subleg fluxes and is an indication of fixed spatial variability of the flux. Finally, the transient variance is the variability of the subleg flux between the different flights (and can be considered random). From Table 2 it is clear that for three of the four legs, the spatial variability is only a minor source of variability and thus the area under the scintillometer path can be considered to be rather homogeneous with respect to the heat flux. The reason for the high contribution of spatial variability in the fourth leg is related to the fact that all four flights in this leg exhibit the strong decrease in flux between the two sublegs to the right (see figure 6 for this effect in the mean flux). It should be noted that for the water vapour flux spatial variance made up of 11 to 49% of the flux. For CO_2 this Figure is 15-45 %.

[2]Given the low flight level, we assume that the mesoscale flux is neglectable, since mesoscale vertical windspeed will be negligible.

Table 2: Decomposition of variance of sensible heat flux at the lowest flight level, following the method of Mahrt et al. (1994).

	Temporal	Spatial	Transient
morning 1	0.30	0.06	0.64
morning 2	0.16	0.17	0.67
afternoon 1	0.31	0.08	0.61
afternoon 2	0.12	0.53	0.35

3.3 *Comparison of structure parameters from aircraft and XLAS*

The aircraft data can also be used to determine the structure parameter of temperature C_T^2 (and other scalars). In that way a direct comparison of aircraft data to the structure parameter of the refractive index observed by the XLAS could be made. However, the structure parameter depends on height (under free convection conditions proportional to $z^{-4/3}$) and the aircraft flight level and the height of the scintillometer path do not coincide. Therefore, we only focus on the spatial variability of the structure parameter of temperature as determined from the aircraft data (see Figure 7). C_T^2 exhibits a similar pattern as the flux (shown in Figure 6): a maximum in the center of the leg. There seems to be a discrepancy between the relative magnitude of the flux for the different legs and the relative magnitudes of C_T^2: the morning values of C_T^2 are higher than the afternoon values, whereas for the fluxes the difference is not that large, and the first morning flight even has a lower flux. This apparent discrepancy is related to the diurnal cycle of the windspeed. In the morning the wind is light (around 3 m/s) and consequently u_* is small. Then, with a given heat flux this leads to a higher C_T^2 than if the windspeed is higher (6 m/s at midday). To determine to what extent this spatial variation is significant relative to temporal and transient variation, a variance analysis similar to that done for the fluxes (Table 2) is made. The results are shown in Table 3. It appears that the distribution of variance of the temperature structure parameter among temporal, spatial and transient variance is similar to that for the fluxes: the spatial variance is only a small part of the variance, underpinning the relative homogeneity of the terrain around the Cabauw tower.

Table 3: Decomposition of variance of the structure parameter of temperature at the lowest flight level, following the method of Mahrt et al. (1994).

	Temporal	Spatial	Transient
morning 1	0.45	0.01	0.54
morning 2	0.42	0.04	0.54
afternoon 1	0.25	0.07	0.68
afternoon 2	0.27	0.11	0.62

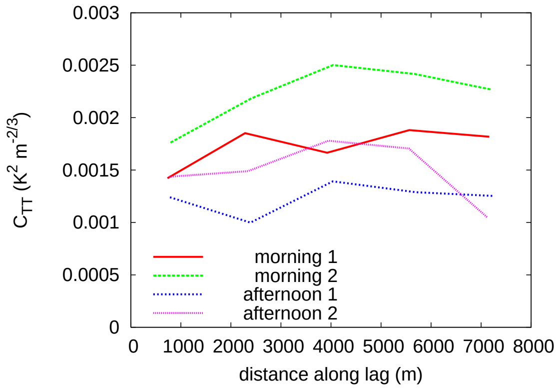

FIG. 7: Spatial variation of the structure paratmer of temperature (C_T^2) as determined from the aircraft data. Data from different flight averaged over the group of seven and four morning flights (morning 1 and 2), and the two times four afternoon flights (afternoon 1 and 2).

4. Conclusion

This is the first time that (X)LAS fluxes have been compared directly with aircraft derived fluxes flown closely along the scintillometer path. Beyrich et al. (2006) also report on a comparison of scintillometer fluxes with aircraft fluxes, but in that case the flight pattern was not designed to match the scintillometer path, and the scintillometer data were used to validate the aircraft fluxes, rather than the other way around. In order to translate the aircraft-derived fluxes to the surface, the flux divergence in the layer between the aircraft path and the surface has been estimated from the rate of change of the temperature in that layer, in combination with the horizontal advection derived from a mesoscale simulation (published elsewhere). This method is shown to work well, both for the heat flux and the water vapour flux.

The main objective of this study was to validate the heat flux derived from a XLAS using aircraft data. The results are convincing: the scintillometer reproduces the area-averaged fluxes as derived from aircraft data.

Finally, the spatial heterogeneity of the fluxes the temperature structure parameter at aircraft flight level has been investigated. Although there appears to be some variation along the path in both quantities, a variance analysis shows that the spatial variance contributes only to a small extent to the total variations. Temporal and transient variances are more important.

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