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**Short Communication**

# Experimental determination of sensible heat flux over a complex terrain by eddy correlation programme

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Abstract

Measurements on instantaneous vertical component of wind and temperature at 4.2 m above ground were made, using Gill propeller anemometer and a thermocouple, over a complex terrain at the Indian Institute of Tropical Meteorology, Pashan, Pune. Daytime hourly samples were taken for 10 and 40 min duration for 9 and 3 days in March 1985 and April 1986 respectively. Sensible heat flux estimated by eddy correlation programme, significant at 1% probability level, shows large diurnal scatter on averaging the covariances over 10 min and no significant improvement on increasing the averaging time to 40 min.

**Key words.** Sensible heat flux, complex terrain, eddy correlation.

## 1. Introduction

As early as in 1950 the eddy correlation technique for direct measurement of eddy fluxes close to the earth's surface was demonstrated by Swinbank[1]. Application of this technique calls for sensors capable of detecting the turbulent fluctuations of wind, temperature and humidity. Dyer[2,3], Dyer *et al*[4,5], Hicks[6,7] and many others have measured fluxes in the atmospheric surface layer using analog multiplying circuits to compute the covariance. Kaimal *et al*[8], Haugen *et al*[9], Högström[10], McBean[11], Dyer *et al*[12] have computed fluxes from turbulence data recorded in digital form on magnetic or paper tape which were either processed real time or run later on a computer. Tsvang *et al*[13], on the basis of a comparison of turbulence measurements by different instruments in the Tsimlyansk field experiment in USSR, observe that comparison of data analysis methods using analog apparatus and a digital computer showed good agreement.

Broadly, the objective of our study is to understand the turbulent transport of heat and momentum in the lowest few meters of the atmospheric boundary layer.

A good amount of work on the study of vertical fluxes of horizontal momentum, sensible heat and water vapour over horizontally uniform terrain, has been done elsewhere. The study of these properties over complex terrains is of contemporary interest since increasing urbanisation locally modifies the turbulent transport of atmospheric properties. Field experiments conducted over 9 days in March 1985 and 3 days in April 1986 to estimate the turbulent flux of sensible heat over a complex terrain are presented here. The fluctuating along wind and vertical component of the wind were measured using Gill propeller anemometers. A thermocouple sensor was used to measure the fluctuating temperature. The raw data was printed out using an indigenous data scanner and printer. The covariance was computed off-line by processing the data on an EC-1040 computer. The scope of this paper is to estimate the sensible heat flux and discuss the sampling time required to obtain a smooth diurnal change of heat flux.

## 2. The site and experimental details

The uneven site is located on the premises of the Indian Institute of Tropical Meteorology at Pashan, Pune. In the north about 300 m away from observation point is the 17 m high building complex of the Institute. A continuous hill of height 90 m above ground surrounds the point in the sector WNW–ENE (225°). About 4–5 km away another hill (crest about the same height in NW) appears as a background in the NNW–WNW sector (45°). The site is also interspersed with low rise buildings and/or trees of average height 5–10 m, a few hundred meters away on the W, N and NE directions. When wind approaches the sensors from N, E, W and S the corresponding aspect ratio is 15, 10, 10 and 5. A background of the site with an elevation view of instrumented masts as photographed from SW and NE of site during March 1985 and April 1986 experiments respectively is shown in fig. 1.

During the March 1985 experiment, measurements of vertical wind component and temperature were made hourly during day time for a period of nine days while in the April 1986 experiment measurements of wind direction and the along wind component were made in addition. From the 1986 experiment, only three days measurements, when data were printed in digital mode, are reported here.

Analog output from sensors was scanned by multiplexing and the instantaneous value of the parameter communicated to the system printer. The system has no facility for storing the data. The minimum print-time interval of the printer is 1 s. In view of these limitations the samples could be retrieved only at a rate of 1 sample per second. In the March 1985 experiment two channels were used, one to measure the vertical wind and the other the temperature. Samples were acquired for 10 min duration and were equally spaced at about 4 s interval. In 10 min, 160 samples were acquired for a given parameter. In the April 1986 experiment three channels were used respectively to record the along wind and vertical components of wind and temperature. Wind direction was recorded on a Yokogawa analog recorder. About 500 samples were acquired over 40 min for a given parameter, equally spaced at about 5 s interval. The time series constructed from measured parameters *viz*. wind and temperature were offset 1 s with respect to one another. This was inevitable since the system could only retrieve the data.

FIG. 1. A view of the experimental site with the instrumented mast used in, (a) March 1985 experiment, and (b) April 1986 experiment.

## 3. Analysis and results

We assume the essential property of ergodicity to hold good for the random variables, wind and temperature, sampled at regular intervals of time in a given sampling period. In the present experiment the high frequency end of eddy spectrum is limited to about 0.1 Hz as samples of each parameter were taken once every 5 s. The samples were screened to include only those above the threshold speed of the anemometer. At any time of the day during the observation period, the total number of samples that qualify for analysis was at least 90%. The time series obtained from the measured vertical wind and temperature were used to determine their fluctuations about the mean. The standard error for wind and temperature was computed. From the fluctuations in vertical wind ($w'$) and temperature ($\theta'$) the covariance and its standard error were computed. The flux of sensible heat, $H_s$, was determined from the relation:

$$H_s = \rho C_p \overline{w'\theta'}$$

where $\rho$ is the density of air and $C_p$ the specific heat under constant pressure.

Using the standard error test and the student $t$ test, significance of estimated covariances in terms of probability level was determined. A tolerance limit of 10% in standard error is adopted.

Figure 2 depicts the time variation of sensible heat flux at 4.2 m above ground during March 15–25, 1985. The flux was estimated by averaging the products of $w'$ and $\theta'$ over 10 min. Values are significant at 1% probability level except those in parentheses which

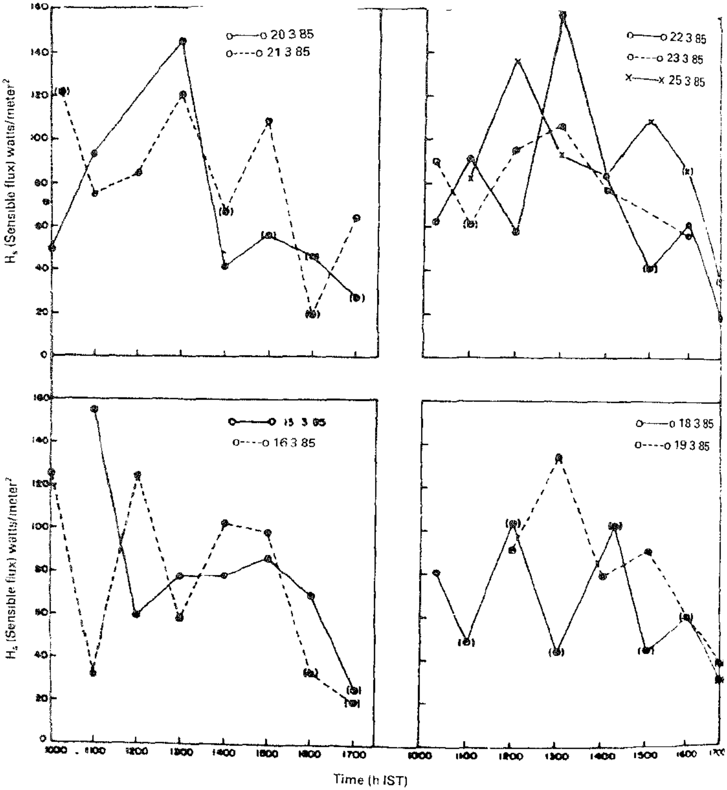

FIG. 2. Time variation of heat flux averaged over 10-min runs for different days of observation in March 1985.

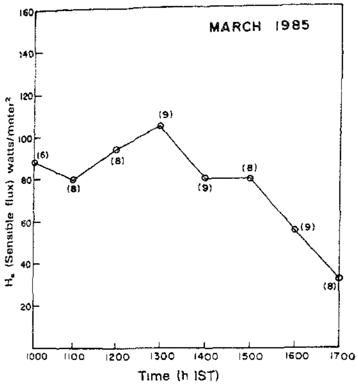

FIG 3 Time variation of mean heat flux (10-min averages) integrated over the period of observation in fig. 2.

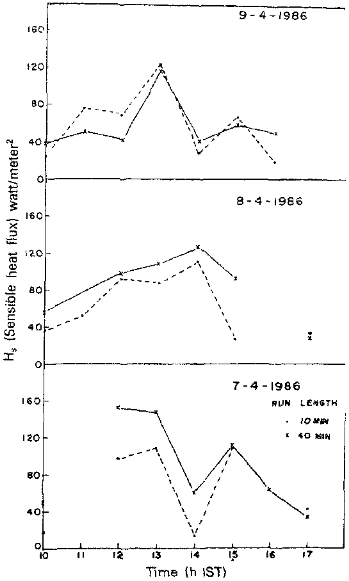

FIG 4. Time variation of heat flux averaged over 10- and 40-min runs during April 7–9, 1986

are at 5%. It can be seen that the diurnal variation of flux is uneven during the period of observation, suggesting that a longer averaging time than the arbitrarily chosen 10 min, might reduce the scatter. Figure 3 depicts the average diurnal variation during this observing period, the number in parentheses indicating the number of days of observations used to obtain the mean flux. A reasonably smooth picture of flux variation is obtained when measurements are averaged over all the days.

In Table I the progression of mean heat flux during the day is shown for March 15–25, 1985. The progression is smooth enough to suggest that notwithstanding the small variations in the daily averages, the general conditions remained the same during the period.

The diurnal variation of heat flux for 10- and 40-min run lengths is shown in fig. 4 for the three consecutive days of observation in April 1986. It is observed that despite a few notable deviations in flux values, the general pattern of change is similar in both 10- and 40-min averages. Negative flux occurs (not shown in figure) at 1100 h on April 7 in

**Table I**
**Progression of heat flux (1000–1700 h IST) at 4.2 m above ground**

| Month<br>Date | March 1985<br>15 | <br>16 | <br>18 | <br>19 | <br>20 | <br>21 | <br>22 | <br>23 | <br>25 |
|---|---|---|---|---|---|---|---|---|---|
| No. of observations | 7 | 8 | 8 | 6 | 7 | 8 | 8 | 6 | 7 |
| Mean sensible heat flux $W\,m^{-2}$ | 84 | 74 | 65 | 82 | 66 | 82 | 72 | 81 | 90 |

the 40-min averaged value and at 1600 h on April 7 in the 10-min averaged value with its standard error 10% but the 40-min averaged value is positive. At 1600 h on April 8 and at 1700 h on April 9, both the 10- and 40-min averaged values of flux are negative. The reasons for these negative values are not clearly understood.

## 4. Discussion and conclusion

Measurement of turbulent fluctuations of wind and temperature in the atmospheric surface boundary layer, to estimate the flux of sensible heat or momentum, presents a more serious problem to the experimenter in the sense that the sensors normally do not respond to the entire range of eddy sizes contributing to the flux. Alignment of sensors parallel to the coordinate axes of wind to measure the respective component of wind velocity is yet another problem over a complex terrain. Many authors have discussed the error due to non-verticality of the sensors[14–17] and suggested that per degree tilt the error could be 8[14] to 28%[16]. Under light winds the buoyant force (acting vertically to local terrain) contributing to the vertical wind component could very well be discerned. The bias due to non-verticality of sensors is bound to occur either way. A judicious selection of site from the perspective of aspect length, etc., and careful analysis of data could to a large extent help in the elimination of contaminated data.

The upper and lower bounds for frequency bandwidth for heat flux is $f = 0.001 (f = nz/\bar{u})$ on the low frequency side and $f = 3$ on the high frequency side[18]. In the present study the high frequency is limited to about $f = 0.2$, which is a decade short of the required range. For 10 to 40 min averaging time, the lower bound for frequency bandwidth varies from $f = 0.003$ to 0.0008, which seems to be adequate.

Kansas experiments show that a minimum averaging time of one hour is needed for stable flux estimates at heights 5–20 m above ground[18]. In the flux measurements using evapotron, Dyer[3,4] observed considerable scatter, despite the use of longer (30-min) runs, particularly in light winds. Large-scale eddies contribute measurably to variability in the flux when shorter (5-min) runs are taken but they average out to a negligible value over longer periods (hourly or daily). Statistical test performed on the present data shows that the estimated fluxes are significant at 1 or 5% level; most of the values at 1% level.

To summarise, we estimated the sensible heat flux by discrete sampling of turbulent wind and temperature and computing off-line the covariance using fluctuations of these quantities over a chosen averaging time. The diurnal change of heat flux showed large scatter on averaging the flux over 10 min which did not improve significantly on increasing the averaging time to 40 min. The mean sensible heat flux estimated from diurnal variations for the period March 18–25, 1985 is 68 w/m$^2$ and that for the period April 7–9, 1986 is 52 w/m$^2$.

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