Supplementary Material S2: Corrections applied and EC flux calculations using EddyPro®

EddyPro checks for signal quality and gas analyzer signal strength (which depends on the cleanliness of sensor optical windows and/or presence or absence of rain drops/fog in the measuring volume). A missing samples allowance of 10% was set for the raw data in the flux averaging intervals and linear interpolation of the data is done by Eddy pro within this limit. The effect of wind blowing normal to the sonic path on the speed of sound (sonic temperature) is corrected for in the CSAT3 firmware(CSAT3 3-D Sonic Anemometer Instruction Manual). Other corrections are as follows.

1. Calculate one-minute averaged wind vector from raw data and find the mean tilt angle of the sensor by requiring that the mean slope of the best fit line to the scatter plot of horizontal velocity versus vertical component of velocity of the sample be closest to zero. The mean tilt angles are calculated from one minute averaged data considering data of ~ 15-20 days. Figure S1.1 shows one such example. This tilt correction is applied to 20 Hz sampled velocity before passing data on to the EddyPro program.

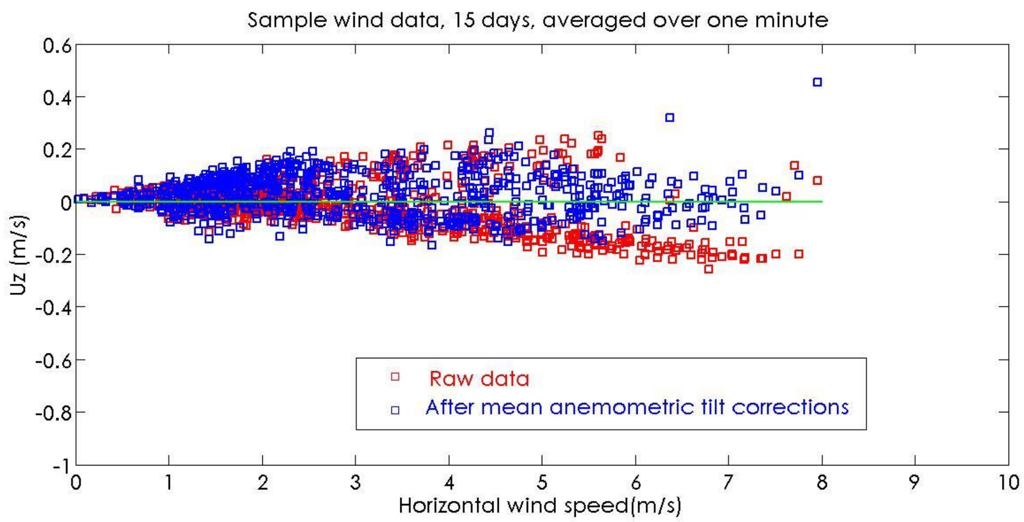

Figure S2.1. Correcting for the mean tilt of the sensor with respect to the vertical.

2. For each of the flux calculation interval, a streamwise rotation is applied in EddyPro, using the traditional double rotation method (an initial rotation of the wind vector about the z axis and then a second rotation about the new y axis that nullifies *w* velocities).

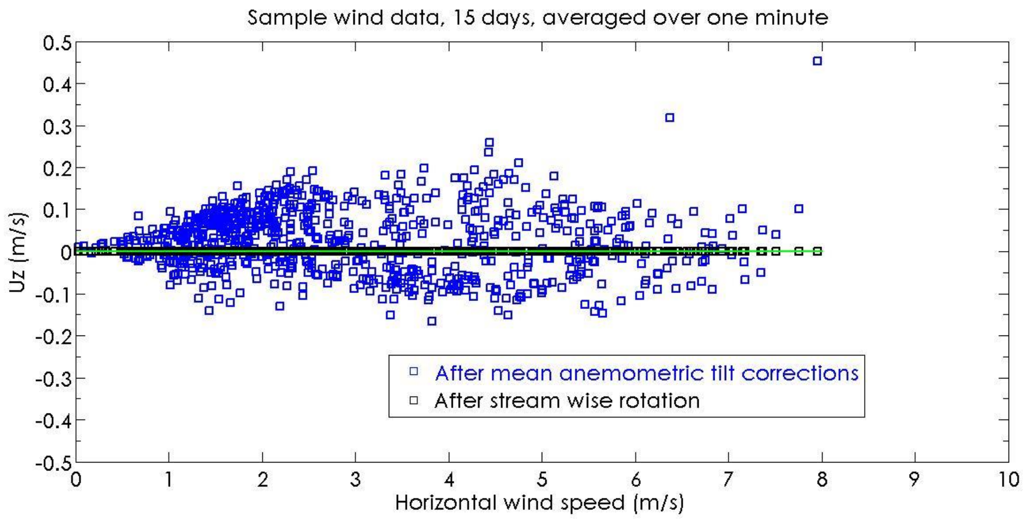

Figure S2.2. Vertical component of velocity before and after the EddyPro corrections to each 15-minute time interval.

3. The turbulent fluctuations for each of the flux averaging intervals are extracted from the high frequency data using linear detrending (eg. Gash and Culf, 1996 , Moncrieff et al., 2004 and Rannik and Vesala, 1999.). Since there exists a finite distance (~ 1cm) between the sonic anemometer and the open path gas analyser, there would be a finite time lag between their measurements of the same air parcel. This is compensated for in EddyPro using the “covariance maximisation” procedure, where a time lag that maximises the covariance of the two variables is determined within a window of plausible time lags (eg., Fan et al., 1990)

4. The effect of air density fluctuations (on account of fluctuations in temperature, pressure and concentration of trace gases, water vapour in particular) on the mixing ratio measurements is compensated using the WPL correction terms (Webb et al. 1980).

5. Following 9 EddyPro tests are applied to assess the statistical quality of the raw time series data (Vickers and Mahrt 1997). For each test and variable, EddyPro outputs a flag to indicate the outcome: Passed: 0 ; Failed: 1 ; Not selected: 9

- Spike Count and Removal: detecting and eliminating outliers
- Absolute limits: Determining whether the measured values are outside a user-defined plausibility window
- Amplitude Resolution: Determining whether the measurements can sufficiently resolve turbulent fluctuations within their variation range.
- Drop outs: Determining short periods when the time series is stuck at a value that is statistically different from the averaged value for the interval.
- Skewness and Kurtosis: Flagging variables if their third and fourth moments exceed thresholds.
- Discontinuities: Detecting discontinuities that lead to semi-permanent changes.
- Time lags: Determining whether actual/calculated time lags are too different from expected time lags.
- Angle of attack: Determining whether the angle of attacks during an interval exceeds a threshold.
- Steadiness of Horizontal wind: Assessing whether the along-wind and crosswind components undergo systematic reduction to check for stationarity of horizontal wind.

6. Apply frequency response corrections to account for high pass filtering effects (Moncrieff et al. (2004)) from the finite averaging time and low pass filtering effects (Moncrieff et al. (1997))arising from instrumentation limitations. The random uncertainty of flux measurements due to possible sampling errors are calculated using the method of Finkelstein and Sims (2001).

7. Quality flags are calculated for all the fluxes based on the results of two tests : stationarity test and developed turbulent conditions test (Foken et al. 2004, Foken and Wichura, 1996). The combined flag attains the value “0” for best quality fluxes, “1” for fluxes suitable for general analysis such as budgets and “2” for fluxes that should be discarded.

An important assumption in the EC flux calculations is that the flow is turbulent and stationary, and for this reason, the duration of averaging time interval has bearing on the calculated fluxes and associated uncertainties. Flow stationarity is difficult to achieve for atmospheric flows when averaging times are longer than 30 minutes (e.g., Panofsky and Dutton 1984, p96). Choosing a shorter time interval increases uncertainties in the fluxes because of inadequate sampling of turbulent scales present in a flow and may result in low frequency (co-) spectral attenuation. We tested with 15 and 30 minute averaging time intervals. 15-minute averaging interval has higher probability of satisfying stationarity condition and thus, less data gaps compared to 30 minute averaging intervals, however, the uncertainty in the former fluxes is about 2% higher compared to the latter. Between missing fluxes and having slightly larger uncertainty, we chose the latter, and all fluxes shown here are based on 15-minute averaging time. Fluxes of only those time intervals that passed all the statistical tests, specified quality thresholds and considered as good for surface energy balance calculations are included for further analysis. Another cause of missing data is signal quality or signal strength (SS) and we removed data below quality thresholds. Data losses are frequent under fog and rains. Relative humidity is close to 100% during rains and fog, and it is likely that LH values are small during such periods. Fog occurrence is common at some sites especially at night and early morning hours. If drop in SS is associated with fog, then corresponding LH is set to zero during fog hours. It was also noted that water vapor and CO_2 signals are not good when SS fluctuates (typically during rainfall). SS range is 0 to 1, and flux data of time intervals when rms of SS (during the averaging time interval) is more than 0.01 have been removed.

While EC method is the most direct way of calculating SH and LH when ABL is turbulent, this method has limitations and gaps do exist in the time series owing to sensor signal strength and flow non-stationarity issues. The main focus in this work is the seasonal evolution of SH and LH. For this purpose, 5-day running averages (pentads) are constructed. Over a land-surface, SH and LH fluxes exhibit large diurnal variation. To account for this, averaging is first done over a diurnal cycle and a pentad average is accepted only if at least 93% (i.e., 90 out of maximum 96 samples) of diurnal cycle has valid data and the pentad time interval has at least 320 valid values out of maximum 480 (i.e., 67%).

SH and LH exhibit strong diurnal variation over land (e.g., Figure 7 in Turner et al. in this volume). Turbulent heat flux (THF =SH+LH) is mostly produced during periods of (high) solar heating over a land surface. In order to understand this aspect of surface fluxes over the Indian landmass, we computed monthly average values considering all valid data between 0900 and 1600 LST (henceforth daytime). Thus, in the results shown, flux timeseries are pentad averages covering the entire diurnal cycle, whereas, monthly values are daytime value.

References:

CSAT3 3-D Sonic Anemometer Instruction Manual, www.campbellsci.com

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