# *Interactive comment on* "Using sonic anemometer temperature to measure sensible heat flux in strong winds" *by* S. P. Burns et al.

## Reply to Johannes Laubach's 2nd Comment

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The additional comments by Johannes Laubach are greatly appreciated. Our replies to his comments are below.

Comment 1: *1) First, let's try to be clear about the direction of the heat flux error. Fig. 1 in the manuscript shows a time series where at high wind speed during the night (around Day = 42 and 43 < Day < 43.5) the heat flux using the thermocouple is downwards (negative) while using the sonic it is upwards (positive). So far, I had understood from the manuscript that this was the main observation of interest. Apparently, Thomas Foken and the Anon Ref shared this understanding. However, none of the shown examples of spectra and cospectra represents this situation. In Fig. 3 (Day) all heat fluxes are positive. In Fig. 3 (Night) all are negative, and the one using the sonic has the smaller magnitude, indicating serious decorrelation of the w and Ts signals, not a spurious correlation increase. In the figures of your reply to my first Comment, the same is true. (In Fig. 4 of the manuscript, also all daytime heat fluxes are positive and all nighttime heat fluxes are negative, as one would expect.) So I think it would be helpful if you could select some periods where w-Ts and w-Ttc have opposite sign.*

Reply to Comment 1: This is a very astute observation. The apparent lack of positive nighttime CSAT heat flux data (Fig. 3b) is because the CU CSAT being examined during that period (Nov 2011) is CSAT s/n 0198 while the heat flux shown in Fig. 1 is from Feb 2010 (when CSAT s/n 0328 was deployed at the tower, see Table 1 for details). We purposely avoided using CSAT s/n 0328 in the more detailed figures (such as those with the spectra) because the calculated heat flux with this CSAT was even more different than the other CSATs (e.g., compared to the thermocouple heat flux). In fact, s/n 0328 being so different was how the problem was initially noticed...and we originally suspected there was something wrong with that particular CSAT. CSAT s/n 0328 was used in Fig. 1 to show how dramatic the problem could be. This also allowed the lines in Fig. 1 for each sensor to be clearly separated from each other. Now that we have more information we realize that the error in s/n 0328 is worse than the other CSATs, but during the factory calibration process it was deemed acceptable. At the current time we do not know why it is more sensitive to the Ts error than the other CSATs.

Comment 2: *2) In all the power spectra of sonic temperature that you show there is a "rising tail", indicating very high noise level. Fig. 3 and 4 show that the amplitude of this tail increases with wind speed, and I would hope that Campbell Scientific were interested in looking into the cause of this (see the two hypotheses in my initial Comment). Another effect of high wind speed is to shift the true turbulence spectra towards larger frequencies, where the true fluctuations and the instrument noise then combine and make it hard to filter the noise out.*

Reply to Comment 2: Larry Jacobsen from Campbell Scientific agreed to become a co-author on the revised paper and kindly shared his knowledge and expertise with us. This has enabled us to fully explain the CSAT heat flux problem and suggest an empirical solution (see sections 3.4 and 3.5 in the revised manuscript). We agree that when the true temperature variance is small (such as for high winds at night) there is a dramatic de-coupling between CSAT w' and Ts' (shown by the CSAT w,T coherence in Fig. 5b1 of the revised manuscript). In this situation, Ts' acts more like u'. It is not apparent that we can easily separate out the effects of small true T variance from the shifting of the turbulent scales shifting towards higher frequencies in high winds. However, during the day (when the true T variance is larger than at night) there is not such a dramatic loss in CSAT w,T coherence (e.g., Fig. 5a1) which suggests the magnitude of the T variance is more important than the scales. Though the decoupling is more apparent under the high-wind nighttime conditions, the CSAT Ts error occurs in a similar way for both day and night conditions which indicates the error is not directly related to the degree of w', Ts' decoupling.

Comment 3: *3) From Fig. 2 in your "Response to J. Laubach" it is further apparent that a digital filter with 1 Hz cutoff successfully suppresses spurious w-Ts-correlation above 1 Hz. However, the main problem lies in the range between 0.02 and 1 Hz, where the w and Ts signals are substantially de-correlated. Whether it is possible to correct for this by a better despiking algorithm is not clear from the figures. (I suspect not, see my next point.) One would need to zoom in on the time axis in Fig. 1, to periods $<$ 1 minute, to get a better idea what is going on.*

Reply to Comment 3: In our previous response we tried low-pass filter cut-off frequencies of 0.1 and 0.5 Hz. Now that we have clearly identified the problem there is no need to further explore this aspect of the study.

Comment 4: *4) The shown power spectra can further be distinguished by their behaviour at $f < 0.1$ Hz. In some cases (Fig. 3 Day, Fig. 4 bottom right panel) the sonic and thermocouple agree well in this range. In the other examples, the thermocouple shows the larger power. When this power difference occurs during the day, some of it may be due to radiation error of the thermocouple. This is not correlated with w, and thus the daytime cospectra of w-Ts and w-Ttc agree well with each other for $f < 0.1$ Hz. However, when such a power difference between Ts and Ttc occurs at night (Fig. 3b, Fig. 4 second row), it is associated with a significant magnitude reduction of the w-Ts cospectrum, indicating serious de-correlation between w and Ts. This de-correlation occurs because the high spike (noise) level masks the true low-frequency variations, and the despiking algorithm is not able to restore them correctly.*

Reply to Comment 4: We agree. Plus, there seems to be contamination of Ts' by u' for high-winds at night (e.g., the phase difference shown in Fig. 5b1 of the revised manuscript).

Comment 5: *5) I have used CSAT-3 sonics myself and dealt with some high-frequency noise. However, I have never seen them as noisy as here - but then, neither have I worked in frosty conditions, nor with such high wind speeds. My feeling is that conditions at your site have simply put the CSAT-3 outside its operating range, and I hope that you can work out in this paper if the problem is high wind speed as such, or only at low temperatures, or only during occurrence of particle drift, as Thomas Foken suggests.*

Reply to Comment 5: From our analysis we do not see a strong affect of temperature on the heat flux error. We believe we have explained the source of the problem in the revised manuscript. It also seems that a well-calibrated CSAT3 using ver3 of the firmware will operate acceptably in the NWT winter-time conditions.

Comment 6: *6) Re snow drift: can that be indirectly addressed, by checking if data from snow-free periods (at this site or elsewhere) are subject to similar decorrelation?*

Reply to Comment 6: We did this check and the details are described in our reply to Thomas Foken. The short answer is that the number of spikes detected is affected by humidity, but the heat flux problem is present in both humid and dry conditions.

Comment 7: *7) A possible conclusion from all this is that heat flux measurements in conditions as encountered by you (see 5) how to specify them) must be made with separate fastresponse temperature sensors. Since high wind speed provides enhanced ventilation, any radiation error will be ameliorated and thus be minor. (High-frequency loss due to sensor separation also decreases with increasing wind speed, making this a viable option.)*

Reply to Comment 7: We agree that a thermocouple should be used (until proven unnecessary). This was similar to one of our conclusions in the previous version of the manuscript, but we modified our statement to emphasize that a fast-response temperature sensor should be used in sites that experience high winds.