Eddy Correlation Measurements of Sensible Heat Flux near the Earth's Surface

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ABSTRACT

A three-dimensional pressure-sphere anemometer and fast thermometer system (P.S.A.T.) was used to measure vertical heat flux density in the atmospheric surface layer at 1–4 m above alta fescue and snap beans. Good agreement with independent measurements was obtained, which shows the the P.S.A.T. is sufficiently small and has adequate high-frequency response and accuracy for eddy correlation measurements within 1 m of the surface. Also obtained with the P.S.A.T. were $\overline{(u'T')}/\overline{(w'T')}$, $r_{u,T}$, $r_{w,T}$ and σ_T/T_*, and their dependence upon stability. When the atmosphere was thermally stable, slow wave motions frequently increased σ_T even though turbulent mixing was lacking.

1. Introduction

The turbulent vertical heat flux H in the atmospheric surface layer over a horizontally uniform surface can be determined from

$$H=\rho c_p \overline{w'T'}, \qquad (1)$$

where ρ is the air density, c_p the specific heat of air, w the vertical wind velocity, and T the air temperature. The bar denotes a time average and the prime an instantaneous deviation from the time-averaged quantity. The major difficulty with making eddy correlation measurements of turbulent heat transport is in measuring the vertical wind. This requires an accurate and stable anemometer that measures the wind components with a sufficient high-frequency response for use close to the surface where the fetch requirements are minimum. At present, the most promising anemometers are sonic anemometers, either pulsed wave (Mitsuta, 1966) or continuous wave (Kaimal *et al.*, 1968), and the pressure-sphere anemometer (Thurtell *et al.*, 1970). The pressure-sphere anemometer is smaller than sonic anemometers and thus can be used closer to the surface where eddies are smaller.

This paper describes the measurement of turbulent heat transport with the pressure-sphere anemometer and a small, fast-response resistance thermometer. Measurements of heat flux above alta fescue are compared with independent measurements made by others at the University of California at Davis as part of the 1967 Cooperative Field Experiment sponsored by the Atmospheric Sciences Laboratory, U. S. Army Electronics Command, Ft. Huachuca, Ariz. Also presented are measurements of heat flux made in 1968 over snap beans at the University of Wisconsin Hancock Experiment Farm. A summary of the standard deviation σ_T of temperature divided by the dimensionless temperature scale T_*, and of correlation coefficients for wind and temperature are also given for measurements over the above two surfaces.

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2. Equipment, sites, and comparison measurements

a. Pressure sphere anemometer-thermometer assembly

A fine-wire resistance thermometer was mounted parallel to the horizontal ports of the pressure sphere (Thurtell *et al.*, 1970), as shown for a 3-cm diameter sphere in Fig. 1. The closest edge of the thermometer was about 1.25 cm from the 3-cm anemoclinometer and about 2.5 cm from the 8-cm anemoclinometer. The thermometer was placed so that the sensitive element was slightly upwind of the leading edge of the pressure sphere; tests showed that this forward placement was necessary to prevent thermal modification of the air that flowed to the thermometer past the large thermal mass of the sphere. The thermometer was outside the angle of acceptance of the anemoclinometer and tests showed that the flow patterns around the sphere were not significantly affected.

The fine-wire resistance thermometer consisted of about 55 cm of platinum-coated, 5.6 μ diameter, tungsten

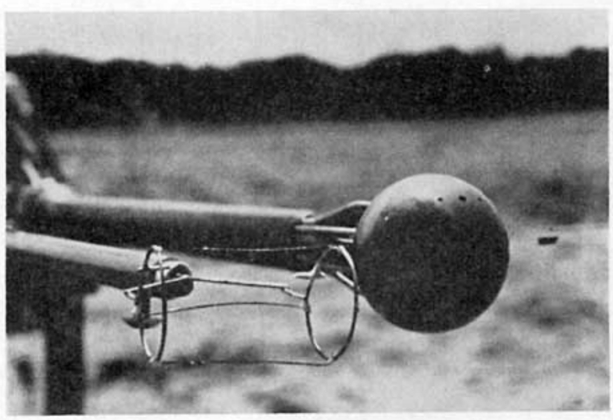

Fig. 1. Configuration of the thermometer and the pressure sphere.

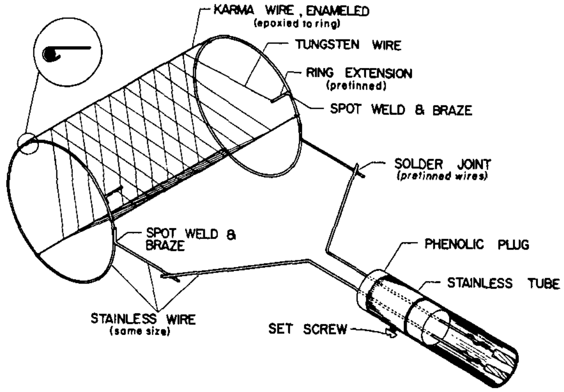

FIG. 2. Resistance thermometer details.

wire,[2] wound on a frame as shown in Fig. 2. Tungsten was chosen because of its high tensile strength and the platinum coating was necessary for easy soldering. Since the time constant of the thermometer was only ~1 msec, the analog signal from the thermometer bridge was filtered electrically to match the response of the wind measuring system. Radiation could cause the wire to heat up as much as 0.09C under extreme conditions, but a wind gust would not change the offset by more than a few hundreths of a degree Celcius. Self-heating was limited to <0.01C. We believed the thermometer, exposed to radiation, measured temperature fluctuations to within ±0.01C, and properties were not dependent upon wind speed[3].

When the 1967 data were obtained, the anemometer was rotated in azimuth manually into the mean wind at the beginning of each half-hour run. During 1968, a motor assembly, controlled by the anemometer, rotated the mast to point the anemometer into the wind. The azimuth rotation of the mast was monitored with a potentiometer attached to the base of the mast and was included in the calculation of the components of the wind vector.

b. Data handling

The current through the thermometer was kept nearly constant at 0.3 mA by its bridge, which was located about 5 m from the thermometer. The bridge output was fed directly into a floating differential amplifier with a 1000 gain, to provide a signal with a temperature sensitivity of about 0.6C V^{-1}. The amplifier output was transmitted through 150 m of cable to the instrument trailer. The thermometer and anemometer signals were fed to a scanner-converter and an EMR computer as described by Thurtell *et al.* The sampling rate was 40 sec^{-1} in 1967 and 150 sec^{-1} in 1968.

The outputs of the thermometer bridges were filtered in the amplifiers to match the phase shifts and response of the pressure-sphere anemometer and also to avoid high-frequency noise. The response of the two systems are shown in Fig. 3 as well as those for the anemoclinometers. The curves for the anemoclinometers are roughly representative of the vertical wind component.

c. Site description

A description of the site of the 1967 Cooperative Field Experiment, and our instrument locations, as well as the locations of other relevant instruments may be found in Thurtell *et al.*

The 1968 measurements at Hancock, Wisc., were on a 100×160 m field of snap beans planted in rows spaced at 90 cm. The snap beans were about 30 cm high and provided about 50% cover over Plainfield sand. The fetch was 60 m to the north, 50 m to the east and west, and 100 m to the south. Beyond these boundaries to the south was alfalfa extending for 150 m to a 15 m high woods and to the west was an alfalfa field extending 100 m to a 10 m high shelter belt; to the northwest were low crops extending 200 m to a shelter belt, and to the east was alfalfa extending 300 m to a woods. The wind was predominately from the south and west during the tests.

d. Independent measurements of sensible heat flux

During the 1967 experiment, Dr. C. R. Stearns of the University of Wisconsin measured wind, temperature and vapor pressure profiles at three locations in a triangular array. At the same locations, he measured net radiation and soil heat flux density for energy balance calculations. The sensible heat flux was calculated from the energy balance using Bowen's ratio, $B=\gamma\Delta T/\Delta e$, determined from vertical temperature and vapor pressure differences measured over the same height intervals within 120 cm of the surface. An aerodynamic calculation of the sensible heat flux also was made using the wind and temperature profiles to find

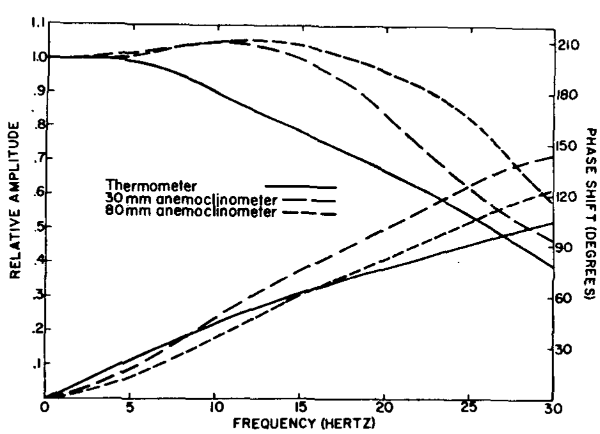

FIG. 3. Frequency response and phase shift of the thermometer system and of the anemometer system.

[2] Sigmund Cohn, Mount Vernon, N. Y. (0.00022-inch diameter, with about 4–7% weight platinum coating).

[3] Further information on the construction and characteristics of the thermometer can be obtained by contacting the authors.

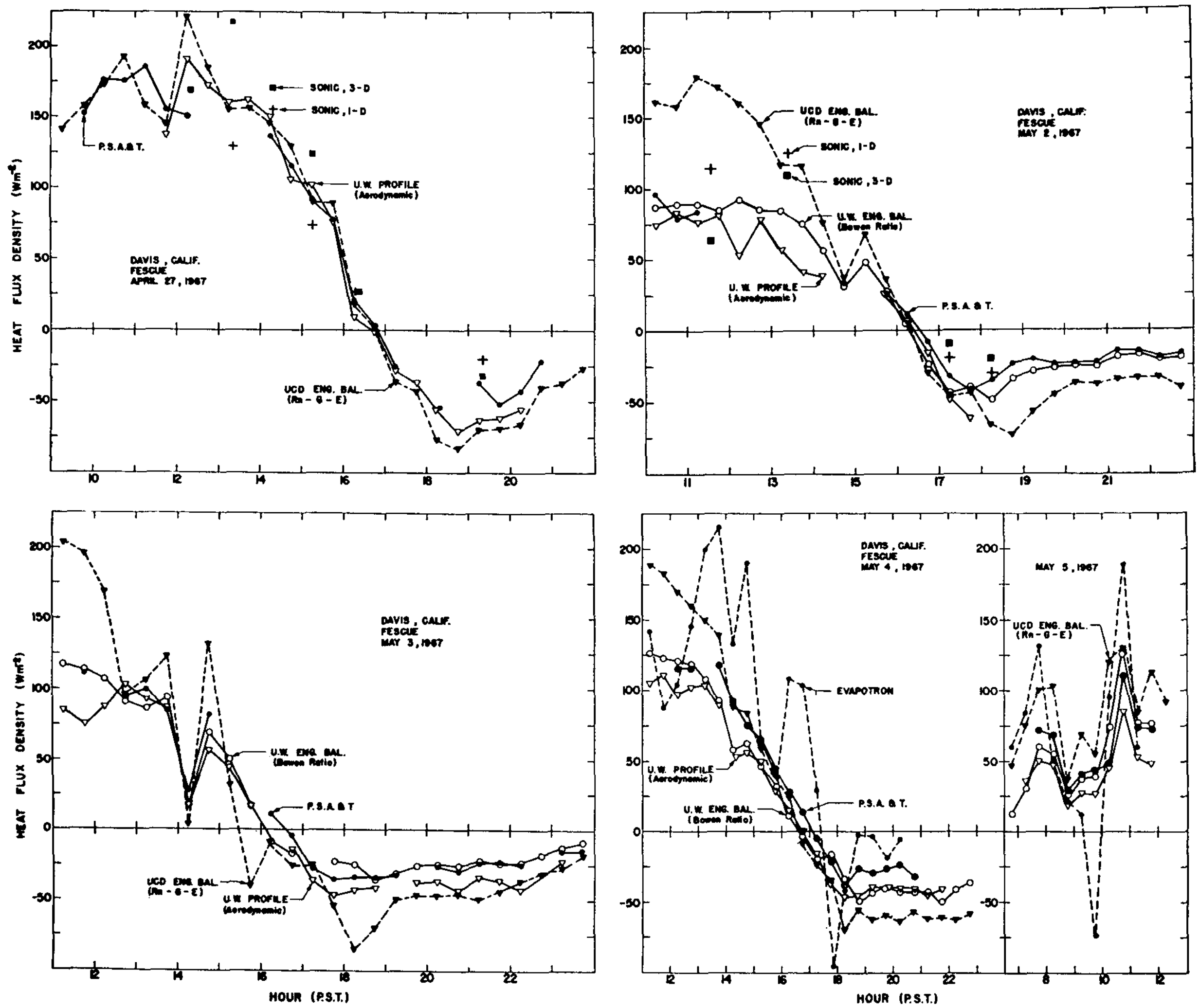

FIG. 4. Comparisons of heat flux density estimates at Davis, Calif., for 27 April to 2–5 May 1967.

the shear stress with a KEYPS-type analysis, and then using similarity ($K_H = K_M$) and the profiles to find the heat flux. Dr. Stearns supplied us data from both analyses.

The University of California-Davis group measured the evaporation with a 6 m diameter weighing lysimeter (Pruitt and Angus, 1960). In addition, they measured net radiation and soil heat flux near the lysimeter. The sensible heat flux density was calculated by differencing the energy balance terms as $H = R_n - G - E$. The Davis group also measured the sensible heat flux directly with an Evapotron (Dyer and Maher, 1965). Both measurements were supplied to us by Dr. W. O. Pruitt of the University of California-Davis.

The University of Washington group measured the sensible heat flux both with a one-dimensional sonic anemometer thermometer (Kaimal and Businger, 1963) and with a three-dimensional unit (Mitsuta, 1966). These data were supplied by Dr. J. A. Businger.

The comparison data at Hancock were obtained by differencing measurements of net radiation, soil heat flux density and evaporation. The evaporation was measured with a 2.1×5.5 m weighing lysimeter (Black *et al.*, 1968), the net radiation with a large Funk radiometer, and the soil heat flux with soil heat flux plates (Fuchs and Tanner, 1968) and integrating soil thermometers (Tanner, 1958).

3. Heat flux density comparisons

During the 1967 experiment, fetches were easily in excess of 100 m, except for small changes in elevation, since the wind was predominately from the south and southwest where fields had similar vegetation and roughness.

Heat flux estimates by the pressure-sphere anemometer and thermometer system (P.S.A.T.) were averaged from two 1 m high units and one 4 m high unit to give the results shown in Fig. 4. There was no syste-

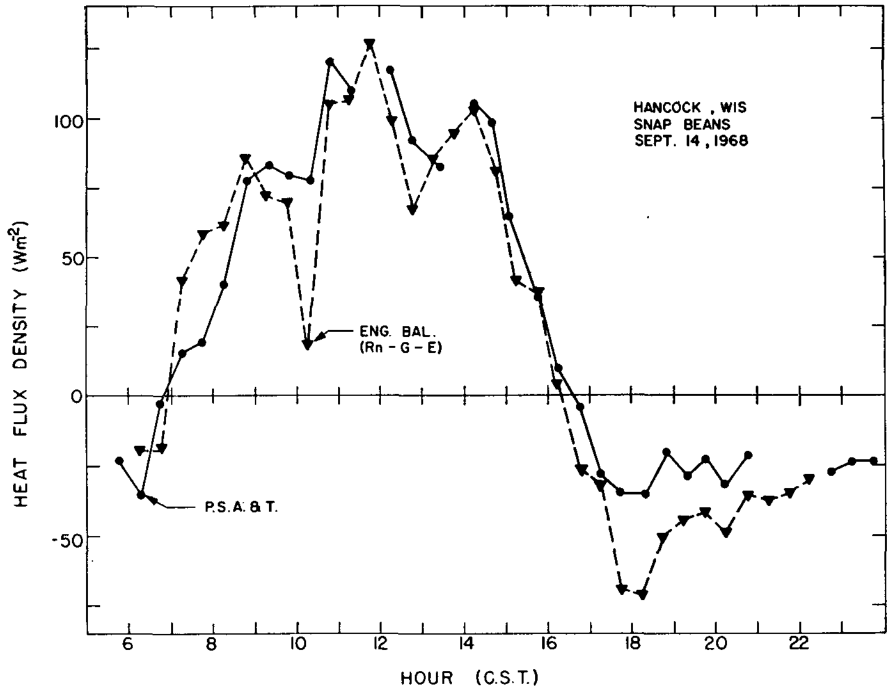

FIG. 5. Heat flux density estimates over snap beans.

matic difference of heat flux measured at the two heights except from 1615–2015 on 27 April, when the data from the higher mast were discarded. Heat flux data from a three-dimensional, sonic anemometer-thermometer at 4 m above the surface and a one-dimensional, sonic anemometer-thermometer at 2.2 m agreed well with the P.S.A.T.; the scatter of estimates at our three different P.S.A.T. sites frequently is of the same order as the differences between our data and that of the sonic anemometer-thermometer.

The eddy-flux from the Evapotron is shown on Fig. 4 for 4 and 5 May. The wide fluctuations may have been due to the averaging process to remove the mean wind and temperature terms since a time constant of 1 min is used in this system.

Several indirect estimates of sensible heat flux are also shown in Fig. 4. The energy balance estimates obtained from differencing the energy balance, $H=R_n-G-E$, appear high during the day and low at night. Since $|R_n|$ and $|E|$ are much larger than $|H|$, a small relative error in these terms could produce a large relative error in $|H|$.

The results from the Bowen ratio energy balance and those from the aerodynamic method are the averages of heat flux data from three sites. These methods are nearly independent, but not completely so, because they use the same temperature profiles. Both methods show remarkably good agreement with the P.S.A.T.

In Fig. 5 is shown the average of heat flux estimates at two P.S.A.T. sites. Both sites were 117 cm above the soil surface until 1030 when one site was moved to 210 cm above the surface. Since estimates of heat flux by the P.S.A.T. at 210 cm from the soil surface were not systematically different from the 117-cm site, fetch was considered adequate. On another day, we compared measurements with one P.S.A.T. at 75 cm and the other at 117 cm and found no systematic differences.

The energy balance estimate of heat flux leads the P.S.A.T. estimate in the morning. This was probably due to a time lag in the evaporative flux caused by unrepresentative heat storage in the lysimeter (Black

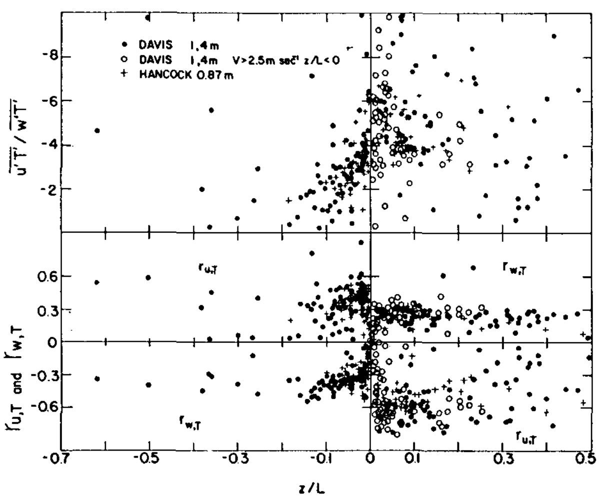

FIG. 6. Correlation coefficients of wind and temperature and $(\overline{u'T'})/(\overline{w'T'})$ as a function of stability.

et al., 1968). This also could have caused an overestimate of the magnitude of the heat flux after sunset. The low value at 1015 was caused by an unexplainably large estimate of evaporative flux.

4. Temperature structure

When the data used in this section were collected, H and τ were constant with height, within the accuracy of our measurements; thus, we can use H and τ as scaling factors as described by Monin and Obukhov (1954). They define a dimensionless height ratio z/L where z is the height from the surface and $L=-u_*^3\rho c_pT/(kgH)$ $[u_*=(\tau/\rho)^{\frac{1}{2}}$ is the friction velocity, $k=0.428$ is von Kármán's constant, and $g=980$ cm sec^{-2}]. The relationships obtained between our measurements of z/L and our measurements of the correlation coefficients $r_{u,T}$ and $r_{w,T}$, and of the ratio $\overline{(u'T')}/\overline{(w'T')}$ are given in Fig. 6. Fig. 8 shows the relation of z/L to a dimensionless standard deviation of temperature, σ_T/T_*, where σ_T is the standard deviation of air temperature and $T_*=-\overline{H/(k\rho c_pu_*)}$.

It appears that $|\overline{(u'T')}/\overline{w'T')}|\approx 4$ for $z/L=0.1$ and ≈ 2.5 for $z/L=-0.05$. The large scatter indicates that more meaningful results might have been obtained from using sampling periods shorter than the 30 min used. For instance, Zubkovskii and Tsvang (1966) obtained less scatter by using running means of the winds and temperatures from electrical filters with time constants of 100 and 80 sec, respectively. Fig. 6 shows that air temperatures are more closely coupled with horizontal winds than with vertical winds since $|r_{u,T}|>|r_{w,T}|$. This is especially true for stable conditions. As shown in Fig. 7, the fluctuations of air temperature and vertical wind during unstable conditions are much larger and faster than during stable conditions; however, it has been observed that slow wave motion (not evident in Fig. 7) frequently occurs at night when the wind speed is low. Then the temperature at a stationary height in a highly stratified atmosphere fluctuates as much as 3C every 50–200 sec, the period of the slow waves. This oscillation substantially increases σ_T and probably accounts for some small values of $r_{w,T}$ and $|r_{u,T}|$ for large positive values of z/L.

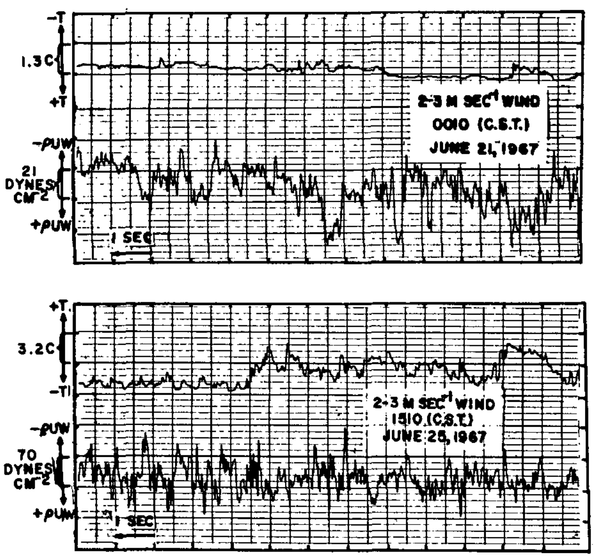

FIG. 7. Fluctuations of T and ρuw for stable conditions at 2.0 m (top) and unstable conditions (bottom) above bare Plainfield sand at Hancock, Wisc.

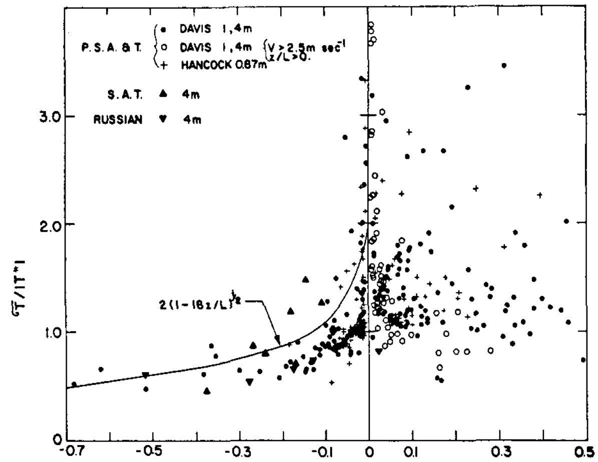

FIG. 8. Standard deviation of dimensionless temperature as a function of stability.

In Fig. 8, σ_T/T_* is plotted vs z/L and appears to scale well for unstable conditions, except near $z/L=0$, where $T_*=0$. A function suggested by Dyer (1965) is drawn following Panofsky *et al.* (1967), and data from Russian sonic anemometers and resistance thermometers (Mordukhovich and Tsvang, 1966) and data from a one-dimensional sonic anemometer-thermometer (Businger *et al.*, 1967) are also included. The P.S.A.T. data agree well with the Russian data, but appear lower than the data summarized by Panofsky *et al.*

The large scatter for stable conditions may be caused in part by small absolute errors in τ and H, since both are about ten times smaller at night than during the day; however, slow wave motion may increase σ_T without increasing the heat flux enough to keep σ_T/T_* from increasing whenever these large-scale disturbances occur. Since Mordukhovich and Tsvang used a running mean of temperature with a time constant of 80 sec, temperature oscillations with periods >20 sec are substantially attenuated, causing their estimates of σ_T/T_* to have less scatter and be lower than our estimates. Measurements during stable conditions, when the wind speeds were at least 2.5 m sec^{-1} at 1 m, have less scatter; mixing is probably adequate then to prevent domination by large-scale disturbances.

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