

1 **Uncertainties in temperature statistics and fluxes determined by**
2 **sonic anemometer due to wind-induced vibrations of mounting arms**

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19 **Abstract**

20 Accurate air temperature measurements are essential in eddy covariance systems, not only
21 for determining sensible heat flux but also for applying the density effect corrections (DEC) to
22 water vapor and CO₂ fluxes. However, the influence of wind-induced vibrations of mounting
23 structures on temperature fluctuations remains a subject of investigation. This study examines 30-
24 min average temperature variances and fluxes using eddy covariance systems, combining
25 Campbell Scientific Anemometer Thermometry (CSAT3B) with closely co-located fine-wire
26 thermocouples alongside LI-COR CO₂/H₂O gas analyzers at multiple heights above a sagebrush
27 ecosystem. The variances of sonic temperature after humidity corrections (T_s) and sensible heat
28 fluxes derived from T_s are underestimated (e.g., by approximately 5% for temperature variances
29 and 4% for sensible heat fluxes at 40.2 m, respectively) as compared with those measured by a
30 fine-wire thermocouple (T_c). Spectral analysis illustrates that these underestimated variances and

31 fluxes are caused by the lower energy levels in the T_s spectra than the T_c spectra in the low
32 frequency range (natural frequency < 0.02 Hz). This underestimated T_s spectra in the low
33 frequency range become more pronounced with increasing as wind speeds, especially when wind
34 speed exceeds 10 m s^{-1} . Moreover, the underestimated temperature variances and fluxes cause
35 overestimated water vapor and CO_2 fluxes through DEC. Our analysis suggests that these
36 underestimations when using T_s are likely due to wind-induced vibrations affecting the tower and
37 mounting arms, altering the time of flight of ultrasonic signals along three sonic measurement
38 paths. This study underscores the importance of further investigations to develop corrections for
39 these errors.

40

41 **Keywords: Eddy covariance, CO_2 fluxes, Fine-wire thermocouple, Sonic temperature; High**
42 **winds**

43

44

45 1. Introduction

46 The eddy covariance (EC) technique has been widely used to measure turbulent fluxes of
47 heat, water vapor, CO_2 , and other scalars between terrestrial ecosystems and the atmosphere (Chu
48 et al., 2021; Lee et al., 2014; Missik et al., 2021; Tang et al., 2019; Wang et al., 2010). It is
49 instrumental in studying micrometeorological processes in the atmospheric surface layer (Eder et
50 al., 2013; Gao et al., 2018; Guo et al., 2009; Li et al., 2018; Zhang et al., 2010). Despite
51 considerable advancement in the EC technique (Burns et al., 2012; Frank et al., 2013; Fratini et
52 al., 2012; Horst et al., 2015; Liu et al., 2001; Mauder et al., 2007; Mauder and Zeeman, 2018;
53 Wilczak et al., 2001), uncertainties in EC fluxes remain a great concern (Loescher et al., 2005;
54 Massman and Clement, 2006; Peña et al., 2019), including the notable issue of the surface energy
55 balance closure (Mauder et al., 2020). Thus, improving the accuracy of EC flux measurements
56 and identifying the potential sources of uncertainties in these fluxes are critically important.

57 In most EC applications, sonic-derived air temperature after corrections is usually
58 employed for determining sensible heat fluxes (H) (Liu et al., 2001; Schotanus et al., 1983).
59 However, erroneous H determined by sonic anemometers have been reported especially under high
60 wind conditions (e.g., Burns et al., 2012; Smedman et al., 2007). For instance, Smedman et al.
61 (2007) utilizing two co-located Gill sonic anemometers (Models R2 and R3) observed that sonic-

62 determined H exhibited larger magnitudes than H measured with an alternative temperature sensor.
63 They also noted that for wind speed exceeding 10 m s^{-1} , a correction highly dependent on wind
64 speed is essential for sonic-determined H (Smedman et al., 2007). Burns et al. (2012), employing
65 a Campbell Scientific sonic anemometer (Model CSAT3) and a co-located type-E thermocouple
66 (wire diameter of 0.254 mm), reported substantial errors for H determined from the CSAT3 sonic
67 anemometer with a firmware of version 4.0 for wind speed above 8 m s^{-1} . Such large errors in H
68 result from inaccurate sonic-derived temperature due to an underestimation of the speed of sound,
69 though errors caused by sonic anemometer transducer shadowing can also cause errors in H (Frank
70 et al., 2013; Horst et al., 2015). Wind-induced vibrations in the tower and mounting arms,
71 particularly under windy conditions, were speculated to be potential contributors, causing spikes
72 in the signals of sonic temperature (Burns et al., 2012). However, the precise impact of vibration-
73 induced errors in sonic-derived temperature on temperature variances and sensible heat fluxes,
74 especially for tall towers under strong wind conditions, has remained unexplored.

75 Accurate air temperature measurements are not only important for determining H but also
76 crucial for estimating other scalar fluxes (e.g., water vapor and CO_2) through density effect
77 corrections (DEC hereafter; Detto and Katul, 2007; Gao et al., 2020; Lee and Massman, 2011;
78 Sahlée et al., 2008; Webb et al., 1980). The measured high-frequency time series of densities of
79 water vapor, CO_2 , and other scalars are subjected to the effects of density fluctuations of dry air
80 and other components in the atmosphere, as well as the fluctuations of air pressure (Lee and
81 Massman, 2011; Webb et al., 1980). Correcting for these effects involves applying corrections to
82 either the calculated raw fluxes or to the high-frequency time series of the scalar density
83 fluctuations (Webb et al., 1980; Detto and Katul, 2007; Gao et al., 2020; Sahlée et al., 2008). Any
84 errors or uncertainties in sonic-derived temperature are anticipated to propagate, and in some
85 certain cases, be amplified by the correction algorithms applied to the scalar fluxes, leading to
86 heightened uncertainties in these fluxes (Liu et al., 2006).

87 The objective of this study is to scrutinize the uncertainties in temperature statistics and
88 fluxes determined by sonic anemometers, with particular attention to the potential influence of
89 vibrations of the tower and mounting arms under high wind speeds. The data employed were
90 collected from three levels of Campbell Scientific sonic anemometers (Model CSAT3B) alongside
91 co-located fine wire thermocouples and open-path infrared gas analyzers. By comparing the
92 sensible heat fluxes calculated using air temperature from the sonic anemometers and the

93 thermocouples, we assess vibration-induced errors in sensible heat fluxes at the three heights. The
94 findings reveal that the sonic anemometers underestimate the temperature variances and fluxes
95 compared to the thermocouples. Furthermore, we investigate the propagation of these vibration-
96 induced errors to water vapor and CO₂ fluxes through the density effect corrections.

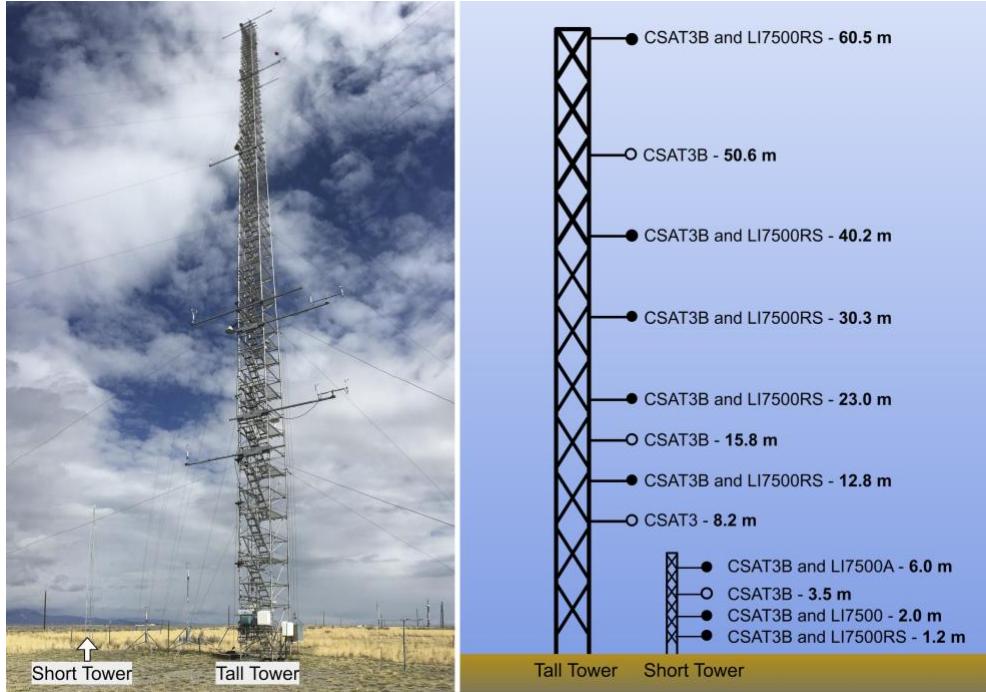
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98 **2. Materials and methods**

99 **2.1 Experiment and data**

100 The experiment was conducted at the National Oceanic and Atmospheric Administration
101 (NOAA) Grid 3 area (Station ID: GRI) situated on the western edge of the Snake River Plain in
102 southeastern Idaho, USA (43.59°N, 112.94°W; 1,500 m above mean sea level; Figure 1). The
103 closest mountains are located approximately 13 km northwest from GRI. Based on the data from
104 multiple automated meteorological observation stations in the area, southwesterly and
105 northeasterly winds prevail during the day and night, respectively (Finn et al., 2016). Under these
106 prevailing winds, GRI has a relatively flat and uniform upwind fetch (Finn et al., 2018; Lan et al.,
107 2018). The vegetation primarily comprises shrubs and grasses, each with a roughness length and
108 displacement height of a few centimeters (Finn et al., 2016).

109 The experiment utilized a 62-m tower and a 10-m aluminum tower (UT30, Campbell
110 Scientific, Inc.) at the Grid 3 area to mount the sensors (Figure 1). The 62-m tower was guyed at
111 eight levels and the 10-m tower was guyed at one level. 3.6 m (12-ft) retractable square booms
112 were horizontally braced to the 62-m tower to attach the sensors. The CSAT3s and IRGAs were
113 mounted on 1-ft pipes, which were securely attached to the end of each boom. As a result, the
114 CSAT3s and IRGAs were positioned at least 2.0 m away from the tower structure. On the 10-m
115 tower, 1.8 m (6-ft) poles were utilized to mount the CSAT3s and IRGAs, positioning the sensors
116 approximately 1.5 m away from the tower's frame structures.



117

118 **Figure 1.** Photos of the 62-m and 10-m towers at the Idaho National Laboratory (INL) site in
 119 southeastern Idaho, and the instrumentational configuration of the field study.

120

121 Throughout the experiment, multiple levels of EC systems were deployed (Figure 1). These
 122 EC systems included two models of 3D sonic anemometers from the same manufacturers (Model
 123 CSAT3B and CSAT3, Campbell Scientific, Inc.) and three models of infrared gas analyzers from
 124 the same manufacturers (IRGA; Model LI7500RS, LI7500A, and LI7500, LICOR, Inc.). CSAT3s
 125 measured the three-dimensional wind velocity components (u , v , and w) and the sonic air
 126 temperature (T_{s_m}), while IRGAs measured the densities of water vapor (ρ_v) and CO₂ (ρ_c). Co-
 127 located with CSAT3s and IRGAs, Type-E fine wire thermocouples (Model FW3, Campbell
 128 Scientific, Inc.) were used to measure air temperature (T_c) at six heights of 2.0 m, 8.2 m, 12.8m,
 129 15.8 m, 23.0 m, and 40.2 m. FW3 thermocouple is composed of a chromel wire and a constantan
 130 wire with diameters of 0.0762 mm. The FW3 determines T_c by measuring the voltage potential
 131 differences created at the junction of the two wires due to the temperature difference, whereas T_{s_m}
 132 is determined based on the relationship between sonic virtual temperature and the speed of sound
 133 (Liu et al., 2001). This distinction in temperature measurement principles between CSAT3s and
 134 FW3 implies that the measured T_{s_m} and T_c are independent of each other. Furthermore, T_c is
 135 expected to remain unaffected by vibrations of the tower and mounting arms. In this study, we also

136 recorded the inclination of the CSAT3B (e.g., pitch and roll angle measurements) given by an
137 integrated inclinometer in the CSAT3B. Pitch angle is defined as the angle between the
138 gravitationally horizontal plane and the CSAT3B x-axis, and roll angle is defined as the angle
139 between the gravitationally horizontal plane and the CSAT3B y-axis. The sonic roll and pitch
140 angles were stored as 30-min averages.

141 Three dataloggers (Model CR1000X, Campbell Scientific, Inc.) were employed to sample
142 the high-frequency instruments (i.e., sonic anemometer, fine-wire thermocouple, and gas analyzer)
143 at 10 Hz. Each datalogger was equipped with a GPS receiver (Model GPS16X-HVS, Garmin
144 International, Inc.) to synchronize the datalogger clocks. Additionally, a variety of meteorological
145 measurements were conducted at GRI, including net radiation, air temperature, relative humidity,
146 soil moisture, soil temperature, and soil heat fluxes. In this study, we examined the data collected
147 at three different heights (40.2 m, 23.0 m, and 12.8 m) from 25 April to 31 July 2021, considering
148 structural differences between the tall tower and short tower setups as well as potential influences
149 from the roughness sublayer on measurement at lower levels.

150

151 **2.2 Post-field data processing**

152 The data processing mainly entailed despiking, double rotation for the wind components
153 (Wilczak et al., 2001), sonic temperature conversion (Liu et al., 2001; Schotanus et al., 1983), and
154 application of DEC to the raw fluxes of latent heat and CO₂ (Webb et al., 1980). However,
155 corrections for the effects of humidity and density fluctuations in this study are applied to the
156 turbulent fluctuations of sonic temperature, ρ_v , and ρ_c , respectively (Dettò and Katul, 2007; Gao
157 et al., 2020; Sahlée et al., 2008; Schotanus et al., 1983; Webb et al., 1980). For each 30-min
158 interval, the corrected turbulent fluctuations of sonic temperature (T'_s), ρ'_v , and ρ'_c are determined
159 by,

$$T'_s(t) = T'_{s_m}(t) - 0.51 \frac{\rho'_v(t)}{\bar{\rho}_a} \bar{T}, \quad (1)$$

$$\rho'_v(t) = (1 + \mu\sigma)\rho'_{v_m}(t) + (1 + \mu\sigma)\frac{\bar{\rho}_v}{\bar{T}} T'_s(t), \quad (2)$$

$$\rho'_c(t) = \rho'_{c_m}(t) + \bar{\rho}_c(1 + \mu\sigma)\frac{T'_s(t)}{\bar{T}} + \mu\frac{\bar{\rho}_c}{\bar{\rho}_a}\rho'_v(t). \quad (3)$$

160 where T'_{s_m} , ρ'_{v_m} , and ρ'_{c_m} represent measured sonic temperature, water vapor and CO₂ densities,

161 respectively; \bar{T} , $\bar{\rho}_a$, $\bar{\rho}_v$, and $\bar{\rho}_c$ are averages of air temperature, air density, water vapor and CO₂
 162 densities, respectively; $\mu = m_d/m_v$ (m_d and m_v are the molecular mass of dry air and water
 163 vapor, respectively); $\sigma = \bar{\rho}_v/\bar{\rho}_d$ ($\bar{\rho}_d$ is the density of dry air). The prime symbol denotes the
 164 turbulent fluctuations relative to the 30-min block average. As shown in the equations above, there
 165 is interdependence between T'_s and ρ'_v , and thus T'_s and ρ'_v must be determined iteratively. In this
 166 study, the corrections are iterated twice. Note that in semiarid sites like ours, the adjustments to T'_s
 167 due to fluctuations in specific humidity ($\frac{\rho'_v(t)}{\bar{\rho}_a}$) are typically negligible (not shown here) as
 168 compared to the adjustment to ρ'_v due to fluctuations in T'_s (as demonstrated in Section 3.5). The
 169 corrected time series of fluctuations facilitate the investigation of coherent structures and scalar
 170 similarity between temperature and other scalars (Detto and Katul, 2007; Sahlée et al., 2008). Here
 171 and throughout, T_s refers to the air temperature measured by sonic anemometers after humidity
 172 corrections, T_{s_m} the sonic temperature directly measured before corrections, and T_c the air
 173 temperature measured by fine-wire thermocouples (FW3).

174

175 2.3 Ensemble empirical mode decomposition (EEMD)

176 The ensemble empirical mode decomposition (EEMD) (Huang et al., 1998; Huang and Wu,
 177 2008) is applied to decompose the 30-min turbulence time series into three subsequences,
 178 corresponding to the high, middle, and low frequency ranges, respectively. EEMD is a favored
 179 method in analyzing non-linear and non-stationary turbulence data (Gao et al., 2018; Hong et al.,
 180 2010; Liu et al., 2021; Huang et al., 1998; Huang and Wu, 2008). Through the sifting process in
 181 EEMD, a 30-min time series is decomposed into thirteen oscillatory components $C_j(t)$ ($j = 1, 2, \dots,$
 182 13) and an overall residual $r_{13}(t)$. Each oscillatory component generally exhibits one
 183 characteristic frequency (Hong et al., 2010; Gao et al., 2018), while the overall residual is either
 184 monotonic or containing only one extremum, from which no more oscillatory components can be
 185 further decomposed. Hence,

$$x(t) = r_{13}(t) + \sum_{j=1}^{13} C_j(t). \quad (4)$$

186 As detailed in Section 3.2, after comparing the power spectra of T_s and T_c , two frequency
 187 boundaries, 0.02 and 0.2 Hz, are identified. The oscillatory components are then categorized into
 188 three frequency ranges (I, II, and III, respectively). The oscillatory components with mean

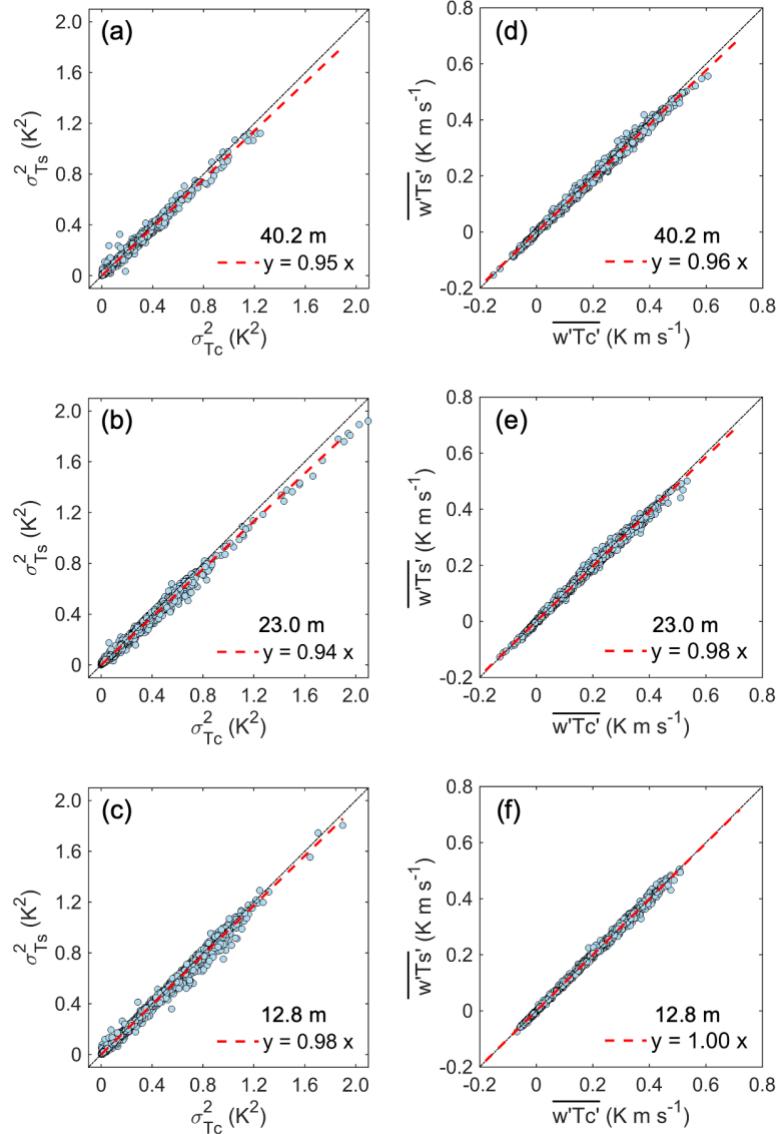
189 frequencies falling within the corresponding ranges are added together to generate the three
190 subsequences. Specifically, oscillatory components with the mean frequencies smaller than 0.02
191 Hz are summed and labeled as regime I (i.e., $x'_I = \sum_{j=10}^{13} C_{j,x} + r_{13}$, where $x = w, T_s$, and T_c),
192 between 0.02 Hz and 0.2 Hz as regime II (i.e., $x'_{II} = \sum_{j=6}^9 C_{j,x}$), and larger than 0.2 Hz as regime
193 III (i.e., $x'_{III} = \sum_{j=1}^5 C_{j,x}$).

194

195 **3 Results and discussion**

196 **3.1 Comparison of the CSAT3B- and FW3-derived temperature variances and fluxes**

197 Figure 2 illustrates the comparisons between the variances and fluxes obtained using T_s
198 and T_c at different heights. Here, we use $\sigma_{T_c}^2$ and $\overline{w'T'_c}$ as reference values since T_c is less sensitive
199 to the effects of humidity and wind speeds than T_s (Burns et al., 2012; Smedman et al., 2007).
200 Generally, the variances of T_s ($\sigma_{T_s}^2$) are smaller than variances of T_c ($\sigma_{T_c}^2$), typically by 2%–5%
201 (Figures 2a-2c). These lower variances result in a lower sensible heat flux ($\overline{w'T'_s}$). Specifically, at
202 23.0 and 40.2 m, $\overline{w'T'_s}$ is underestimated by approximately 2% and 4%, respectively, as compared
203 to the sensible heat fluxes derived from the FW3 (i.e., $\overline{w'T'_c}$) (Figures 2d and 2e). However, at 12.8
204 m, $\overline{w'T'_s}$ and $\overline{w'T'_c}$ are quite comparable (Figure 2f). These results confirm that errors in H were
205 not entirely due to errors in the vertical velocity (Frank et al., 2013; Horst et al., 2015). Further
206 examination of Figure 2 reveals that the differences between $\sigma_{T_s}^2$ and $\sigma_{T_c}^2$, as well as between $\overline{w'T'_s}$
207 and $\overline{w'T'_c}$, increase with the increasing measurement heights. Additionally, our tests indicate that
208 the influence of solar heating on measurements of FW3 is negligible, primarily due to the thin wire
209 diameter of 0.0762 mm (Text S1 and Figure S1).



210

211 **Figure 2.** Comparison of temperature variances and sensible heat fluxes computed using T_s and
 212 T_c at the heights of 40.2, 23.0 and 12.8 m, respectively.

213

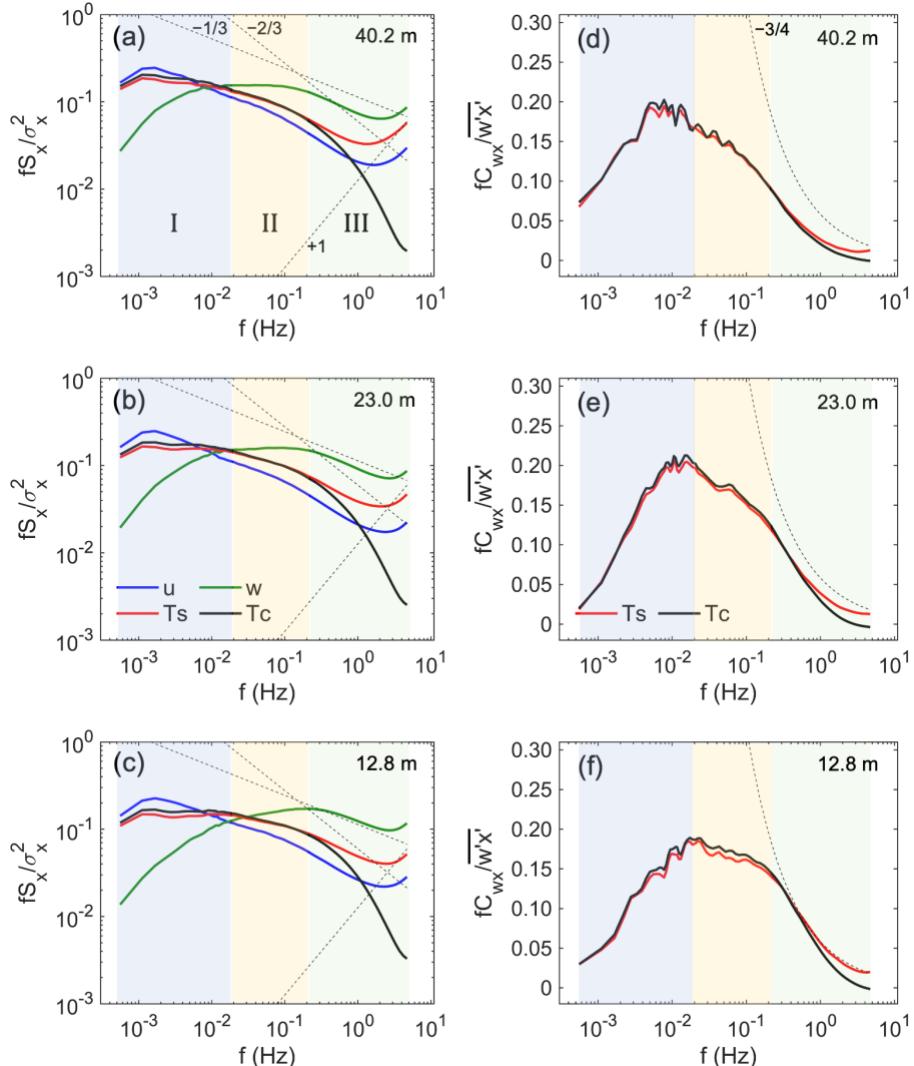
214 What mechanisms could have caused the observed differences? Previous studies found that
 215 CSAT3 sonic anemometers with a previous version of firmware could cause errors in T_s (Burns et
 216 al., 2012). However, this should not be the case for our study because the CSAT3B modes were
 217 used at these heights, and they have an improved design compared to the original CSAT3. Our
 218 results suggest that the differences are dependent on the measurement heights. As the measurement
 219 heights increase, the dominant length scale of coherent structures is also enlarged (Zhang et al.,

220 2011). Therefore, we conjecture that the processes that lead to such differences are most likely
221 scale dependent, motivating us to examine the spectra and cospectra in the next subsection.

222

223 **3.2 Spectral comparisons**

224 To gain further insight into the differences between $\sigma_{T_s}^2$ and $\sigma_{T_c}^2$ as well as the associated
225 fluxes (i.e., $\overline{w'T_s'}$ and $\overline{w'T_c'}$), the spectra of u , w , T_s and T_c and the $w-T_s$ and $w-T_c$ cospectra at
226 different heights are examined. Figures 3a-3c show the mean normalized Fourier power spectra of
227 u , w , T_s , and T_c as a function of natural frequency (f). Note that the power spectra were computed
228 every half hour using fast Fourier transform and normalized by the corresponding variances before
229 averaging. It is also interesting to note that the u , w , and T_s spectra deviate from the well-known
230 $-5/3$ power law in the high frequency range of $f > 0.2$ Hz, exhibiting similar features as previous
231 studies (e.g., Burns et al., 2012). For $f > 2$ Hz, fS_u , fS_w , and fS_{T_s} appear to follow the f^{+1} slope,
232 likely due to white noise and/or aliasing (Kaimal and Finnigan, 1994). In the 0.2 Hz $< f < 2$ Hz
233 range, the distortion of fS_u , fS_w , and fS_{T_s} from the $-5/3$ power law is enhanced as the
234 measurement heights decrease. The upturned distortion for 0.2 Hz $< f < 2$ Hz might be associated
235 with spikes (Gao et al., 2020; Stull, 1988) that are not excluded from the 10 Hz time series during
236 despiking. The T_c spectra appear to follow the $-5/3$ power law for 0.2 Hz $< f < 1$ Hz, although are
237 slightly attenuated for $f > 1$ Hz, likely because the thermal mass of the thermocouple wire limits
238 its response time (Burns et al., 2012).



239

240 **Figure 3.** Mean normalized power spectra of u , w , T_s , and T_c , and cospectra of the w - T_s , and w -
241 T_c , at three heights of 40.2, 23.0, and 12.8 m, respectively. All power spectra and cospectra are
242 normalized by the corresponding variance and covariance before averaging. The dashed lines show
243 a $f^{-1/3}$, $f^{-2/3}$, f^{+1} , and $f^{-3/4}$ slope. Note that the frequency domain can be divided into three
244 regions by comparing the T_s and T_c spectra.
245

246 It is also noted that the magnitude of the T_c spectra is higher than that of the T_s spectra in
247 the low frequency range of $f < 0.02$ Hz, but their magnitude is comparable in the middle frequency
248 range of $0.02 \text{ Hz} < f < 0.2$ Hz. These results indicate that turbulent eddies with scales less than
249 0.02 Hz contribute more to $\sigma_{T_c}^2$ than $\sigma_{T_s}^2$. Hence, the underestimation of $\sigma_{T_s}^2$ is mostly caused by the

250 lower magnitude of the T_s spectra in the low frequency range, whereas $\sigma_{T_s}^2$ is overestimated to
251 some extent due to the upturned distortion of the T_s spectra in the high frequency range.

252 Figures 3d-3f show the distribution of the mean normalized w - T_s and w - T_c cospectra as a
253 function of f . Each cospectra is normalized by the corresponding covariances before averaging.
254 For $f > 0.2$ Hz, especially when $f > 0.5$ Hz, the w - T_s cospectra are generally higher than the w -
255 T_c cospectra, consistent with the higher spectra of T_s . Compared to the power law of $-3/4$, the
256 calculated $\overline{w'T_s'}$ are overestimated, while $\overline{w'T_c'}$ is slightly underestimated. For 0.002 Hz $< f < 0.2$
257 Hz, the normalized w - T_s cospectra are slightly lower than the normalized w - T_c cospectra,
258 indicating that turbulent eddies with scales in the frequency range of 0.002 Hz $< f < 0.2$ Hz
259 contribute more to $\overline{w'T_c'}$. Overall, the underestimation of the CSAT3B-derived fluxes is also scale-
260 dependent, and the underestimation of $\overline{w'T_s'}$ in the middle to low frequency range is offset by the
261 overestimation in the high frequency range to some extent.

262 According to the comparison of the T_s and T_c spectra, the whole frequency domain can be
263 divided into three ranges: I) $f < 0.02$ Hz, II) 0.02 Hz $< f < 0.2$ Hz, and III) $f > 0.2$ Hz. For $f <$
264 0.02 Hz, the magnitude of the T_c power spectra is slightly higher than that of the T_s spectra at all
265 levels, but the magnitude of the T_s and T_c spectra is comparable in the middle frequency range of
266 0.02 Hz $< f < 0.2$ Hz. For $f > 0.2$ Hz, the T_c spectra first follow the $-5/3$ power law and are then
267 attenuated, whereas the T_s spectra are distorted upward. Based on this division, in section 3.3, the
268 30-min time series is divided into the three frequency ranges and the contributions of these
269 different scales to $\sigma_{T_s}^2$, $\sigma_{T_c}^2$, $\overline{w'T_s'}$, and $\overline{w'T_c'}$ at different heights are then quantified.

270

271 **3.3 Scale-dependent contributions to variances and fluxes**

272 To quantify the contributions of different scales to the corresponding temperature variances
273 and fluxes, we apply the EEMD approach to decompose the 30-min time series of w' , T_s' , and T_c'
274 into various oscillatory components, which are then categorized into the three frequency ranges
275 discussed earlier (i.e., I, II, and III). Figures 4a-4c depict that for regime I, the ratios between the
276 variances of T_s and T_c are generally lower than 1.0 (approximately 0.89 on average). This suggests
277 that turbulent eddies with scales less than 0.02 Hz contribute approximately 11% more to $\sigma_{T_{c,I}}^2$
278 than $\sigma_{T_{s,I}}^2$. With these turbulent eddies contributing about 41%–57% to the total variances (Figures
279 5a-5c and Table 1), the 11% difference between $\sigma_{T_{c,I}}^2$ and $\sigma_{T_{s,I}}^2$ would cause 4%–6% difference

280 between the total variances of T_s and T_c . As for fluxes, turbulent eddies with scales less than 0.02
 281 Hz contribute approximately 6% more to $\overline{w'T'_s}_I$ than $\overline{w'T'_c}_I$. With these turbulent eddies
 282 accounting for about 26%–45% of the total fluxes (Figures 5d-5f and Table 1), the 6% difference
 283 in $\overline{w'T'_s}_I$ and $\overline{w'T'_c}_I$ would cause 2%–3% difference in the total fluxes. Further, given that the
 284 contribution of regime I to the total temperature variances and fluxes increases with measurement
 285 height (Figure 5 and Table 1), the underestimation becomes more significant at higher levels.

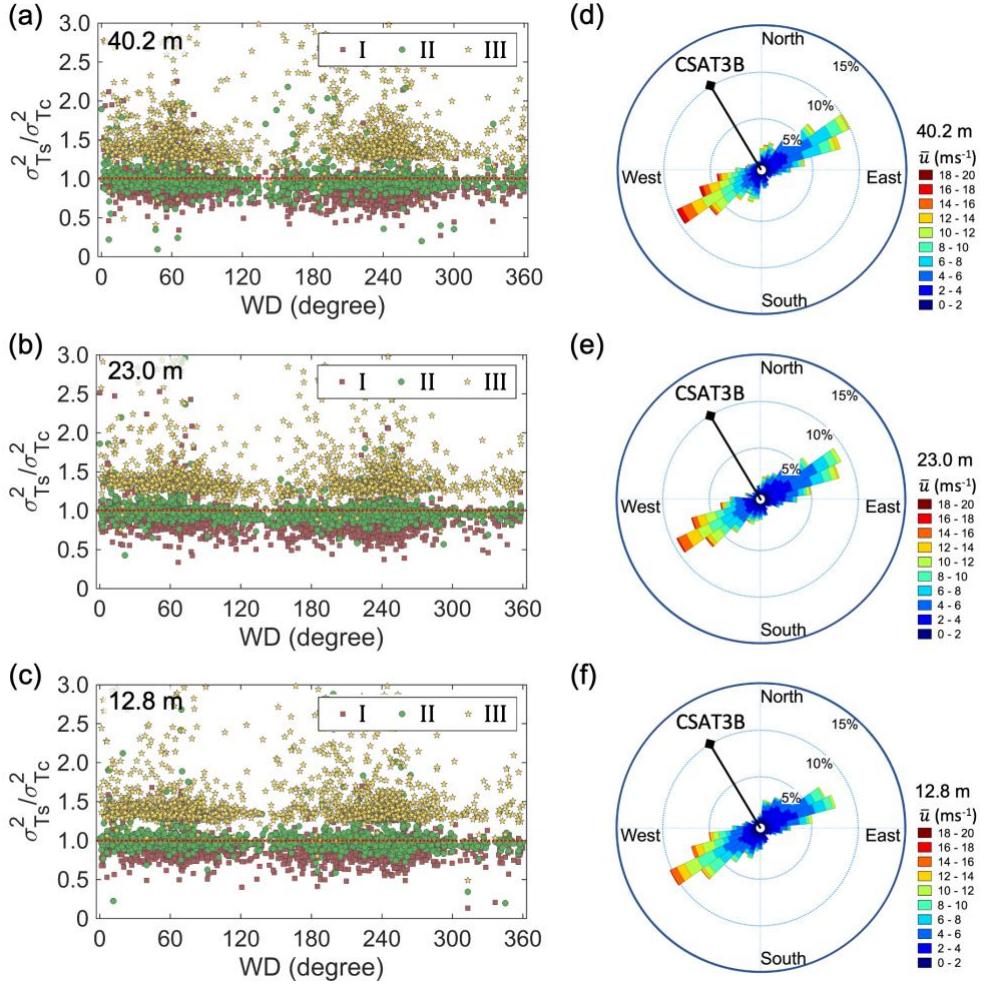
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287 **Table 1.** Contributions of the three frequency ranges to the total temperature variances and fluxes
 288 of T_s and T_c , as well as the mean ratios of temperature variances and fluxes of T_s and T_c for each
 289 range.

		40.2 m	23.0 m	12.8 m
$\sigma_{Ts,i}^2 / \sigma_{Ts}^2$	I	0.51	0.46	0.41
	II	0.32	0.36	0.37
	III	0.17	0.18	0.22
$\sigma_{Tc,i}^2 / \sigma_{Tc}^2$	I	0.57	0.52	0.47
	II	0.34	0.36	0.38
	III	0.10	0.12	0.15
$\sigma_{Ts,i}^2 / \sigma_{Tc,i}^2$	I	0.89	0.88	0.89
	II	0.98	0.98	0.99
	III	1.49	1.42	1.44
$\overline{w'Ts'}_i / \overline{w'Ts'}$	I	0.43	0.34	0.26
	II	0.42	0.47	0.48
	III	0.14	0.19	0.26
$\overline{w'Tc'}_i / \overline{w'Tc'}$	I	0.45	0.36	0.27
	II	0.43	0.48	0.50
	III	0.12	0.16	0.23
$\overline{w'Ts'}_i / \overline{w'Tc'}_i$	I	0.94	0.94	0.95
	II	0.98	0.99	0.99
	III	1.17	1.23	1.19

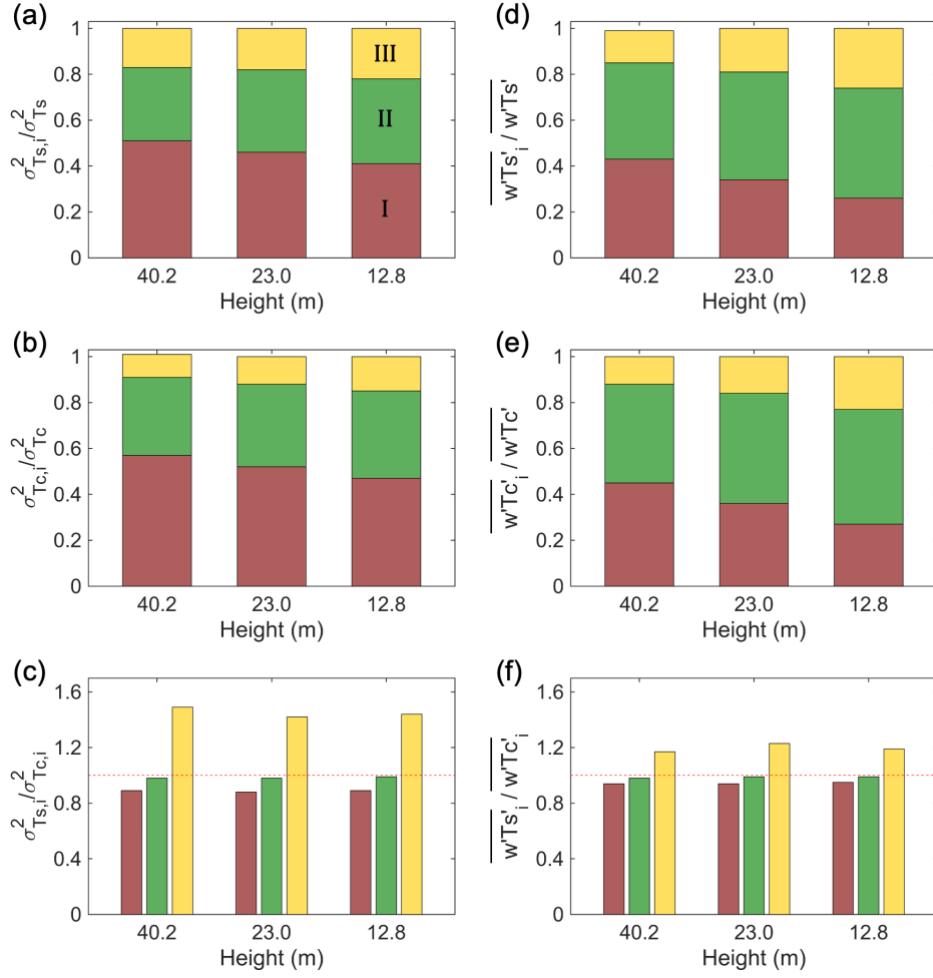
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292

293 **Figure 4.** (a-c) Distribution of ratios of half-hourly variances of T_s and T_c with wind directions
 294 and (d-f) wind roses at the heights of 40.2, 23.0, and 12.8 m, respectively. The square, circle, and
 295 pentagram markers represent the ratios of the variances in the three frequency ranges. The black
 296 lines in d-f refer to directions of the mounting arms of instruments.
 297



298

299 **Figure 5.** Contributions of the three frequency ranges to the total temperature variances and fluxes
300 of T_s and T_c , respectively, as well as the mean ratios of the temperature variances and fluxes of T_s
301 and T_c for each regime.

302

303 For regime II, the ratios between the variances of T_s and T_c and the associated fluxes are
304 close to 1.0 with minimal scatter. This indicates that turbulent eddies with scales between 0.02 Hz
305 and 0.2 Hz contribute consistently to the temperature variances and fluxes. These turbulent eddies
306 contribute 32%–38% and 42%–50% to their total variances and fluxes, respectively (Figure 5 and
307 Table 1). For regime III, the ratios between the variances of T_s and T_c average about 1.45 at the
308 three heights due to the distorted spectra in this regime for both T_s and T_c . This indicates that
309 turbulent eddies with scales larger than 0.2 Hz contribute roughly 45% less to $\sigma_{T_{c,III}}^2$ than $\sigma_{T_{s,III}}^2$.
310 With these turbulent eddies contributing about 12%–26% to the total variances (Figures 5a-5c and
311 Table 1), the 45% difference in $\sigma_{T_{c,III}}^2$ and $\sigma_{T_{s,III}}^2$ would cause 5%–7% difference in the total

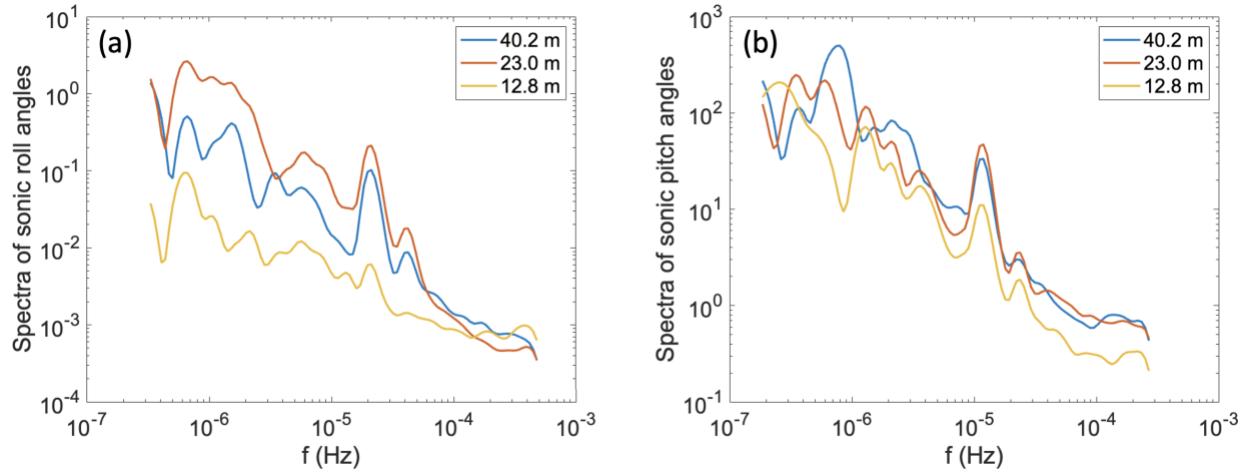
312 variances of T_s and T_c . As for fluxes, turbulent eddies with scales larger than 0.2 Hz contribute
313 approximately 20% less to $\overline{w'T'_{c\,III}}$ than $\overline{w'T'_{s\,III}}$. With these turbulent eddies accounting for 12%–
314 26% of the total fluxes (Figures 5d–5f and Table 1), the 20% difference in $\overline{w'T'_{c\,III}}$ and $\overline{w'T'_{s\,III}}$
315 would cause 2%–4% difference in the total fluxes. These results suggest that the observed
316 underestimation of the T_s variances and fluxes is primarily attributed to the large turbulent eddies
317 with frequencies less than 0.02 Hz, which is offset to some extent by the contribution from small
318 turbulent eddies with frequencies larger than 0.2 Hz.

319

320 **3.4 Potential causes for the scale-dependent differences**

321 The potential causes for the scale-dependent differences between the T_s and T_c spectra
322 include measurement errors, solar heating of thermocouples, and tower and mounting arm
323 vibrations, among others (e.g., the deficiency in the design of sonic anemometers in response to
324 different wind speed conditions). The T_c spectra follow similar declining features in the high
325 frequency range independent to wind speed (Text S2 and Figure S2), suggesting that
326 measurements of the fine-wire thermocouples were not noticeably affected by increased wind
327 speed, and therefore operational errors could be excluded from the causes for the observed
328 difference. Additionally, the consistent differences between the power spectra of T_s and T_c under
329 nighttime and daytime conditions (Text S1 and Figure S1) suggest that the impact of solar heating
330 on thermocouples was also not the cause for the differences between the T_s and T_c variances and
331 fluxes.

332 As the wind speed increases, the tower vibrations become more pronounced, especially at
333 higher levels, as indicated by the more energetic peaks in the power spectra of sonic roll and pitch
334 angles (Figure 6). For wind speed below approximately 10 m s⁻¹ at 40.2 m, the ratios of the T_s and
335 T_c variances for regime I show no obvious change with wind speed. However, for wind speed
336 above 10 m s⁻¹, the ratios decrease further as wind speed increases (Figure 7a). The ratios of the
337 temperature fluxes of T_s and T_c exhibit a similar pattern to the variances (Figure 7d). For regime
338 II, the ratios of both the variance and fluxes of T_s and T_c show no obvious relations with wind
339 speed (Figures 7b and 7e). For regime III, the ratios of both the variance and fluxes of T_s and T_c
340 illustrate large scatter, especially when wind speed is below 10 m s⁻¹, but still show no obvious
341 trends as wind speed increases (Figures 7c and 7f).



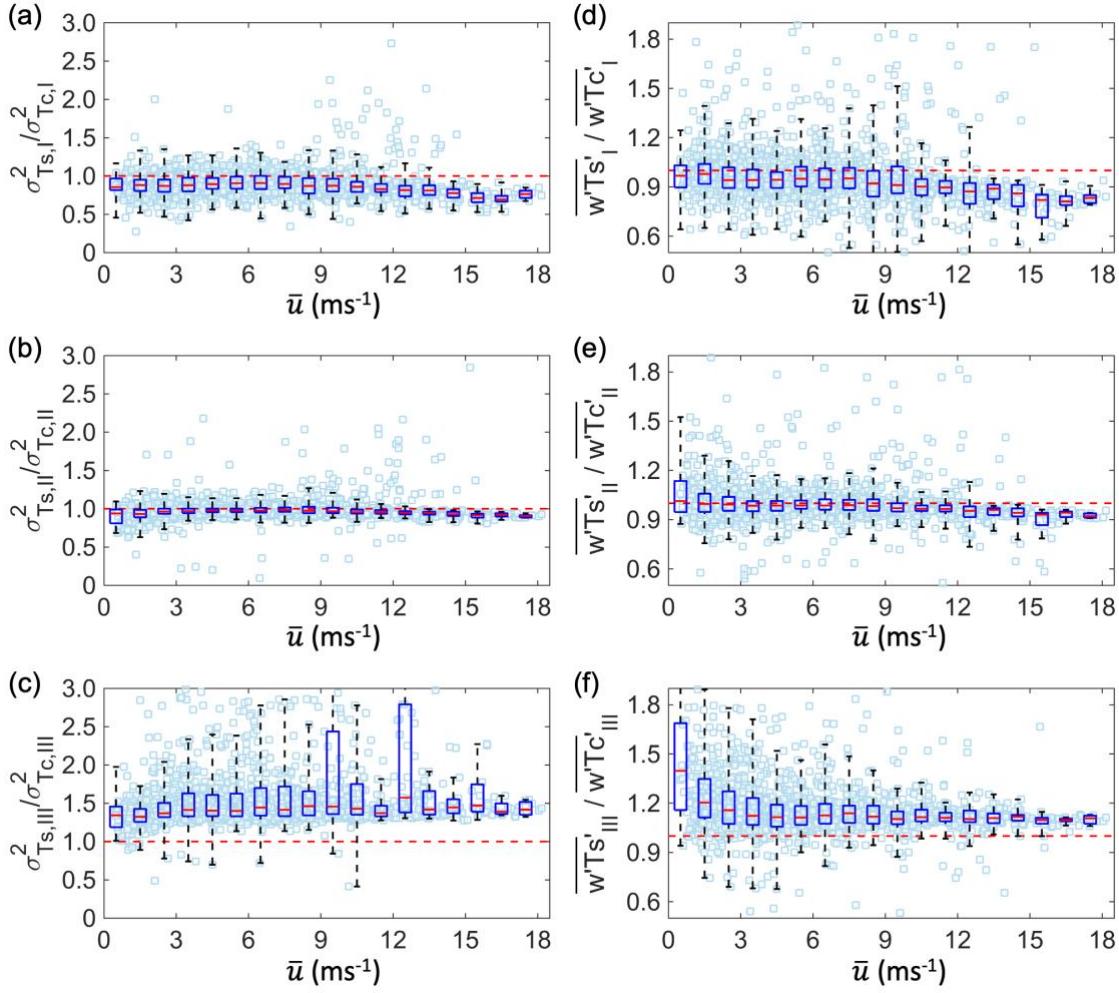
342

343 **Figure 6.** Power spectra of the sonic (a) roll and (b) pitch angles measured by CSAT3B at the
 344 three heights. The sonic roll and pitch angles were stored as 30-min averages during the experiment.

345

346 We thus hypothesize that the enhanced tower vibrations under strong winds lead to an
 347 early or delayed detection of the sonic pulse. This results in overestimations or underestimations
 348 of the speed of sound and thus errors in the 10 Hz time series of sonic temperature. In this study,
 349 for wind speeds below 10 m s^{-1} , the ratios of the variances (and fluxes) of T_s to those of T_c are
 350 scattered around 1.0 for regime I. However, for wind speed above 10 m s^{-1} , the ratios decrease as
 351 wind speed further increases (Figure 7). Therefore, tower and mounting arm vibrations were most
 352 likely the cause for the differences in the temperature variance and fluxes. Under this circumstance,
 353 such vibrations may also affect sonic-measured wind components along with T_s , resulting in errors
 354 in all the calculated fluxes. However, rigorous tests of this hypothesis seem necessary through
 355 testing sonic anemometers in wind tunnels or fields with different mounting strategies.

356



357

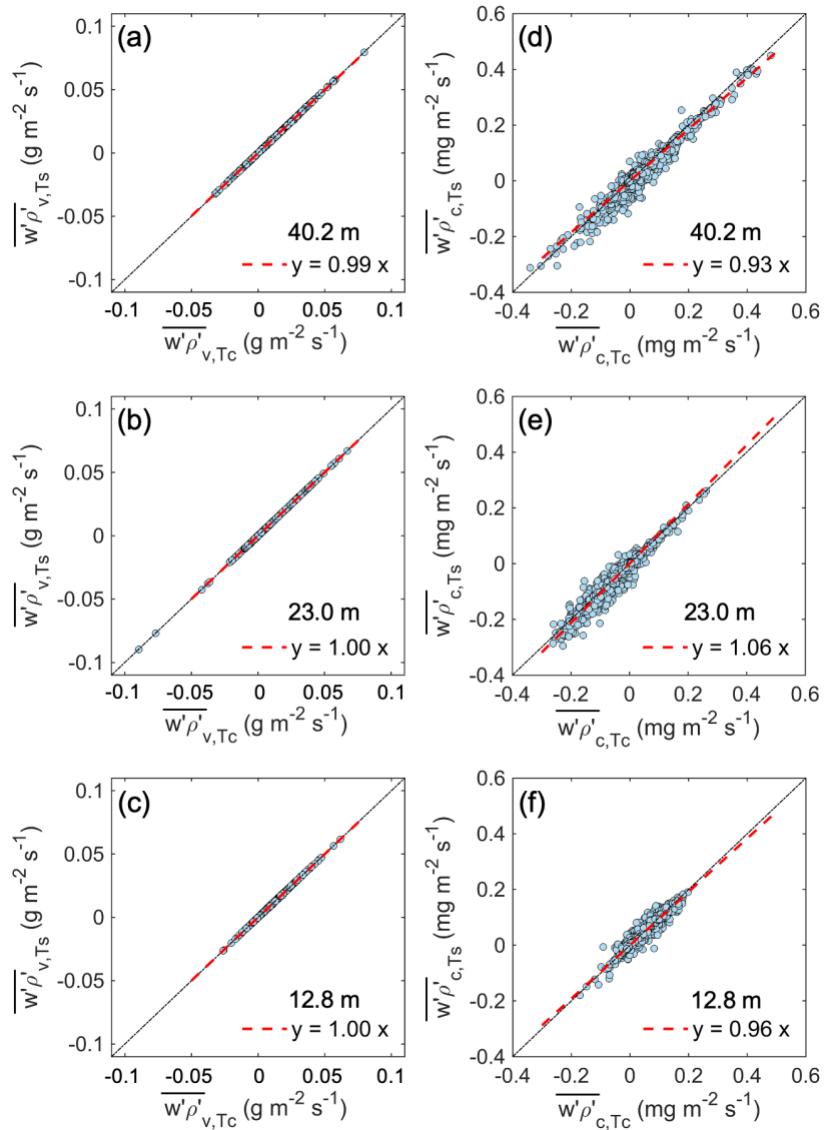
358 **Figure 7.** Ratios of (a, b, and c) half-hourly variances of T_s and T_c and (d, e, and f) covariances of
 359 w - T_s and w - T_c corresponding to the low, middle, and high frequency ranges, respectively, as a
 360 function of the mean wind speed (\bar{u}) at 40.2 m.

361

362 **3.5 Implications to water vapor and CO₂ fluxes**

363 Given that equations (2) and (3) are used to adjust the measured densities of water vapor
 364 and CO₂ by open-path CO₂/H₂O gas analyzers in EC systems, any errors in temperature
 365 measurements would be propagated to water vapor and CO₂ time series through these two
 366 equations. In equations (2) and (3), T_s can be replaced by T_c to achieve the adjusted time series of
 367 densities of water vapor and CO₂ for FW3. The adjusted time series of water vapor and CO₂ by
 368 the fluctuating parts of T_s and T_c , respectively, are then decomposed into three frequency ranges
 369 to quantify the influence of T_s on variances and fluxes of water vapor and CO₂.

370 The variances of ρ_v are not influenced by using either T_s or T_c for the density effect
 371 corrections (Table S1) because the fluctuations in ρ_v are not very sensitive to the density effects,
 372 especially at semiarid sites like ours (Gao et al., 2020). Therefore, for the water vapor fluxes, there
 373 only exist minor differences (< 1%) between the fluxes corrected by T_s and T_c for the three
 374 frequency ranges, while the overall water vapor fluxes corrected by T_s and T_c are comparable at
 375 the three heights (Figures 8a-8c).



376

377 **Figure 8.** Comparison of water vapor and CO₂ fluxes corrected by temperature from sonic
 378 anemometers and fine wire thermocouples, respectively, at the three heights.

379

380 As for CO₂, the differences between T_s and T_c in the three frequency ranges are propagated
381 differently to the adjusted variances of ρ_c (Table S2). More importantly, there exist relatively large
382 differences (but still within 10%) between the CO₂ fluxes adjusted by T_s and T_c (Figures 8d-8f).
383 In general, CO₂ fluxes are more sensitive to errors or uncertainties in temperature measurements
384 than water vapor fluxes (Liu et al., 2006). Therefore, precise measurements of air temperature are
385 critical for quantifying ecosystem CO₂ fluxes.

386

387

388 **4 Conclusions**

389 Temperature variances and the associated fluxes are examined by using sonic anemometers
390 and co-located fine-wire thermocouples at three levels above a sagebrush ecosystem. Compared
391 to temperature variances and fluxes determined by thermocouples, sonic anemometers were found
392 to underestimate the variances and fluxes by approximately 5% and 4%, respectively, at the height
393 of 40.2 m. In the high frequency range, the distortion in T_s spectra contributed to the heat fluxes
394 by 2–4%, whereas the attenuation in T_c spectra led to underestimated fluxes. However, the primary
395 source of the underestimation in temperature variances and fluxes by the sonic anemometers was
396 identified in the low frequency range. This phenomenon became more profound with increasing
397 wind speed, and thus, heightened vibrations of the tower and mounting arms. Furthermore, when
398 adjusting the density effects using the attenuated temperature, our results indicate that CO₂
399 variances and fluxes are more sensitive to errors or uncertainties in temperature measurements
400 compared to those of water vapor at the semiarid site.

401 Our findings highlight the critical importance of accurate measurements of air temperature
402 fluctuations in EC flux measurements. The inclusion of additional high-frequency temperature
403 measurements using fine-wire thermocouples is thus strongly recommended for EC systems.
404 Furthermore, the observed underestimation of sonic temperature variances and fluxes suggests that
405 the measured wind velocity components may also be biased due to the tower vibrations. Therefore,
406 we recommend further investigation of the influence of mounting arm vibrations on wind velocity
407 components by sonic anemometers.

408

409 **Data availability**

410 The data used in this study are available from Heping Liu upon request.

411

412 **Code availability**

413 The code used in this study are available from Zhongming Gao and Heping Liu upon
414 request.

415

416 **Author contributions**

417 ZG and HL designed the study with substantial input from all coauthors. ZG, HL, DL, and
418 BY conducted the fieldwork and obtained and processed the EC data. ZG drafted the manuscript.
419 All authors contributed to the result analysis and interpretation, commented on and approved the
420 final paper.

421

422 **Competing Interests**

423 The authors declare that they have no known competing financial interests or personal
424 relationships that could have appeared to influence the work reported in this paper.

425

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