Response to Referee #2's comments on "Air temperature equation derived from sonic temperature and water vapor mixing ratio for air flow sampled through closed-path eddy-covariance flux systems"

X.H. Zhou, T. Gao, E.S. Takle, X.J. Zhen, A.E Suyker, T. Awada, J. Okalebo, J.J. Zhu
https://doi.org/10.5194/amt-2021-160

Overall Comment

The paper is clearly written and makes a valuable scientific contribution with the derivation of equation (23), an equation based on first principles that can be used to compute high frequency air temperature from measurements with closed path eddy covariance systems. As shown in the paper, equation (23) is an advance beyond the previously used approximations, equations (4) and (5). And, as described in the paper, high frequency air temperature computed from equation (23) has potential to improve flux calculations with the eddy covariance technique. The paper should be published, but full consideration should be given the comments below, as there is opportunity to improve the paper before publication. While the paper does make a valuable scientific contribution with the derivation of equation (23), there are three things that would make the paper much stronger, and a more useful scientific contribution:

Author response
We thank Referee #2 so much for his/her professional review, understanding on our study topic, and constructive comments on improvement of manuscript. This overall comment agrees with the overall comments from the two referees for the previous version.

Discussion Comments

1. A more thorough analysis and discussion of the why the temperatures derived from the CPEC310 measurements in the field and equation (23) did not more closely match the temperature used as a reference (the platinum resistance thermometer (PRT) inside the fan aspirated radiation shield). There is a small section about this in lines 440-445. The suggestion that the PRT inside the fan-aspirated shield might be reading low, in lines 442-443, could be further investigated. For example, was the PRT calibrated before or after it was used to make measurements in the field? If so, was it reading low? It is likely that the PRT was not reading low, at least not by about 0.5 C, which suggests the temperatures derived from equation (23) are biased high (about 0.55 C in January and about 0.44 C in July). In lines 517-518 there is some brief commentary on systematic error in Ts measurements due to fixed deviation in measurements of sonic path lengths. Seems possible that this systematic error is the source of the bias in temperature from equation (23) when compared to temperature from the PRT in the fan-aspirated shield. There is also a suggestion that some of the difference in temperature may be due to non-ideal weather conditions, in lines 497-502. Given that weather variables were measured, it should be possible to filter the data for ideal weather conditions.

Author response:
This comment is related to several issues. We categorize the issues into four: a. PRT calibration, b. PRT (platinum resistance thermometer) accuracy, c. Equation error, and d. Data filtering. We address the issues separately in four categories as followings:

a. PRT calibration
Both CSAT3A (updated version) and PRT sensor were new when the field tests for this

study were started, but both were not recalibrated after the field tests because both sensors continued to be employed for ongoing program tests. The data from the field as shown in Fig. 4 verified the relationship of the equation-computed T (air temperature) error to sonic anemometer and gas analyzer specifications [i.e., measurement errors in sonic temperature (T_s) and water vapor mixing ratio (χ_{H2O}). See Eq. 25 and Figs. 2 and 4]. Although PRT may drift in T measurement and CSAT3A may drift in T_s measurement, for convincing analysis, we better use the specified accuracies of T from PRT (±0.2 °C) and T_s from CSAT3A (±1.0 °C). Although equation-computed T is biased high about 0.55 C in January and about 0.44 C in July, as shown in Fig. 2, the biases are within the range as described by Eq. (25) in terms of sensor specifications. We would be criticized by other referees if we further narrow the accuracy range of equation-computed T through finding a greater error from either T_s or PRT-measured T.

b. PRT accuracy

See line 443, ±0.2 instead of ±0.5 °C is used for discussion on PRT accuracy. It is well-known, the PRT accuracy in T is specified as ±0.2 °C by R.M. Young. The referee wrongly read the accuracy in Line 443.

c. Equation error

We believe that our developed T equation (Eq. 23) does not have any error. The equation-computed T has an error, but the error arises from the measurement instead of equation. The measurement errors are in T_s and χ_{H2O}. The error of equation-computed T was analytically expressed in terms of T_s, χ_{H2O}, and their measurement accuracies in Eq. (25) (i.e., error equation). The T equation and its error equation are exact ones. The derivation of both equations has been reviewed by four referees and checked by our co-authors.

It is common for sonic anemometers to have a systematic error in T_s to be ±0.5 ºC or little greater, which is the reason that the T_s accuracy is specified by Larry Jacobsen (anemometer authority) to be ±1.0 ºC. The fixed deviation in measurements of sonic path lengths is asserted as the source for bias of T_s (Zhou et al., 2018). This bias brings an error to equation-computed T. If the T equation were not exact, the error in equation-computed T would be introduced not only from a T_s error and a χ_{H2O} error, but also from an equation error. The objective of this study is to avoid equation error. Referee #2 categorizes the measurement error in T_s into the equation error. The reduction in a measurement error relies on the manufacturing technologies. In turn, the application of this exact equation can be used to improve this technology (see our response b to Referee #1's comment 9).

Acknowledging this point of Referee #2, we may need further clarifying discussion among lines 440 to 445.

d. Data filtering

The data for this study were not subjectively filtered. The data of the sonic anemometer and gas analyzer were filtered by their measurement diagnosis (see lines 549-551), but the data from RTD were not filtered. Subjectively filtering data would bring controversy to data analyses. The quality of data shown in Fig. 4 are the real quality of field data from the close-path eddy-covariance (CPEC) system.

We suspect that unfavorable weather contributed to a T_s error. We could have filtered out unfavorable weather cases to create a lower error estimate. But since most field experiments include periods when weather increases a T_s error, we reasoned that including a weather contribution to error would avoid overstating instrument accuracy under typical (unfiltered) applications.

Acknowledging this point of Referee #2, we need more clarification of discussion in section 10.1.

<u>*Author proposed revision*</u>

a. Revision is not needed.

b. Revision is not needed.

c. The last sentence in line 444 is replaced with the following paragraph:
"*It is common for sonic anemometers to have a systematic error in T_s to be ±0.5 ºC or little greater, which is the reason that the T_s accuracy is specified by Larry Jacobsen (anemometer authority) to be ±1.0 ºC for updated CSAT3A. The fixed deviation in measurements of sonic path lengths is asserted as a source for bias of T_s (Zhou et al., 2018). This bias brings an error to equation-computed T. If the T equation were not exact as Eqs. (4) and (5), there would be an additional equation error. In our study case, this bias from fixed deviation possibly is around 0.5 ºC. With this bias, the equation-computed T is still accurate as specified by Eqs. (25) and (27) and even better.*"

d. Add a short paragraph in the end of section 10.1.
"*Certainly, filtering out the T_s data in the periods of unfavorable weather could narrow the error range of equation-computed T. The unfavorable weather was suspected to contribute the stated error. Filtering out unfavorable weather cases could create a lower error estimate. But since most field experiments include periods when weather increases a T_s error, we reasoned that including a weather contribution to error would avoid overstating instrument accuracy under typical (unfiltered) applications. Therefore, both T_s and χ_{H_2O} data in this study were not programmatically or manually filtered based on weather.*"

2. A more thorough analysis and discussion of the error in temperature computed from equation (23) in relation to the applications. From lines 544-558, it seems the main application of computing temperature from equation (23) and high frequency measurements is an accurate estimate of high frequency dry air density (ρ_d) for water vapor flux calculations, and calculation of sensible heat flux from air temperature, without the need of a humidity correction. If this is the case, then it would be useful to have an indication of how accurate high frequency ρ_d and air temperature need to be and some commentary on whether the temperatures derived from the field data collected in this study and equation (23) are within this accuracy range. As stated above, it appears from field data that fixed deviation in the sonic path length may be the cause of the bias of about 0.5 C. If high frequency air temperature is high by about 0.5 C when computed with equation (23), can it practicably be used to improve flux calculations?

<u>*Author response*</u>

As our response to Referee #1, the deeper discussion on equation applications goes beyond the scope of this study (see response b to Referee #1's comment 9). For Referee's concern, in addition to section 10.3.2, additional discussion could be given below.

We can use the equation of state to estimate what the change in dry air density (ρ_d) can be caused from the difference in T of ±0.5 °C. However, this estimation cannot be used to assess the practical improvement for flux calculations because, to assess the improvement, comparison is needed. This concern can be clarified by the following two arguments:

a. Currently, beyond Campbell Scientific flux software, Eqs. (4) and (5) are used for sensible heat flux computations. Both equations are all approximate equations (see Appendices A and B). Our equation is an exact one. Compared to either approximate equation, our exact equation must be an improvement on the mathematical representation of sensible heat flux. If the equation for sensible heat flux is approximate, then even a perfect measurement gives only an approximate value for flux. The explanations in this paragraph could be expected by Referee #2 to support the discussion among lines 544-558.

b. Currently, in CO_2, H_2O and trace gas flux measurements, mean ρ_d for flux calculations is estimated from T and RH (relative humidity) along with atmospheric pressure. T and RH are measured mostly by a slow-response T-RH probe without fan-aspiration (e.g. HMP155A, Vaisala Corporation, Helsinki, Finland) (Zhu et al. 2021). As shown by Fig. 6, equation-computed T is better than probe-measured T because the former is insensitive to solar radiation. The air moisture measured by an infrared analyzer in CPEC systems must be more accurate than probe-measured air moisture. The better equation-computed T along with better air moisture has no reason not to improve ρ_d estimation from the convention method. The explanations in this paragraph may be expected by Referee #2 to enhance the discussion in section 10.3.1.

Author proposed revision

a. Add the following to the end of section 10.3.2.

"*Without our exact T equation, in any flux software, either Eqs. (4) or (5) has to be used for sensible heat flux computation. Both equations are approximate ones (see Appendices A and B). Compared to either, our exact equation must be an improvement on the mathematical representation of sensible heat flux. If the equation for sensible heat flux is approximate, then even a perfect measurement gives only an approximate value for flux.*"

b. Add one short paragraph to section 10.3.1.

"*Currently, in CO_2, H_2O and trace gas flux measurements, mean ρ_d for flux calculations is estimated from T and RH along with P. T and RH are measured mostly by a slow-response T-RH probe without fan-aspiration (e.g. HMP155A. Zhu et al. 2021). As shown in Fig. 6, equation-computed T is better than probe-measured T. The air moisture measured by an infrared analyzer in CPEC systems must be more accurate than probe-measured air moisture. The belter equation-computed T along with more accurate air moisture has no reason not to improve the estimation for mean ρ_d.*"

c. Due to citation of Zhu et al. (2021) in b above, add one more reference below line 825.

"Zhu, J.J., Gao, T., Yu, L.Z., Yu, F.Y., Yang, K., Lu, D.L., Yan, Q.L., Sun, Y.R., Liu, L.F., Xu, S., Zhang, J.X., Zheng, X., Song, L.N., Zhou, X.H. Functions and applications of Multi-tower Platform of Qingyuan Forest Ecosystem Research Station of Chinese Academy of Sciences (Qingyuan Ker Towers). Bulletin of Chinese Academy of Sciences 3, 351-361, 2021."

3. This study was conducted with only Campbell Scientific instruments. It would be helpful if there was some commentary on use of the proposed technique with other instruments. While Campbell Scientific instruments are widely used for flux measurements using the eddy covariance technique, other companies make 3D sonic anemometers and high frequency gas analyzers that are also widely applied for eddy covariance. Even if brief, any discussion the authors can provide about applicability of the proposed technique with non-Campbell Scientific instruments will make the paper more general. Right now, the information in the paper is specific

to only those users who have Campbell Scientific instruments.

Author response

For the applications of our developed T equation to all combinations of sonic anemometers and infrared analyzers with different models and brands, we developed error equations (24) to (27) to estimate the error of high-frequency T from any combination of sonic and infrared instruments as long as their measurement specifications are given. Our developed T equation (23) including error equation (25) completes this theory, which has not been done from any previous studies (Ishii 1932, Barrett and Suomi 1949, Schotanus et al. 1983, Kaimal and Gaynor 1991, Swiatek 2018).

The T equation (Eq. 23) and its error equations (Eq. 24-27) that we developed are applicable to all combinations of sonic anemometers and infrared analyzers with different models and brands. To implement these improved equations in other instrument combinations will require the hardware specifications of these instruments to complete the necessary modifications to their software.

As this comment indicates, Referee #1 has been aware of the wide applicability of our equations to other CPEC systems. Revision is needed to convey his/her comment. The applicability is discussed in section 10.2. We propose further clarification in response to this comment in the same way as to Referee #1's comment 8.

Author proposed revision

Insert four sentences into line 237 after "…… 2018a).", saying: "*Sonic anemometers and infrared analyzers with different models and brands have different specifications from their manufacturers. Any combination of sonic and infrared instruments has a combination of the ΔT_s and $\Delta\chi_{H_2O}$ that are specified by their manufacturers. In turn, from Eq. (25), the combination generates ΔT of equation-computed T for the corresponding combination of the sonic and infrared instruments with given models and brands. Therefore, Eqs. (23) and (25) are applicable to any CPEC system beyond our study model.*"

Editorial Comments

Beyond these three content recommendations, there are two things that would improve organization of the paper:

1. Move sections 6 and 7 to an appendix. These sections contain important material, but provide a level of detail that is not essential to the main body of the paper.

Author response

This manuscript is a thorough study on high-frequency T derived from T_s and χ_{H_2O}. If the details provided are not enough in main text, readers would feel inconvenient during reading. We moved a large amount of material to the appendices to improve the readability of the main body of the manuscript (Appendices A, B, and C). Because the central goal of the paper was to focus on the high-frequency T, we decided not to move sections 6 and 7, since this would frequently send the reader to the appendix and disrupt the reader's brain of thought to learn about this new development.

Author proposed revision

Revision is not preferred.

2. Use headers to better separate the material. For example, section 1 is Introduction, section 2 is Background, and section 10 is Discussion. Following this formant, sections 3 and could be called Theory. Section 5 could be called Materials and Methods. If sections 6 and 7 are not moved to an appendix, they should be included with section 5 under Materials and Methods. Sections 8 and 9 could be called Results.

Author response

The suggested headers are concise.

Author proposed revision

Adopt suggested headers.

3. Some necessary edits.

Author response

Many thanks to Referee #2 for his/her, not only quality, but also thorough review. We very much appreciate these comments and improvements.

This version of manuscript was reviewed and revised by our authors, but it did not go through a proofreading process. A proofreading process is needed for next version.

Author proposed revision

In the end of next version, we will have this manuscript through a professional proofreading process.

Line 17: temperar should be temperature.

Author proposed revision

In line 17, correct "tempera" into "*temperature*".

Line 20: senosrs should be sensors.

Author proposed revision

In line 20, correct "senosrs" into "*sensors*".

Line 30: CPEC300 is a specific product and needs to be defined (meaning the instruments included with this model should be listed and the manufacturer should be listed).

Author response

This line is inside Abstract. The details in model and manufacturer are not preferred in Abstract.

Author proposed revision

Revision is not preferred.

Line 44: Panofsky and Dutton (1984) is cited, but is not found in the reference list.

Author proposed revision

Between lines 799 and 800, insert:

Panofsky, H.A., and Dutton, J.A. Atmospheric turbulence: models and method for engineering applications, A Wiley-Interscience Publication, John & Sons, Inc. New York, 397, 1984.

Line 66: suffered to should be changed to suffered by.

Author proposed revision
In line 66, correct "to" to "*by*".

Line 110: contaminated should be contamination.

Author proposed revision
In line 110, correct "contaminated" to "contamination".

Line 152: a should be removed after unmeasurable by.

Author proposed revision
In line 110, remove "*a*" after "by".

Lines 243-244: CSAT3A and EC155 are specific Campbell Scientific products, so they should be denoted as such (like at the beginning of the sentence where CPEC310 is denoted as a Campbell Scientific product).

Author response
We feel redundant if "(Campbell Scientific Inc., Logan, UT, USA)" is repeated three times in one sentence separately for CPEC300, CSAT3A, and EC155.

Author proposed revision
In lines 243, replace "including" with "*whose major components are*". This revision indicates that CSAT3A and EC155 belong to a CPEC310 system. As long as CPEC310 system is denoted by (Campbell Scientific Inc., Logan, UT, USA), CSAT3A and EC155, as two components of CPEC310, do not need this denotation.

Line 262: Multiple temperature variables are used in equation (27). Subscript c appears to denote calibration, subscript z appears to denote zero, subscript s appears to denote sonic, and unclear what subscript r denotes. Some clarification and definition is required.

Author response
Subscript r denotes "the range of air temperature". See lines 264 and 265, "….. and T_{rl} and T_{rh} are the low- and the high-end values, respectively, over the operational air temperature range of CPEC systems". This expression may not be clear to readers. Further revision could be better for this expression.

Author proposed revision
The above sentence can be revised as *"….. and T_{rl} and T_{rh} are the low- and the high-end values over an operational range of ambient air temperature for CPEC systems, respectively"*.

Lines 323-324: EC100 is a specific Campbell Scientific product and needs to be denoted as such. It seems the EC100, EC155, and CSAT3A are all components of the CPEC310. If this is the case, it would be helpful if there is a better description of the CPEC310.

Author response
We believe that Referee refers to line 325-333. In a CPEC310 system, all components except for barometer are all Campbell Scientific parts. The excepted barometer is labelled with "Freescale Semiconductor, TX, USA". We read through this paragraph several times and feel the description overall is clear after the revision above for line 243.

Author proposed revision
See author suggested revision above for line 243.

Line 341: CR6 needs to be defined as a datalogger and denoted as a Campbell Scientific product.

Author response
See line 341, "A CR6, supported by EasyFlux_CR6CP (revised version for this study, Campbell Scientific Inc. UT, USA) ………". It is clear because "CR6" also occurs in EasyFlux_"CR6"CP. Additional "Campbell Scientific Inc. UT, USA" in the same sentence is less readable.

Author proposed revision
Revision is not preferred.

Line 357: Sentence needs to be reworded. The phrase even impossible is out of place. Perhaps remove the phrase even impossible from the sentence and then write another sentence to describe how it is impossible to sample fast enough to capture all eddies.

Author proposed revision
In line 357, "even impossible" may be revised as "*although impossible*".

Line 527: Acronym OPEC is used without being defined. Needs to be defined as open path eddy covariance.

Author response
Yes, OPEC in flux community commonly refers "open-path eddy-covariance". In lines 527 and 528, the acronym OPEC is more specifically defined by "(e.g. CSAT3A+EC150 and CSAT3B+LI7500)". This definition may be too specific. The sentence needs rewording.

Author proposed revision
In lines 527 and 528, the sentence is revised as "*Some open-path eddy-covariance (OPEC) flux systems (e.g. CSAT3A+EC150 and CSAT3B+LI7500)* ……….".

Line 609: thermometry can be removed.

Author proposed revision
In line 609, remove "*-thermometry*".

Line 674: Diving should be dividing by.

Author proposed revision
In line 674, correct "*Diving*" into "*Dividing*".

Lines 682 and 685: expending should be expanding.

Author proposed revision
In line 682 and 685, correct "expending" into "expanding".

References

Barrett, E. W. and Suomi, V. E.: Preliminary report on temperature measurement by sonic means, J. Atmos. Sci., 6, 273–276, 1949.

Ishii, C.: Supersonic velocity in gases: especially in dry and humid air. Scientific Papers of the Institute of Physical and Chemical Research, Tokyo, 26, 201–207 pp., 1932.

Kaimal, J. C., and Gaynor, J. E.: Another look to sonic thermometry, Boundary-Layer Meteorol., 56, 401-410, 1991.

Schotanus, P., Nieuwstadt, F. T. M., and DeBruin, H. A. R.: Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations, Boundary-Layer Meteorol., 26, 81-93, 1983.

Swiatek, E: Derivation of Temperature (Tc) from the Sonic Virtual Temperature (Ts), vapor density (ρv)/vapor pressure (e) and pressure (P). Campbell Scientific Inc. Logan, UT, 1-5 pp., 2018

Zhou, X., Yang, Q., Zhen, X., Li, Y., Hao, G., Shen, H., Gao, T., Sun, Y., and Zheng, N.: Recovery of the three-dimensional wind and sonic temperature data from a physically deformed sonic anemometer, Atmos. Meas. Tech., 11, 5981–6002, doi:10.5194/amt-11-5981-2018, 2018.

Zhu, J.J., Gao, T., Yu, L.Z., Yu, F.Y., Yang, K., Lu, D.L., Yan, Q.L., Sun, Y.R., Liu, L.F., Xu, S., Zhang, J.X., Zheng, X., Song, L.N., Zhou, X.H. Functions and applications of Multi-tower Platform of Qingyuan Forest Ecosystem Research Station of Chinese Academy of Sciences (Qingyuan Ker Towers). Bulletin of Chinese Academy of Sciences 3, 351-361, 2021.