WPL and SND Corrections in Flux Computations

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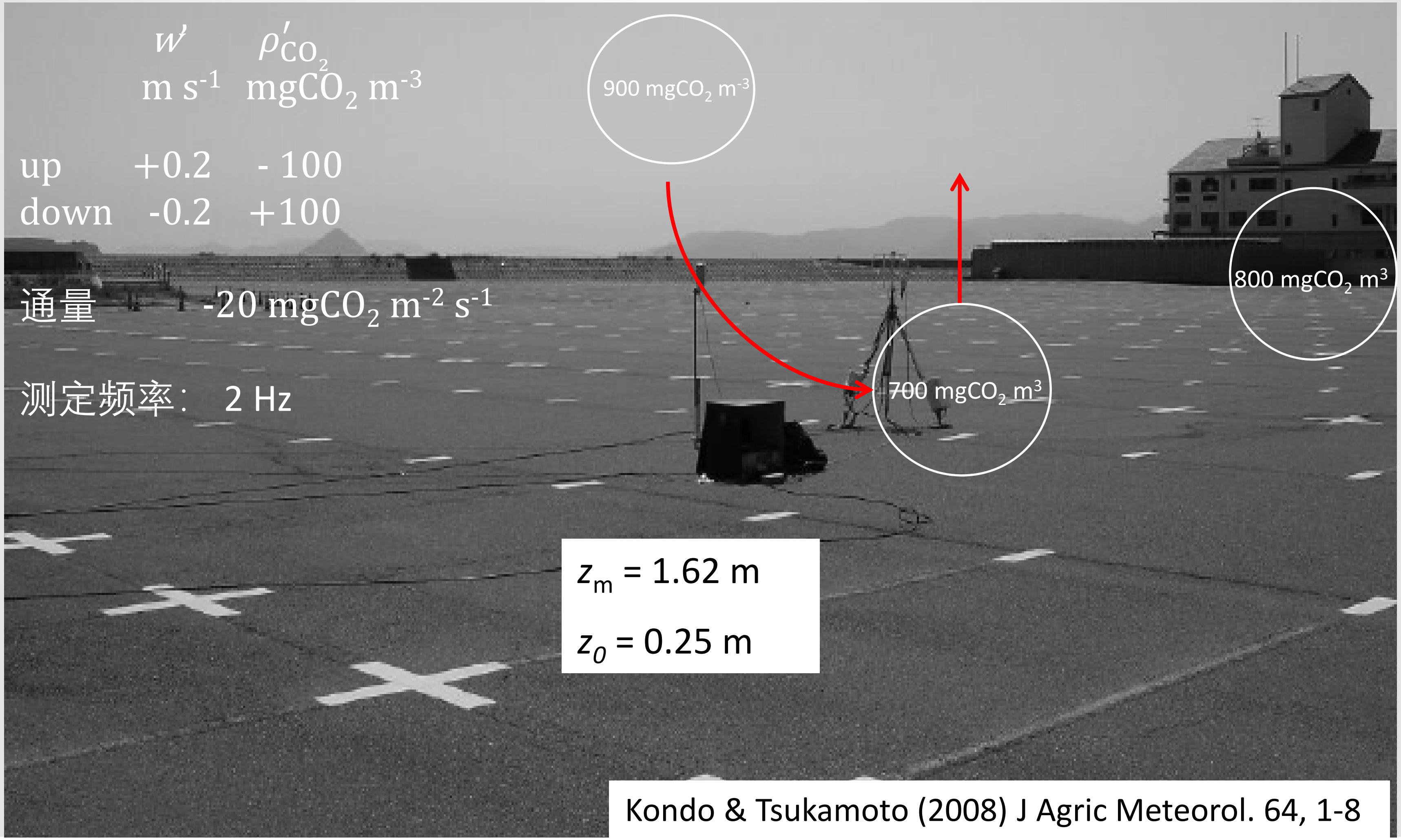
WPL correction: 修正空气密度在传感器变化对通量测定影响

–在没有CO_2交换下垫面，可测出明显的地面对CO_2的吸收



	w' m s^{-1}	ρ'_{CO_2} mgCO$_2$ m^{-3}
up	+0.2	- 100
down	-0.2	+100

通量 -20 mgCO$_2$ m^{-2} s^{-1}

测定频率： 2 Hz

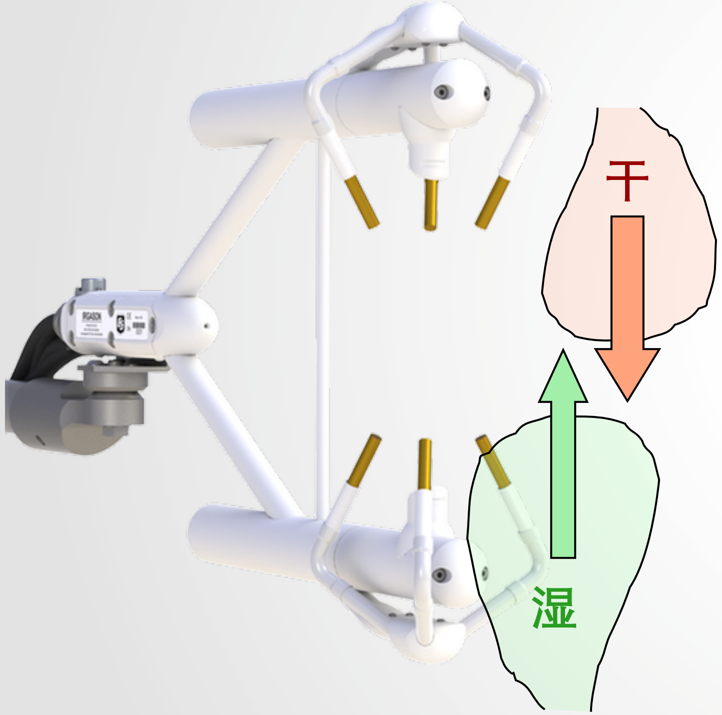
$z_m = 1.62$ m

$z_0 = 0.25$ m

Kondo & Tsukamoto (2008) J Agric Meteorol. 64, 1-8

垂直风速的麻烦

$$F_{CO_2} = \overline{w\rho_{CO_2}} = \overline{w'\rho'_{CO_2}} + \overline{w}\,\overline{\rho}_{CO_2}$$



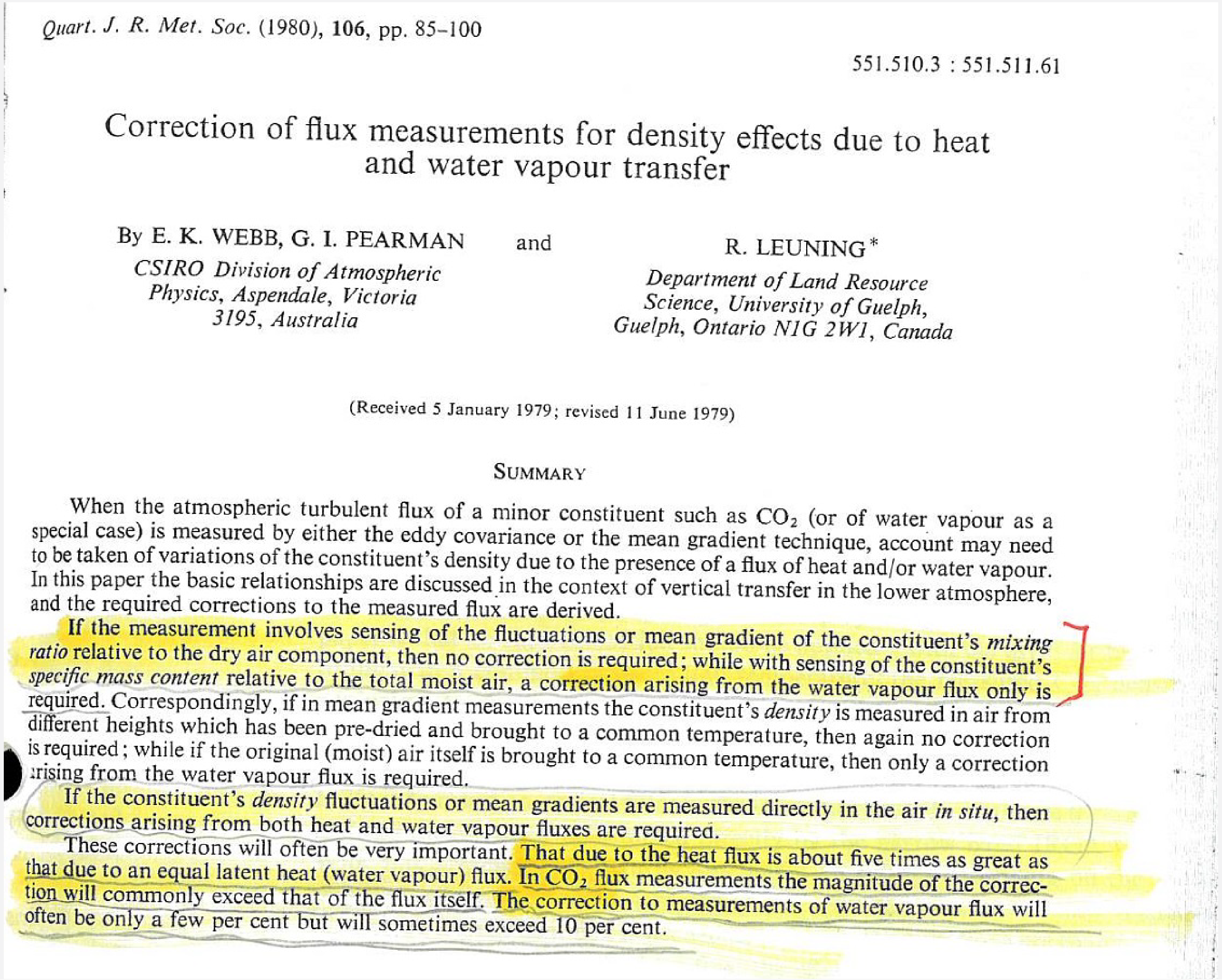
$$\overline{w} \neq 0$$

1. 水和CO_2出入地面和植物体
2. 感热通量引起的空气密度的变化

LE - 200 ~ 600 W m^{-2}

$\overline{W}$ – 0.75 ~ 1.5 mm s^{-1}

CAST 分辨率：0.25 ~ 2.00 mm s^{-1}



Quart. J. R. Met. Soc. (1980), **106**, pp. 85–100

551.510.3 : 551.511.61

Correction of flux measurements for density effects due to heat and water vapour transfer

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SUMMARY

When the atmospheric turbulent flux of a minor constituent such as CO_2 (or of water vapour as a special case) is measured by either the eddy covariance or the mean gradient technique, account may need to be taken of variations of the constituent's density due to the presence of a flux of heat and/or water vapour. In this paper the basic relationships are discussed in the context of vertical transfer in the lower atmosphere, and the required corrections to the measured flux are derived.

If the measurement involves sensing of the fluctuations or mean gradient of the constituent's *mixing ratio* relative to the dry air component, then no correction is required; while with sensing of the constituent's *specific mass content* relative to the total moist air, a correction arising from the water vapour flux only is required. Correspondingly, if in mean gradient measurements the constituent's *density* is measured in air from different heights which has been pre-dried and brought to a common temperature, then again no correction is required; while if the original (moist) air itself is brought to a common temperature, then only a correction arising from the water vapour flux is required.

If the constituent's *density* fluctuations or mean gradients are measured directly in the air *in situ*, then corrections arising from both heat and water vapour fluxes are required.

These corrections will often be very important. That due to the heat flux is about five times as great as that due to an equal latent heat (water vapour) flux. In CO_2 flux measurements the magnitude of the correction will commonly exceed that of the flux itself. The correction to measurements of water vapour flux will often be only a few per cent but will sometimes exceed 10 per cent.

$$\overline{w\rho_d} = 0$$

$$\overline{w}\,\overline{\rho}_d + \overline{w'\rho_d'} = 0$$

$$\overline{w} = -\frac{\overline{w'\rho_d'}}{\overline{\rho}_d}$$

大气压 (*P*) 是干空气 (*P$_d$*)和水 (e)气压之和

$$P = P_d + e$$

$$P_d = \frac{R^*}{m_d}\rho_d T$$

$$e = \frac{R^*}{m_{H_2O}}\rho_{H_2O} T$$

$$\frac{P}{R^* T} = \frac{\rho_d}{m_d} + \frac{\rho_{H_2O}}{m_{H_2O}}$$

$$\frac{\rho_d}{m_d}+\frac{\rho_{H_2O}}{m_{H_2O}}=\frac{P}{R^*}\times\frac{1}{T}$$

$$\frac{1}{T}=\frac{1}{(\bar{T}+T')}=\frac{1}{\bar{T}\left(1+\frac{T'}{\bar{T}}\right)}$$

$$T=\bar{T}+T'$$

$$\frac{\rho_d}{m_d}+\frac{\rho_{H_2O}}{m_{H_2O}}=\frac{P}{R^*}\times\frac{1}{\bar{T}}\left\{1-\frac{T'}{\bar{T}}+\left(\frac{T'}{\bar{T}}\right)^2-\left(\frac{T'}{\bar{T}}\right)^3+\dots.\right\}$$

$$\begin{cases}\dfrac{\bar{\rho}_d}{m_d}+\dfrac{\bar{\rho}_{H_2O}}{m_{H_2O}}=\dfrac{P}{R^*}\times\dfrac{1}{\bar{T}}\left\{1+\dfrac{\overline{T'^2}}{\bar{T}^2}-\dfrac{\overline{T'^3}}{\bar{T}^3}+\dots\right\}\\[2ex] \dfrac{\rho'_d}{m_d}+\dfrac{\rho'_{H_2O}}{m_{H_2O}}=\dfrac{P}{R^*}\times\dfrac{1}{\bar{T}}\left\{-\dfrac{T'}{\bar{T}}+\dfrac{T'^2-\overline{T'^2}}{\bar{T}^2}-\dfrac{T'^3-\overline{T'^3}}{\bar{T}^3}+\dots.\right\}\end{cases}$$

$$\begin{cases} \dfrac{\overline{\rho}_d}{m_d} + \dfrac{\overline{\rho}_{H_2O}}{m_{H_2O}} = \dfrac{P}{R^*\overline{T}} \left\{ 1 + \dfrac{\overline{T'^2}}{\overline{T}^2} - \dfrac{\overline{T'^3}}{\overline{T}^3} + \ldots \right\} \\ \\ \dfrac{\rho'_d}{m_d} + \dfrac{\rho'_{H_2O}}{m_{H_2O}} = \dfrac{P}{R^*\overline{T}} \left\{ -\dfrac{T'}{\overline{T}} + \dfrac{T'^2 - \overline{T'^2}}{\overline{T}^2} - \dfrac{T'^3 - \overline{T'^3}}{\overline{T}^3} + \ldots. \right\} \end{cases}$$

$$\frac{P}{R^*\overline{T}} = \left(\frac{\overline{\rho}_d}{m_d} + \frac{\overline{\rho}_{H_2O}}{m_{H_2O}} \right) \left\{ 1 + \frac{\overline{T'^2}}{\overline{T}^2} - \frac{\overline{T'^3}}{\overline{T}^3} + \ldots \right\}^{-1}$$

$$\frac{\rho'_d}{m_d} + \frac{\rho'_{H_2O}}{m_{H_2O}} = \left(\frac{\overline{\rho}_d}{m_d} + \frac{\overline{\rho}_{H_2O}}{m_{H_2O}} \right) \left\{ 1 + \frac{\overline{T'^2}}{\overline{T}^2} - \frac{\overline{T'^3}}{\overline{T}^3} + \ldots \right\}^{-1} \left\{ -\frac{T'}{\overline{T}} + \frac{T'^2 - \overline{T'^2}}{\overline{T}^2} - \frac{T'^3 - \overline{T'^3}}{\overline{T}^3} + \ldots. \right\}$$

$$\frac{\rho'_d}{m_d}+\frac{\rho'_{H_2O}}{m_{H_2O}}=\left(\frac{\bar{\rho}_d}{m_d}+\frac{\bar{\rho}_{H_2O}}{m_{H_2O}}\right)\left\{-\frac{T'}{\bar{T}}+\frac{T'^2-\overline{T'^2}}{\bar{T}^2}-\frac{T'^3-\overline{T'^3}}{\bar{T}^3}+....\right\}\left\{1+\frac{\overline{T'^2}}{\bar{T}^2}-\frac{\overline{T'^3}}{\bar{T}^3}+...\right\}^{-1}$$

$$\Big\downarrow$$

$$\boxed{\frac{\rho'_d}{m_d}+\frac{\rho'_{H_2O}}{m_{H_2O}}=-\left(\frac{\bar{\rho}_d}{m_d}+\frac{\bar{\rho}_{H_2O}}{m_{H_2O}}\right)\frac{T'}{\bar{T}}}$$

$$\Big\downarrow$$

$$\rho'_d=-\frac{m_d}{m_{H_2O}}\rho'_{H_2O}-\bar{\rho}_d\left(1+\frac{m_d}{m_{H_2O}}\frac{\bar{\rho}_v}{\bar{\rho}_d}\right)\frac{T'}{\bar{T}}\xrightarrow[\frac{\bar{\rho}_{H_2O}}{\bar{\rho}_d}=\sigma]{\frac{m_d}{m_{H_2O}}=\mu}\boxed{\rho'_d=-\mu\rho'_{H_2O}-\bar{\rho}_d\left(1+\mu\sigma\right)\frac{T'}{\bar{T}}}$$

$$\rho_d' = -\mu\rho_{H_2O}' - \bar{\rho}_d\left(1+\mu\sigma\right)\frac{T'}{\bar{T}}$$

$$\bar{w} = -\frac{\overline{w'\rho_d'}}{\bar{\rho}_d}$$

$$\bar{w} = \mu\frac{\overline{w'\rho_{H_2O}'}}{\bar{\rho}_d} + \left(1+\mu\sigma\right)\frac{\overline{w'T'}}{\bar{T}}$$

$$\overline{w} = \frac{\mu}{\overline{\rho}_d}\overline{w'\rho'_{H_2O}} + \frac{1+\mu\sigma}{\overline{T}}\overline{w'T'}$$

$$F_{CO2} = \overline{w\rho_{CO2}} = \overline{w'\rho'_{CO2}} + \overline{w}\overline{\rho}_{CO2}$$

$$\boxed{F_{CO2} = \overline{w'\rho'_{CO2}} + \left(\frac{\mu}{\overline{\rho}_d}\overline{w'\rho'_{H_2O}} + \frac{1+\mu\sigma}{\overline{T}}\overline{w'T'}\right)\overline{\rho}_{CO2}}$$

$$\bar{w} = \frac{\mu}{\bar{\rho}_d}\overline{w'\rho'_{H_2O}} + \frac{1+\mu\sigma}{\bar{T}}\overline{w'T'}$$

$$F_{H_2O} = \overline{w\rho_{H_2O}} = \overline{w'\rho'_{H_2O}} + \bar{w}\bar{\rho}_{H_2O}$$

$$F_{H_2O} = \overline{w'\rho'_{H_2O}} + \left[\frac{\mu}{\bar{\rho}_d}\overline{w'\rho'_{H_2O}} + \frac{1+\mu\sigma}{\bar{T}}\overline{w'T'}\right]\bar{\rho}_{H_2O}$$

$$\begin{cases} F_{CO2} = \overline{w'\rho'_{CO2}} + \left(\dfrac{\mu}{\bar{\rho}_d} \overline{w'\rho'_{H_2O}} + \dfrac{1+\mu\sigma}{\bar{T}} \overline{w'T'} \right) \bar{\rho}_{CO2} \\ \\ F_{H_2O} = \overline{w'\rho'_{H_2O}} + \left[\dfrac{\mu}{\bar{\rho}_d} \overline{w'\rho'_{H_2O}} + \dfrac{1+\mu\sigma}{\bar{T}} \overline{w'T'} \right] \bar{\rho}_{H_2O} \end{cases}$$

$\overline{w'T'}$ is needed.

Sonic temperature (T_s)

$$T = \frac{c^2}{\gamma R}$$

T Air temperature

γ Ratio of moist air specific heat between constant pressure and constant volume

R gas constant of moist air

$$T_s = \frac{c^2}{\gamma_d R_d}$$

c Speed of sound

γ_d ratio of dry air specific heat between constant pressure and constant volume (1.400279)

R_d gas constant of dry air (287 J K^{-1} kg^{-1})

T_s of moist air is T that its dry air component can reach at the same enthalpy as the moist air has (Zhou et al., 2022)

TEMPERATURE MEASUREMENT WITH A SONIC ANEMOMETER AND ITS APPLICATION TO HEAT AND MOISTURE FLUXES

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Abstract. The possibility of measuring heat and moisture fluxes using sonic anemometer data is investigated. Theoretical relations for the temperature variance and heat flux are derived. In the first part of this paper, these relations are verified by experimental data, involving a sonic anemometer, a fast thermocouple and a Lyman-α hygrometer. In the second part we propose two simple procedures to estimate heat flux from sonic anemometer data. The first one requires a rough estimate of the Bowen ratio; for the second one the net radiation is needed. Using the last method, a good estimate of the moisture flux is also obtained.

1. Introduction

The measurement of the turbulent fluxes of momentum, heat and moisture is an important objective in experimental boundary-layer research. For these measurements, the sonic anemometer has become an important research tool (Kaimal, 1979). Sonic anemometers have been used in many experiments for the measurement of wind velocity fluctuations (Haugen *et al.*, 1971; Kaimal *et al.*, 1976); modern sonic anemometers also provide temperature measurements, but these are seldom used for flux computations (Kaimal, 1969; Friehe, 1976).

In this paper we explore the merits of the sonic anemometer for the measurement of temperature fluctuations. For that reason we conducted a field experiment in the summer of 1981 near the meteorological mast at Cabauw, the Netherlands. Apart from a sonic anemometer, we employed a fast thermocouple and a Lyman-α hygrometer. With this array of instruments, we could measure the three vertical turbulent fluxes: momentum, heat and moisture.

The first problem that we were faced with, involved errors in the velocity measurements due to flow distortion by the sonic anemometer. These errors are caused by the wake of the sound transducers, and result in an underestimation of the wind velocity (Kaimal, 1979; Wyngaard, 1981). They are usually neglected. Here, we have used a calibration curve to correct for this problem.

Subsequently, we investigated the use of a sonic anemometer to measure temperature variance and heat flux. This possibility has not been explored much until now. However,

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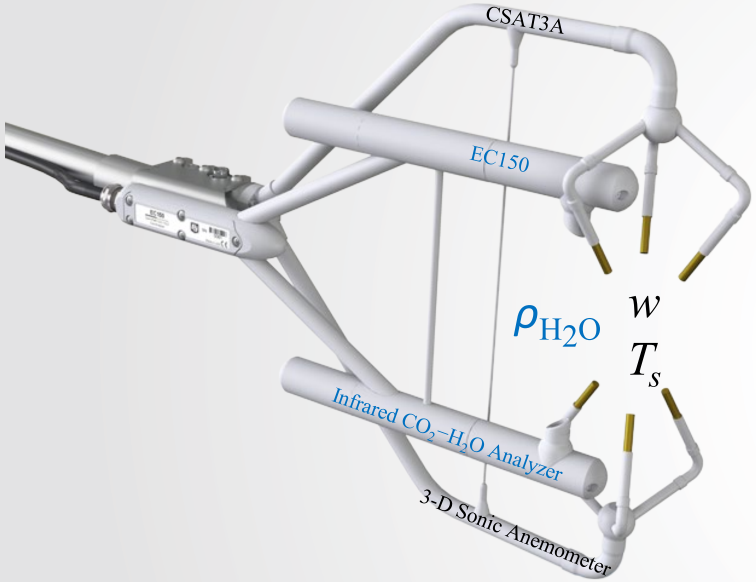
* To whom correspondence should be directed.

Boundary-Layer Meteorology **26** (1983) 81–93. 0006–8314/83/0261–0081$01.95.

Relationship of T_s to T in OPEC systems



$$T = T_s\left[1 - 0.51\frac{\rho_{H_2O}}{\rho_a}\right]$$

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

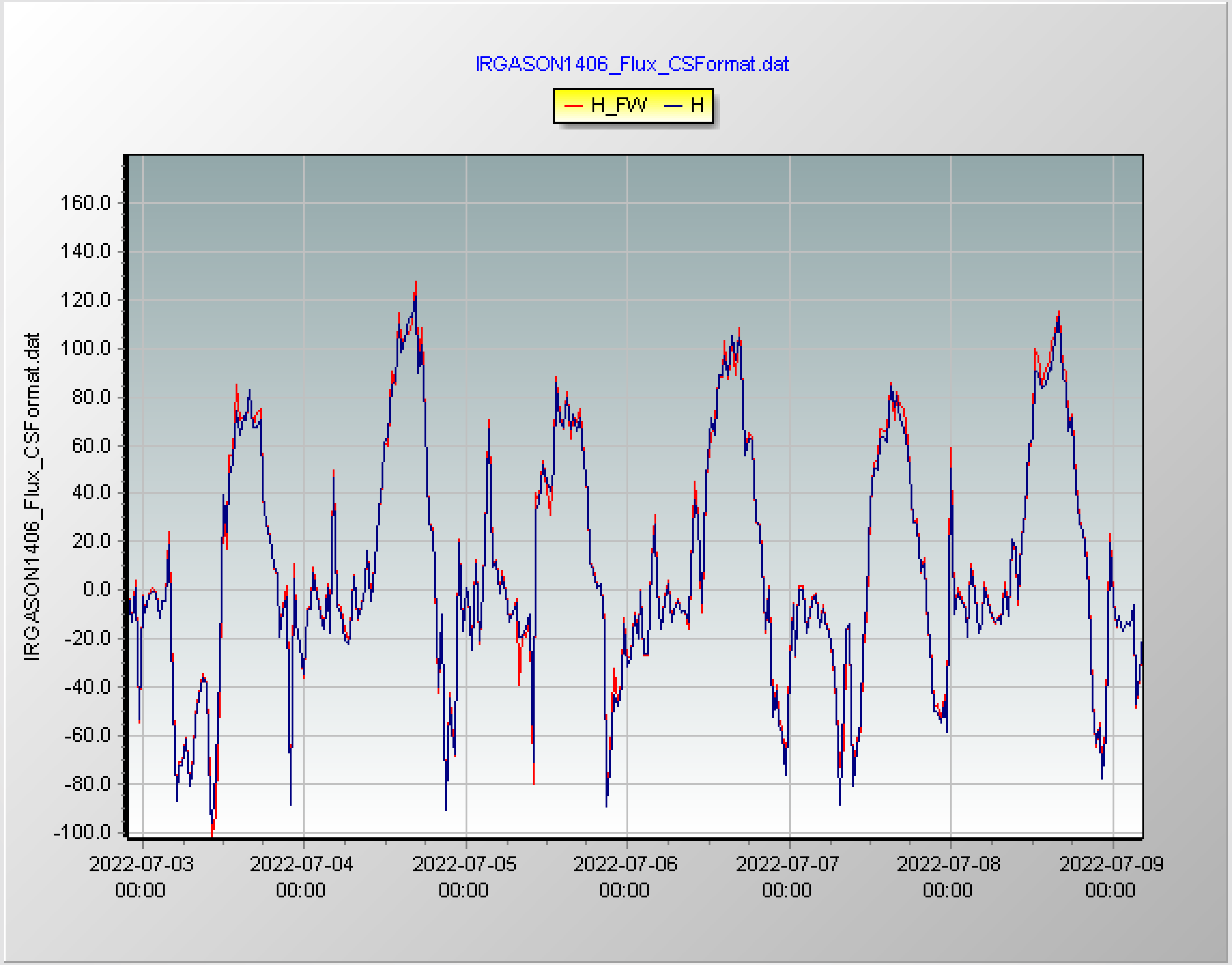
Moisture correction for T_s flux to be sensible heat flux for open-path eddy-covariance systems

van Dijk, A. 2002.
The Principles of Surface Flux Physics, Dept of Meteorol and Air Quality, Agr. Univ. Wageningen, 40–41 pp.

$$T = T_s\left[1 - 0.51\frac{\rho_{H_2O}}{\rho_a}\right]$$

$$T' = T_s'\left[1 - 0.51\left(\overline{\frac{\rho_{H_2O}}{\rho_a}}\right)\right] - 0.51\left(\frac{\rho_{H_2O}}{\rho_a}\right)'\overline{T}_s$$

$$\overline{w'T'} = \overline{w'T_s'}\left[1 - 0.51\left(\overline{\frac{\rho_{H_2O}}{\rho_a}}\right)\right] - 0.51\frac{\overline{w'\rho_{H_2O}'}}{\overline{\rho}_a}\overline{T}_s$$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Relationship of T to T_s and H_2O mixing ratio (χ_{H_2O}) for closed-path eddy-covariance systems

$$\varepsilon = \frac{M_w}{M_d}$$

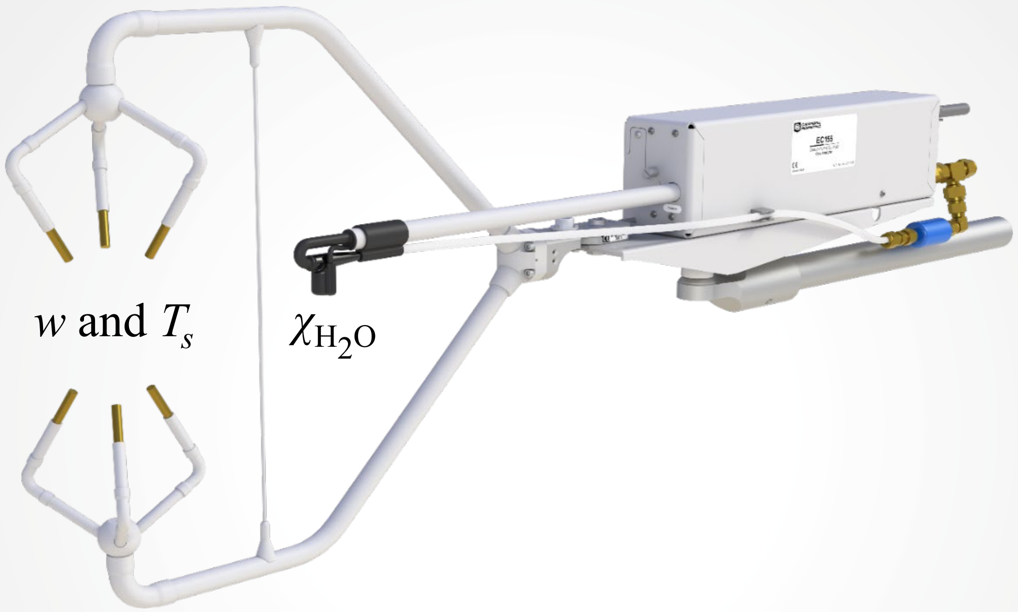
$$T = T_s \frac{\left(1+\varepsilon\chi_{H_2O}\right)\left(1+\varepsilon\gamma_v\chi_{H_2O}\right)}{\left(1+\chi_{H_2O}\right)\left(1+\varepsilon\gamma_p\chi_{H_2O}\right)}$$

$$\gamma_v = \frac{C_{vw}}{C_{vd}} = 2.04045$$

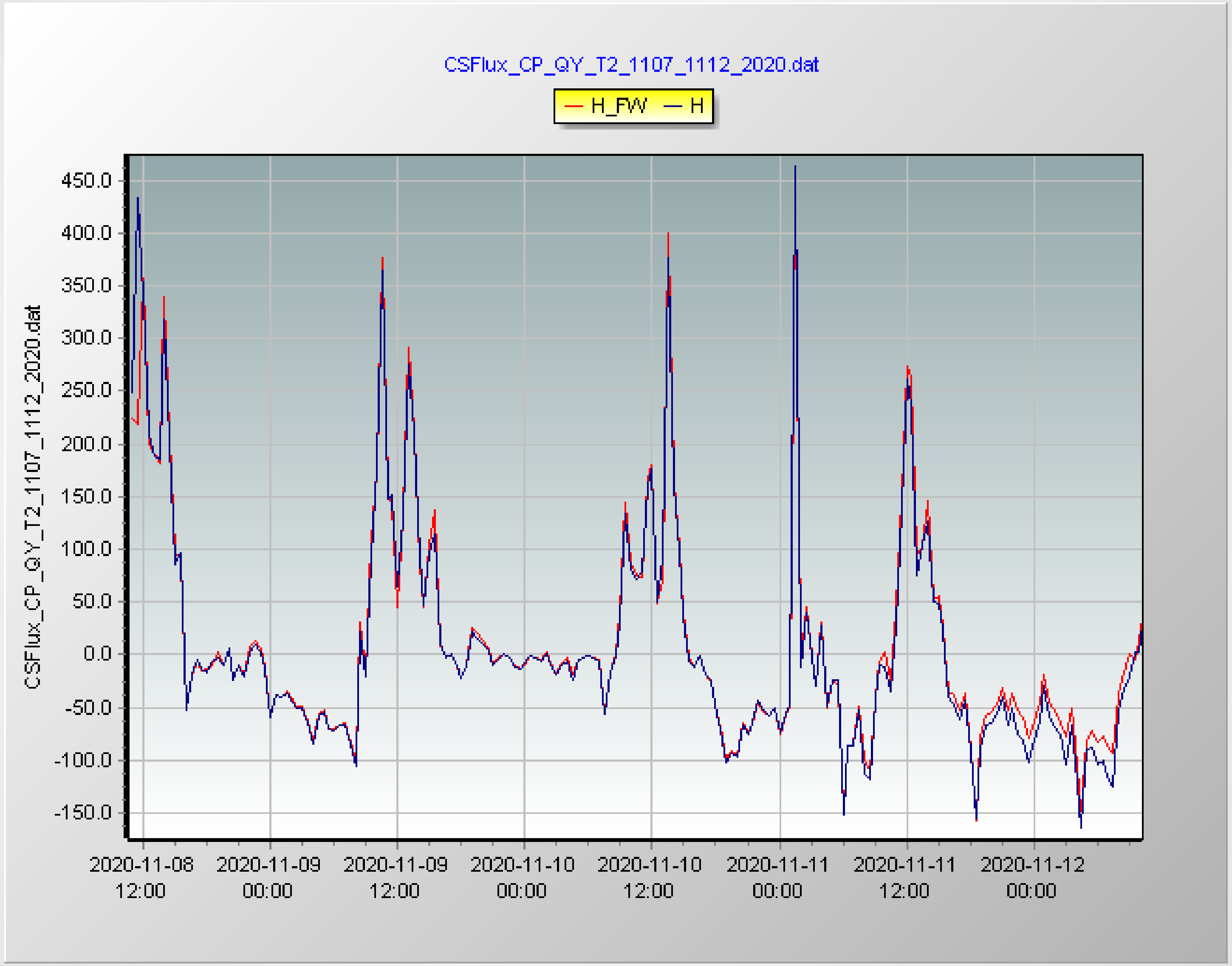
$$\gamma_p = \frac{C_{pw}}{C_{pd}} = 1.94422$$

Zhou, XH, T Gao, ES Takle, XJ Zhen, AE Suyker, T Awada, J Okalebo, JJ Zhu. 2022. Air temperature equation derived from sonic temperature and water vapor mixing ratio for boundary-layer flow through closed-path eddy-covariance flux systems. Atmos Meas Tech 15: 95–115, https://doi.org/10.5194/amt-15-95-2022.

Moisture correction for T_s flux to be sensible heat flux for closed-path eddy-covariance systems



$$\overline{w'T'} = \frac{\overline{T}}{\overline{T}_s}\overline{w'T_s'} + \overline{T}\left[\frac{\varepsilon+\varepsilon\gamma_v\left(1+2\varepsilon\overline{\chi}_{H_2O}\right)}{\left(1+\varepsilon\overline{\chi}_{H_2O}\right)\left(1+\varepsilon\gamma_v\overline{\chi}_{H_2O}\right)} - \frac{1+\varepsilon\gamma_p\left(1+2\overline{\chi}_{H_2O}\right)}{\left(1+\overline{\chi}_{H_2O}\right)\left(1+\varepsilon\gamma_p\overline{\chi}_{H_2O}\right)}\right]\overline{w'\chi_{H_2O}'}$$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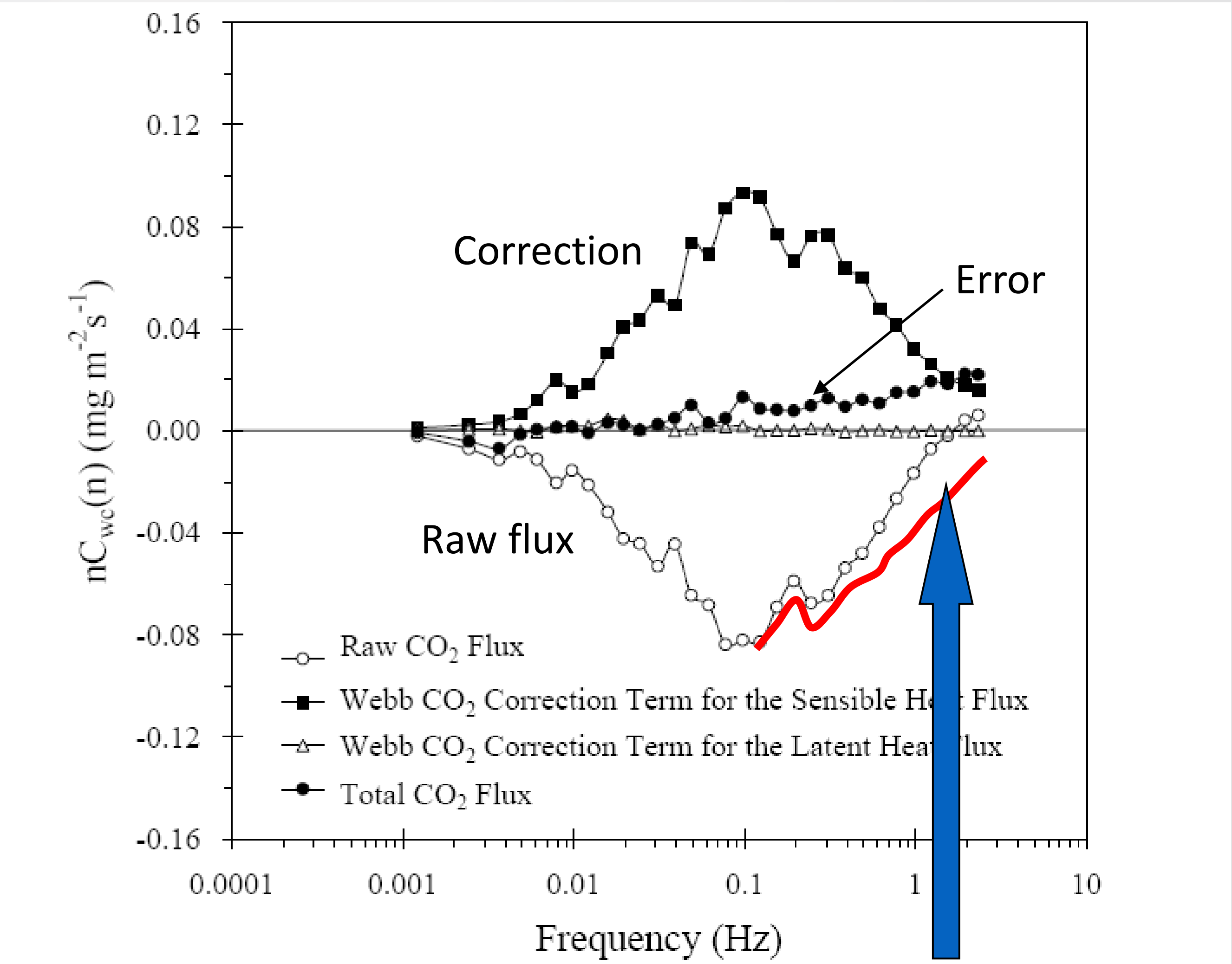
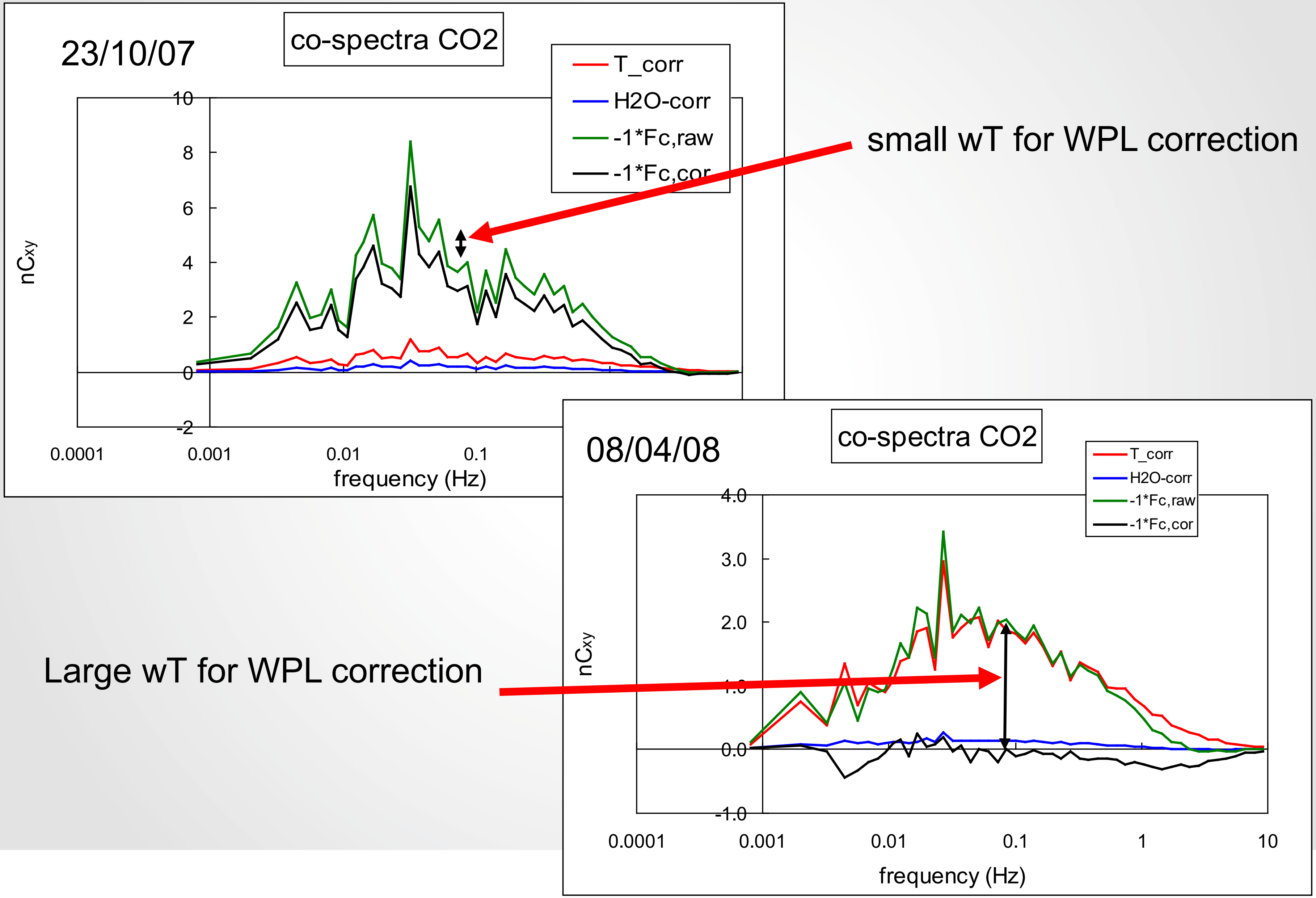
Error due to differing frequency responses for cospectra of

$$\overline{w'T'} \text{ and } \overline{w'\rho'_{CO_2}}$$



Need to correct for loss of covariance before WPL correction

Magnitude in WPL correction



small wT for WPL correction

Large wT for WPL correction

Milestone references

Webb, E.K., G.I. Pearman, R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water transfer. Quart. J. Met. Soc. 106: 85-100.

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

Other references

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Welcome to Logan

where the state-of-the-art flux systems are manufactured for ChinaFlux community.

Bruce Bugbee