Calibration of an Airborne Lyman-Alpha Hygrometer and Measurement of Water Vapor Flux Using a Thermoelectric Hygrometer

C. A. FRIEHE

Department of Mechanical Engineering, University of California, Irvine, CA 92717

R. L. GROSSMAN AND Y. PANN

CIRES, University of Colorado/NOAA, Boulder, CO 80309

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ABSTRACT

An improved calibration technique for an airborne Lyman-alpha hygrometer is presented. Like previous methods, it relies upon simultaneous measurement of absolute humidity determined from a slower response hygrometer. We show that a substantial improvement in the Lyman-alpha calibration is obtained by accounting for the time lag of the slower instrument.

To show our technique we use data from Lyman-alpha and thermoelectric devices on the NCAR Electra during an investigation of the nearly neutral boundary layer over the Arabian Sea as part of the WMO/ICSU Summer Monsoon Experiment. We also show that for near-neutral conditions the eddy-correlation water vapor flux can be adequately estimated using the fast response vertical velocity data from a gust probe and slower response data from the thermoelectric device, which has been properly advanced to account for the time lag.

1. Introduction

The accurate measurement of atmospheric water vapor is important to many meteorological studies. In the turbulent boundary layer, the vertical flux of water vapor is an important factor in the determination of static and dynamic stability. Over the ocean, the upward flux represents a large evaporative heat loss from the sea and a simultaneous latent heat gain by the atmosphere. Water vapor fluctuations also affect optical and electromagnetic indices of refraction.

The measurement of water vapor has been a difficult experimental task (Wexler, Ed., 1965). On research aircraft, slow-response thermoelectric instruments are usually used to accurately measure the average dew point, a measure of water vapor content. Their response time has been thought to be too slow for accurate determination of water vapor fluctuations and flux. For these measurements, water vapor density or vapor pressure is usually measured with very fast response Lyman-alpha hygrometers (Tillman, 1965; Buck, 1985) or microwave refractometers (Bean and Dutton, 1966). The calibration of these fast response instruments is often uncertain, and accuracy is improved by strategies which refer to the more accurate, slow response dew point devices. Previous calibration techniques for Lyman-alpha hygrometers (Lenschow and Stankov, 1981; Richner, 1985) used the slower response thermoelectric instruments for reference, but did not take into account the difference in instrument response times.

Here we present a simple improvement for the calibration of an aircraft Lyman-alpha hygrometer which uses a slower thermoelectric dew point device adjusted for its time lag. We also show that when the thermoelectric dew point output is adjusted for its time lag, satisfactory water vapor flux values in nearly neutral conditions can be obtained.

2. Instrumentation and data

The thermoelectric EG&G Model 137 dew point instrument which was used on the NCAR Electra operates by electrically heating or cooling, via a Peltier device, a thin metal disc until dew forms on it. The presence of dew is detected optically, and the optical signal is fed into a feedback circuit which controls the disc temperature so that a constant state of dew is maintained on the disc. The disc temperature is measured with a platinum resistance thermometer. Adjustments are provided for dew film thickness (a film too thick results in a temperature gradient across the dew) and dew drop size (drop radius too small results in a high dew point temperature due to the Kelvin effect). Below 0°C, frost, instead of dew, is assumed to be present. On an aircraft, the optical sensor is mounted on the inside of the skin of the aircraft with a nozzle in the free air-stream which has entrance and exit holes positioned to force the ambient air past the sensor disc at a specified flow rate. Angular positioning of the nozzle provides for flow rate adjustment. The response time of the instrument to changes in ambient moisture is difficult to determine or measure. Frequently, variation of the many adjustments results in an over-damped or under-damped, oscillating, condition. With proper adjustment, response time is of the order of a few seconds. Cooling rates can be $3.0°C\ s^{-1}$. Accuracy is $\pm 0.5°C$ above freezing and $\pm 1.0°C$ below freezing.

The Lyman-alpha hygrometer operates on the principle of Beers' Law absorption of light by the density of water vapor in the atmospheric path between light source and detector tubes (Tillman, 1965). For maximum absorption by water vapor, the Lyman-alpha line (121.56 nm) in the vacuum ultraviolet is used. This requires that the tube windows be of lithium or magnesium fluoride. Buck (1985) describes the design of an aircraft unit and also gives theoretical equations accounting for deviation from Beers' Law due to light beam columniation, spectral impurity of the source, etc. Priestley and Cartwright (1982) developed a simple detector circuit which gives frequency response to 10 kHz. It is not possible to use the Lyman-alpha alone to measure absolute water vapor density; tube aging, and window contamination are the main factors which prevent a stable, predictable calibration.

Therefore, in practice, the thermoelectric device is used for slow, accurate dew point measurements, while the Lyman-alpha is used for rapid measurements of turbulent water vapor density fluctuations. As noted before, the Lyman-alpha output signal is calibrated against water vapor density calculated from the dew point, temperature, and pressure after the experiment. Although the microwave refractive index dependence on pressure, temperature, and water vapor density is well-known (Bean and Dutton, 1966), secondary effects of refractometer cavity changes with temperature and complex electronic amplification of the signal for fast-response microwave refractometers usually require reference to thermoelectric dew point measurements as well.

The study was motivated by the crucial need to have water vapor flux data for monsoon boundary layer investigations which used the NCAR Electra during the 1979 FGGE Summer MONEX program (Fein and Kuettner, 1980; WMO, 1981). For two of the three boundary layer flights in Summer MONEX, the NCAR Lyman-alpha was not working for all or important parts of the mission, so in addition to calibrating the Lyman-alpha when it was operating properly, we present a method to calculate water vapor flux from the thermoelectric dew point data.

Data from the thermoelectric dewpointer and the Lyman-alpha hygrometer from an Electra boundary layer flight on 24 June 1979 over the Arabian Sea are used. The Lyman-alpha hygrometer (L-α) was located in the central part of the Electra nose boom; the thermoelectric dew point sensor (TD) was on the forward fuselage. After passing through anti-aliasing filters of 10 and 1 Hz the analog data were digitized and recorded at 50 s/sec (L-α) and 5 s/sec (TD). A sample time series of water vapor density (TD) at 1 Hz, and L-α voltage and air temperature at 10 Hz are shown in Fig. 1. The separation between the sensors along the aircraft body was 3.86 m, which at an airspeed of about $100\ m\ s^{-1}$ is equal to a time difference of 0.04 s that was neglected in the comparison. The slow response of the TD signal compared to the L-α in Fig. 1 is evident. The air temperature measured by a fast-response resistance-wire sensor and the L-α show a high degree of anticorrelation at fine scales. This is due to turbulent mixing in the marine boundary layer where updrafts of air from the moist, cool ocean surface and downdrafts from the dry, hot, upper air result in negative correlations of temperature and humidity (Bunker, 1956; Riehl, 1954, 1979; Friehe et al., 1975).

3. Calibration of the aircraft Lyman-alpha hygrometer

To a first approximation, the signal from the Lyman-α detector tube is exponentially dependent on the water vapor density,

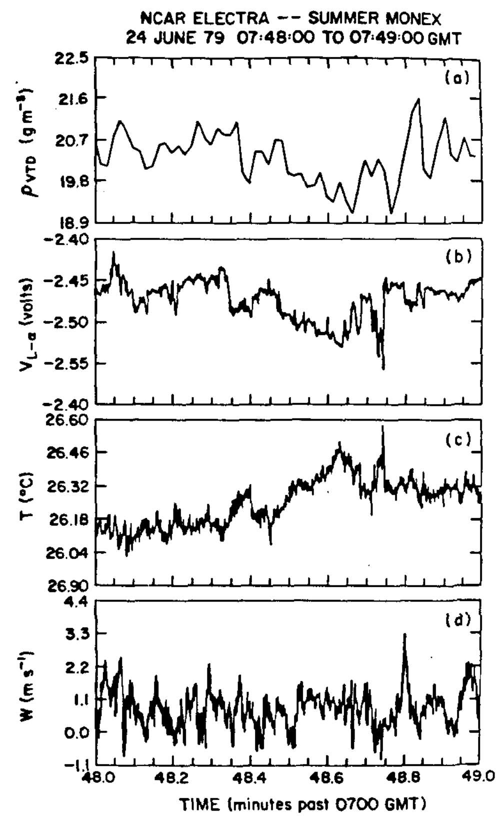

FIG. 1. Example of time series of (a) water vapor density (g m^{-3}) from thermoelectric (EG&G Model 137) dew point instrument; (b) Lyman-alpha output voltage (positive excursion is for higher water vapor density); (c) air temperature from the NCAR fast response K-probe thermometer (°C); and (d) vertical velocity (m s^{-1}) from the NCAR air motion (gust probe) system. Data from crosswind run at 297 m above the Arabian Sea during near neutral conditions on 24 June 1979.

$$I = I_0 e^{-k\rho_v x} \quad (1)$$

where I is detector current, I_0 the detector current with path length set to zero, ρ_v the water vapor density in path, x is path length, and k the absorption coefficient. A log-amplifier is used in the NCAR L-α to give a voltage, $V_{L\text{-}\alpha}$, proportional to ρ_v,

$$V_{L\text{-}\alpha} = \ln I = -\ln I_0 + k\rho_v x, \quad 0 < \rho_v x \leqslant 7. \quad (2)$$

In practice, this is written as $V_{L\text{-}\alpha} = Y + S\rho_v$, where Y and S are to be determined.

Comparison of Figs. 2 and 4 illustrates our calibration method. In Fig. 2a, high frequency L-α voltage (V) data averaged to 1 s/sec are plotted versus 1 s/sec TD water vapor density data unadjusted for its time lag. A slight positive correlation is evident but scatter is large. Scatter is reduced (Fig. 2b) when a 21-point Lanczos filter with a roll-off frequency of 0.005 Hz and cutoff frequency of 0.2 Hz are applied to both signals. The loops, or Lissajous patterns, apparent in Fig. 2b result from two effects: (i) the rise time of the TD signal lagged the L-α signal or (ii) the TD peak signal was lower compared to the L-α signal. In the latter case the rise times of both signals were comparable. The loops

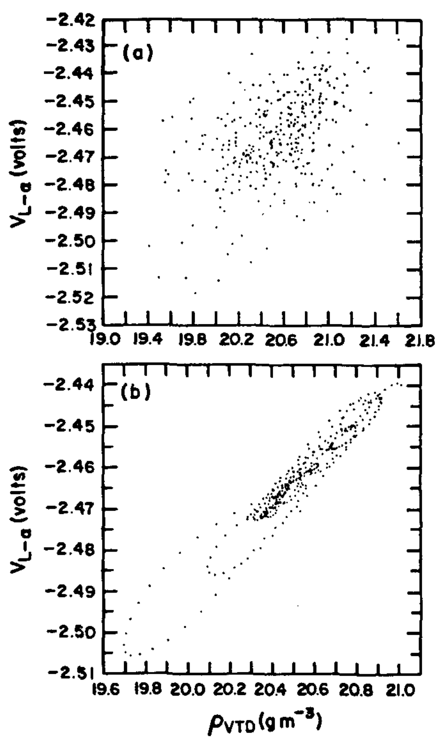

FIG. 2. (a) Calibration plot of Lyman-alpha voltage and water vapor density from the thermoelectric dew point instrument with no adjustment for thermoelectric instrument's time lag. The data have been block averaged to one sample per second. (b) As in (a) but with both time series filtered using a Lanczos filter with a roll-off frequency of 0.005 Hz and a cutoff frequency of 0.2 Hz. Loops are mainly caused by the time lag of the thermoelectric instrument.

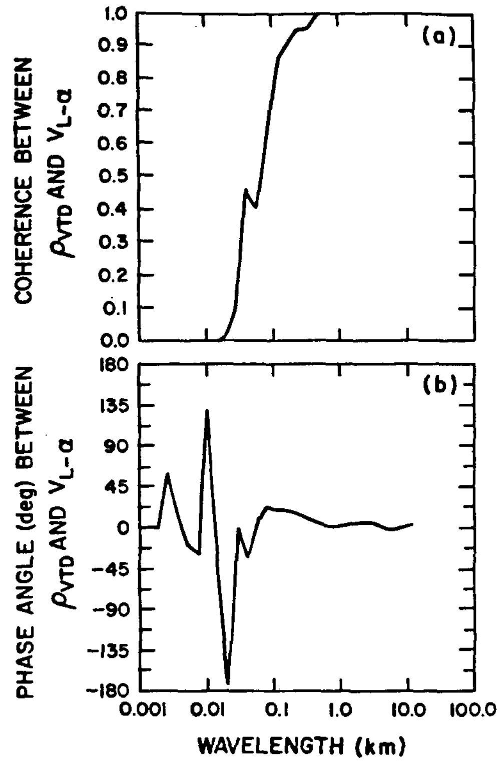

FIG. 3. Coherence (a) and phase (b) spectrum for Lyman-alpha voltage and time lag adjusted thermoelectric water vapor density. Positive phase means Lyman-alpha leads thermoelectric. To obtain frequency divide the wavelength by 100.

occurred when there were sudden, large excursions of humidity.

Inspection of the original time series and cross-spectral analysis of the TD and L-α time series indicated that the TD lagged the L-α by about 2 s. Inspection of the coherence and phase spectrum for the L-α and time-lag-adjusted TD time series (Fig. 3) show they agree very well for wavelengths greater than about 400 m (frequencies less than 0.25 Hz). A calibration plot using the same data as in Fig. 2 is shown in Fig. 4 only with TD advanced by 2 s. This plot exhibits far less scatter and gave reasonably accurate values of slope and intercept from a regression analysis.

In summary, the calibration procedure is as follows:

1) If necessary, interpolate the slower response thermoelectric data so that the sampling time is equivalent to the Lyman-alpha data or block average the Lyman-alpha data to match the sampling time of the thermoelectric data.

2) Visually compare the Lyman-alpha and thermoelectric outputs to estimate the amount of lag. If possible, obtain a raw (unsmoothed) phase spectrum to confirm the visual estimate.

3) Advance the thermoelectric time series by the amount of lag you have estimated.

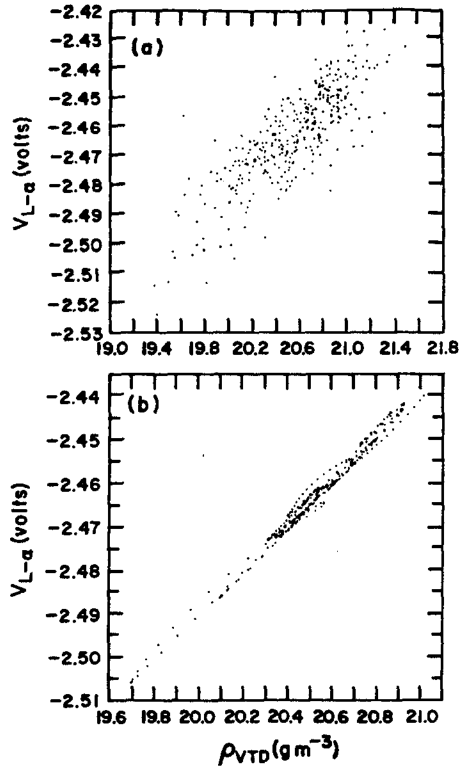

FIG. 4. As in Fig. 2, but with thermoelectric dew point data adjusted for 2 sec time lag. (See text for discussion of loops.)

4) Low-pass filter both time series.

5) Perform a regression analysis on the filtered datasets to obtain a calibration slope, S, and intercept, Y.

There is a height dependence of the calibration coefficients (Fig. 5) due to a decrease in absolute humidity and an increase of secondary oxygen absorption as pressure decreases (Buck, 1975, 1985). From (2) this implies that k decreases with height since x was a constant for this mission. The data in Fig. 5 imply this effect reaches a limiting value at about 90 kPa (900 mb).

4. Calculation of the water vapor flux from the dew point signal

With the Lyman-alpha calibrated by the preceding technique, the water vapor flux, E, is determined by eddy correlation technique as

$$E = \overline{w'\rho_v'} = S\overline{w'V_{L\text{-}\alpha}'} \tag{3}$$

From visual inspection, confirmed by cross-spectral analysis (Fig. 3), the TD signal, advanced by 2 s, closely follows the major low frequency excursions of the turbulently-mixed water vapor density measured by the L-α (Fig. 6). Thus, we consider E to have a high frequency component (E_h) and a low frequency component (E_l) separated by the limit of the TD frequency response

$$E = E_h + E_l, \tag{4}$$

and we assume that the high frequency fluctuations of humidity contributed a constant proportion of the total water vapor flux at a given altitude,

$$\frac{E_h}{E} = \gamma. \tag{5}$$

Substituting (5) into (4) yields

$$\gamma = 1 - \frac{E_l}{E}. \tag{6}$$

The parameter γ is that fraction of E which the slow response instrument cannot measure. The comparison of E_{TD} and $E_{L\text{-}\alpha}$ is good (Fig. 7) and confirms the re-

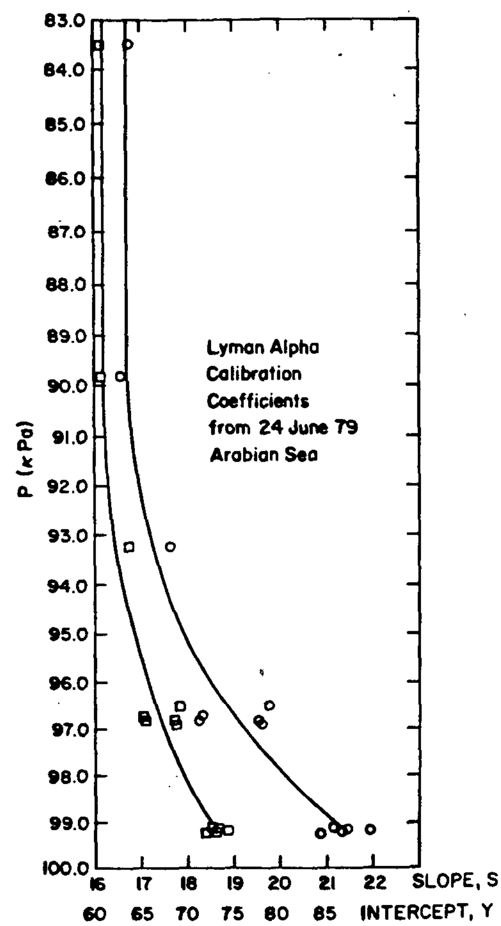

FIG. 5. Height dependence of calibration intercept (squares) Y, and slope (circles) S, from data taken on 24 June 1979 Arabian Sea boundary layer flight mission.

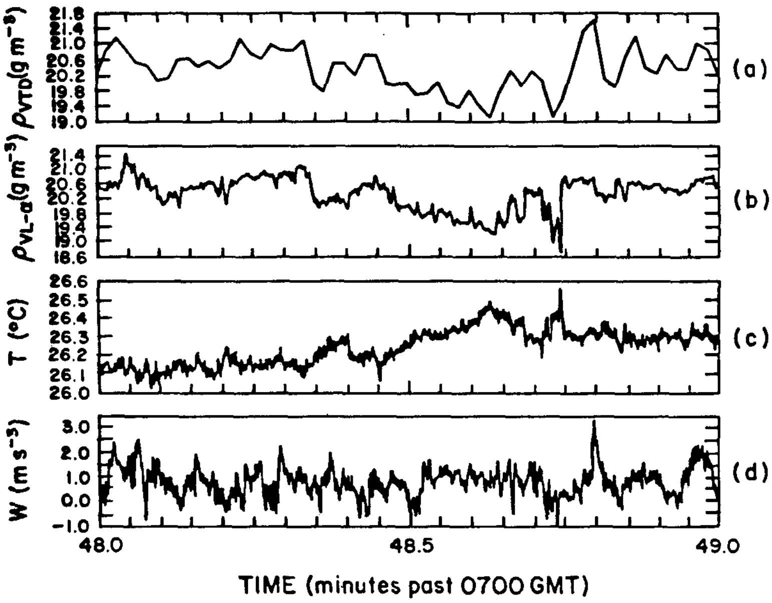

FIG. 6. Data of Fig. 1, with Lyman-alpha calibrated and thermoelectric water vapor density adjusted for time lag.

lationship predicted by (4) and (5). From a linear regression of the eleven points in Fig. 7,

$$E_{L\text{-}\alpha} = -0.005 + 1.121E_{TD} \quad (7)$$

with a standard error of $E_{L\text{-}\alpha}$ on E_{TD} of 0.009. If we assume $E = E_{L\text{-}\alpha}$, then from (6) $\gamma \sim 0.121$. The cospectra of $w'\rho'_{vTD}$ and $w'\rho'_{vL\text{-}\alpha}$ are compared in Fig. 8, which shows that E_{TD} estimated E very well during this flight mission. However, we feel these good results are almost entirely due to the fact that the NCAR TD was carefully adjusted and calibrated for the mean conditions found over the Arabian Sea.

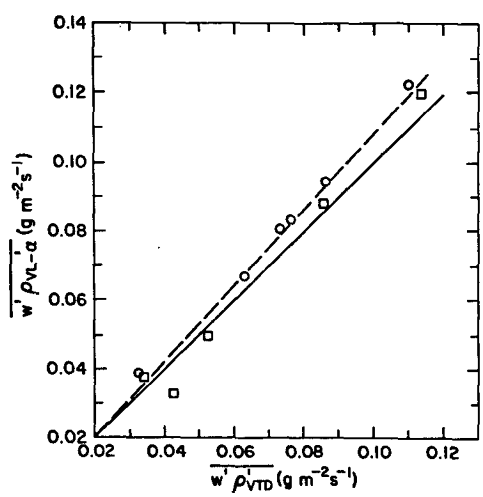

FIG. 7. Plot of vertical water vapor flux estimates using Lyman-alpha and time-lag-adjusted thermoelectric water vapor density. Circles are for data taken between 86–95 m and squares are for data taken between 297–335 m. Solid line has a slope of unity, dashed line is from the regression equation (7).

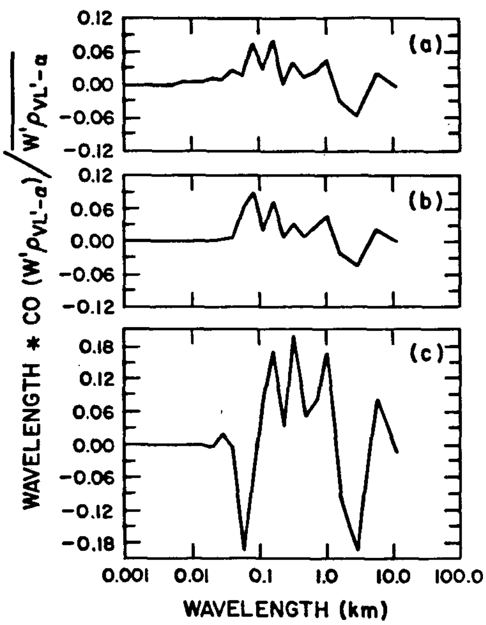

FIG. 8. Cospectra of vertical water vapor flux using data from (a) Lyman-alpha and (b) time-lag-adjusted thermoelectric hygrometers. Notice the lack of short wavelength (high frequency) covariance for the thermoelectric data and the excellent agreement between the two for longer wavelengths. Cospectra of water vapor flux using the unadjusted thermoelectric data (c) shows no resemblance to the other two.

5. Determination of the time lag using temperature data

In the above example, the thermoelectric dew-point time lag was determined by comparison to the Lyman-alpha hygrometer output. However, the important case is when there is no Lyman-alpha signal and (6) must be used. In the surface layer, experiments have shown that the turbulent water vapor and temperature signals are either highly positively or highly negatively correlated, the sign depending on the relative direction of the surface water vapor and heat fluxes (e.g., both fluxes upward gives a positive correlation; water vapor flux up and heat flux down gives a negative correlation, etc.). Since the high frequency temperature output on research aircraft is very reliable, comparison of the thermoelectric dew point signal with a fast-response temperature signal can be used to obtain the time lag. This can be accomplished from visual inspection of the time series, as we have done, or by analysis of raw phase spectrum estimates. We emphasize the use of raw estimates because using smoothed estimates can be confusing.

6. Conclusions and discussion

We have shown that an improved in situ calibration of a Lyman-alpha hygrometer using a thermoelectric dew point instrument as a reference can be obtained by simply adjusting the time series to account for the time lag between the reference and Lyman-alpha.

In the present case, the thermoelectric dew point instrument had sufficiently fast response so that eddy correlation calculation of the water vapor was possible once the time lag was determined and the time series shifted accordingly.

In cases where a fast response hygrometer is not available, reference of the thermoelectric signal to a fast ambient temperature signal can be made near the surface layer to determine the time lag. At the top of and within the boundary layer, the temperature and humidity have been found to be anticorrelated (Wyngaard et al., 1978; Prabhu and Grossman, 1985) so that the reference of the dew point to the temperature should work there too. Midway in the boundary layer, however, the correlation is about zero, so the present technique would not work there. The phase shift determined from near the surface layer or boundary layer top would be the best to use.

The present results are best for a high ambient moisture situation—typical of the tropical marine boundary layer. Our method may be less effective for lower moisture conditions, where the response of the thermoelectric dew point instrument may be too slow or in stable buoyancy conditions where flux estimates require accurate high frequency measurements.

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