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Comparison of sonic anemometer performance under foggy conditions

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ABSTRACT

A sonic anemometer comparison was performed at a mountain cloud forest site in Taiwan to evaluate the effect of fog on sonic anemometers performance, with particular emphasis to their employment in eddy-covariance applications. Four sonic anemometers (Campbell CSAT3, Gill R3-50, METEK USA-1, and R.M. Young 81000VRE) were tested for 15 consecutive days with an overall fog duration of 86 h.

Four aspects were analyzed: (1) spike statistics during foggy and non-foggy conditions, (2) spectral and co-spectral analyses before, during, and after 16 fog events, (3) correlations between turbulence characteristics of wind and temperature, and (4) flux error estimations.

All sonic anemometers produce more spikes when the visibility is below 1000 m, compared to conditions with visibilities above 1000 m. However, the overall number of spikes caused by fog is generally low and therefore of no concern for any of the tested sonic anemometers.

Spectral analyses showed that for most anemometers fog mostly affects spectra of the sonic temperature. Here, the high frequency range is either damped or amplified. These effects worsen with increasing duration and density of fog. In case of the 81000VRE and the USA-1, all three wind component spectra, sonic temperature spectra as well as the co-spectra of $w'T'$ and $w'u'$ show white noise in the high frequency range during dense fog. The CSAT3 shows noise only in the high frequency range of the sonic temperature and the co-spectra of $w'T'$. Smallest sensitivity to fog was observed for the R3-50. Nevertheless, differences in resulting fluxes are usually smaller than the flux error of the measurements. Due to the results of the spectral analysis and small flux errors the R3-50 seems to be suited best for eddy covariance measurements and process studies under dense foggy conditions.

1. Introduction

Three-dimensional sonic anemometer-thermometers (SATs) are high-temporal resolution instruments, commonly used in micrometeorological studies to sample atmospheric turbulence and calculate parameters such as sonic temperature, friction velocity, and Monin–Obukhov length. They are often used in conjunction with gas analyzers in eddy covariance measurements of mass and energy exchange in the boundary layer (Baldocchi, 2003). A SAT calculates wind speed along three transducer pairs by measuring the differences in time-of-flight of ultrasonic signals travelling in opposite directions. Because the speed of sound depends on temperature, the so-called ‘sonic temperature’ can be derived from transit times of the signals along all three axes.

Since the 1960s, when the first prototypes were used to measure fluxes of momentum and sensible heat (Miyake et al., 1971), the instrument design (e.g., vertical vs. horizontal mount, sensibility of the transducers to rain, dripping noses, wicks) and the algorithms to calculate the three wind components and sonic temperature e.g. cross wind correction and averaging over all 3 axis (Liu et al., 2001) have been further developed. Calibrations of sonic anemometers are performed in wind tunnels to account (1) for deflection and attenuation of the mean wind vector due to the instrument and its mounting and (2) for attenuation of the mean wind component along each sensor due to the formation of turbulent wakes behind the transducers (Grelle and Lindroth, 1994). During post-processing, an additional matrix correction can be applied, which ideally includes a correction for azimuth, angle of attack, and various wind speeds (Nakai and Shimoyama, 2012; Nakai et al., 2006; Rotach, 1991). Based on wind tunnel experiments, Vogt and Feigenwinter (2011) showed that errors in sonic anemometer measurements (Campbell CSAT3, Gill R2, Gill HS, METEK USA-1, Young

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81000V) are large for angles of attack larger than ±35°. However, it is partly questionable how well wind tunnel results can be transferred to ambient flow conditions (Vogt and Feigenwinter, 2011).

To assess the suitability of available SATs for eddy-covariance measurements, field comparisons have been performed by several working groups (Loescher et al., 2005; Mauder et al., 2007). These comparisons were conducted under more or less ideal situations: flat terrain, clear skies, and medium horizontal wind speeds.

However, in the reality of long term campaigns throughout the seasons, SATs are also exposed to less ideal conditions such as heavy rain, freezing rain, snow, dust storms, and fog. Data collected under these circumstances may be of poorer quality, e.g. due to disturbance of the measurements path. The associated errors are usually easy to detect by statistical analysis because data are typically out of range, e.g., lying outside the four-fold standard deviation of the mean value of the time series (Lee et al., 2004). These spikes can be removed and replaced, for example, by linear interpolation of neighboring data points. Alternatively, when a data file contains too many spikes, it may be excluded from further analysis. Such a procedure is very simple and effective.

Spectral analyses are applied to detect frequency resolution problems such as attenuation, aliasing, or noise. If unrecognized these problems lead to biased results and misinterpretation of variances. For example, if instrumental noise in temperature and vertical wind speed measurement is correlated, the effect will also be apparent in the respective co-spectra and ultimately, in the calculated sensible heat flux (Vogt et al., 2011).

For mountain cloud forests the frequent appearance of fog is a dominating phenomenon which impacts SAT measurements through (1) occurrence of water droplets inside the measurement path and (2) deposition of droplets on the surface of the transducers. Fog droplets are roughly 10 to 100 times smaller than raindrops and too small to run off directly from the SAT transducers.

As SATs are more and more frequently applied at cloud mountain- and fog influenced sites (e.g. Beiderwieden et al., 2008; Burkard et al., 2002; Eugster et al., 2006; Westbeld et al., 2009; Wrzesinsky, 2003), it is important to get insights on how fog occurrence may influence the measurements. For this reason, a comparison of SATs from various manufacturers was conducted at a mountain cloud forest site in Taiwan. This paper analyzes the effects of fog on SAT measurements and the respective fluxes.

2. Site description

The Chi-Lan Mountain Long Term Ecosystem Research Network site (TERN) is located in the north-eastern part of Taiwan (24°35′N, 121°24′E) in I-Lan County (Chang et al., 2006; Klemm et al., 2006) at 1650 m above mean sea level (MSL).

The site is covered by a uniform forest stand consisting of *Chamaecyparis obtusa var. formosa* and *Chamaecyparis formosensis* in the overstory, and *Rhododendron formosanum* in the understory. The tree population is about 50 years old with a canopy height between 11 and 14 m. The experimental tower is located in a relatively flat section of a valley. The orientation of the valley is from north-west (top, 2100 m above MSL) to south-east (bottom, 500 m above MSL) with an average inclination of 14° (Fig. 1).

According to the Climate Classification of Köppen-Geiger, this area is characterized as Cfb (warm temperate, fully humid, warm summer).

The mean annual precipitation is 4000 mm with large deviations from year to year depending on the intensity of the typhoon season. Additionally, the site is characterized by frequent occurrence of fog. Fog is defined as a suspension of very small, usually microscopic water droplets in the air, generally reducing the horizontal visibility at the Earth's surface to less than 1 km (WMO, 2006). Average daily

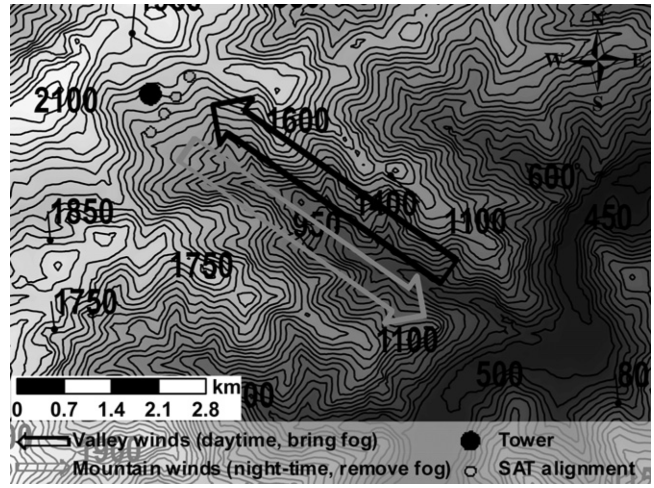

Fig. 1. Topographic map of the valley. The black dot is the location of the tower. The small grey dots represent the alignment of the SATs (see Section 3.1 for distance between the SATs). Black and grey arrows indicate the flow direction during day- and night-time.

fog duration is 4.7 h during the summer months (June–August), while it is as high as 11 h during the rest of the year (Chang et al., 2002). The fog occurrence is usually coupled to thermally driven valley-winds. Warm, humid air cools during the upslope transport and typically drops below the dew point temperature. When the radiative forcing ceases during the early evening and night, the valley winds weaken and eventually turn into dry mountain winds which make the fog disappear.

3. Materials and methods

3.1. Set-up and settings

For the comparison, four commonly used SAT models were used:

81000VRE; Serial No. 02043; R.M. Young Company, Traverse City, MI, USA
CSAT3; Serial No. 0114-2; Campbell Scientific, Inc., Logan, UT, USA
R3-50; Serial No. 442; Gill Instruments, Ltd., Lymington, Hampshire, UK
USA-1 Scientific; Serial No.010402 2808; METEK GmbH, Elmshorn, Germany

The SATs were set up in a row on the measurement tower (T1) at an elevation of 17.1 m a.g.l. and 5.1 m above average canopy height, respectively. Two meter extensions pointing toward SE into the valley were used to set a distance between the tower and the SATs. The instruments were 1.7 m apart from each other. All SATs were oriented with the north spar to the south-eastern direction. Anemometers were placed in the following order from NE to SW: R3-50 (far NE), 81000VRE (NE middle), USA-1 (SW middle), and CSAT3 (far SW) (Fig. 1).

A second tower (T2), used for continuous meteorological and flux measurements (Beiderwieden et al., 2007) was located at a distance of about 20 m in NNE direction from T1. It was not within the predominant wind directions and did therefore not disturb the measurements at T1. Tower T2 was equipped with a visibility sensor (MIRA 3544, Aanderaa Data Instruments; Bergen, Norway), mounted at 21 m a.g.l. and collecting data with a temporal resolution of one minute. A droplet spectrometer (FM100 Fog Monitor, Droplet measurement Technology; Boulder, Colorado, USA) was installed at 24 m a.g.l. on T2 to determine droplet size distribution (DSD) and liquid water content (LWC) for droplets between 2 μm