Measuring solid precipitation using heated tipping bucket gauges: an overview of performance and recommendations from WMO-SPICE

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1. Overview

Tipping bucket (TB) type precipitation gauges are widely used operationally at automated weather stations for the measurement and reporting of precipitation intensity. Often, their data are used to derive precipitation amounts over various time intervals. While TB gauges traditionally have been used for the measurement of liquid precipitation, the addition of heaters has extended their application to colder environments and the measurement of solid precipitation.

The assessment of heated TB gauges is an important component of the Solid Precipitation InterComparison Experiment (SPICE), organized by the World Meteorological Organization Commission for Instruments and Methods of Observation (WMO CIMO). The objectives of this component are to report on the ability of heated TB gauges to detect and measure solid precipitation at sites in several climate regimes, and in some cases, in different test configurations, and to provide recommendations for their use. The heated TB gauges under test in WMO-SPICE are outlined in Table 1.

The test gauges are installed at field sites in different climate regimes: CARE (Canada) and Marshall (USA) in humid and dry continental climate zones, respectively; Formigal (Spain) and Weissfluhjoch (Switzerland) in alpine climate zones; and Sodankylä (Finland) in a sub-arctic climate zone. The Sodankylä site is sheltered, and subject to lower wind speeds than the other sites. Only one of the gauge types under test is shielded, the EML UPG1000 installed at Marshall and Sodankylä. The specific shield configuration at each site is different, as outlined in Table 1.

Table 1: Heated tipping bucket gauges under test in WMO-SPICE, corresponding test sites, and shield configurations.

Gauge	Site(s)	Shield
CAE PMB25R	CARE (Canada), Marshall (USA)	None
EML UPG1000	Marshall (USA), Sodankylä (Finland)	Octagonal with vertical slats Octagonal with L-shaped slats
HSA TBH	CARE (Canada), Marshall (USA)	None
Meteoservis MR3H-FC	CARE (Canada), Marshall (USA), Sodankylä (Finland)	None
Meteoservis MR3H-FC (ZAMG version)	CARE (Canada), Weissfluhjoch (Switzerland)	None
Thies Precipitation Transmitter	Formigal (Spain), Marshall (USA)	None

2. Approach

2.1. Assessment of detection and reporting of solid precipitation

The ability of heated TB gauges to detect and report solid precipitation was assessed relative to a reference configuration at each site. The reference configuration consisted of an automatic weighing gauge, either a Geonor T-200B3 or OTT Pluvio[2], in a Double Fence Intercomparison Reference (DFIR) shield, along with a sensitive precipitation detector (e.g. optical present weather sensors) for the independent confirmation of the occurrence of precipitation. A 'precipitation event' was defined as a 30 minute period during which the reference configuration reported at least 0.25 mm of precipitation, and the precipitation detector observed the occurrence of precipitation at least 60% of the time (18 minutes).

Accumulated precipitation amounts were derived from intensity reports for each TB gauge under test and compared against reports from the corresponding reference configuration over 30 minute intervals. The TB gauges were considered to report precipitation if the accumulation met or exceeded the reporting resolution; effectively, any time the gauge recorded a tip. The comparison results were classified as follows: cases in which the reference reported a precipitation event and the TB reported precipitation (YY cases); cases in which the reference reported a precipitation event, but the TB did not report precipitation (YN cases, or 'misses'); cases in which the reference did not report an event, but the TB reported precipitation (NY cases, or 'false alarms'); and cases in which the reference did not report an event, and the TB did not report precipitation (NN cases).

The performance of the TB gauges under test with respect to the detection of precipitation was assessed qualitatively using skill scores, such as the Probability of Detection (POD) and False Alarm Rate (FAR), calculated using the numbers of YY, YN, NY, and NN cases (e.g. *Sheppard and Joe*, 2000). Performance with respect to the measurement of precipitation was assessed quantitatively using the root mean square error (RMSE) computed from cases when both the reference and TB reported precipitation (YY cases), as well as overall catch efficiencies calculated as the ratio of total TB accumulation to total reference accumulation for all YY, YN, and NY cases over the full intercomparison dataset.

2.2. Characterization of response delays

A caveat of the approach outlined above is that heated TB gauges are subject to response delays due to the following: (1) the time required for the bucket to reach its capacity and tip; (2) the time required for the heater to melt solid precipitation, allowing it to flow into the bucket from the funnel; (3) the time required to trigger heating, if applicable; (4) any evaporation/sublimation of incident precipitation due to gauge heating (e.g. *Savina et al.*, 2012); and (5) wind blowing snow out of the gauge funnel/orifice before it can be melted.

Response delays were characterized for each TB gauge under test using 'response assessment periods,' comprising at least 30 minutes of precipitation, followed by at least 180 minutes without precipitation. The non-precipitating period is intended to allow additional time for the melting and recording of precipitation by the heated TB. The time between the onset of precipitation and the first response of the TB was compiled for all response assessment periods, and used to generate frequency distributions of response delays for each gauge under test. An example of a response assessment period and TB response delay for one sensor under test (SUT) is provided in Figure 1.

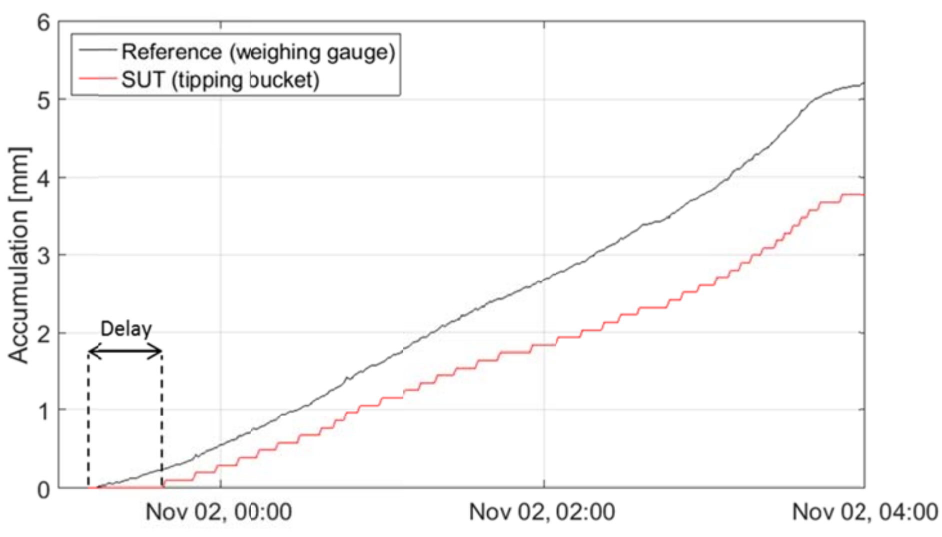

Figure 1: Response assessment period and response delay for a TB gauge under test. Note that the event duration is truncated to illustrate the response delay more clearly.

3. Results

The ability of the heated tipping bucket gauges under test to detect precipitation relative to the reference configuration was assessed qualitatively in terms of the Probability of Detection and False Alarm Rate (among other skill metrics) for 30 minute intervals. The POD was found to vary between 42% and 94% for all TB gauges tested, while the False Alarm Rate varied between 21% and 68%. From a quantitative standpoint, considering all precipitation events in which both the TB gauge and corresponding site reference reported precipitation over 30 minute periods (YY cases), the RMSE was within 0.6 mm for all gauges tested. The overall catch ratios for the TB gauges under test over the duration of the experiment varied between 0.51 and 0.87, with a median value of 0.72.

Differences in the results among the gauges tested are expected due to the following: variations in gauge configuration (including heating and shielding); differences in gauge installation and site configuration; and differences in climate conditions, including the relative distributions of precipitation events by phase (liquid, mixed, and solid). Superimposed on these variations is the influence of response delays for heated TB gauges. An example of a frequency distribution of response delays for a heated TB gauge under test is shown in Figure 2.

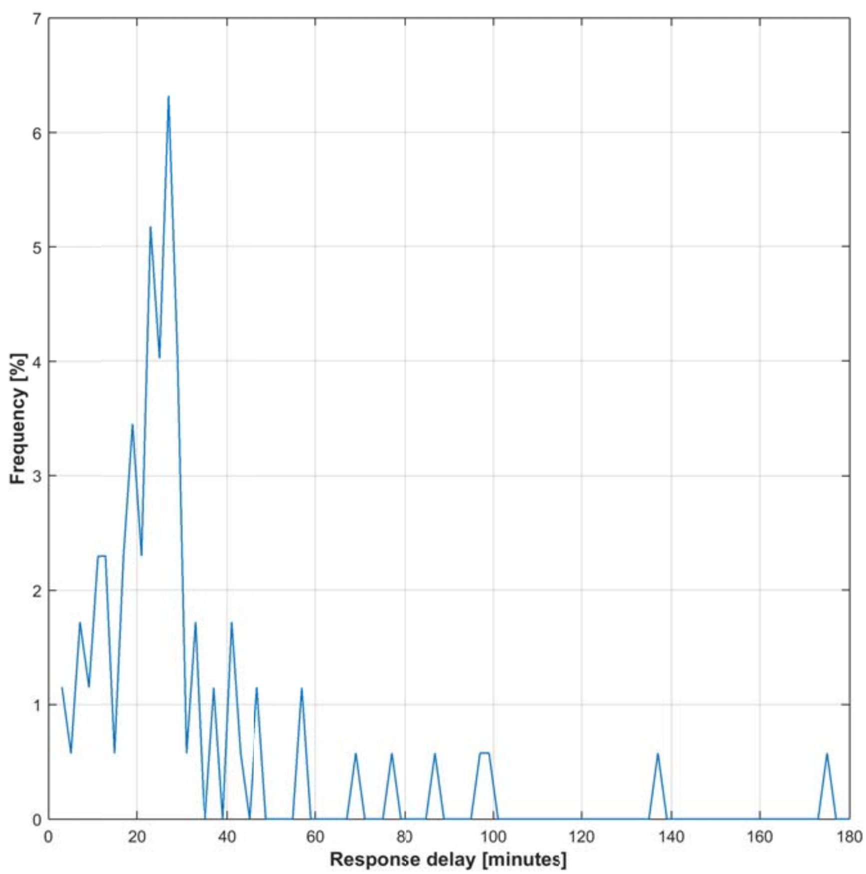

Figure 2: Frequency distribution of response delays from 87 response assessment periods over the duration of the experiment for a heated TB under test.

For all heated TB gauges under test, the response times with the highest frequency were generally within 30 to 60 minutes. As the response time increases, it is more likely that a TB gauge will not respond to precipitation within the same 30 minute interval as the reference (YN cases); rather, it will respond during a later 30 minute interval. This response may occur when the reference does not report precipitation (NY case) or when the reference is reporting precipitation. The implication of the latter scenario is that even when both the TB and reference gauge detect precipitation within a given 30 minute interval (YY cases), the TB may actually be reporting precipitation collected during previous intervals, or may continue to report precipitation in a subsequent interval. Hence, response delays for heated TB gauges will impact the qualitative assessment of performance using skill scores and quantitative assessment in terms of RMSE.

Response delays also influence the assessment of wind speed influence on gauge catch efficiency, computed as the ratio of TB accumulation to reference accumulation over the same 30 minute interval. Scatter is evident in the sample plot of catch efficiency vs. mean wind speed for a TB gauge under test (Figure 3), with numerous values greater than 1 that likely result from response delays. Despite the scatter, a general decrease in catch efficiency is observed with increasing wind speed for events in the solid precipitation regime (mean event temperature ≤ -2 °C).

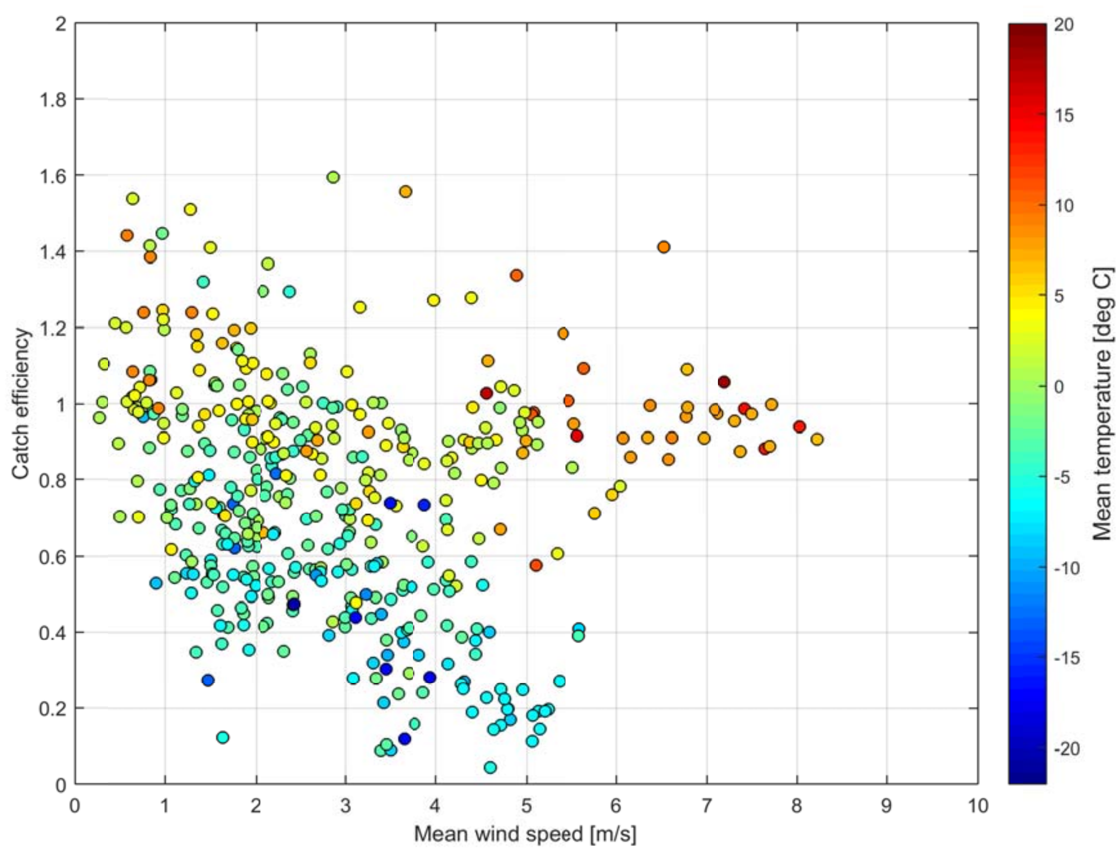

Figure 3: Example of a catch efficiency vs. mean wind speed scatter plot for a heated TB gauge under test (unshielded). The mean event temperature is indicated by colour.

The influences of wind speed and precipitation phase on catch efficiency are more clearly illustrated by box and whisker plots, such as that shown in Figure 4. While results are shown for liquid (mean event temperature ≥ 2 °C) and mixed precipitation (all remaining events not classified as solid or liquid), the result of key interest for SPICE is the reduction of catch efficiency for solid precipitation with increasing wind speed. These results demonstrate the potential for the development of transfer functions to compensate for wind-induced undercatch. Indeed, a similar approach has been used to develop transfer functions for the adjustment of heated tipping bucket gauge data by the Spanish national weather service (*Buisán et al.*, 2016a).

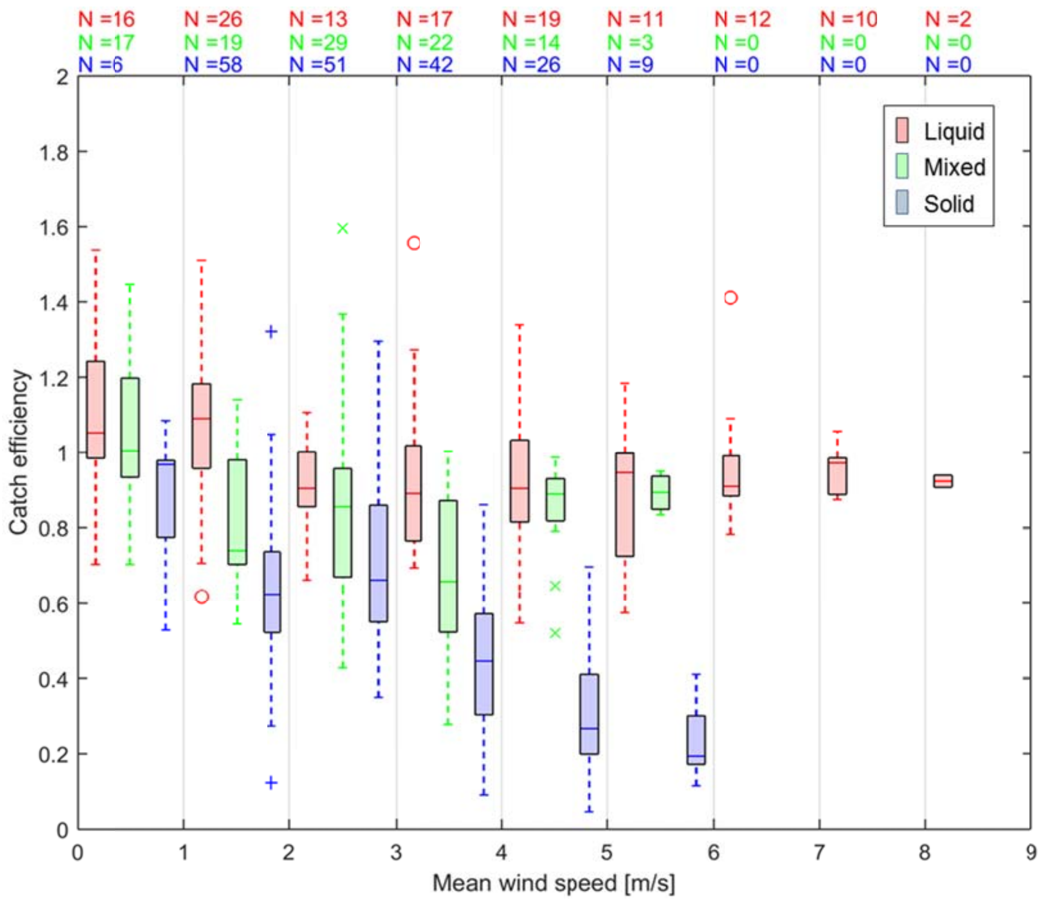

Figure 4: Catch efficiency vs. mean wind speed box and whisker plot for the same heated TB gauge under test as in Figure 3. The predominant precipitation type for each event is determined from the maximum and minimum reported temperature and indicated by colour.

4. Performance considerations and recommendations

- Heating is critical for gauge operation under winter conditions and requisite for the measurement of solid precipitation. Heating can require significant power, which may necessitate investment in site infrastructure. Heating with insufficient power can negatively impact gauge performance. By the same token, heating with excessive power can prevent snow from falling into the gauge (due to heat plume issues) and can lead to evaporation of melted snow. The specific gauge and heating configuration should be selected with consideration given to the availability of site resources (e.g. power) and to the characteristic site conditions.
- The time required for melting can delay the time between the collection of precipitation in the funnel and the gauge response to that precipitation (response delays). Further, heating may result in the evaporation/sublimation of incident precipitation at low intensities
- Heating configurations in which the heaters are triggered by a snow sensor in the funnel have lower power requirements, but are subject to additional response delays, and snow accumulated below the sensor level may be subject to sublimation or wind losses.
- Response delays must be considered when using the gauge in operational settings. Ideally, the reporting interval (i.e. hourly observations) should exceed the maximum expected response delay; however, the potential remains for carry-over of precipitation accumulation from previous intervals, and for delayed responses occurring in subsequent intervals.
- If not already implemented, shielding of the gauge should be considered by the manufacturer and/or potential users as a means of increasing the catch efficiency at higher wind speeds. While not demonstrated in the results above, supporting results are provided elsewhere (e.g. *Buisan et al.*, 2016b). The shield configuration should attempt to minimize the extent of horizontal surfaces upon which snow can accumulate and blow into the gauge.
- The collection of ancillary measurement data is recommended: air temperature and wind speed, to enable the application of adjustments to measurements (i.e. using transfer functions); and reports from a precipitation detector with high sensitivity, to enable the identification of missed events or false alarms due to response delays.
- The application of transfer functions to gauge measurements, if possible/available, is recommended as a post-processing step to account for reductions in the catch efficiency of solid precipitation with increasing wind speed. This recommendation comes with the caveat that the catch ratio data used in the derivation of transfer functions will be impacted by response delays, increasing the uncertainty of the adjusted gauge reports. Considering the catch ratios over longer time periods (e.g. 1 hour) may provide a means of reducing scatter in the catch ratio/wind speed relationship and reducing the uncertainty of related transfer functions.

References

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