Errors in Mobile Mesonet Observations of Equivalent Potential Temperature and Wind Velocity: Results from AVIATE

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1. Introduction

The Airdata Verification and Integrated Airborne Tempest Experiment (AVIATE), a collaboration involving the Research and Engineering Center for Unmanned Vehicles at the University of Colorado at Boulder, the University of Nebraska – Lincoln, and the NOAA National Severe Storms Laboratory (NSSL), was conducted in June 2013. The principal objective of AVIATE was to evaluate the temperature/humidity and wind velocity sensors of the Tempest unmanned aircraft system (UAS) and NSSL mobile mesonet (NSSL-MM).

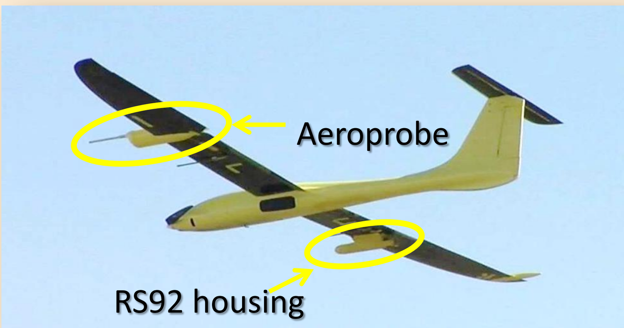

Figure 1. Tempest unmanned aircraft as configured for AVIATE. The NSSL provided the Aeroprobe and funding toward its installation on the Tempest.

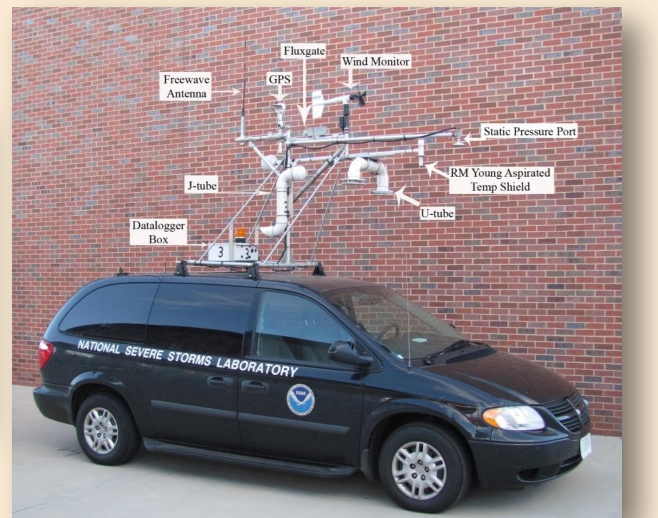

Figure 2. NSSL mobile mesonet

2. Tempest UAS, NSSL Mobile Mesonet

The Tempest UAS (Figure 1; Elston et al. 2011; Frew et al. 2012) is a versatile, state-of-the-art system built on a legacy of successful applications of UAS sampling transient mesoscale phenomena (Elston et al. 2011; Frew et al. 2012; Houston et al. 2012). Refer to Table 1 for a summary of Tempest sensors.

- The RS92 is housed in the tail of a rocket nose and mounted under the wing (Figure 1).
- The Aeroprobe Corp. wind probe (Figure 1) measures aircraft sideslip and angle of attack through differential pressure measured across the probe tip.

The NSSL MM (Figure 2) used for AVIATE is the version of the mobile mesonet first used in the 2010 field phase of VORTEX2 (Wurman et al. 2012). Refer to Table 1 for a summary of NSSL-MM sensors.

- Both the HMP45C and the YSI 405 sensors are integrated into the "U-tube" shielded and aspirated system (Figure 2; Waugh and Frederickson 2010).
- The RM-Young propeller-vane anemometer is mounted ~3.3 m above the ground and ~2.4 m rear of the leading edge of the parent vehicle.

3. Motivation and Methodology

While the individual sensors of the Tempest and the NSSL-MM have previously undergone extensive testing, the performance of these sensors when integrated into each platform needs to be evaluated.

The aim of AVIATE was to **examine sensor performance in realistic (outside of the lab) atmospheric conditions**

Sensor collocation was essential. This collocation was enabled by mounting the Tempest wing to the NSSL-MM instrument rack (Figure 3) such that the wing-mounted temperature/humidity and wind sensors could collect observations contemporaneous with the NSSL-MM sensors and within a nearly identical air stream.

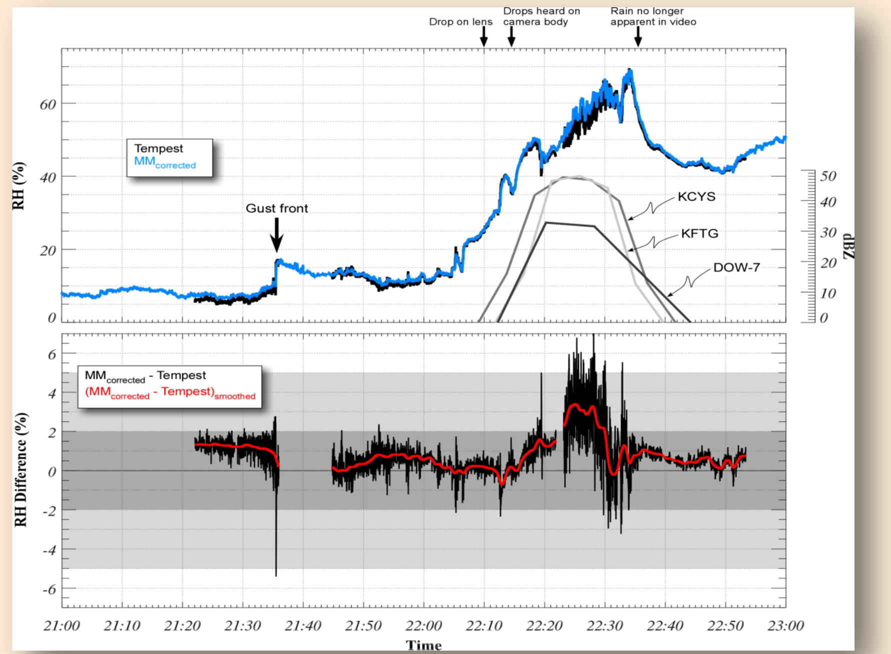

Figure 4. Relative humidity observed by the Tempest (black, top panel) and NSSL-MM (blue, top panel) along with the unsmoothed differences (black, bottom panel) and smoothed differences (red, bottom panel) during the 21 June 2013 system comparison. NSSL-MM relative humidity is corrected following Richardson et al. (1998). Radar reflectivity is plotted in gray on the top panel. A rack-mounted Go-Pro camera recorded video of the Aeroprobe during the transect.

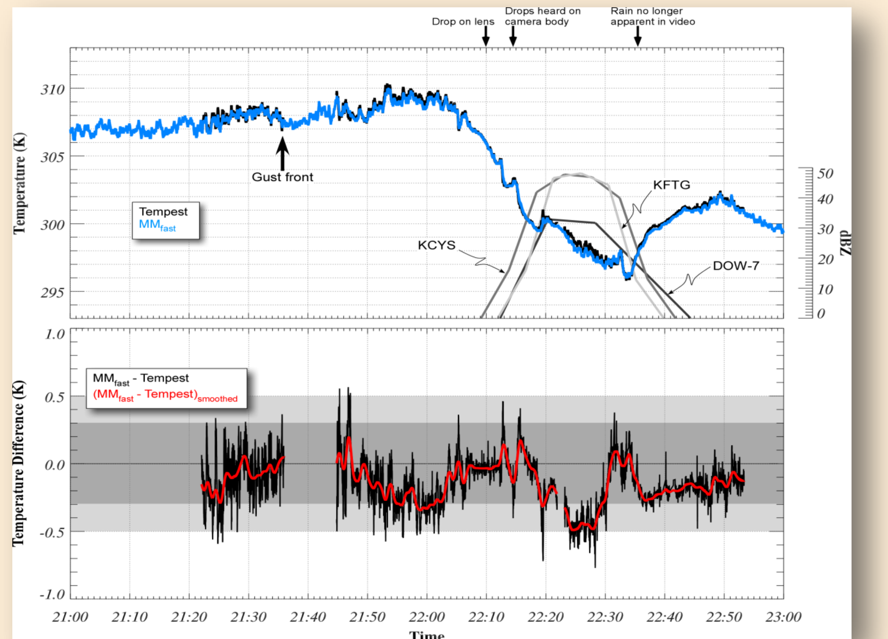

Figure 5. As in Figure 4 except for temperature (K)

Table 1. Sensor Summary

Variable	Tempest	NSSL-MM
Temperature (fast response)	Vaisala RS92 core (MIST integration) Accuracy: ±0.5 K Response time: <0.4 s	YSI 405 thermistor Accuracy: ±0.1 K Response: 10 s
Temperature (slow response)	N/A	Campbell Scientific HMP45c ±2 K Unspecified response time
Humidity	Vaisala RS92 core (MIST integration) Accuracy: ±5% Response time: <0.5 s	Campbell Scientific HMP45c ±2% 15 s
Wind	Aeroprobe Corporation Five-Hole Pitch+Yaw Probe ±1º flow angle ±1 m/s (or 1%)	RM Young Wind Monitor (four blade helicoid propeller and vane) ±3º flow angle ±0.3 m/s (or 1%)

Figure 3. Sensor collocation of the integrated system

4. 21 June 2013 System Comparison

On 21 June 2013, the integrated system was used to target a thunderstorm complex and associated gust front in northeast Colorado.

Principal Findings

- Overall, the time series structure and instantaneous magnitudes demonstrate consistency between the NSSL-MM and Tempest temperature and humidity sensors (Figures 4 and 5)
- The Tempest RS92 shows no evidence of erroneous wet-bulbing (Figures 4 and 5)
- The NSSL-MM corrected RH tends to be slightly higher (+0.82%) than the Tempest RH and the temperature tends to be slightly lower (-0.15 K) (Figures 4 and 5)
- RH values for the NSSL-MM during precipitation averaged 1.3% higher than the RH measured by the Tempest, increasing to 2.7% for the period of heaviest precipitation. (Figure 4)
- The Tempest humidity sensor detected an RH increase of 6.5% across adjacent observations separated by 0.42 s (Figure 6). The NSSL-MM humidity sensor required 17 s for a 90% response to this change.

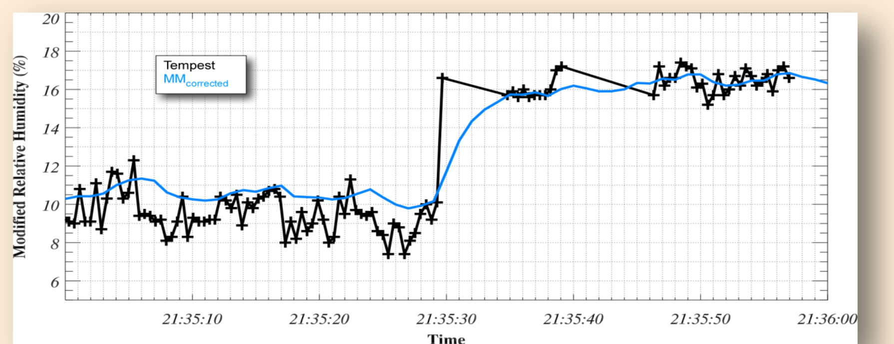

Figure 6. Relative humidity observed by the Tempest (black) and NSSL-MM (blue) for the gust front transect on 21 June 2013.

5. CFD Simulations

Steady-state finite element CFD simulations were conducted to determine theoretical wind speed perturbations above the NSSL-MM (Figure 7).

Principal Findings

- Simulated wind speed perturbations at the location of the NSSL-MM anemometer for highway speeds (30-35 m/s) were 1.2-1.4 m/s (Figure 8).
- The relationship between simulated hoirzontal air speeds at the anemometer and Aeroprobe locations closely matched the observed relationship between the anemometer and (corrected) Aeroprobe horizontal air speeds (Figure 9).

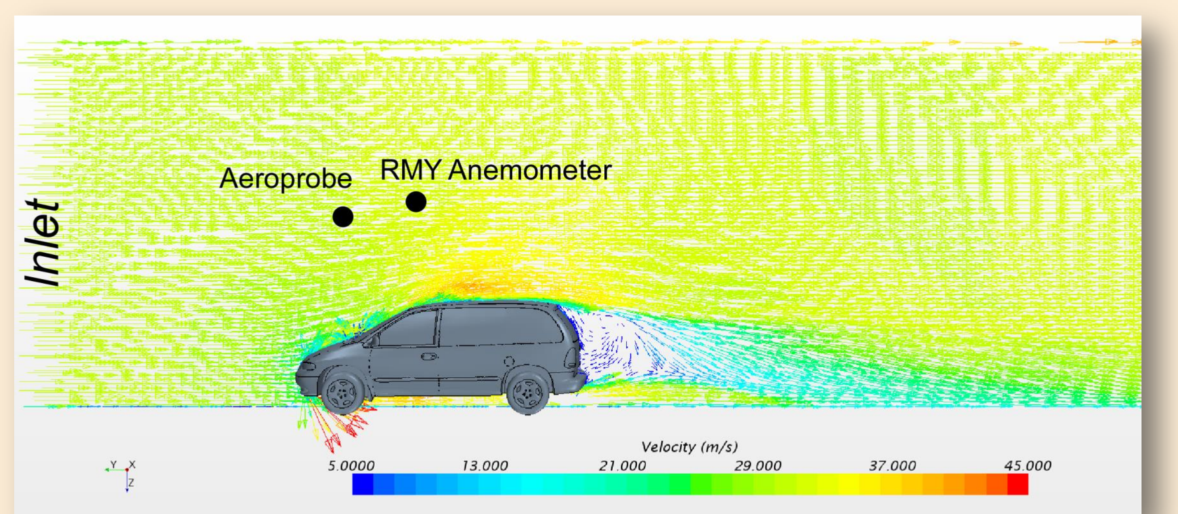

Figure 7. Simulated air flow over the NSSL-MM parent vehicle.

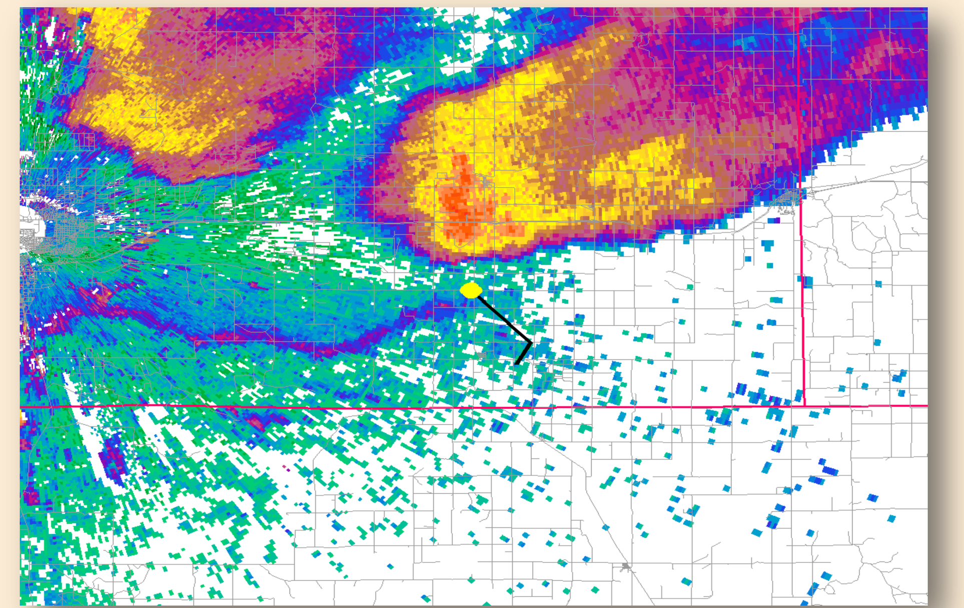

Figure 10. NSSL-MM position relative the gust front sampled on 15 June 2013.

Table 2. Modeled sensor (e-fold) response time

Variable	Response Time
Temperature (fast response)	33 s
Temperature (slow response)	268 s
Corrected Humidity	12 s

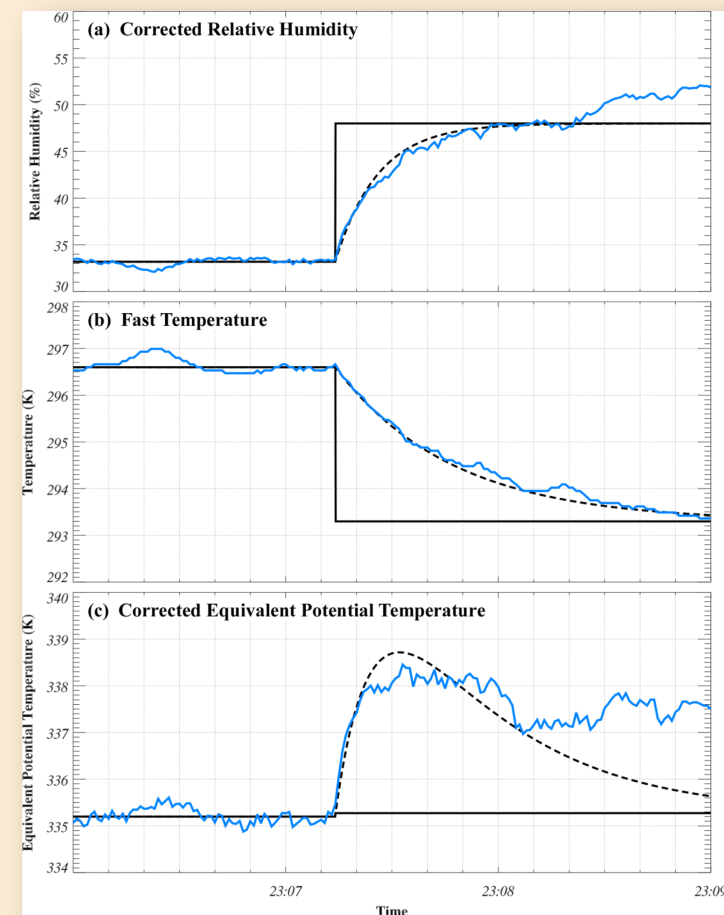

Figure 11. a) Relative humidity (%), b) temperature (K), and c) θ_e (K), from the 15 June 2013 gust front transect. Observed values are in blue, approximate "actual" profiles assuming step functions appear as continuous black curves, and modeled profiles appear as broken black curves.

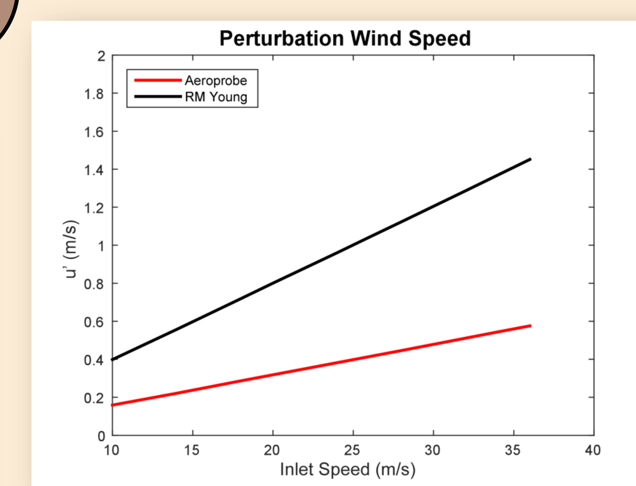

Figure 8. Simulated perturbation wind speed as a function of inlet speed at the location of the Aeroprobe (red) and NSSL-MM RM Young anemometer (black).

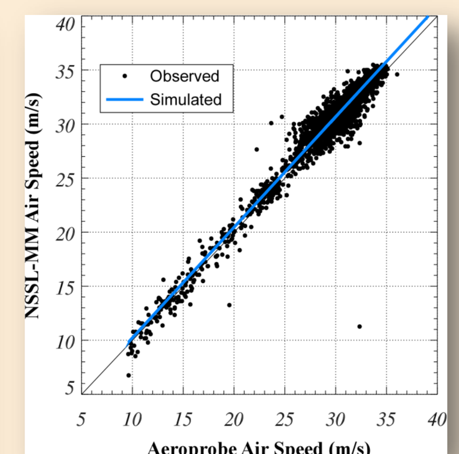

Figure 9. Observed (black dots) and simulated (blue line) NSSL-MM horizontal air speed (m/s) vs. contemporaneous Aeroprobe air speed.

6. Impact of Sensor Response on θ_e

On 15 June 2013, the NSSL-MM transected a gust front in southeast WY (Figure 10). In order to evaluate the accuracy of θ_e, the sensor response to the gust front was modeled using an exponential response to a step-function perturbation. Modeled sensor responses were based on the work of Waugh (2012) and are summarized in Table 2.

Principal Findings

- The modeled sensor response closely matches the actual sensor response within the ~1 min following gust front transect (Figure 11a,b)
- Based on the modeled sensor response, it is concluded that the observed θ_e was approximately 3 K too high immediately on the cool side of the gust front (Figure 11c)

The magnitude of the θ_e error was quantified for several hypothetical gust fronts.

- The largest θ_e error (+9.3 K) was found for a doubled temperature gradient across the boundary (Figure12a)
- The largest error (+12.3 K) relative to the "best case scenario" in which the sensors have the same response time (parity) exists for the gust front with twice the relative humidity gradient and airmasses that are 10 K warmer (Figure 12b)
- Significant errors extend several kilometers into the cold pool (Figure 12)

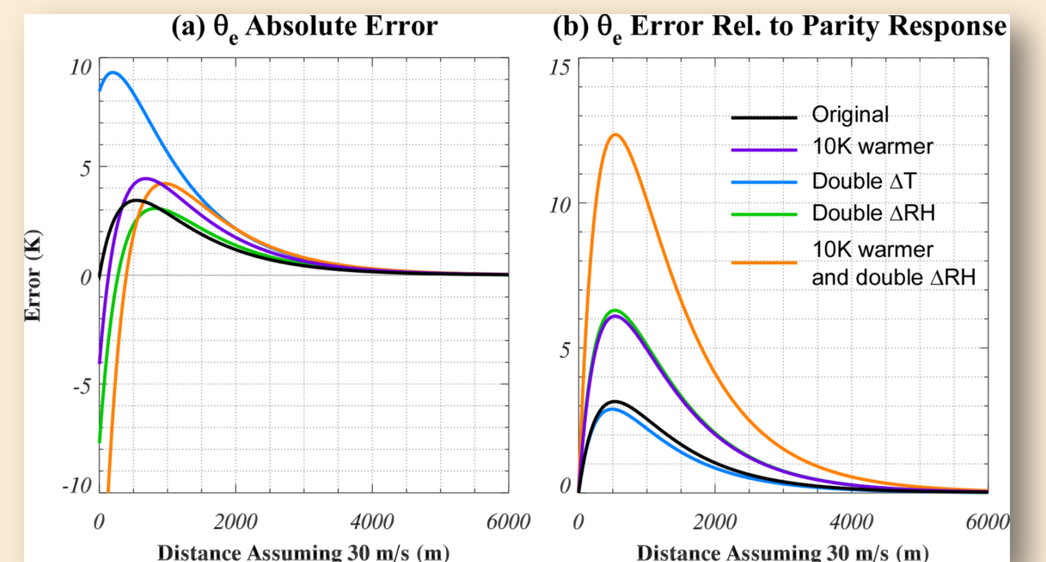

Figure 12. Errors in θ_e calculated assuming a step function profile across hypothetical gust fronts. a) The absolute error relative to actual θ_e profile. b) The error calculated relative to the "best case scenario" in which the response times between the temperature and humidity sensors are identical (parity).

7. Conclusions

- Tempest and NSSL-MM observations were generally well within the bounds of sensor accuracy, exceeding these bounds at gust fronts and in precipitation.
- Differences in humidity within precipitation might be attributable to slight systematic differences in the airstream sampled by the NSSL-MM and Tempest humidity sensors.
- CFD simulations indicate that the air stream at the height of the NSSL-MM anemometer could be 1.2-1.4 m/s stronger than the actual air speed. This +4-5% error would significantly exceed the expected sensor accuracy (±1%)
- Potentially significant θ_e errors near airmass boundaries can emerge from differences in the responses of temperature and humidity sensors.
- For the gust fronts considered, the slower response of the temperature sensor results in temperatures that are "too high" thereby erroneously inflating θ_e.