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Biases of the MET Temperature and Relative Humidity Sensor (HMP45) Report

J Kyrouac A Theisen

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ARM CLIMATE RESEARCH FACILITY

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DOE/SC-ARM-TR-192

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J Kyrouac, Argonne National Laboratory
Principal Investigator

A Theisen, ARM Data Quality Office, University of Oklahoma
Co-Investigator

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Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
C	Celsius
DOE	U.S. Department of Energy
DQ	Data Quality
DQR	Data Quality Report
EF	extended facilities
km	kilometer
m	meter
MET	surface meteorological instrumentation
m/s	meters per second
RH	relative humidity

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1.0 Summary

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility Data Quality (DQ) Office was alerted to a potential bias in the surface meteorological instrumentation (MET) temperature when compared with a nearby Mesonet station. This led to an investigation into this problem that was expanded to include many of the other extended facilities (EF) and both the temperature and relative humidity (RH) variables.

For this study, the Mesonet was used as the standard reference due to results that showed an increased accuracy in high-humidity environments along with the fact that the Mesonet had previous documented a problem with the HMP45C sensors. Some differences between the sites were taken into account during the analysis:

1. ARM MET sensors were upgraded from an HMP35 to an HMP45 throughout 2007
2. Mesonet switched to aspirated shields in 2009
   - To mitigate the differences between aspirated and non-aspirated measurements, data were only analyzed when the wind speed was higher than 3 m/s. This reduced the uncertainty for the non- aspirated measurements from 1.51 ºC to 0.4 ºC.
3. ARM MET is mounted 0.5m higher than the Mesonet station (2.0m versus 1.5m)
   - This is assumed to have a negligible effect on the differences.
4. Sites were not co-located
   - For some locations, the distances between sites were as much as 45 km.

As part of the investigation into the differences, the Mesonet had reported that the HMP45 sensors had a low-temperature bias in high-humidity environments. This was verified at two different sites where the ARM measurements were compared with the Mesonet measurements. The Mesonet provided redundant temperature measurements from two different sensors at each site. These measurements compared fairly well, while the ARM sensor showed a bias overnight when the humidities were higher.

After reviewing the yearly average differences in the data and analyzing the RH data during fog events when we assume it should be 100%, we determined that a majority of the sites have a bias in the RH compared to the Mesonet sites, but that only a few sites show a bias in the temperature measurements that are outside the range of instrument uncertainties. We note that there can be a lot of variability across some of the distances between the MET and Mesonet sites and these biases reported herein should not be used as offsets.

All of the MET HMP45 sensors were evaluated by the manufacturer and went through standard (one point: 20°C) temperature and (4 point: 0%, 11%, 33%, 75%) relative humidity calibration to determine their characterization at the time of removal. Consistent with the results of the comparison study, all errors (both temperature and relative humidity) showed the sensor reading lower than expected, and relative humidity errors were larger with increasing humidity. The results of the exit calibration are shown in Table 7**.**

2.0 Problem Definition

A data user alerted the ARM Data Quality (DQ) Office to a potential bias in the MET temperatures at a single extend facility (EF) when compared with a nearby Mesonet station (McPherson et. al. 2007, Brock et. al. 1995). This bias was confirmed at the site in question and the investigation was expanded to include most EFs and both the temperature and relative humidity (RH) variables. The analysis was initially confined to the period 2012-2016 but has since expanded to 2000-2016.

In-person communication with the Mesonet had also reported that they found the HMP45C sensors, which are the same model that ARM has used since ~2007, to have a cold bias in high-humidity environments. The theory behind the cold bias was that moisture was getting into the temperature sensor, which was supported by results from saturating the sensors in the calibration lab. The Mesonet provided additional data that we used in analyzing this problem with the ARM sensors.

3.0 Background

3.1 System Differences

In order to properly assess the differences in data between the ARM MET and Mesonet systems, the physical differences between them had to be determined.

a) ARM MET is mounted at 2.0m versus the MESONET at 1.5m.

b) ARM MET is not aspirated at all EFs except for E13. The MESONET sensors have been aspirated since 2009.

c) ARM MET used an HMP35C up to February 2007, after which HMP45's were installed. These were compared to the temperature recorded by the MESONET's Thermometrics Fasttherm sensor.

d) The distance between ARM and Mesonet sites can be large at times (Table 1).

In addition to the Fasttherm, the MESONET operates an HMP45 sensor for RH measurements and redundant temperature measurements. Personnel from the MESONET had indicated that they found the HMP45 to exhibit a cold bias during times of high humidity, which is part of the reason why they changed to the Fasttherm sensors. The MESONET data provided by ARM through the Data Archive do not include the redundant temperature measurements from the HMP45, but were provided for a shorter period of analysis (Section 4.1).

Table 1. Nearest MESONET site to each ARM facility and the distance between them.

ARM site	MESONET site	Distance (km)
E9	NEWK	40.9
E11	CHER	16.3
E13	BLAC	26.5
E15	LAHO	16.3
E31	CHER	44.8
E32	MEDF	7.25
E33	NEWK	15.5
E34	NEWK	23.2
E35	PERK	15.3
E36	MRSH	8.6
E37	LAHO	18.4
E38	KIN2	19.9
E39	REDR	7.8
E40	PAWN	4.7
E41	NEWK	15.7

3.2 Uncertainty

3.2.1 Temperature

The temperature uncertainty is ± 0.2 ºC at 20 ºC, with uncertainty increasing in either direction as shown in the following figure from the Vaisala HMP45 manual.

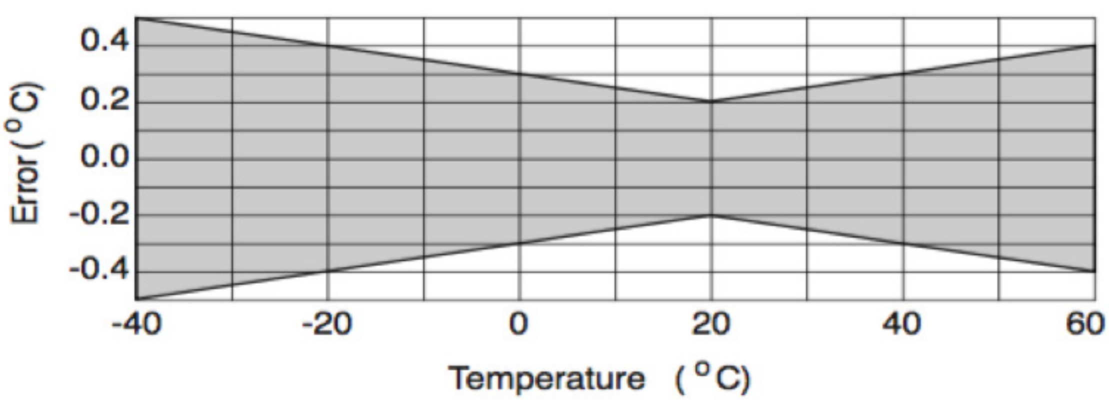

Figure 1. HMP45 uncertainty.

The uncertainty is increased by the use of the RM Young radiation shields. E13 is the only site that uses the 43408 aspirated shield. All other sites are non-aspirated (model 41002).

Aspirated (E13): ± 0.2 ºC

Non-aspirated (all other sites):

Wind speed at 6 m/s: ± 0.2 ºC
Wind speed at 3 m/s: ± 0.4 ºC
Wind speed at 2 m/s: ± 0.7 ºC
Wind speed at 1 m/s: ± 1.51 ºC

ARM MET temperatures and RH recorded while winds were less than or equal to 3 m/s were not used in this study.

3.2.2 Relative Humidity

The relative humidity uncertainty at values between 0% and 90% is ± 2%. At values above 90%, the uncertainty is ± 3%. The temperature dependence on the relative humidity measurement is ± 0.05 % per ºC. Additionally, relative humidity measurement stability is stated by the manufacturer to be better than 1% per year. This creates an additional uncertainty depending on the last calibration date of the sensor.

Without incorporating possible drift, the following instantaneous differences between MET and Mesonet relative humidity readings would be considered acceptable by manufacturer standards:

Between 0% and 90%: ± 4%

Above 90%: ± 6%

The following table lists the maximum cumulative sensor drift (as defined by the manufacturer) for 2016 based on the last calibration date of the sensor. These are worst-case stability uncertainties, assuming a 1% annual cumulative drift.

Table 2. Maximum sensor drift for 2016 based on last calibration of the sensor.

Site	Last calendar year	Maximum drift for 2016
E9	2007	9%
E11	2009	7%
E13	2007	9%
E15	2009	7%
E21	2007	9%
E31	2011	5%
E32	2013	3%
E33	2013	3%

Site	Last calendar year	Maximum drift for 2016
E34	2011	5%
E35	2011	5%
E36	2012	4%
E37	2016	<1%
E38	2011	5%
E39	2015	1%
E40	2015	1%
E41	2016	<1%

For any year, the uncertainty can be estimated by combining the possible 1% per year drift with the standard uncertainty listed above. (Example: 2010 data at E13 may have an uncertainty of up to ± 6% in humidity above 90%—3 years of maximum 1% drift added to a 3% standard uncertainty.) Exit calibrations will be performed to quantify the accuracy state of the sensor upon removal and will be updated herein.

3.3 Process

3.3.1 Sensor Response to High-Humidity Conditions

The MESONET provided data from both the Fasttherm and HMP45 for the CHER (E11) and PERK (E35) sites during the first week of November 2016. These data, along with the RH reported by the HMP45, were compared with the ARM MET data. Differences during the day were compared to differences overnight as higher RH was expected overnight and therefore larger differences in the temperature (Section 4.1).

3.3.2 Sensor Response to Fog Events

It was recommended that the RH data be analyzed during fog events to determine if they are reporting what is physically expected, i.e., that the RH is reported as 100%. Two fog events were used as part of the analysis, both verified by site operations: 11/4/2016 and 10/31/2016. Both events were heavy enough that tipping bucket rain gauges at many of the EFs recorded 1-2 tips.

3.3.3 Yearly Average Differences

Yearly averages for the temperature and RH variables were calculated using the method defined below.

1. Remove ARM data from analysis when the wind speed was less than or equal to 3 m/s.
2. Apply data quality reports (DQR) to ARM data to remove known Incorrect or Suspect data.
3. Average ARM data to the same 5-minute temporal resolution as the Mesonet.
4. Calculate the difference on a sample-by-sample basis for the entire day and average for the year.
5. Determine the sunrise/sunset times and calculate the yearly averages of day and night data.

These data were then analyzed, keeping in mind the sensor upgrades for the MET in 2007 and the Mesonet conversion to aspirated shields in 2009.

4.0 Results

4.1 Sensor Response to High-Humidity Conditions

Figures 1 and 2 show that there is very little difference between the redundant MESONET temperatures but that the MET does exhibit a cold bias in high-humidity conditions (most notably overnight) as previously observed by the MESONET. The distance between sites (15-16km) could explain some of the small variation but not the larger deviations of 3-4 ºC.

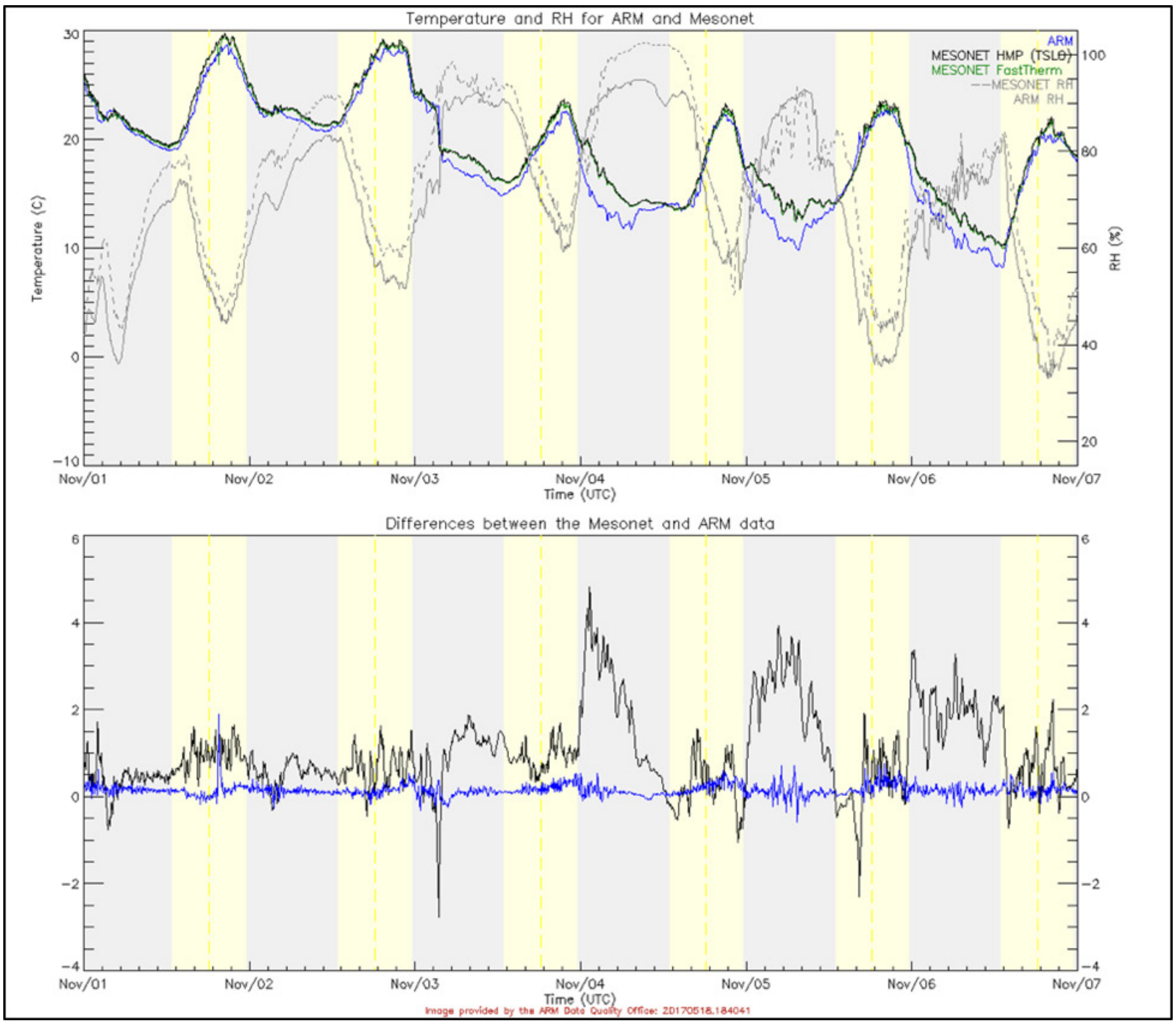

Figure 2. Temperature and RH measurements from the MESONET (PERK) and ARM (E35) sensors for the first week of November 2016 (top panel) and the difference between MESONET temperatures (blue) and ARM-MESONET Fasttherm differences (black) (bottom panel).

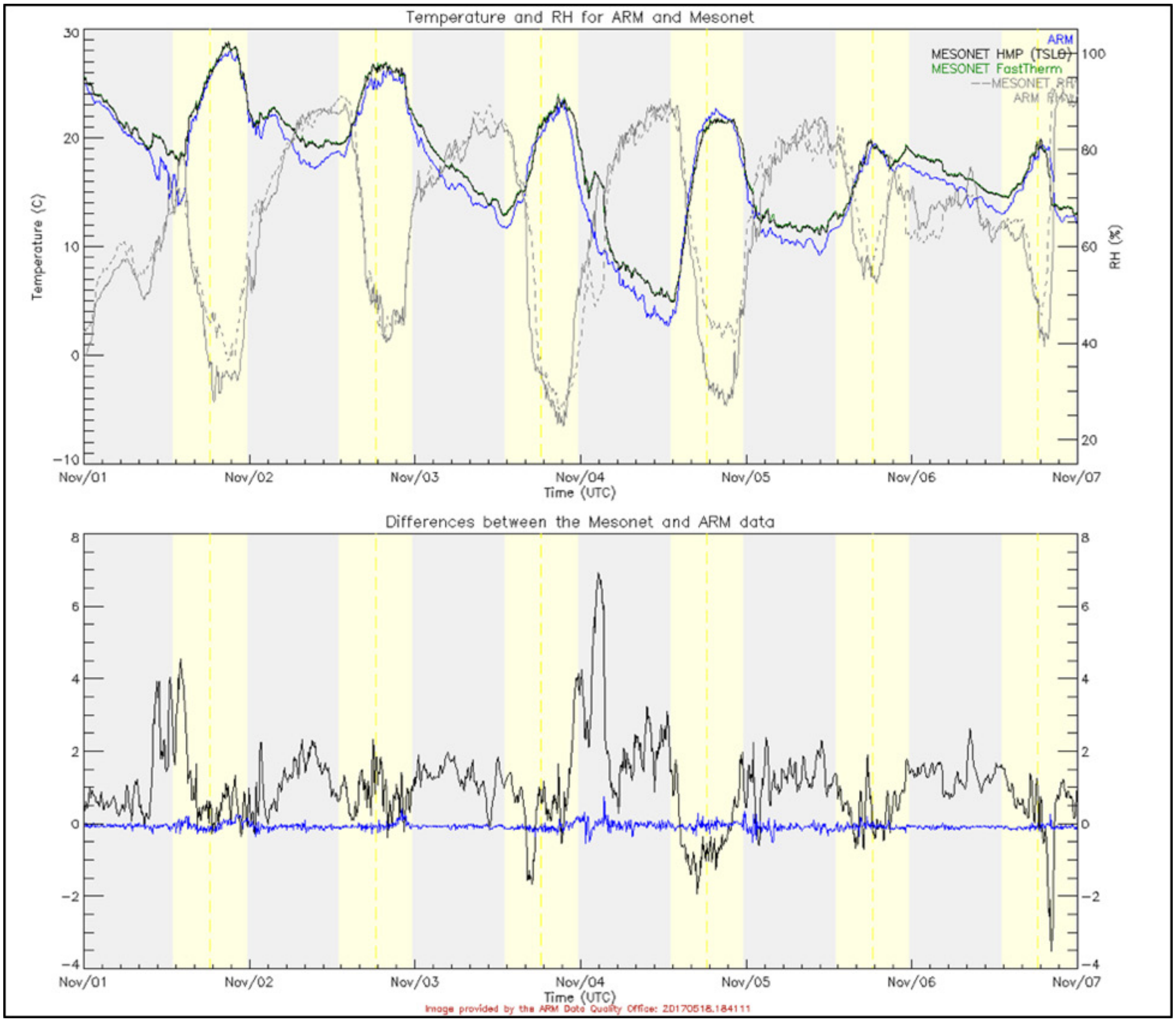

Figure 3. Temperature and RH measurements from the MESONET (CHER) and ARM (E11) sensors for the first week of November 2016 (top panel) and the difference between MESONET temperatures (blue) and ARM-MESONET Fasttherm differences (black) (bottom panel).

4.2 Sensor Response to Fog Events

Figure 4 shows an example of what one would expect during a fog event. The Mesonet RH values are all close to 100% overnight into morning before the fog dissipates. The ARM MET data are slightly lower and max out at 94.4%. A summary of the fog events is included in Table 3 and Table 4. Note: there have only been two ARM sites that maxed out over 99.5% while the Mesonet had 12. A majority of the ARM sites max out in the low-to-mid 90% range. The distance between E9 and the nearest Mesonet site may cause a lot of the difference, but E9 has been documented to have low max RH values (95-96%) since 2012 (Table 5), which lends credence to E9 having a low RH bias.

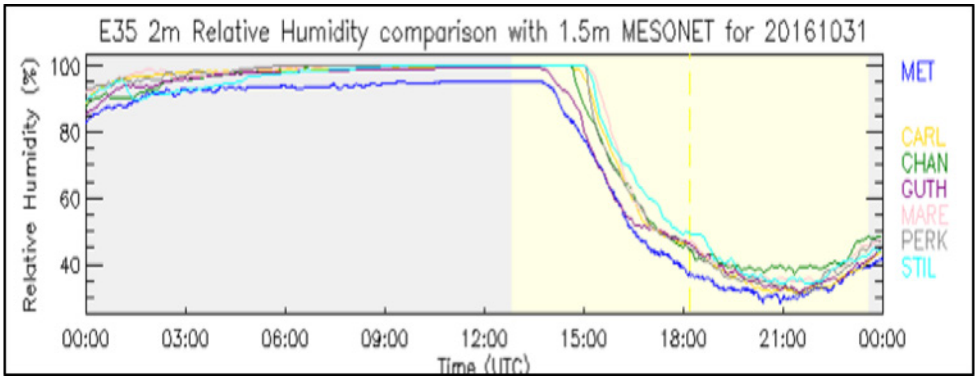

Figure 4. E35 RH during a fog event along with the nearest Mesonet sites.

Table 3. Max RH values for ARM and Mesonet sites for the 10/31/2016 fog event.

20161031	Max RH	Mesonet site	Distance	Max RH	Difference
E9	94.4	NEWK	40.9626	100	-5.60
E11	94.8	CHER	16.3203	98.5	-3.70
E13	93.4	BLAC	26.4709	100	-6.60
E15	97.3	LAHO	16.2921	99.9	-2.60
E21	94.4	OKMU	14.0762	99.7	-5.30
E31	98	CHER	44.7898	98.5	-0.50
E32	99.3	MEDF	7.25578	99.8	-0.50
E33	103.72	NEWK	15.5144	100	3.72
E34	100.8	NEWK	23.245	100	0.80
E35	95.34	PERK	15.3328	100	-4.66
E36	95.76	MRSH	8.59026	100	-4.24
E37	99.1	LAHO	18.3609	99.9	-0.80
E39	95	REDR	7.7854	100	-5.00
E40	98.9	PAWN	4.69055	100	-1.10

Table 4. Max RH values for ARM and Mesonet sites for the 11/04/2016 fog event.

20161104	Max RH	Mesonet Site	Distance	Max RH	Difference
E9	78.3	NEWK	40.9	100	-21.70
E11	90.56	CHER	16.3203	88.6	1.96
E13	93.5	BLAC	26.4709	100	-6.50
E15	84.48	LAHO	16.2921	95.5	-11.02
E21	93.2	OKMU	14.0762	96.9	-3.70
E31	88.5	CHER	44.7898	88.6	-0.10
E32	93.76	MEDF	7.25578	93.4	0.36
E33	103.1	NEWK	15.5144	100	3.10

20161104	Max RH	Mesonet Site	Distance	Max RH	Difference
E34	99.5	NEWK	23.245	100	-0.50
E35	94.84	PERK	15.3328	100	-5.16
E36	95.7	MRSH	8.59026	100	-4.30
E37	98.9	LAHO	18.3609	95.5	3.40
E38	84.5667	KIN2	19.8812	99.7	-15.13
E39	95	REDR	7.7854	99.9	-4.90
E40	99.2	PAWN	4.69055	100	-0.80
E41	96.7	NEWK	15.7743	100	-3.30

Table 5. Yearly maximum RH values recorded at each facility.

	E9	E11	E13	E15	E21	E31	E32	E33	E34	E35	E36	E37	E38	E39	E40	E41	Average
2000	104	104			102.5												103.5
2001	104	102.4			103.3												103.23
2002	104	103	100		104												102.75
2003	104	99.7	100.6	104	104												102.46
2004	99.1	104	104	104	100.2												102.26
2005	99.2	98.2	104	100.5	104												101.18
2006	100.2	98.8	100.4	100.1	104												100.7
2007	100	102.5	100.1	100.7	99.4												100.54
2008	98.3	97.8	99.8		98.1												98.5
2009	97.6	104	99.2	97.8	97.1												99.14
2010	97.7	98.1	99	97.8	99.1												98.34
2011	99.4	96.8	99.1	97.2	97.1												97.92
2012	96.4	96.9	98.3	96.4	95.5	104	98.9	95.4	103.5	98.3	102.9	99.1	96.5				98.62
2013	96.6	97.3	99.6	97	94.2	103.6	104	102.5	102.9	97.9	98.5	98.8	97.4				99.25
2014	95.8	96.2	104	96.9	94.9	99.9	99.7	103.6	102.7	97.4	97.6	99.7	96.4				98.83
2015	95.4	102	95.8	96.5	94.8	99.2	99.5	103.5	102	97.5	97.2	99.8	95.9		103.9		98.78
2016	95.3	95.4	94.9	103.7	95.4	104	99.6	103.9	101.6	96.1	96.1	101	95.6	95.5	99.2	97.8	98.44

4.3 Yearly Average Differences

4.3.1 Temperatures

Assuming that the majority of the temperature values are between 0 ºC and 40 ºC, the max uncertainty due to the sensor is $\pm$0.3ºC (Figure 1). Combining this with the uncertainty due to non-aspirated radiation shields (0.4 ºC) gives a total uncertainty of 0.7 ºC. The uncertainty of the Thermometrics sensor, as reported by the Mesonet, is 0.5 ºC. The maximum difference acceptable that would be considered in the range of instrument uncertainty would be 1.2 ºC. This could be used on a sample-by-sample basis, but cannot be applied to the yearly averages. If a bias of -2ºC switched to a positive 2ºC bias halfway through the year, the average difference would be 0ºC.

Figure 5 shows the yearly averaged differences at the EFs (ARM-Mesonet). There is no agreement in the general trends of the differences, which depend on the site. Histograms of the data from 2016 are provided in Figure 6. Ideally, these distributions would be centered on 0ºC, but that is not the case with most of the sites. Assuming that the average difference is consistent throughout 2016, which it is not, then the nighttime data at E21 and E35 would be the only sites outside the range of instrument uncertainty followed by the nighttime data at E11 and E31, although the latter are still within range. E21 is expected to have larger differences than other site due to its location on a tower in the tree canopy. The complete list of yearly average temperature differences can be found in the appendix (Figure 8).

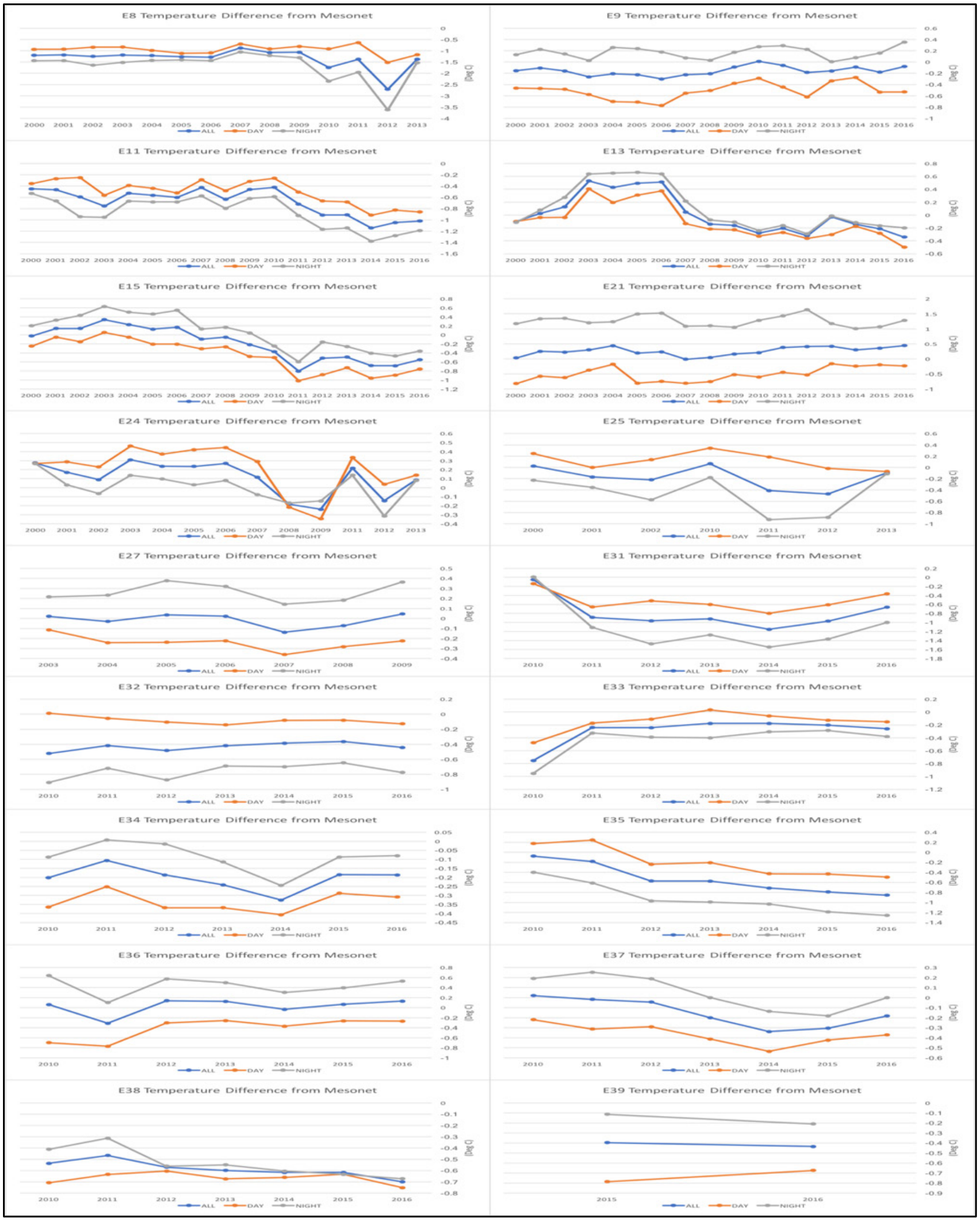

Figure 5. Yearly average temperature differences between the MET and Mesonet (ARM-Mesonet) sites.

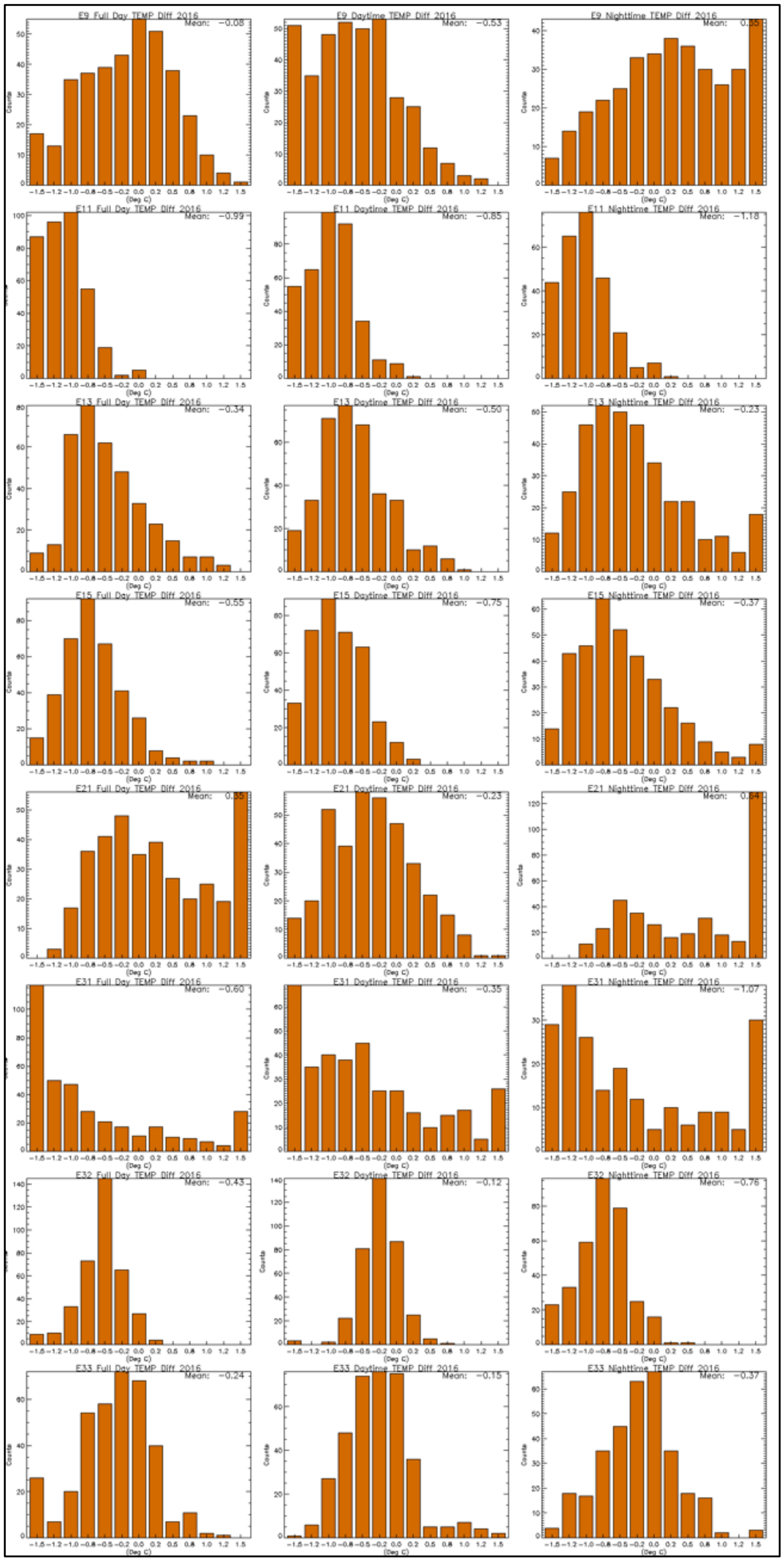

Figure 6. Histograms of the difference values in 2016 for all time, daytime, and nighttime data.

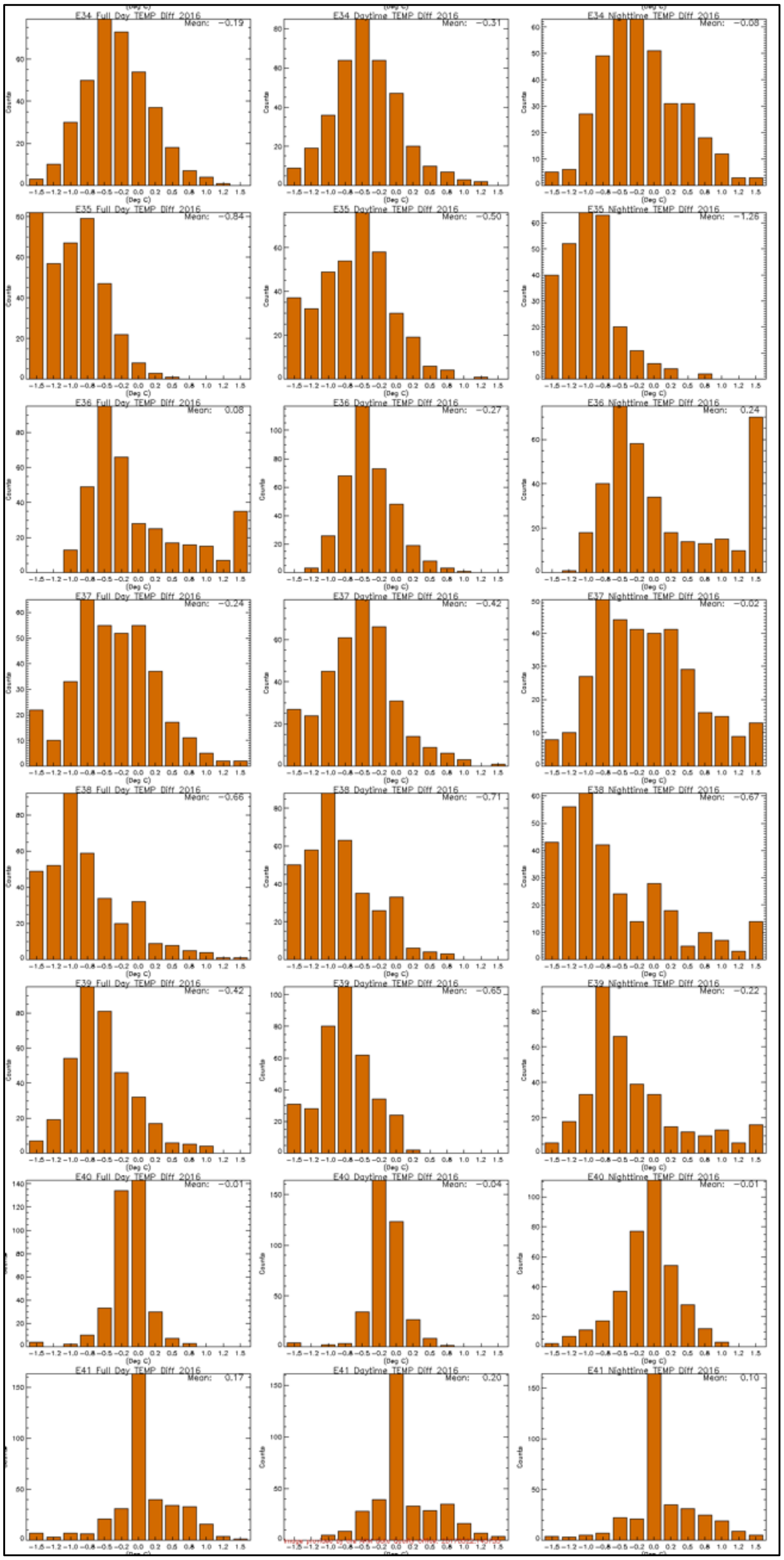

Figure 6. Continued…

4.3.2 Relative Humidity

The larger differences (ARM-Mesonet) in the RH that is seen in the time series (Figure 7) and 2016 histograms (Figure 8) can be attributed to the sensor drift documented in Section 3.2.2, along with the distance between sites. Hubbard (1994) found that in order to explain 90% of the variability in RH between two sites, they needed to be less than 30 km apart. Most of the ARM sites are less than 30 km from the corresponding Mesonet location, but E9 and E31 are not.

Many of the older EFs (E8-27) show a general increase in the magnitude of the difference over time that could be attributed to the instrument bias. E9, E13, and E21 were last calibrated in 2007 and therefore could have a possible drift of up to 9% (Table 2). These are also the same sites where we are seeing the largest differences; -6.37%, -7.15%, and -8.52% respectively. As discussed earlier, E21 is not a standard installation and larger differences are expected. E15 is another one of the older sites that has large differences, -5.51%. The potential drift with this site is 7%. The complete list of yearly average RH differences can be found in the appendix (Table 9).

All current sites except for E33 show a negative bias in the most recent 2016 data. Of the 19 sites analyzed, 14 had larger differences overnight than during the day. This could be related to the previous findings with the temperature being biased in high-humidity environments, but the exact cause is currently unknown.

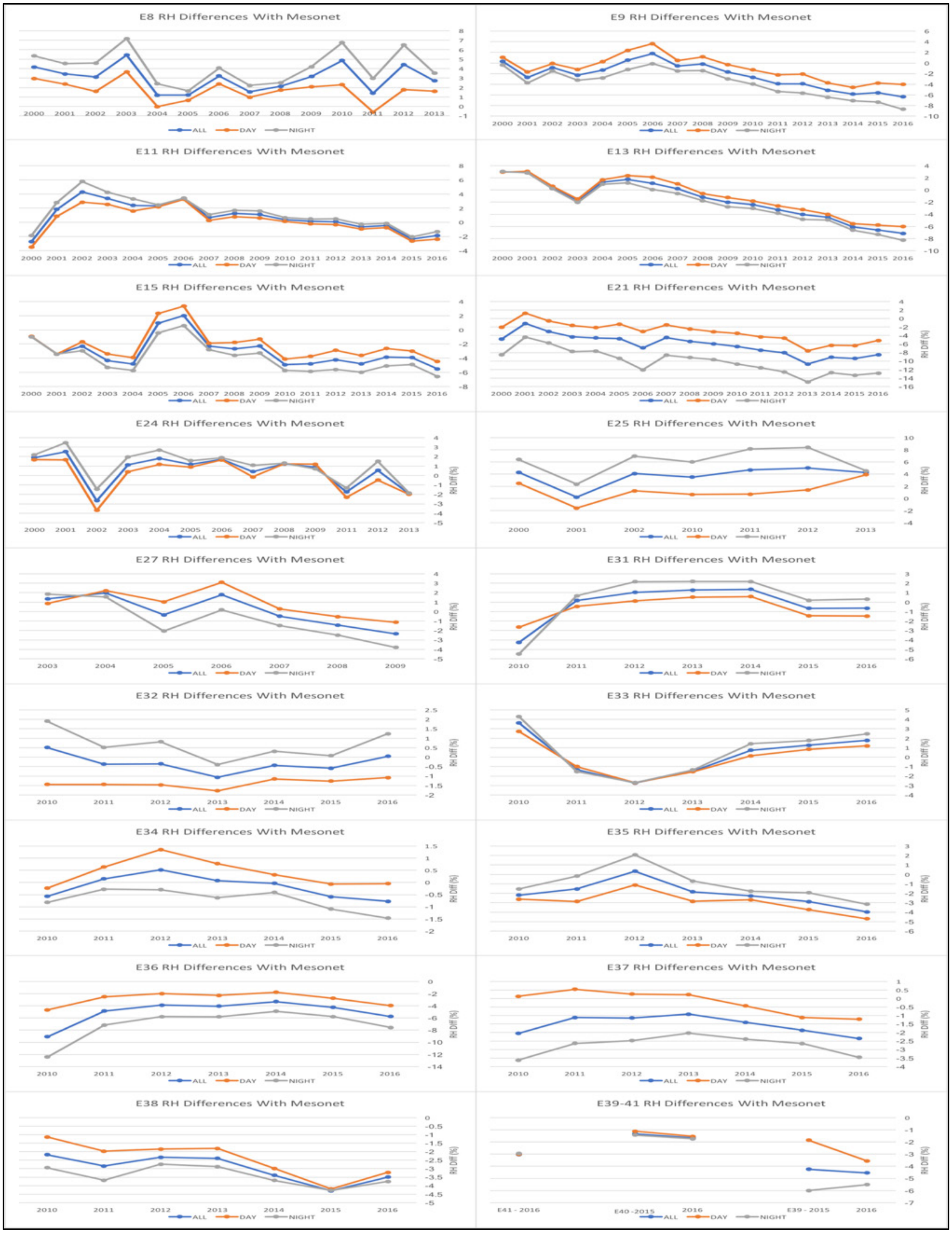

Figure 7. Yearly average RH differences between the MET and Mesonet (ARM-Mesonet) sites.

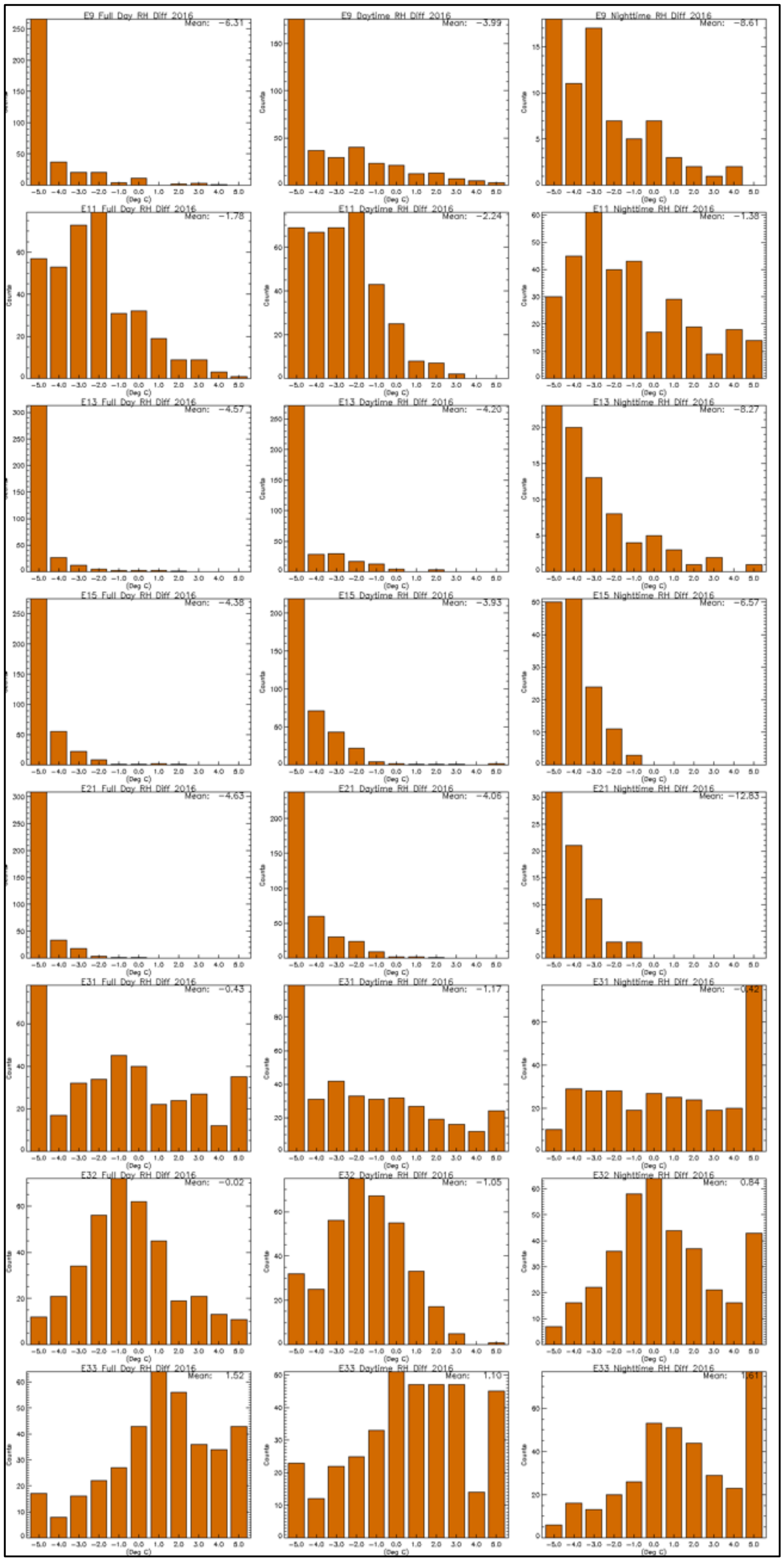

Figure 8. Histograms of the difference values in 2016 for all time, daytime, and nighttime data.

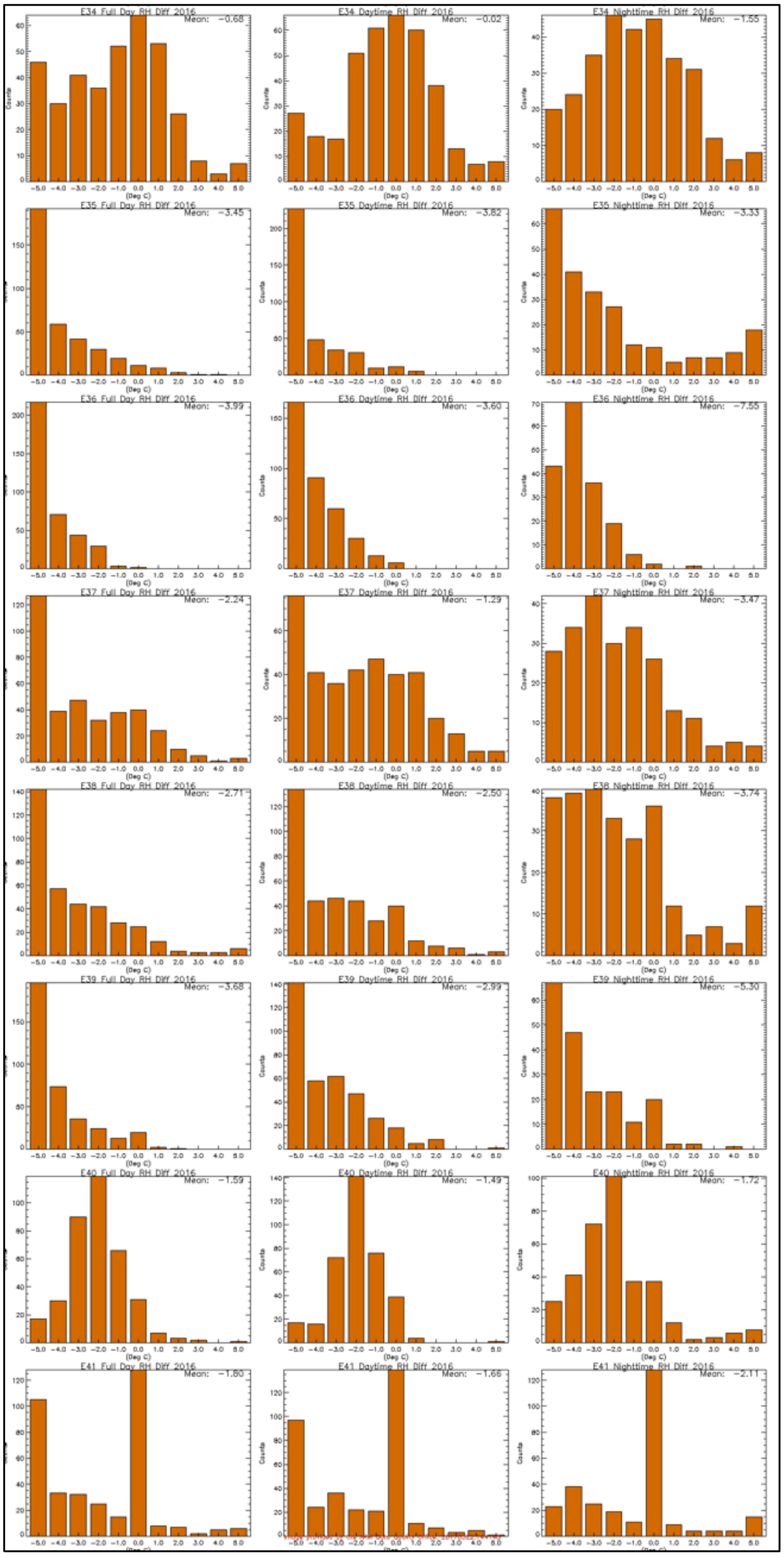

Figure 8. Continued…

5.0 Discussion

The HMP45 sensors have been shown by the Mesonet to have a low-temperature bias in high-humidity environments and this was confirmed to be present in the ARM data as well. Overall, the temperature differences between the ARM and Mesonet stations when wind speeds were greater than 3 m/s were within reason for all but a few sites. There were some larger differences in the RH data that could be attributed to the sensor drift due to the length of time sensors were left in the field without proper calibration. Due to the analysis performed, the calibration check procedure for the MET systems is currently being revised.

The differences provided in this document should not be used as offsets for the data. As found, the differences are not linear. The uncertainties described in Section 3.2 should be applied to the data as the user sees fit.

Throughout 2017 and 2018, the MET systems will be upgraded to new sensors including an aspiration shield:

- HMP155 temperature/humidity
- RM Young aspirated radiation shields
- PTB330 barometers.

The data loggers have been upgraded to support improved instrument performance and easier calibration and maintenance. When these sensors were replaced, they were sent to the vendor for exit calibrations to quantify the performance. This report has now been updated accordingly.

6.0 Documentation of the Bias

The instrument mentor has submitted a number of data quality reports (DQR) to alert the data users of potential problems. Please review the official DQRs in the links provided below for the most up-to-date information.

These DQRs were entered to outline sensor performance issues based on replacement dates at each site. Data are coded as “suspect" if the sensor failed any field calibration checks during that time. Data are coded as “does not affect quality” if the sensor has not failed field calibration checks, but is still susceptible to drift and may have increased uncertainty due to lack of recent calibration.

Table 6. List of Data Quality Reports submitted by the mentor documenting the biases.

DQR ID	Submitter	Submit Date	Subject	Quality
D170322.11	Jenni Kyrouac	4/2/17	SGP/MET/E37 - Temperature/humidity sensor not calibrated annually	Does not affect quality
D170322.9	Jenni Kyrouac	4/2/17	SGP/MET/E36 - Temperature/humidity sensor failed a 6-month field calibration check	Suspect
D170322.1	Jenni Kyrouac	4/2/17	SGP/MET/E15 - Temperature/humidity sensor failed a field calibration check	Suspect
D170321.11	Jenni Kyrouac	4/2/17	SGP/MET/E15 - Temperature/humidity sensor failed a field calibration check	Suspect
D170321.10	Jenni Kyrouac	4/2/17	SGP/MET/E15 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Suspect
D170321.8	Jenni Kyrouac	4/2/17	SGP/MET/E13 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Suspect
D170320.12	Jenni Kyrouac	4/2/17	SGP/MET/E11 - Temperature/humidity sensor failed a field calibration check	Does not affect quality
D170320.1	Jenni Kyrouac	4/2/17	SGP/MET/E9 - Temperature occasionally failed 6-month field calibration checks	Suspect
D170322.15	Jenni Kyrouac	4/2/17	SGP/MET/E41 - Temperature/humidity sensor not calibrated annually	Does not affect quality
D170322.14	Jenni Kyrouac	4/2/17	SGP/MET/E40 - Temperature/humidity sensor not calibrated annually	Does not affect quality
D170322.13	Jenni Kyrouac	4/2/17	SGP/MET/E39 - Temperature/humidity sensor not calibrated annually	Does not affect quality
D170322.12	Jenni Kyrouac	4/2/17	SGP/MET/E38 - Temperature/humidity sensor failed a 6-month field calibration check	Does not affect quality
D170322.10	Jenni Kyrouac	4/2/17	SGP/MET/E36 - Temperature/humidity sensor failed a 6-month field calibration check	Does not affect quality

DQR ID	Submitter	Submit Date	Subject	Quality
D170322.8	Jenni Kyrouac	4/2/17	SGP/MET/E35 - Temperature/humidity sensor not calibrated annually	Does not affect quality
D170322.7	Jenni Kyrouac	4/2/17	SGP/MET/E34 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Does not affect quality
D170322.6	Jenni Kyrouac	4/2/17	SGP/MET/E33 - Temperature/humidity sensor not calibrated annually	Does not affect quality
D170322.5	Jenni Kyrouac	4/2/17	SGP/MET/E32 - Temperature/humidity sensor failed a 6-month field calibration check	Does not affect quality
D170322.4	Jenni Kyrouac	4/2/17	SGP/MET/E31 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Does not affect quality
D170322.3	Jenni Kyrouac	4/2/17	SGP/MET/E21 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Does not affect quality
D170322.2	Jenni Kyrouac	4/2/17	SGP/MET/E15 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Does not affect quality
D170321.9	Jenni Kyrouac	4/2/17	SGP/MET/E13 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Does not affect quality
D170321.5	Jenni Kyrouac	4/2/17	SGP/MET/E11 - Temperature/humidity sensor may have a cold and dry bias	Does not affect quality
D170320.9	Jenni Kyrouac	4/2/17	SGP/MET/E9 - Temperature/humidity sensor occasionally failed 6-month field calibration checks	Suspect

7.0 Manufacturer Evaluation

All HMP45 sensors were sent to the manufacturer for standard (one point: 20°C) temperature and (4 point: 0%, 11%, 33%, 75%) relative humidity calibration to determine their characterization at the time of removal. Consistent with the results of the comparison study, all errors (both temperature and relative humidity) showed the sensor reading lower than expected, and relative humidity errors were larger with increasing humidity. The errors reported by the manufacturer were also consistent with the expected drift (Table 2), though lower in magnitude; the sites with the largest expected drift reported the largest deviations in humidity. An exception is E39, where the humidity errors were larger than the expected 1%. Alternatively, E36 showed almost no error, while expecting a 4% drift.

Table 7. Results from PMP45 exit calibrations.

Site	Temp. Error	RH Error at 33%	RH Error at 75%
E9	-0.45	-3.89	-5.12
E11	-0.77	-3.13	-4.05
E13	-0.79	-3.27	-4.49
E15	-0.82	-2.69	-4.08
E21	ok	-2.48	-4.73
E31	-0.43	ok	ok
E32	ok	ok	ok
E33	-0.38	ok	-2.36
E34	-0.71	-2.30	-3.36
E35	-1.52	-3.15	-3.57
E36	ok	-2.37	ok
E37	ok	ok	-2.39
E38	ok	-2.96	-3.36
E39	-0.98	-3.19	-3.82
E40	ok	ok	ok
E41	ok	-2.67	-2.69

*Tolerance for temperature is ±0.2°C. Tolerance for relative humidity is ±2%. Contact instrument mentor for detailed calibration reports.

8.0 References

Brock, FV, KC Crawford, RL Elliott, GW Cuperus, SJ Stadler, HL Johnson, and MD Eilts. 1995. “The Oklahoma Mesonet: A technical overview.” *Journal of Atmospheric and Oceanic Technology* 12: 5-19, doi:10.1175/1520-0426(1995)012<0005:TOMATO>2.0.CO;2.

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Appendix A

Table 8. Average bias between ARM and MESONET temperature from 2000-2016. Table is broken down by ARM facility and the differences are calculated for the entire day, just night, and just day. Shaded cells indicate difference greater than 1ºC in magnitude.

	E8			E9			E11			E13			E15		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016				-0.08	-0.53	0.35	-1.02	-0.86	-1.19	-0.34	-0.50	-0.20	-0.55	-0.76	-0.36
2015				-0.18	-0.53	0.16	-1.05	-0.83	-1.28	-0.21	-0.28	-0.17	-0.68	-0.89	-0.47
2014				-0.09	-0.28	0.08	-1.14	-0.92	-1.38	-0.14	-0.17	-0.12	-0.68	-0.96	-0.41
2013	-1.38	-1.18	-1.53	-0.16	-0.33	0.00	-0.91	-0.68	-1.14	-0.03	-0.30	-0.01	-0.49	-0.73	-0.26
2012	-2.71	-1.52	-3.62	-0.19	-0.62	0.22	-0.91	-0.66	-1.17	-0.32	-0.36	-0.29	-0.52	-0.88	-0.16
2011	-1.38	-0.64	-1.95	-0.06	-0.45	0.29	-0.72	-0.51	-0.92	-0.21	-0.27	-0.16	-0.80	-1.02	-0.60
2010	-1.74	-0.92	-2.35	0.01	-0.29	0.27	-0.42	-0.26	-0.59	-0.28	-0.33	-0.24	-0.37	-0.50	-0.25
2009	-1.07	-0.80	-1.31	-0.09	-0.38	0.17	-0.46	-0.32	-0.62	-0.16	-0.23	-0.11	-0.22	-0.48	0.04
2008	-1.08	-0.92	-1.22	-0.21	-0.51	0.03	-0.64	-0.48	-0.79	-0.14	-0.22	-0.08	-0.05	-0.26	0.17
2007	-0.88	-0.70	-1.05	-0.23	-0.55	0.07	-0.43	-0.29	-0.57	0.05	-0.13	0.21	-0.10	-0.31	0.13
2006	-1.28	-1.10	-1.44	-0.30	-0.77	0.18	-0.60	-0.52	-0.68	0.51	0.37	0.64	0.17	-0.21	0.54
2005	-1.27	-1.12	-1.41	-0.22	-0.71	0.24	-0.56	-0.44	-0.68	0.49	0.31	0.66	0.13	-0.20	0.46
2004	-1.21	-0.98	-1.43	-0.21	-0.70	0.26	-0.53	-0.39	-0.67	0.43	0.20	0.65	0.23	-0.05	0.50
2003	-1.19	-0.84	-1.52	-0.26	-0.58	0.03	-0.75	-0.56	-0.95	0.53	0.40	0.64	0.34	0.05	0.63
2002	-1.25	-0.84	-1.64	-0.16	-0.48	0.14	-0.59	-0.25	-0.94	0.13	-0.04	0.27	0.14	-0.15	0.43
2001	-1.19	-0.93	-1.43	-0.11	-0.47	0.23	-0.47	-0.27	-0.66	0.03	-0.04	0.08	0.14	-0.05	0.32
2000	-1.20	-0.94	-1.44	-0.15	-0.46	0.13	-0.45	-0.36	-0.53	-0.10	-0.10	-0.11	-0.02	-0.25	0.20

	E21			E24			E27			E31			E32		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016	0.44	-0.23	1.28							-0.66	-0.37	-1.00	-0.44	-0.13	-0.77
2015	0.36	-0.20	1.07							-0.97	-0.61	-1.37	-0.36	-0.08	-0.65
2014	0.30	-0.24	1.01							-1.15	-0.80	-1.55	-0.39	-0.08	-0.70
2013	0.42	-0.16	1.17	0.09	0.14	0.08				-0.92	-0.60	-1.28	-0.42	-0.14	-0.69
2012	0.41	-0.53	1.64	-0.14	0.04	-0.31				-0.96	-0.52	-1.47	-0.48	-0.11	-0.87
2011	0.38	-0.44	1.43	0.22	0.33	0.14				-0.89	-0.66	-1.11	-0.42	-0.06	-0.72

2010	0.21	-0.60	1.28							-0.05	-0.14	0.01	-0.52	0.01	-0.91
2009	0.17	-0.52	1.05	-0.24	-0.34	-0.15	0.04	-0.22	0.36						
2008	0.05	-0.76	1.10	-0.18	-0.22	-0.17	-0.07	-0.28	0.18						
2007	-0.01	-0.81	1.09	0.12	0.29	-0.08	-0.14	-0.36	0.14						
2006	0.23	-0.75	1.53	0.27	0.44	0.08	0.02	-0.22	0.32						
2005	0.20	-0.80	1.50	0.24	0.42	0.03	0.04	-0.24	0.38						
2004	0.44	-0.18	1.24	0.24	0.37	0.10	-0.03	-0.24	0.23						
2003	0.30	-0.37	1.21	0.31	0.46	0.14	0.02	-0.11	0.22						
2002	0.23	-0.62	1.35	0.09	0.23	-0.06									
2001	0.25	-0.57	1.34	0.17	0.29	0.03									
2000	0.03	-0.82	1.17	0.27	0.27	0.27									

	E33			**E34**			**E35**			**E36**			**E37**		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016	-0.26	-0.15	-0.38	-0.19	-0.31	-0.08	-0.85	-0.49	-1.26	0.13	-0.27	0.53	-0.18	-0.37	0.00
2015	-0.20	-0.13	-0.29	-0.19	-0.29	-0.09	-0.79	-0.43	-1.19	0.07	-0.26	0.39	-0.31	-0.42	-0.18
2014	-0.18	-0.06	-0.31	-0.33	-0.41	-0.25	-0.71	-0.43	-1.03	-0.04	-0.37	0.30	-0.34	-0.54	-0.14
2013	-0.18	0.03	-0.40	-0.24	-0.37	-0.11	-0.57	-0.21	-0.99	0.12	-0.26	0.50	-0.20	-0.41	0.00
2012	-0.24	-0.11	-0.39	-0.19	-0.37	-0.02	-0.57	-0.24	-0.97	0.14	-0.30	0.57	-0.04	-0.29	0.19
2011	-0.24	-0.17	-0.32	-0.11	-0.25	0.01	-0.18	0.24	-0.61	-0.31	-0.77	0.10	-0.02	-0.31	0.25
2010	-0.75	-0.48	-0.95	-0.20	-0.36	-0.09	-0.08	0.18	-0.40	0.06	-0.70	0.64	0.02	-0.22	0.19

	E38			**E39**			**E40**			**E41**		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016	-0.70	-0.75	-0.67	-0.43	-0.67	-0.21	-0.03	-0.06	-0.01	0.25	0.31	0.16
2015	-0.62	-0.63	-0.63	-0.40	-0.79	-0.11	-0.16	-0.26	-0.09			
2014	-0.62	-0.66	-0.60									
2013	-0.60	-0.67	-0.55									
2012	-0.57	-0.60	-0.56									
2011	-0.47	-0.63	-0.31									
2010	-0.54	-0.71	-0.41									

Table 9. Average bias between ARM and MESONET RH from 2000-2016. Table is broken down by ARM facility and the differences are calculated for the entire day, just night, and just day. Shaded cells indicate differences greater than 5% in magnitude.

	E8			E9			E11			E13			E15		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016				-6.37	-4.02	-8.68	-1.86	-2.37	-1.31	-7.15	-6.03	-8.27	-5.51	-4.47	-6.57
2015				-5.58	-3.76	-7.35	-2.34	-2.63	-2.04	-6.59	-5.78	-7.33	-3.91	-2.99	-4.90
2014				-5.85	-4.59	-7.09	-0.44	-0.73	-0.14	-6.09	-5.55	-6.62	-3.86	-2.64	-5.08
2013	2.71	1.62	3.52	-5.13	-3.75	-6.44	-0.63	-0.94	-0.28	-4.48	-4.00	-4.93	-4.79	-3.62	-5.98
2012	4.43	1.77	6.49	-3.90	-2.08	-5.64	0.09	-0.31	0.49	-4.03	-3.24	-4.83	-4.24	-2.89	-5.59
2011	1.39	-0.60	2.97	-3.91	-2.24	-5.35	0.15	-0.22	0.47	-3.25	-2.62	-3.84	-4.79	-3.74	-5.85
2010	4.85	2.30	6.74	-2.70	-1.31	-3.97	0.40	0.14	0.67	-2.41	-1.82	-3.05	-4.91	-4.12	-5.73
2009	3.16	2.08	4.20	-1.69	-0.30	-2.98	1.11	0.62	1.61	-2.01	-1.24	-2.76	-2.29	-1.32	-3.28
2008	2.12	1.71	2.50	-0.18	1.16	-1.44	1.25	0.79	1.68	-1.20	-0.60	-1.77	-2.68	-1.79	-3.59
2007	1.54	0.97	2.21	-0.56	0.48	-1.50	0.69	0.29	1.09	0.20	0.99	-0.59	-2.32	-1.88	-2.81
2006	3.22	2.38	4.06	1.78	3.63	-0.12	3.33	3.24	3.42	1.09	2.12	0.08	1.99	3.34	0.60
2005	1.22	0.66	1.65	0.53	2.39	-1.23	2.35	2.21	2.45	1.75	2.37	1.17	0.95	2.31	-0.44
2004	1.19	-0.02	2.40	-1.35	0.23	-2.81	2.40	1.61	3.31	1.28	1.65	0.94	-4.80	-3.92	-5.72
2003	5.43	3.65	7.17	-2.30	-1.22	-3.23	3.38	2.54	4.25	-1.78	-1.49	-2.04	-4.34	-3.41	-5.30
2002	3.11	1.59	4.58	-0.87	-0.10	-1.51	4.29	2.83	5.76	0.37	0.59	0.19	-2.30	-1.69	-2.94
2001	3.43	2.36	4.54	-2.70	-1.68	-3.73	1.84	0.86	2.80	2.92	3.06	2.81	-3.42	-3.42	-3.42
2000	4.17	2.95	5.33	0.33	1.08	-0.35	-2.73	-3.49	-1.87	2.98	2.93	3.04	-0.94	-0.92	-0.98

	E21			E24			E27			E31			E32		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016	-8.52	-5.18	-12.83							-0.65	-1.47	0.31	0.05	-1.08	1.24
2015	-9.39	-6.37	-13.33							-0.67	-1.45	0.19	-0.59	-1.26	0.08
2014	-9.12	-6.32	-12.73							1.35	0.59	2.17	-0.44	-1.15	0.31
2013	-10.70	-7.58	-14.92	-1.95	-2.00	-1.87				1.27	0.51	2.18	-1.06	-1.78	-0.40
2012	-8.06	-4.59	-12.57	0.52	-0.50	1.49				1.04	0.11	2.15	-0.35	-1.47	0.81
2011	-7.44	-4.31	-11.56	-1.74	-2.32	-1.33				0.16	-0.45	0.66	-0.37	-1.45	0.52
2010	-6.57	-3.48	-10.72							-4.27	-2.65	-5.48	0.51	-1.44	1.90
2009	-5.94	-3.12	-9.63	0.89	1.18	0.68	-2.35	-1.13	-3.80						
2008	-5.38	-2.47	-9.19	1.21	1.24	1.31	-1.44	-0.54	-2.50						
2007	-4.48	-1.49	-8.61	0.40	-0.16	1.08	-0.49	0.27	-1.48						
2006	-6.92	-3.06	-12.05	1.72	1.64	1.88	1.77	3.09	0.17						
2005	-4.75	-1.35	-9.39	1.17	0.88	1.55	-0.35	1.03	-2.07						
2004	-4.57	-2.14	-7.67	1.80	1.18	2.69	1.97	2.21	1.55						
2003	-4.33	-1.65	-7.76	1.12	0.39	1.95	1.34	0.87	1.85						

2002	-3.07	-0.59	-5.78	-2.67	-3.69	-1.44									
2001	-1.18	1.22	-4.39	2.51	1.66	3.45									
2000	-4.82	-2.04	-8.56	1.87	1.67	2.18									

	E33			E34			E35			E36			E37		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016	1.77	1.19	2.46	-0.78	-0.05	-1.47	-3.97	-4.69	-3.16	-5.74	-3.95	-7.57	-2.35	-1.21	-3.45
2015	1.25	0.83	1.75	-0.59	-0.07	-1.09	-2.89	-3.74	-1.94	-4.26	-2.76	-5.78	-1.86	-1.12	-2.65
2014	0.74	0.14	1.42	-0.04	0.32	-0.41	-2.27	-2.69	-1.79	-3.30	-1.76	-4.90	-1.40	-0.43	-2.39
2013	-1.49	-1.54	-1.36	0.08	0.77	-0.63	-1.85	-2.85	-0.70	-4.05	-2.30	-5.79	-0.92	0.22	-2.04
2012	-2.74	-2.71	-2.69	0.51	1.35	-0.30	0.33	-1.12	2.06	-3.87	-1.99	-5.78	-1.14	0.26	-2.48
2011	-1.33	-1.00	-1.52	0.15	0.64	-0.28	-1.54	-2.88	-0.18	-4.86	-2.51	-7.17	-1.11	0.55	-2.64
2010	3.61	2.71	4.28	-0.57	-0.24	-0.82	-2.20	-2.63	-1.54	-9.08	-4.68	-12.43	-2.05	0.13	-3.62

	E38			E39			E40			E41		
	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT	ALL	DAY	NIGHT
2016	-3.50	-3.22	-3.75	-4.54	-3.56	-5.51	-1.67	-1.54	-1.75	-3.05	-3.01	-2.95
2015	-4.30	-4.19	-4.27	-4.24	-1.86	-6.00	-1.33	-1.12	-1.43			
2014	-3.39	-2.99	-3.69									
2013	-2.39	-1.82	-2.88									
2012	-2.33	-1.85	-2.74									
2011	-2.85	-1.98	-3.68									
2010	-2.18	-1.14	-2.94									

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