Climatology of Supercooled Liquid Water in Colorado

Prepared for the U.S. Bureau of Reclamation – Technical Services Center
Denver Federal Center - Denver , Colorado

William J. Badini
Meteorologist

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By

William J. Badini
Meteorologist – HDR Inc.

To Technical Services Center, Bureau of Reclamation
Denver Federal Center – Denver, Colorado

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Introduction

One of the key components in determining the potential effectiveness of cloud seeding techniques as a means of augmenting seasonal snowpack is determining ‘where’ and ‘when’ resources would best be deployed. It is generally accepted that the presence of Supercooled Liquid Water (SLW) in clouds are a requirement for ‘cold season’ precipitation augmentation techniques to be successful. Enhanced knowledge of areas where naturally occurring SLW is available for seeding and what types of resources maybe best be deployed to take advantage of SLW is important. From the standpoint of timing, improved knowledge of when naturally occurring conditions for seeding are more likely to be present in the basin(s) of interest assists in the planning process. Such timing factors are not only important in real-time operations (ex: the scheduling of resources during ensuing 24 hour period) but, also in terms of the number of ‘opportunities’ available from a seasonal standpoint (i.e. the number and duration of storms on average). This study attempted to tackle both of these questions by examining a handful of locations across the state of Colorado where seasonal snowpack accumulates during the wintertime months. More specifically conditions were assessed with respect to the two following questions: 1) what are the atmospheric conditions (temperature, dewpoint, ect.) in place during periods when SLW might be present? This is important because the effectiveness of various weather modification techniques can be quite reliant on these exact conditions and 2) how often do ‘natural’ conditions exist, where SLW may exist at a given location?

This study attempted to examine some of these questions by examining a high-resolution, high-temporal objective analysis dataset of the atmosphere over extended periods of time. A calibration was performed over a period of time between data from the objective analysis and automated weather observations that were taken at relatively high altitudes, representative of where seeding agents would more likely be deployed. The results of this calibration period (the Winter of 2002-2003) were somewhat mixed as differences between the temperature-dewpoint spread between the analysis and the actual observations appear to agree in terms of long-term trends (i.e. multi-day periods) on a general basis. However, when examining a critical factor such as explicitly determining periods where the atmosphere is at/or near saturation, this database demonstrates certain deficiencies. A planned long-term extrapolation of the objective analysis conditions, with respect to this database was not performed due to time constraints. However, an analysis of a 3-year dataset of the in-situ observed data from the high-altitude stations were performed and some preliminary conclusions regarding the thermodynamic (i.e. temperature/dewpoint) and temporal conditions of the *potential* presence of SLW will be addressed.

Methodology

The objective analysis used in the study was the North American Regional Reanalysis (NARR) (Mesinger et. al. 2004) produced by the National Centers for Environmental Prediction (NCEP-NOAA). This re-analysis is performed at a much higher spatial and temporal resolution than prior reanalysis datasets that are currently available. The NARR utilized a 32-km resolution version of the ETA model forecast/analysis system with output produced every 3-hours from 1979 through 2003 (25 years). Output is available in 50 millibar intervals in the vertical coordinate 700 mb (about 10000' above sea-level) and above and in 25 mb intervals below 700mb. However, data below 700 mb was not considered due to the lower elevation of these levels. The data was acquired in GRIB format from NCEP and converted to a format compatible with the GEMPAK (General Meteorological Package) program. After the format conversion was completed, a routine was utilized to extract interpolated values from the analyses to the latitude and longitude of the high-altitude observations stations for direct comparison. The interpolated fixed-millibar data was then converted from a standardized ASCII text format into Microsoft Excel for post-processing.

The surface-based observations that were used as a source of verifications are high-altitude AWOS (Automated Weather Observing Stations) that have been placed at or near the top of various mountain ranges in Colorado. A major benefit of locations of these weather stations is to assist aviation concerns with regards to lower-level flight conditions in and near Colorado's mountains. A map showing the location of these stations can be seen in Figure 1.

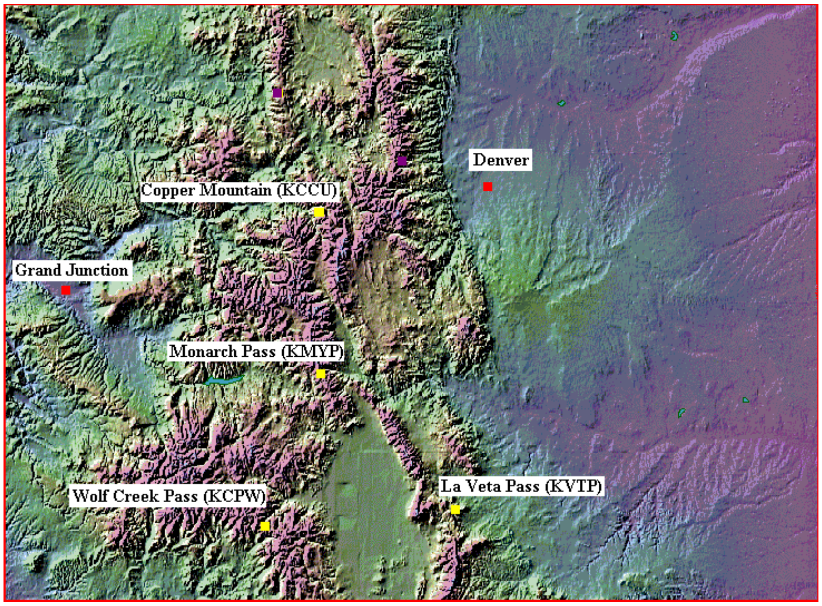

Figure 1. Topographic map of Colorado with the AWOS stations used in the study.

Four AWOS stations were used, Wolf Creek Pass (KPCW) , Copper Mountain (KCCU), Monarch Pass (KMYP) and La Veta Pass (KVTP). Two other stations, data from the

Storm Peak Lab, near Steamboat Springs and Corona Pass, positioned just east of the Continental Divide west-northwest of Denver were also planned on being used but, consistent data availability (esp. Corona Pass) and time constraints inhibited their inclusion. The other sites are distributed across the state in a relatively uniform format and were hoped to give some sense of the variability of conditions across the state. Actual observed data was collected from the National Climatic Data Center and formatted into Microsoft Excel. Since observations from the site are automated, observations are issued typically once every 20 minutes although intermittent gaps in the data did exist.

Results

NARR Analysis Dataset – AWOS Comparisons

The point-to-point comparisons of the AWOS and NARR data were accomplished by parsing the AWOS data to single out the closest observation to the time of the NARR analysis time. A majority of the time, this difference in time was no more than 10 minutes although, if data did not exist for a particular time, the 'window' for the surface observations was expanded to a 30-minute window centered on the NARR analysis time. As for resolving NARR data from the vertical perspective, a single level of data was used in the comparisons. This level was selected based on the average values of the geopotential height of the millibar level at the interpolated point. The differences between these values can be seen in Table 1 which shows the 'average' height of the analysis point and the fixed elevation of the AWOS sites.

AWOS Site	AWOS Elevation (ft.)	Interpolated NARR point used (MB)	Avg. height of NARR point. (ft.)	AWOS minus Avg.NARR (ft.)
KCCU	12070	650	12031	39
KMYP	12080	650	12056	24
KCPW	11756	650	12091	-335
KVTP	10214	700	10142	72

Table 1. Elevation of the AWOS sites and 'average' elevation of the corresponding NARR interpolated data point.

Monthly comparisons between the interpolated NARR values and corresponding observed AWOS data values were extracted for the period of November 2002 to April 2003. The first variable was a comparison of the Air Temperature – Dewpoint difference at given observation times. This was performed to examine the NARR's ability to detect observed conditions that were at, or near saturation. A second variable observed was the concurrent differences between air temperature of the AWOS observations and the NARR data. A graphical summary of these variables can be found in the Data Appendix. From this analysis, the following generalized conclusions can be made:

1) The ability of the NARR to detect periods of saturation/near saturation is affected by an apparent bias towards under-analyzing atmospheric moisture content.
2) 3-hourly by 3-hourly changes in the difference between the air temperature of the NARR and the AWOS sites show a definitive pattern of a problem with diurnal oscillations in temperatures. This is apparently due to the NARR's inability to properly detect the diurnal fluctuations of daily temperatures as rapidly as that of the actual observed data.

The NARR dataset was also separated and analyzed with respect to the ability of the NARR to detect saturated or near saturated conditions during observation periods where two specific categories of conditions were met:

1) AWOS observations where the difference between the air temperature and dewpoint were 3 C or less and the observed air temperature was between -2 C and -7 C.
2) AWOS observations where the difference between the air temperature and dewpoint were 3 C or less and the observed air temperature was between -7 C and -15 C.

This establishment of these two parameters was made based on information provided by a summary of various research efforts by Super and Heinbach (2005). Although site-specific variations may exist, in general, the use of AgI as a seeding agent is considered to reach its' peak efficiency at temperatures below -7 C and above -15 C , assuming that SLW is present. The use of propane as a seeding agent can work at a warmer range of temperatures with a maximum efficiency from -2 C to -7 C, again assuming that SLW is present in a cloud layer. For the purpose of brevity, these conditions were classified as 'warm cloud' (WC) and 'cold cloud' (CC) respectively.

The following tables show the percent of time when the values of the NARR temperature-dewpoint spread is 1) 3 C, or less 2) between 3 and 6 C or 3) greater than 6 C and the observed AWOS conditions were met were either in the WC or CC category as defined above.

Station – KCCU	'Warm Cloud' (T-Td ≤ 3C) and (-2C≤T≤-7C)
NARR T-Td ≤ 3 C	25.5%
3C < NARR T-Td ≤ 6 C	25.5%
NARR T-Td ≥ 6 C	48.9%

Table 2. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KCCU during potential 'Warm Cloud' conditions.

Station – KCCU	‘Cold Cloud’ (T-Td ≤ 3C) and (-7C≤T≤-15C)
NARR T-Td ≤ 3 C	50.1%
3C < NARR T-Td ≤ 6 C	25.1%
NARR T-Td ≥ 6 C	24.8%

Table 3. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KCCU during potential ‘Cold Cloud’ conditions.

Station – KMYP	‘Warm Cloud’ (T-Td ≤ 3C) and (-2C≤T≤-7C)
NARR T-Td ≤ 3 C	11.4%
3C < NARR T-Td ≤ 6 C	30.7%
NARR T-Td ≥ 6 C	58.0%

Table 4. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KMYP during potential’ Warm Cloud’ conditions.

Station – KMYP	‘Cold Cloud’ (T-Td ≤ 3C) and (-7C≤T≤-15C)
NARR T-Td ≤ 3 C	22.8%
3C < NARR T-Td ≤ 6 C	39.9%
NARR T-Td ≥ 6 C	37.3%

Table 5. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KMYP during potential ‘Cold Cloud’ conditions.

Station – KCPW	‘Warm Cloud’ (T-Td ≤ 3C) and (-2C≤T≤-7C)
NARR T-Td ≤ 3 C	15.8%
3C < NARR T-Td ≤ 6 C	20.5%
NARR T-Td ≥ 6 C	63.7%

Table 6. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KCPW during potential ‘Warm Cloud’ conditions.

Station – KCPW	‘Cold Cloud’ (T-Td ≤ 3C) and (-7C≤T≤-15C)
NARR T-Td ≤ 3 C	16.7%
3C < NARR T-Td ≤ 6 C	40.7%
NARR T-Td ≥ 6 C	63.7%

Table 7. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KCPW during potential ‘Cold Cloud’ conditions.

Station – KVTP	‘Warm Cloud’ (T-Td ≤ 3C) and (-2C≤T≤-7C)
NARR T-Td ≤ 3 C	14.6%
3C < NARR T-Td ≤ 6 C	29.8%
NARR T-Td ≥ 6 C	55.6%

Table 8. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KVTP during potential ‘Warm Cloud’ conditions.

Station – KVTP	‘Cold Cloud’ (T-Td ≤ 3C) and (-7C≤T≤-15C)
NARR T-Td ≤ 3 C	21.5%
3C < NARR T-Td ≤ 6 C	52.3%
NARR T-Td ≥ 6 C	26.2%

Table 9. Percent of time when interpolated NARR temperature – dewpoint spreads were in various categories at KVTP during potential ‘Cold Cloud’ conditions.

The preceding data suggests that the NARR’s ability to detect a near saturated atmosphere during conditions that the AWOS data suggests that SLW might exist is far less than optimal. This data suggests that it could be quite difficult to ascertain the number of hours where SLW may exist through NARR interpolation, unless a more robust or sophisticated statistical adjustment was applied on a station-by-station basis.

AWOS Observation Dataset Analysis

In the above section, the raw data from the NARR appear to show that if anything, this dataset will notably under predict the number of hours where the temperature/dewpoint combinations are thermodynamically in the range where SLW may exist at or just above mountain ridge top locations. With this in mind, the attention for the remainder of this study was shifted to the actual observed data from the AWOS site. The original component of the NARR study was expected to analyze 25 years of data. However, the winter of 2002-2003 was the first winter season where the AWOS data was complete. Since this time, there have been two more complete winter seasons where AWOS data was collected and archived at the NCDC, 2003-2004 and 2004-2005.

All of the available observation data from these stations for these three seasons were compiled and separated into their respective months' for the October to April period. Then the same 'warm cloud' and 'cold cloud' conditions were established and the data parsed to determine the following: What is the percentage of time (vs. the total amount of observations) where 'Warm Cloud' and 'Cold Cloud' conditions could potentially exist? The author readily admits that the relationships of actual surface observations to actual inferences of SLW are not 1:1. However, it is hoped that this data will shed some initial light as to the potential distribution of thermodynamic conditions in place when SLW has the potential to be present at/near mountain crest barriers. The results can be found in the tables below:

Station - KCCU			
Month	% of Observ. w/ Potential 'Cold Cloud' conditions	% of Observ. w/ Potential 'Warm Cloud' conditions	Total % of Observ. w/ Potential SLW conditions (WC & CC)
October	4.3 %	6.6 %	10.9%
November	26.5 %	14.4 %	40.9%
December	26.9 %	5.0 %	31.9%
January	36.9 %	9.5 %	46.4%
February	30.2 %	5.9 %	36.1%
March	26.9 %	8.4 %	35.3%
April	16.2 %	20.1 %	26.3%

Table 10. Percentage of observations where the KCCU AWOS sites indicates potential 'Cold Cloud' and 'Warm Cloud' conditions for the winters of 2002-3, 2003-4 and 2004-5.

Station - KMYP			
Month	% of Observ. w/ Potential 'Cold Cloud' conditions	% of Observ. w/ Potential 'Warm Cloud' conditions	Total % of Observ. w/ Potential SLW conditions (WC & CC)
October	3.9 %	10.2 %	14.1%
November	27.4 %	21.9 %	49.3%
December	33.7 %	14.4 %	48.1%
January	38.6 %	17.7 %	56.3%
February	46.9 %	9.5 %	56.4%
March	30.2 %	11.7 %	41.9%
April	16.4 %	19.8 %	36.2%

Table 11. Percentage of observations where the KMYP AWOS sites indicates potential 'Cold Cloud' and 'Warm Cloud' conditions for the winters of 2002-3, 2003-4 and 2004-5.

Station - KCPW			
Month	% of Observ. w/ Potential 'Cold Cloud' conditions	% of Observ. w/ Potential 'Warm Cloud' conditions	Total % of Observ. w/ Potential SLW conditions (WC & CC)
October	1.0 %	11.0 %	12.0%
November	16.6 %	23.6 %	40.2%
December	34.8 %	9.8 %	44.6%
January	17.8 %	20.3 %	38.1%
February	41.9 %	19.3 %	61.3%
March	17.3 %	20.3 %	37.4%
April	10.0 %	25.3 %	35.4%

Table 12. Percentage of observations where the KCPW AWOS sites indicates potential 'Cold Cloud' and 'Warm Cloud' conditions for the winters of 2002-3, 2003-4 and 2004-5.

Station - KVTP			
Month	% of Observ. w/ Potential 'Cold Cloud' conditions	% of Observ. w/ Potential 'Warm Cloud' conditions	Total % of Observ. w/ Potential SLW conditions (WC & CC)
October	1.4 %	2.2 %	3.6%
November	4.5 %	16.4 %	20.9%
December	16.8 %	17.6 %	34.4%
January	8.8 %	20.6 %	29.4%
February	15.1 %	25.1 %	40.2%
March	7.2 %	16.0 %	23.2%
April	0.3 %	17.8 %	18.1%

Table 13. Percentage of observations where the KVTP AWOS sites indicates potential 'Cold Cloud' and 'Warm Cloud' conditions for the winters of 2002-3, 2003-4 and 2004-5.

These results should not be construed as a complete 'climatology' given that the data comes from only a three-year period of record however, the number of observations that were counted in this study averaged on the order of 4000 per months' worth of data. This is thanks in large part due to the extremely high temporal nature in which the AWOS station records data. Nevertheless, should these preliminary results act as a 'mirror' into the characteristics of the thermodynamic conditions in these regions we would draw the following conclusions:

1) The distribution of the number of observations where either 'cold cloud' or 'warm cloud' conditions exist tend to peak in the December to February period as one might expect. However, the data also suggests that a fair number of hours where

SLW may exist in the months of March and April. This can be of notable importance in years where the mid-to-late winter snowpack is verifying below long-term seasonal normals. However, the month of October holds little potential for significant period of potential SLW regardless of location.

2) Data from the two sites in the central mountains (KCCU and KMYP) tend to suggest that 'cold cloud' conditions exist for longer periods of time than 'warm cloud' conditions might. This trend holds for most of the period when significant snows can fall through March. The two sites in the southern tier of the state (KCPW and KVTP) suggests that significant opportunities exist for both AgI and propane-based precipitation augmentation efforts. In the case of KCPW, this is true 'on the edges' of winter as the number of hours with potential 'cold cloud' conditions is greater in November, March and April. For KVTP, this site is not only further south but, also at a lower elevation (just above 10,000') and indicates that propane could be a better augmentation agent in the long run. Snowpack in the 10,000'-11,000' range is important for significant snowpack accumulates in these elevations that result in spring-summer runoff.

Conclusions

The use of a standardized dataset to determine the long-term potential for Supercooled, Liquid Water, the key ingredient in successful 'cold season' precipitation augmentation, still remains somewhat elusive in the absence of in-situ observations. The potential use of the relatively high temporal and spatial characteristics of the North American Regional Reanalysis (NARR) should be considered to be a cumbersome and challenging dataset for the purposes of determining climatology of SLW potential. In addition, an examination of the NARR-AWOS observations indicates that some challenges may arise in the relatively complex terrain of the Rocky Mountains with regards to the NARR data. The best potential to determine longer-term climatologies may still lie in near ridge top in-situ observations. As of January 2006, a number of new real-time AWOS stations have been added to the higher elevations of the state. These stations, in concert with the stations used in this study could provide more firm insight into the spatial and temporal construction of weather modification programs in Colorado.

The examination of the 3 years of real-time, ridge top data that was available indicates that a good number of opportunities appear to exist for precipitation augmentation efforts, even if the true number of opportunities for SLW presence is a third of the number of hours indicated by the AWOS data. In addition, this limited amount of data also suggests that lower elevation barriers and barriers located further south in the state (e.g. the San Juans and Sangre de Cristos) could further benefit from the use of propane as an agent for precipitation modification either in concert with AgI or as a stand alone agent. However, the data also suggests that early season and 'spring' snows in the Central Mountains could benefit from a 'stand-by' propane based program especially if late season snowpacks are lagging seasonal averages but, the spring brings a seasonal amount of

SLW opportunites. Also, an extrapolated look at the number of periods of potential SLW presence in the late winter and spring months (Feb.-Apr) can be almost as important as the ‘core’ months of December and January. This is particularly useful knowledge in years where mid-winter snowpacks are severely lagging long-term averages.

References

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Super A.B and Heimbach, J.A. 2005: Feasibility of Snowpack Enhancement from Colorado Winter Mountain Clouds: Emphasis on Supercooled Liquid Water and Seeding with Silver Iodide and Propane. Report to the U.S. Bureau of Reclamation, Technical Services Center.

Data Appendix – Climatology of Supercooled Liquid Water in Colorado

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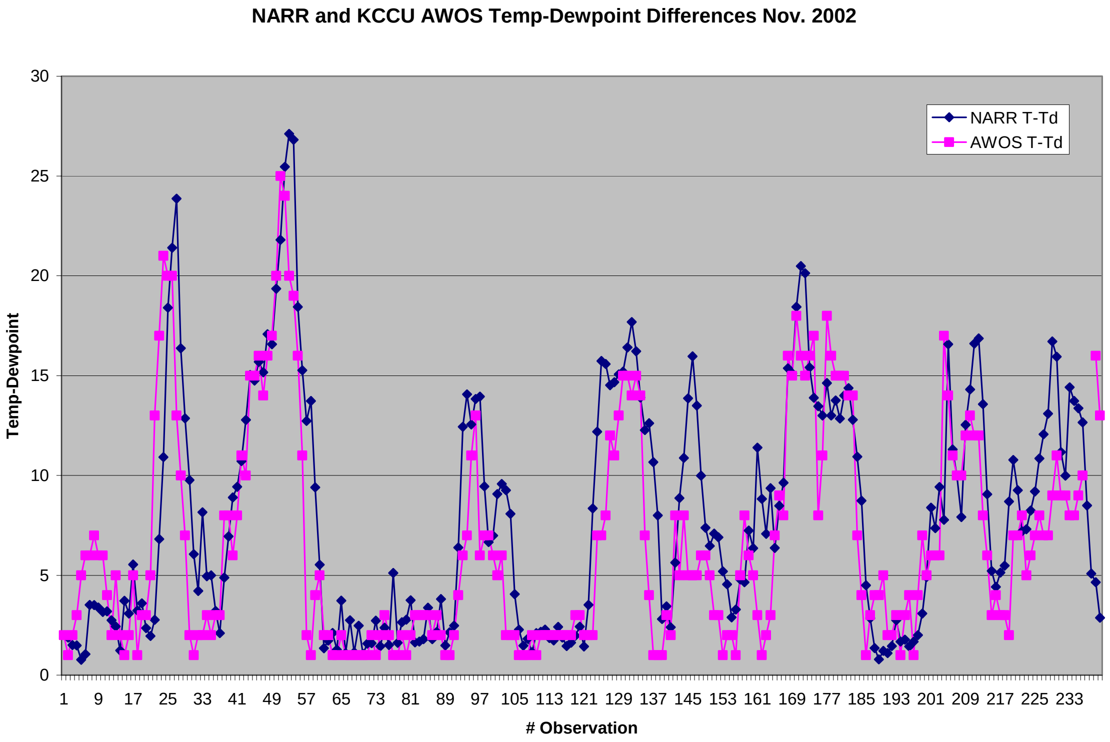
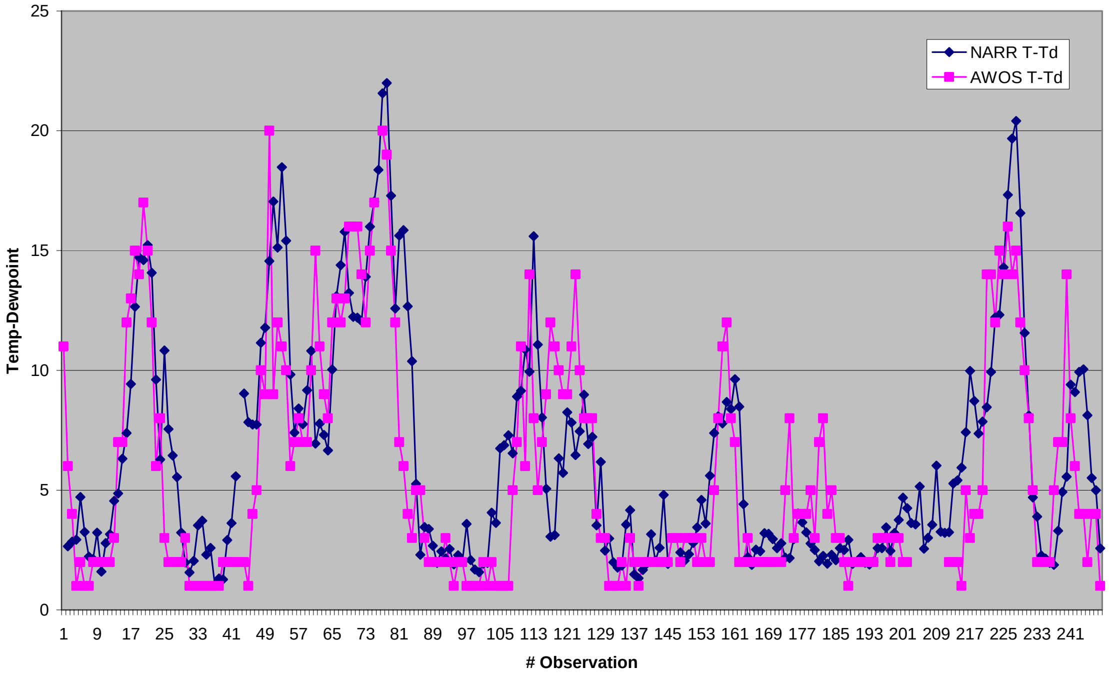
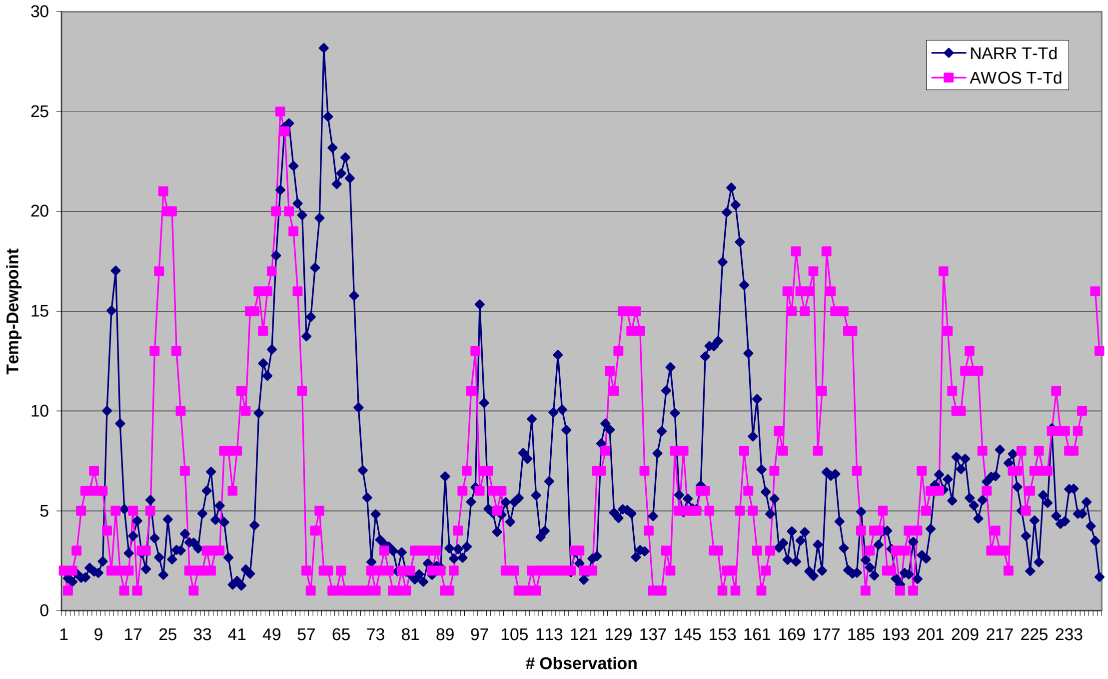
Charts of Temperature – Dewpoint spreads between the NARR and AWOS observations for the November 2002 to April 2003 period.



NARR and KCCU AWOS Temp-Dewpoint Differences Dec. 2002



NARR and KCCU AWOS Temp-Dewpoint Differences Jan 2003



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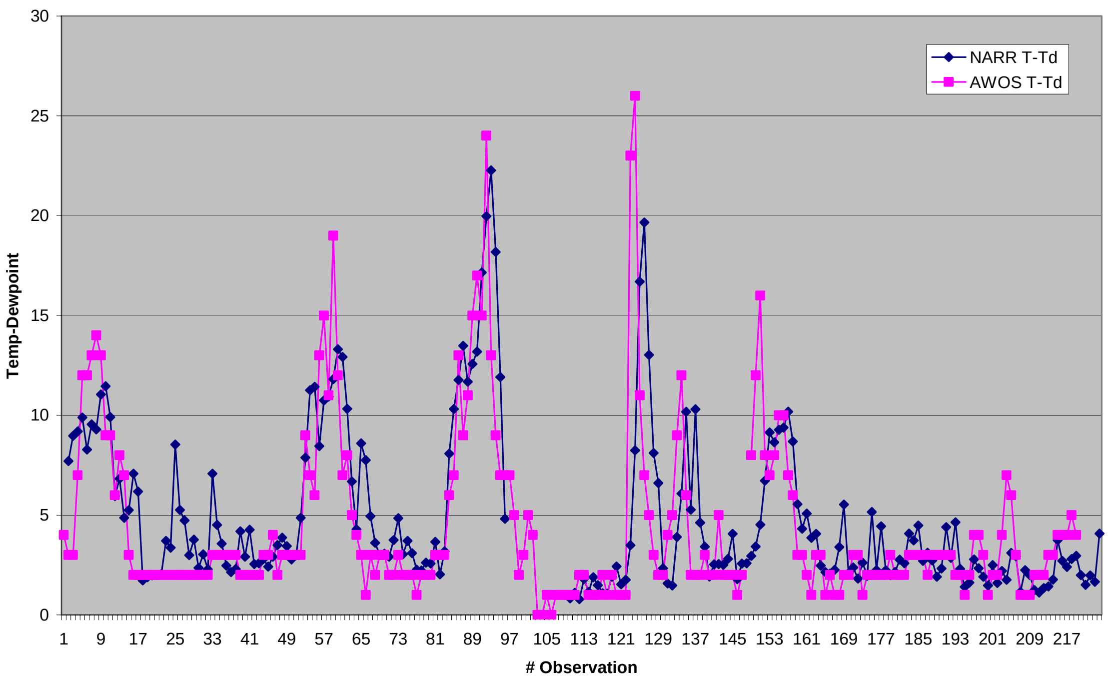
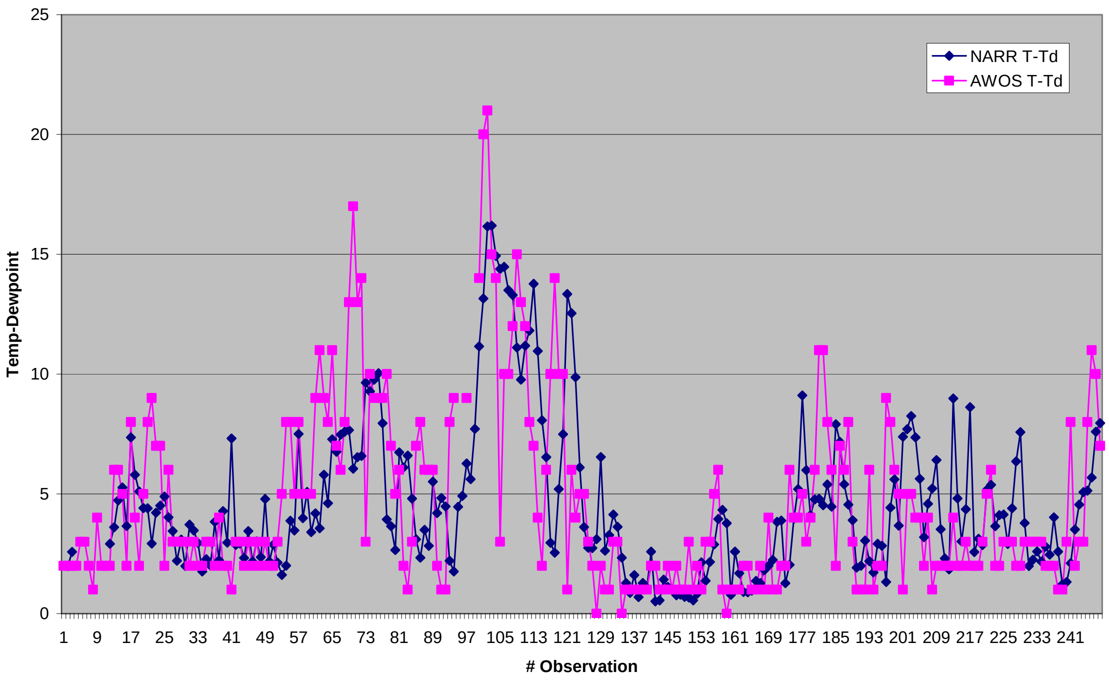
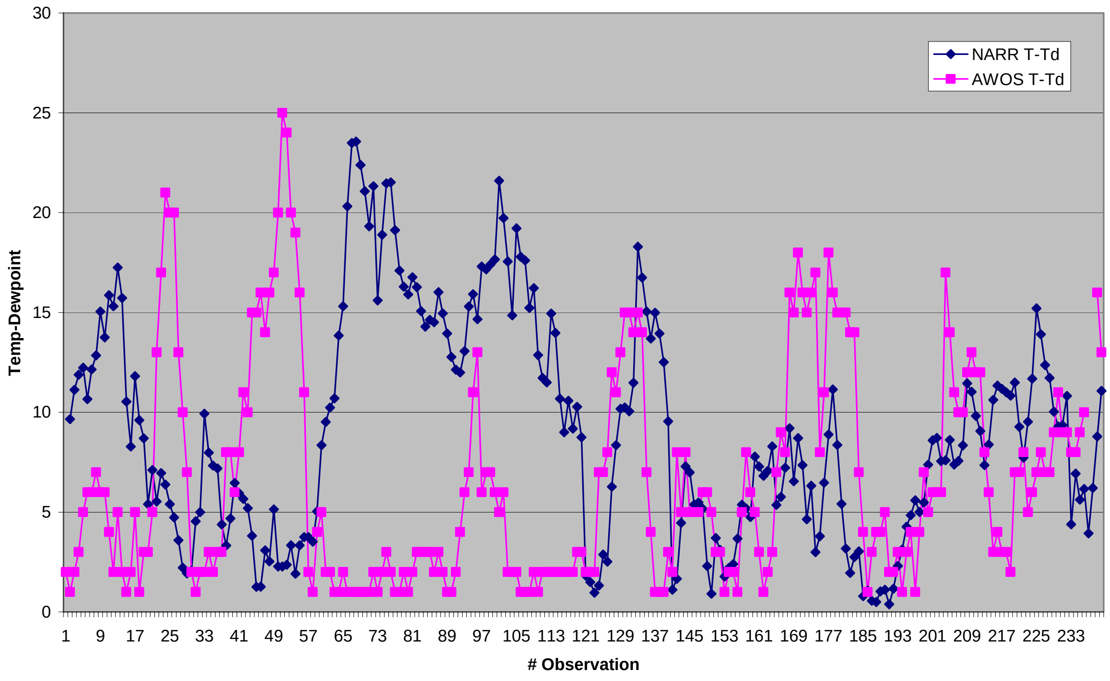
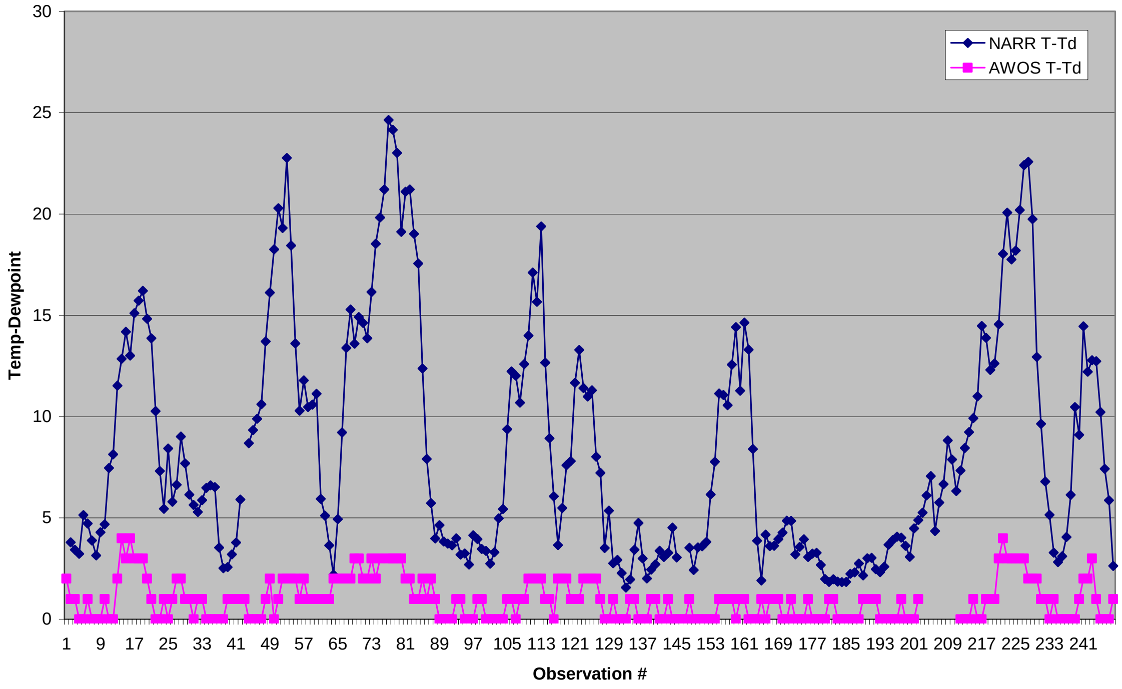


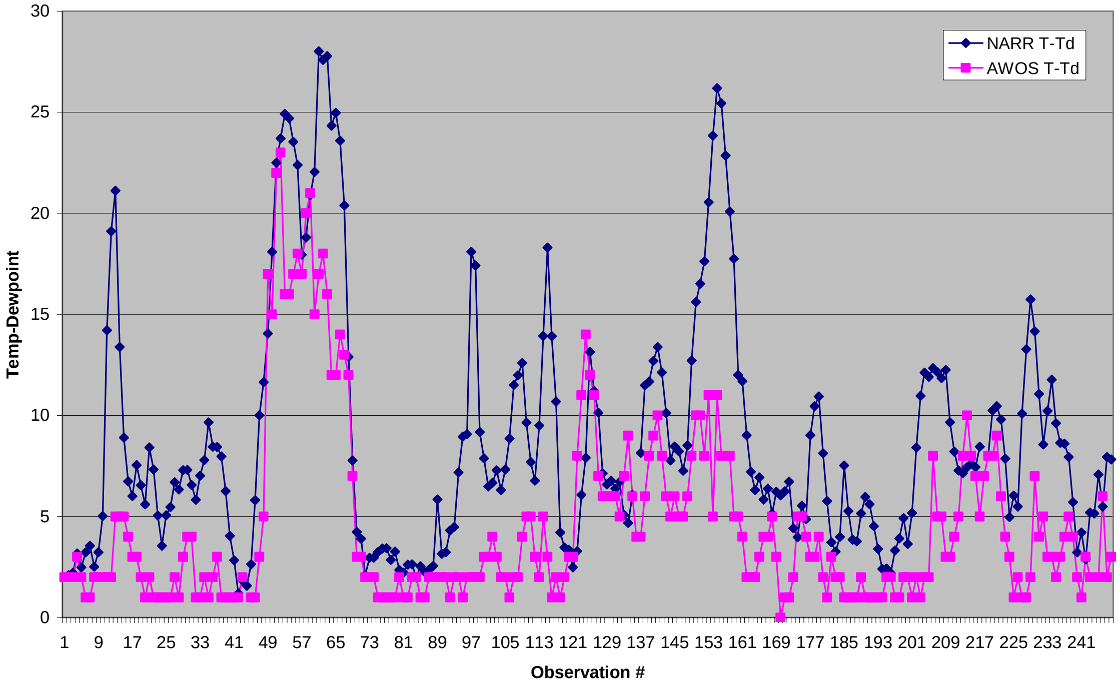
NARR and KCCU AWOS Temp-Dewpoint Differences Mar 2003



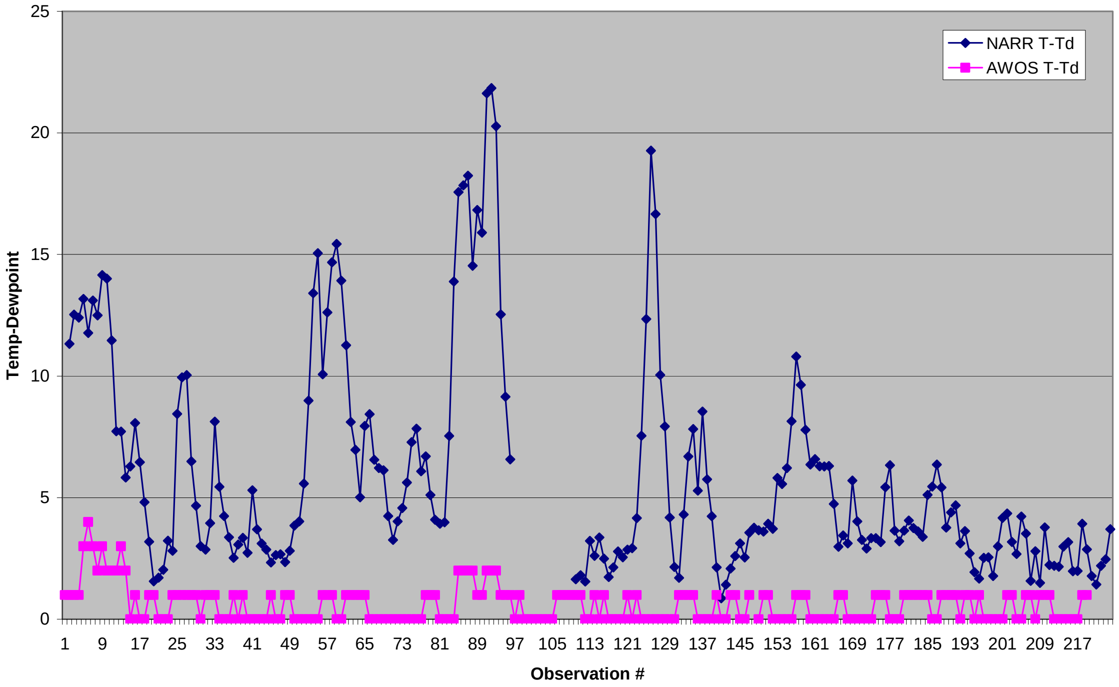

Interpolated NARR and KCCU AWOS Temp-Dewpoint Differences Apr 2003


NARR and KMYP AWOS Temp-Dewpoint Differences Dec. 2002

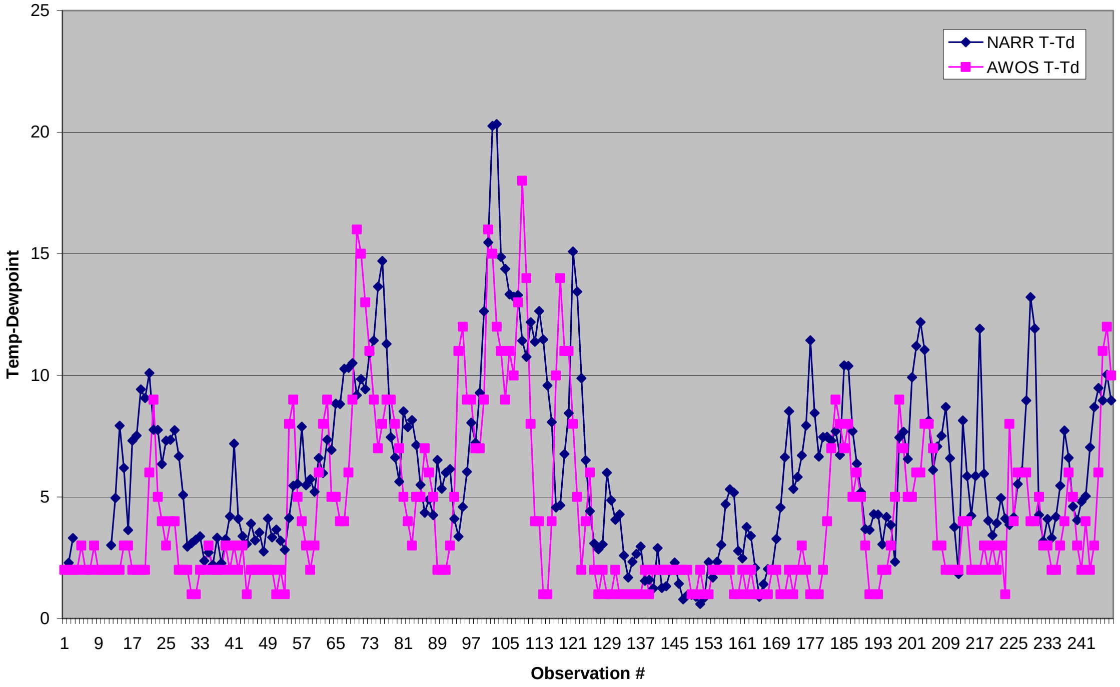
NARR and KMYP AWOS Temp-Dewpoint Differences Jan 2003



NARR and KMYP AWOS Temp-Dewpoint Differences Feb 2003



NARR and KMYP AWOS Temp-Dewpoint Differences Mar 2003



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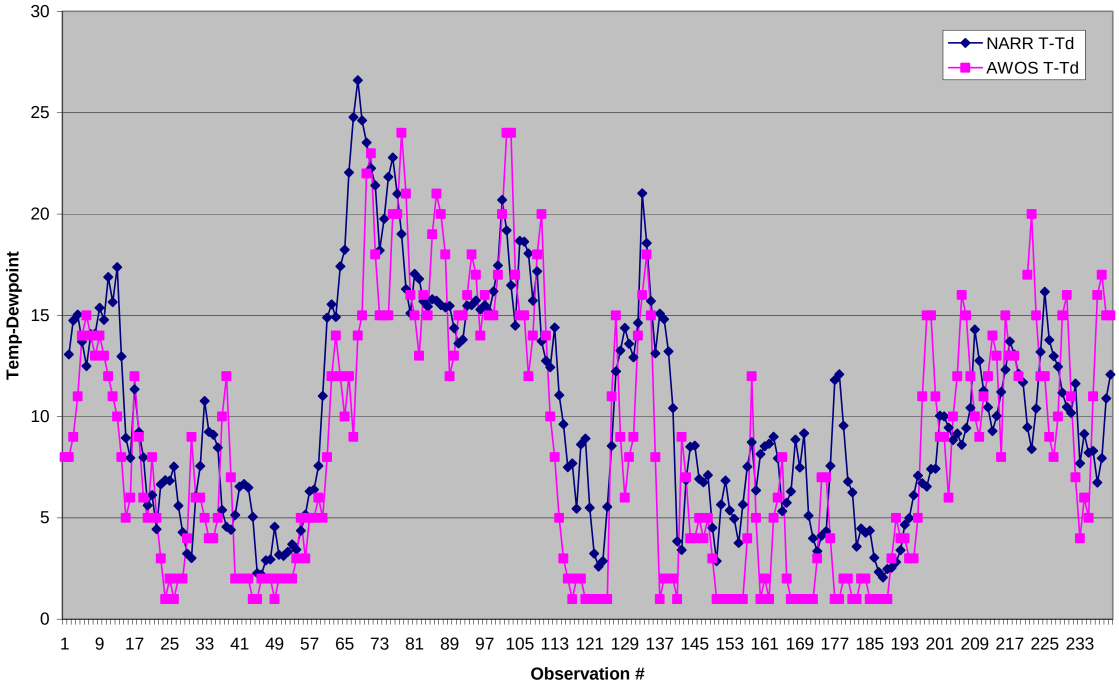

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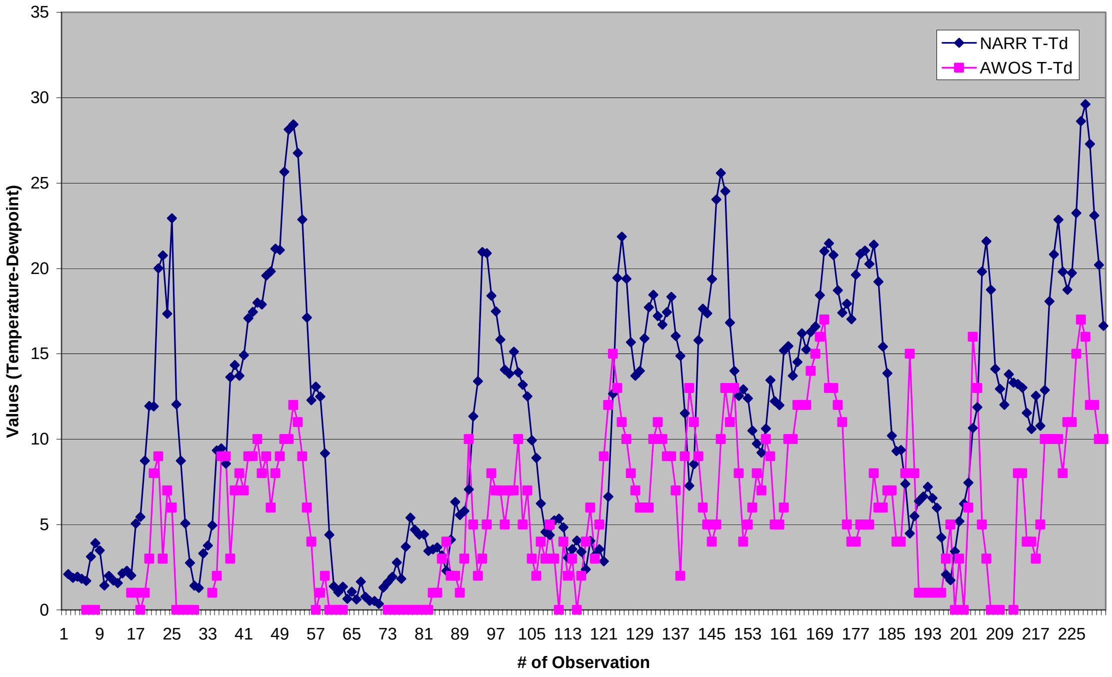

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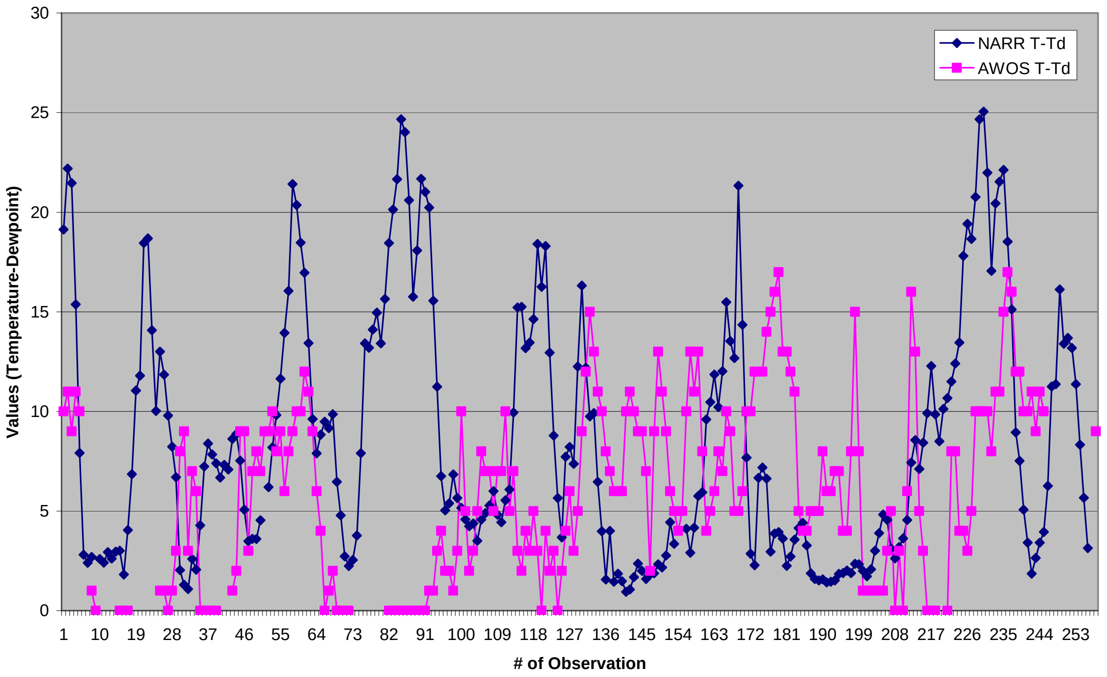
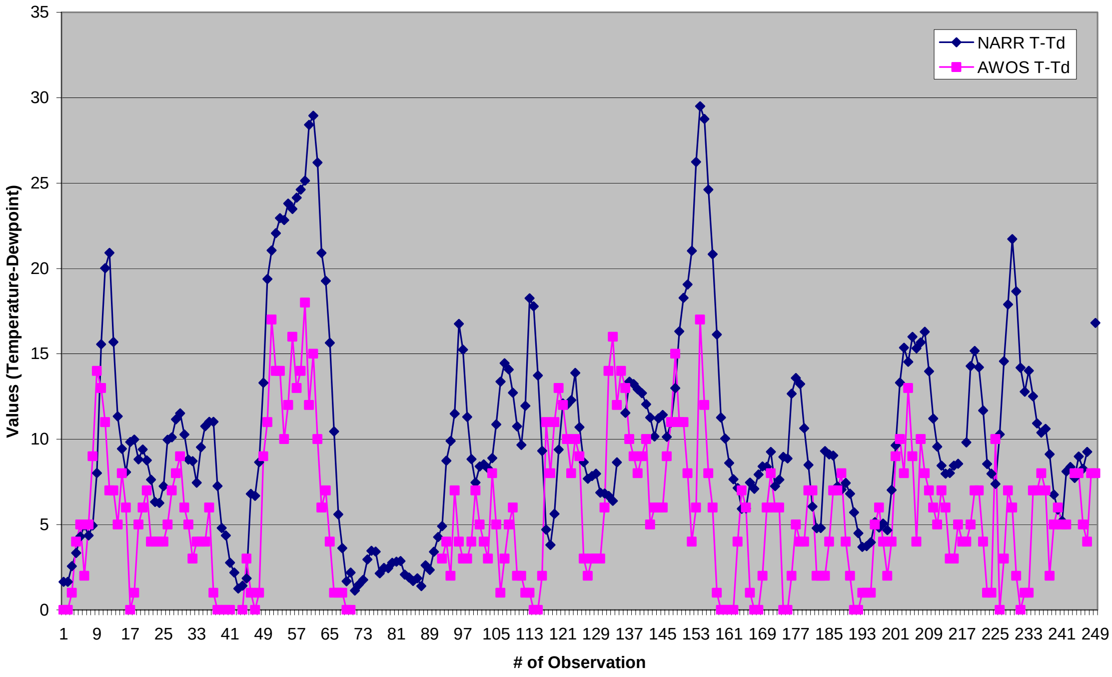


NARR and KCPW - AWOS Temp-Dewpoint DifferencesJan. 2003



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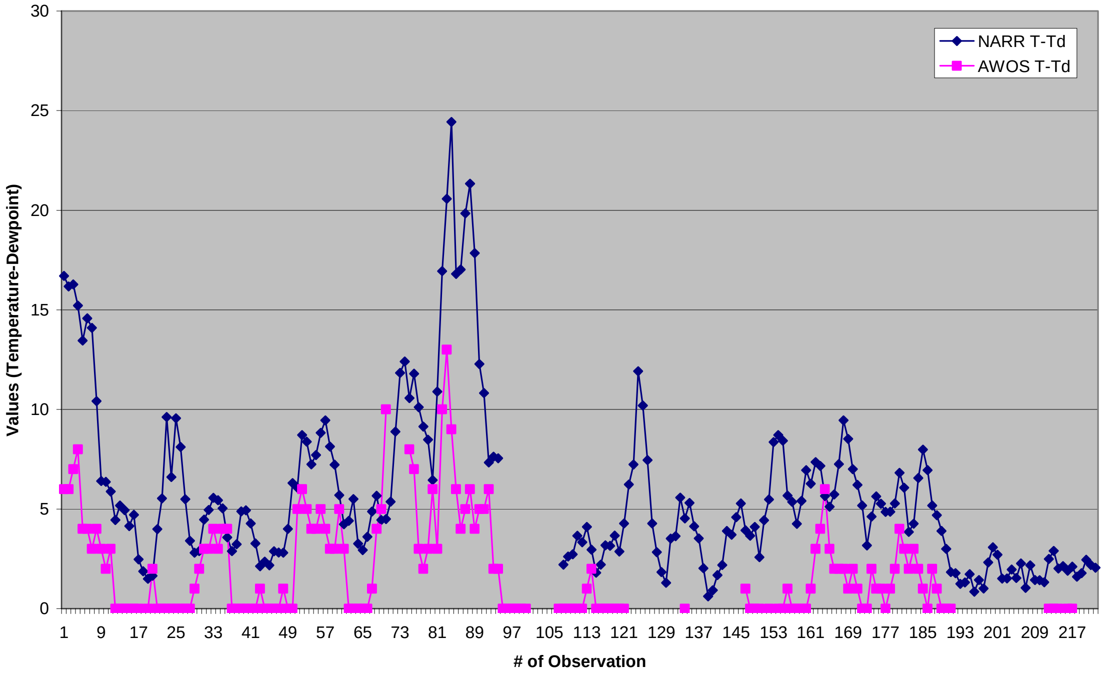

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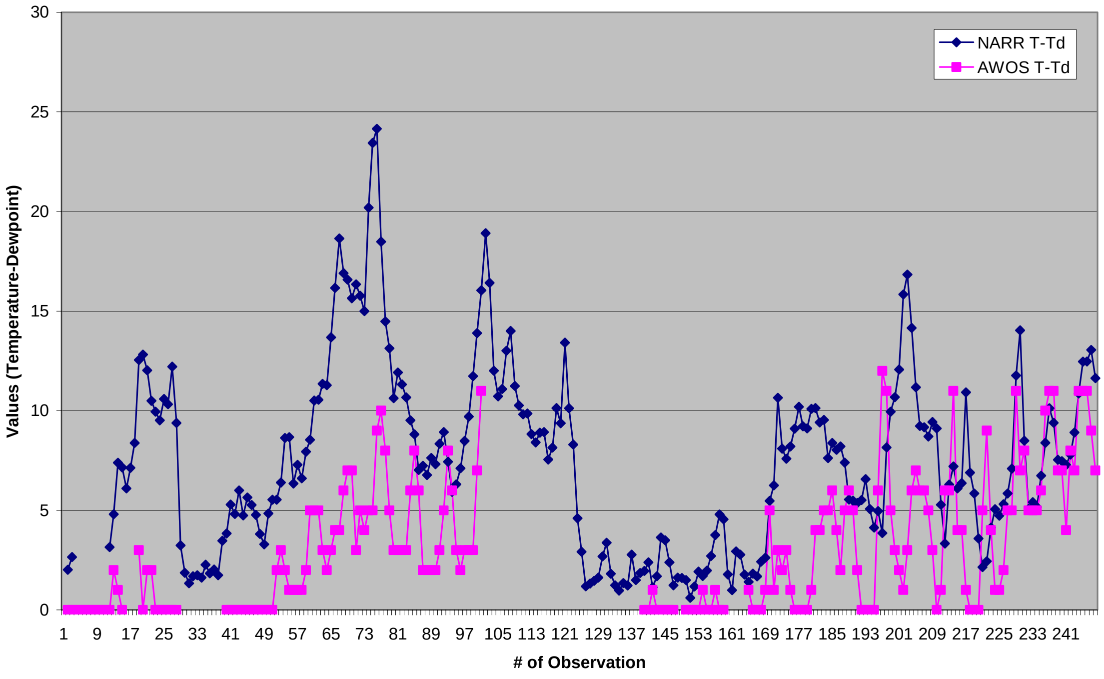

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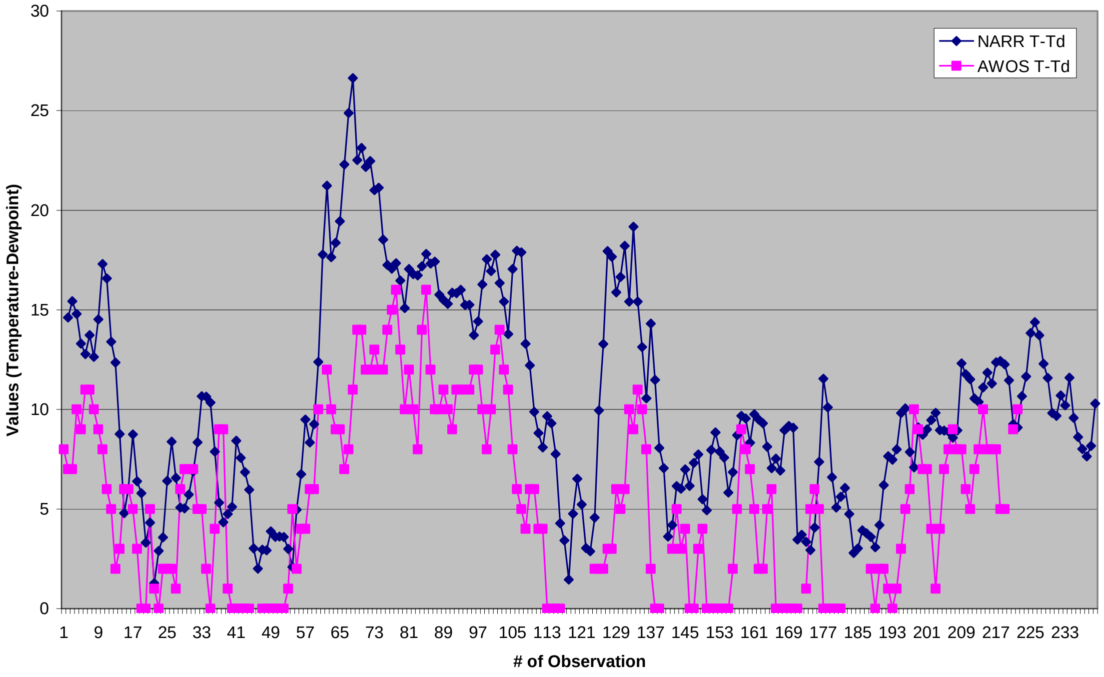
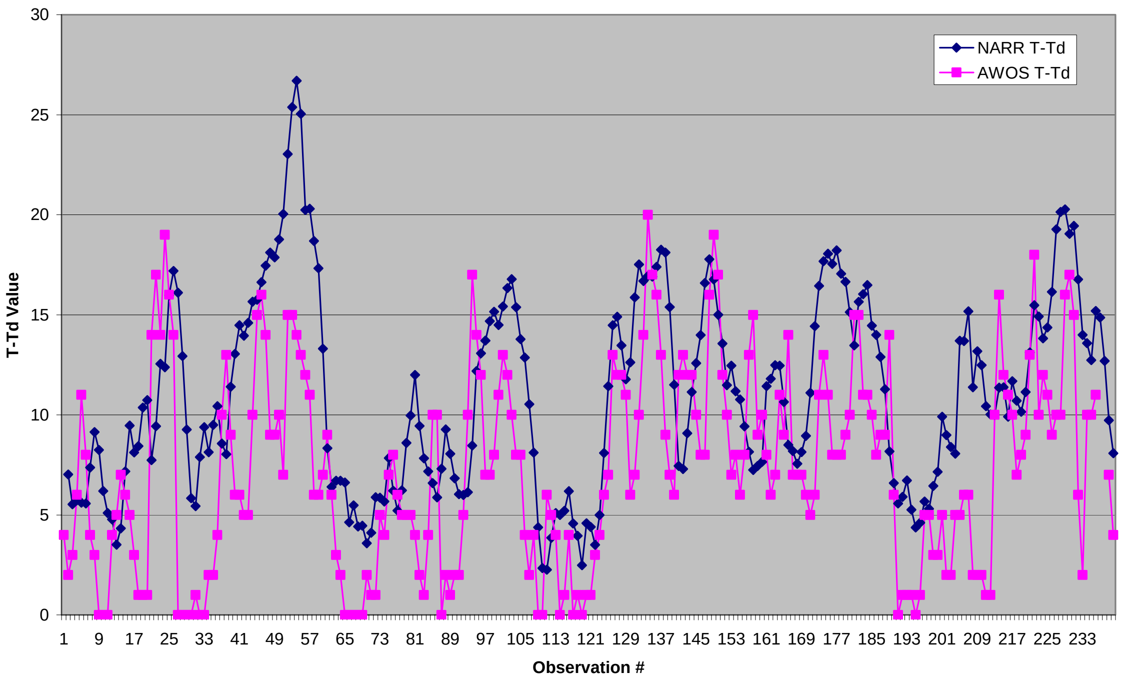


NARR and KVTP AWOS Temp-Dewpoint Differences Nov. 2002



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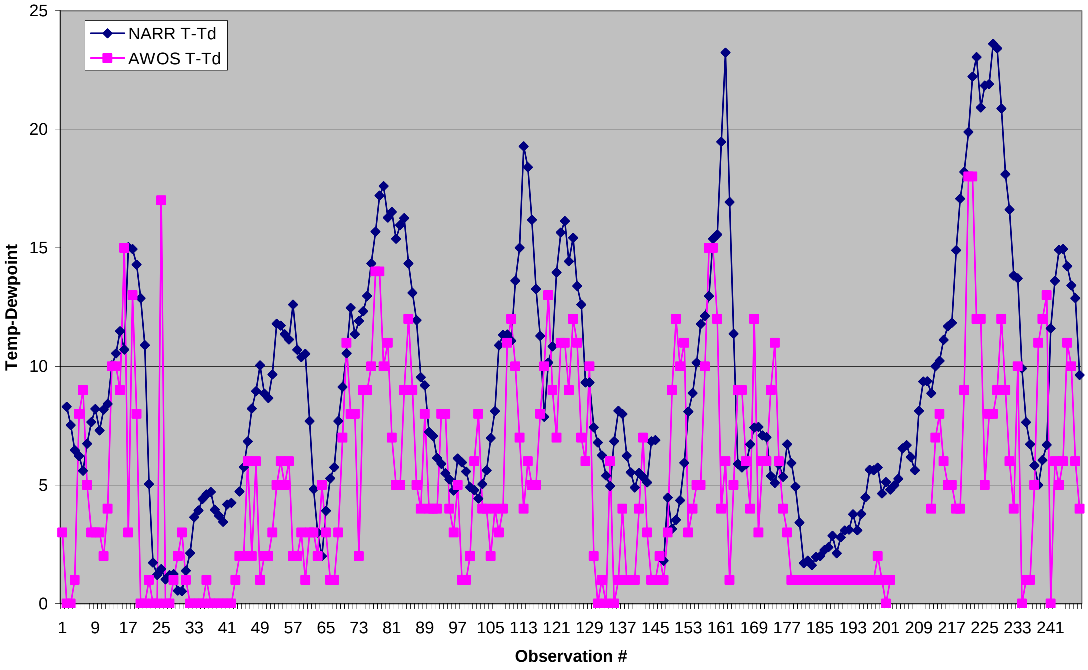

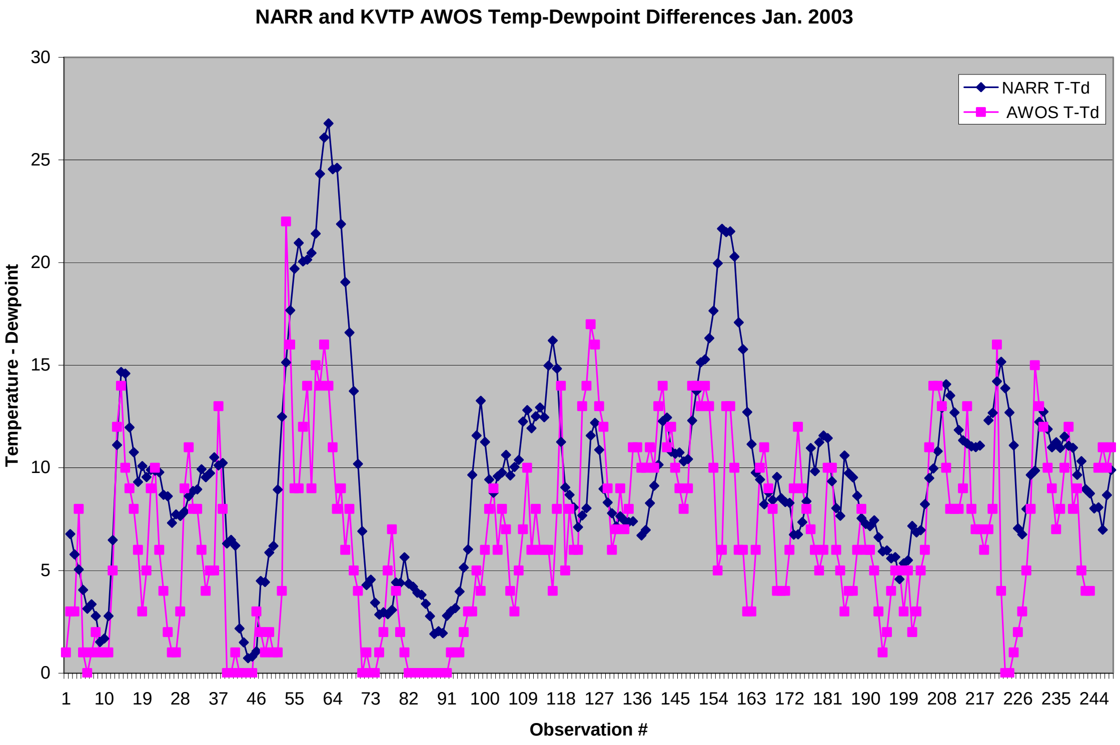
NARR and KVTP AWOS Temp-Dewpoint Differences Jan. 2003
NARR T-Td
AWOS T-Td
Temperature - Dewpoint
0
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28
37
46
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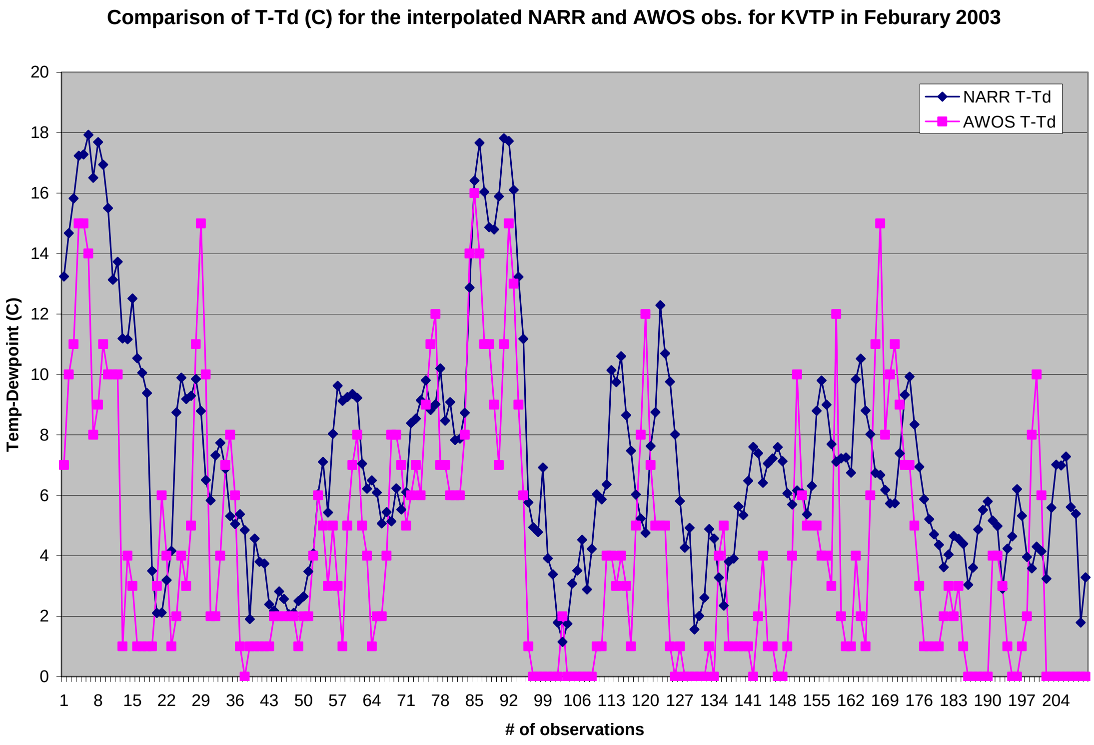
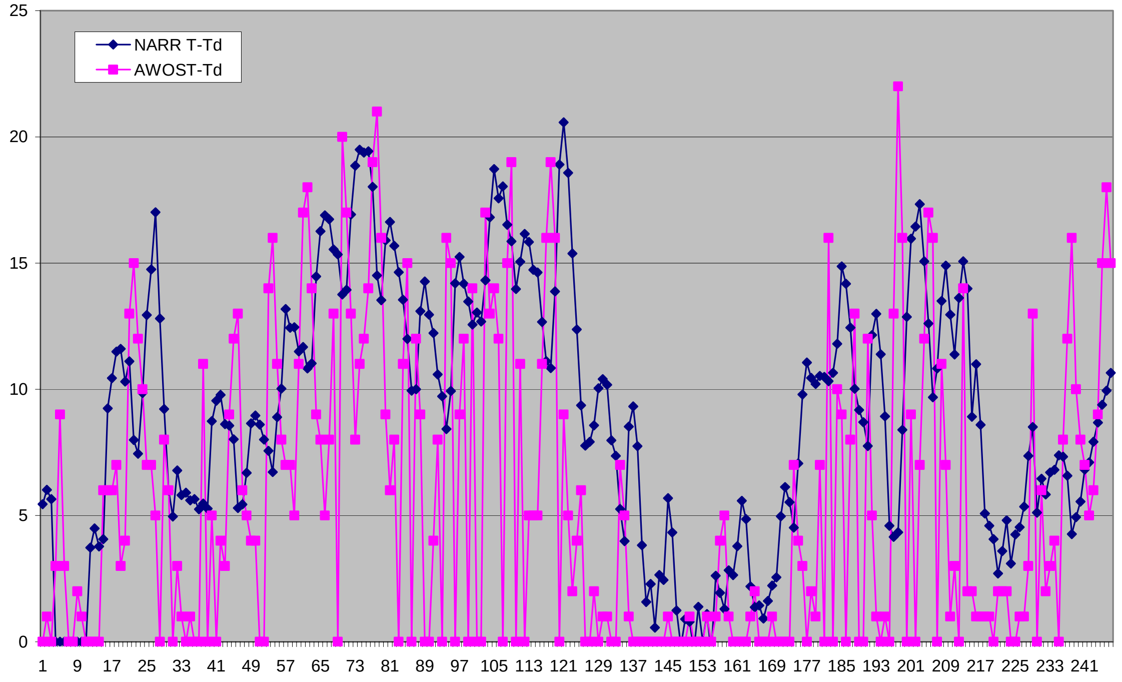
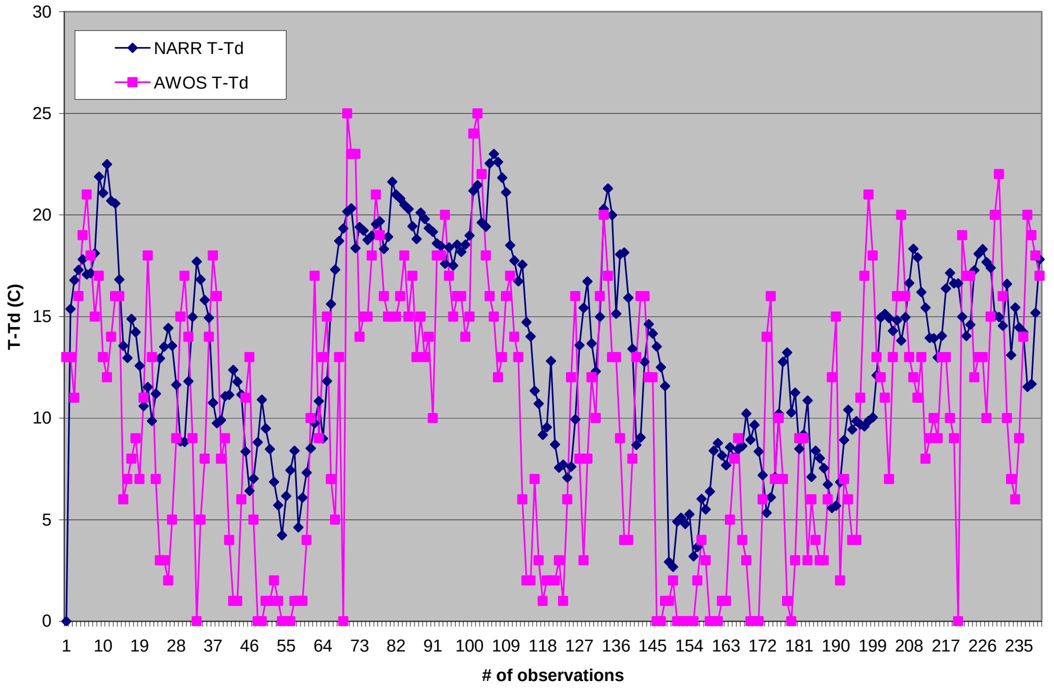
64
73
82
91
100
109
118
127
136
145
154
163
172
181
190
199
208
217
226
235
244
Observation #


Comparison of T-Td (C) for the interpolated NARR and AWOS obs. for KVTP in Feburary 2003
NARR T-Td
AWOS T-Td
Temp-Dewpoint (C)
0
2
4
6
8
10
12
14
16
18
20
1
8
15
22
29
36
43
50
57
64
71
78
85
92
99
106
113
120
127
134
141
148
155
162
169
176
183
190
197
204
# of observations

Comparison of T-Td (C) for the interpolated NARR and AWOS obs. for KVTP in March 2003

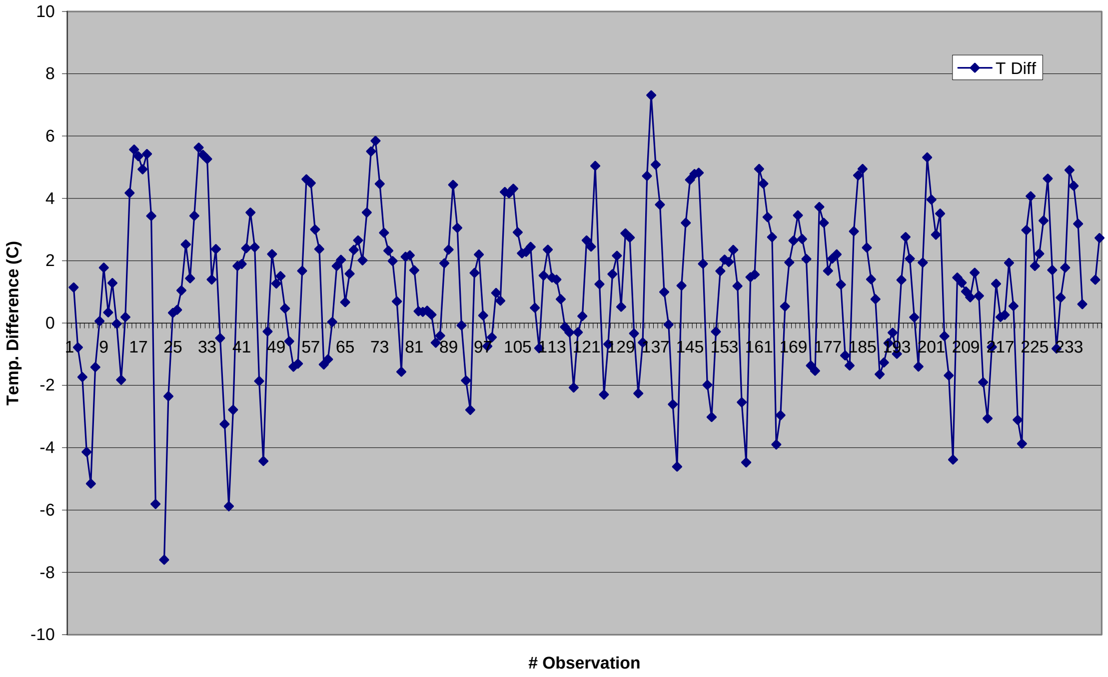


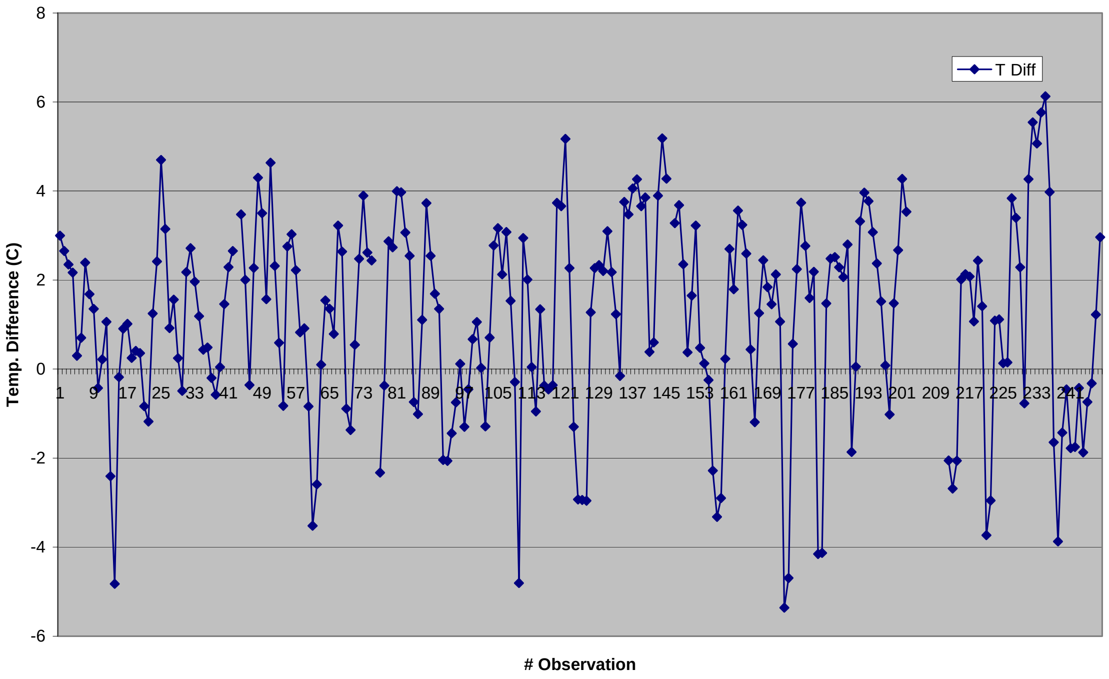
Comparison of T -Td of the interpolated NARR and AWOS observations for April 2003

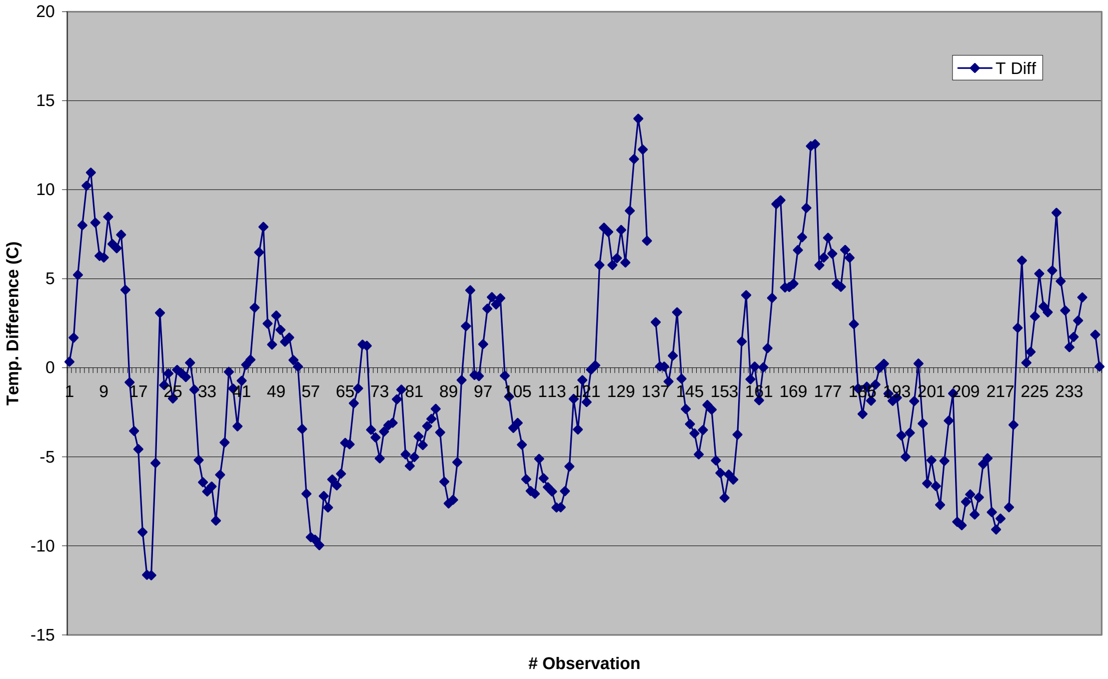


Charts of Temperature differences between the NARR and AWOS observations for the various sites for the period of November 2002 to April 2003.

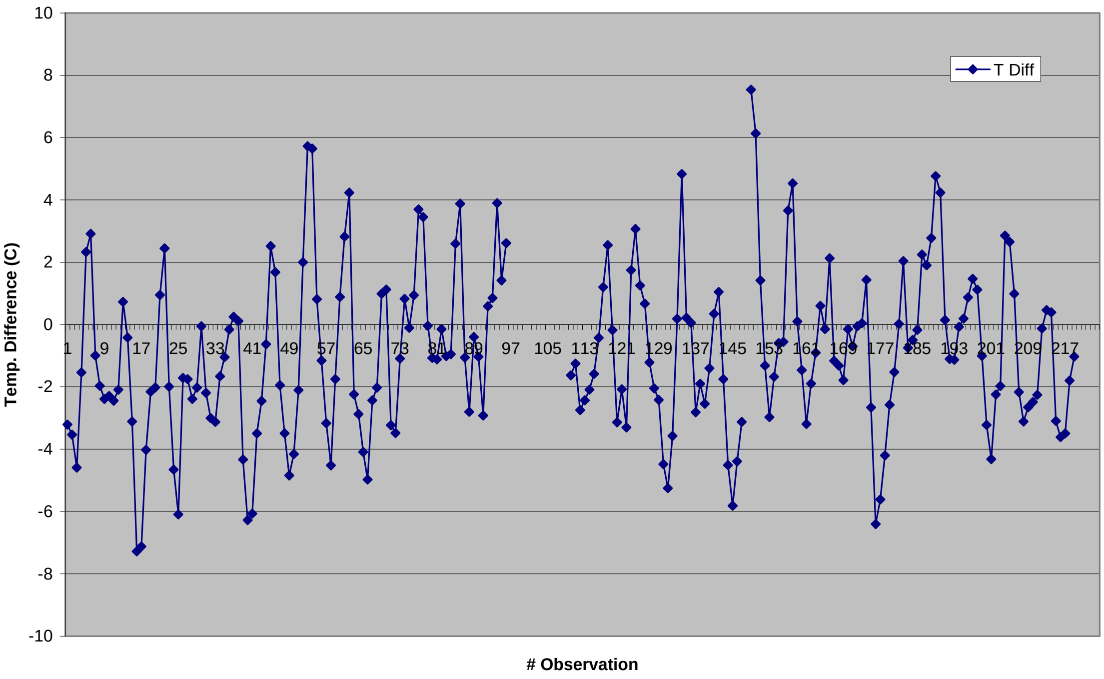
NARR and KCCU AWOS Temp Differences Nov. 2002



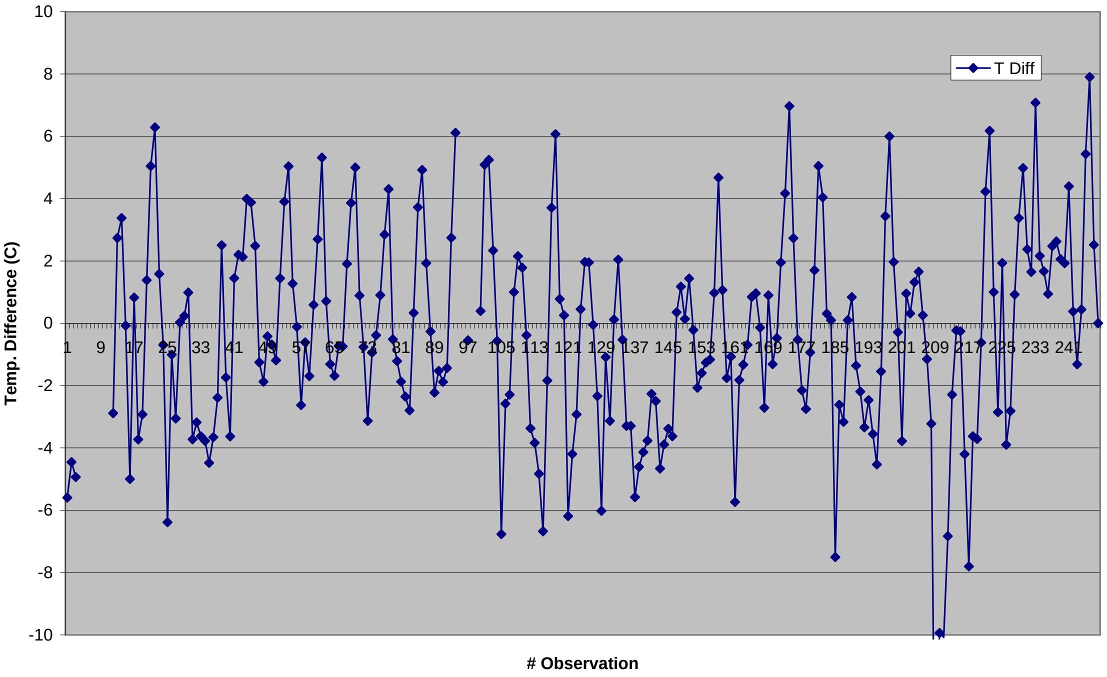

NARR and KCCU AWOS Temp Differences Dec. 2002


NARR and KCCU AWOS Temp Differences Jan 2003

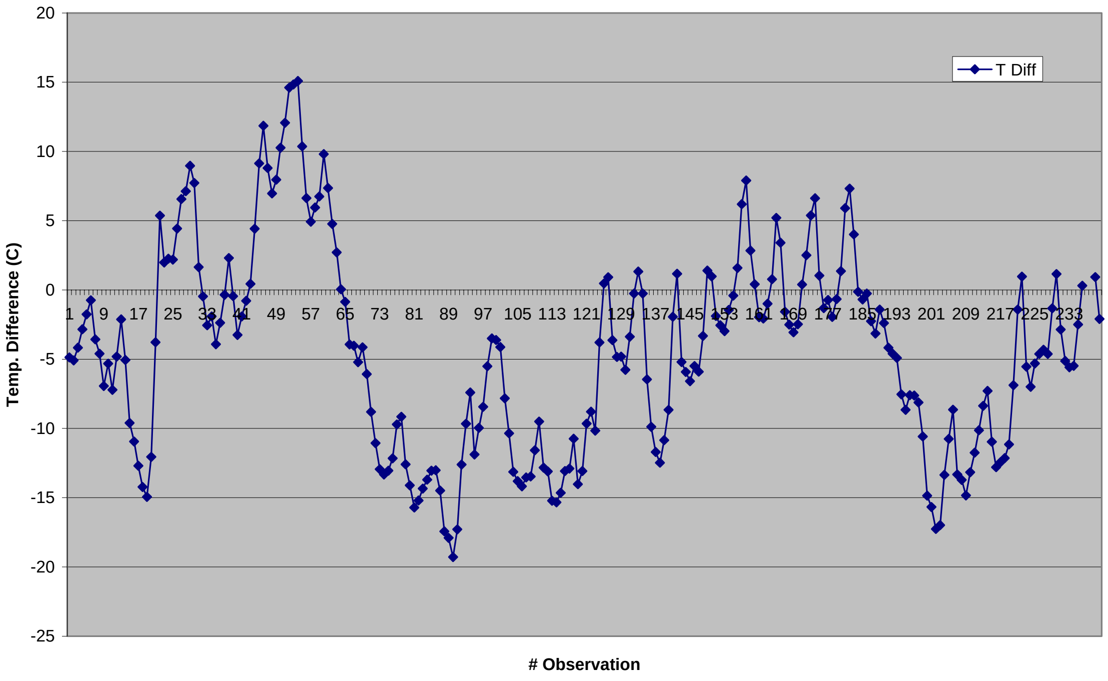
NARR and KCCU AWOS Temp-Dewpoint Differences Feb 2003



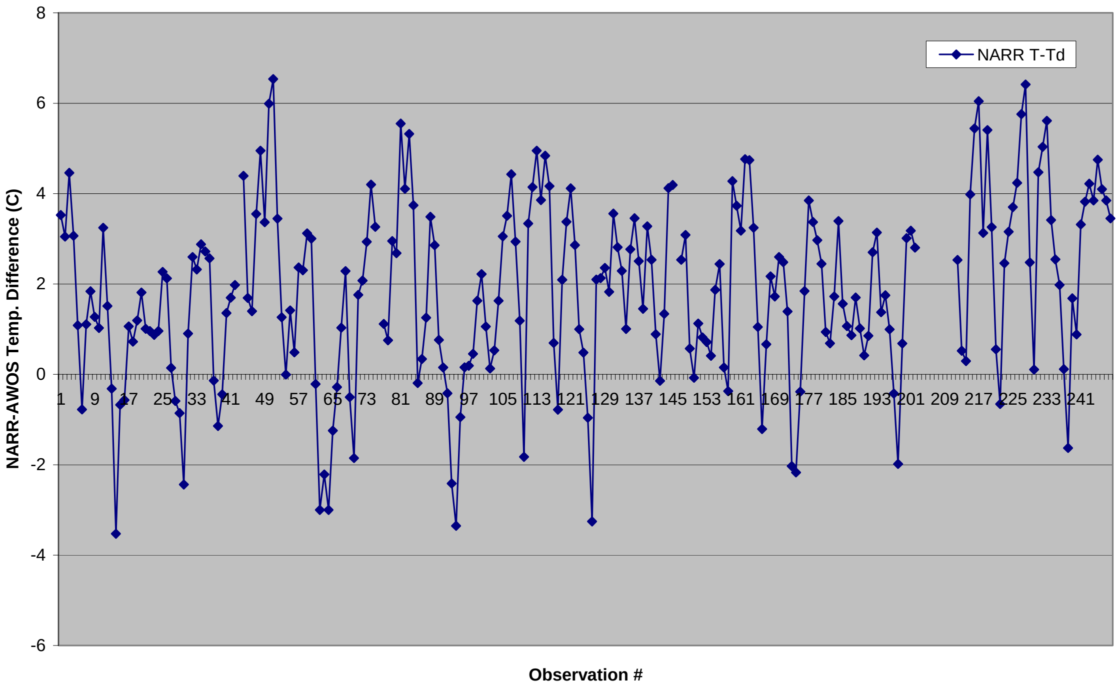
NARR and KCCU AWOS Temp-Dewpoint Differences Mar 2003



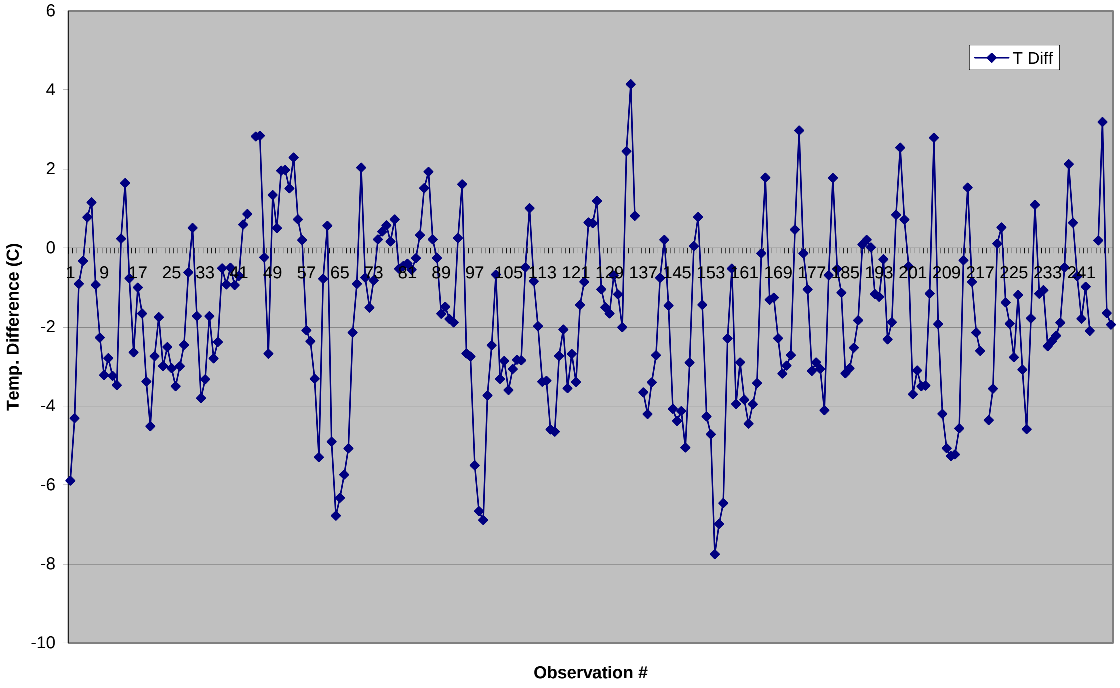
NARR (700 MB) and KCCU AWOS Temperature Differences - Apr 2003



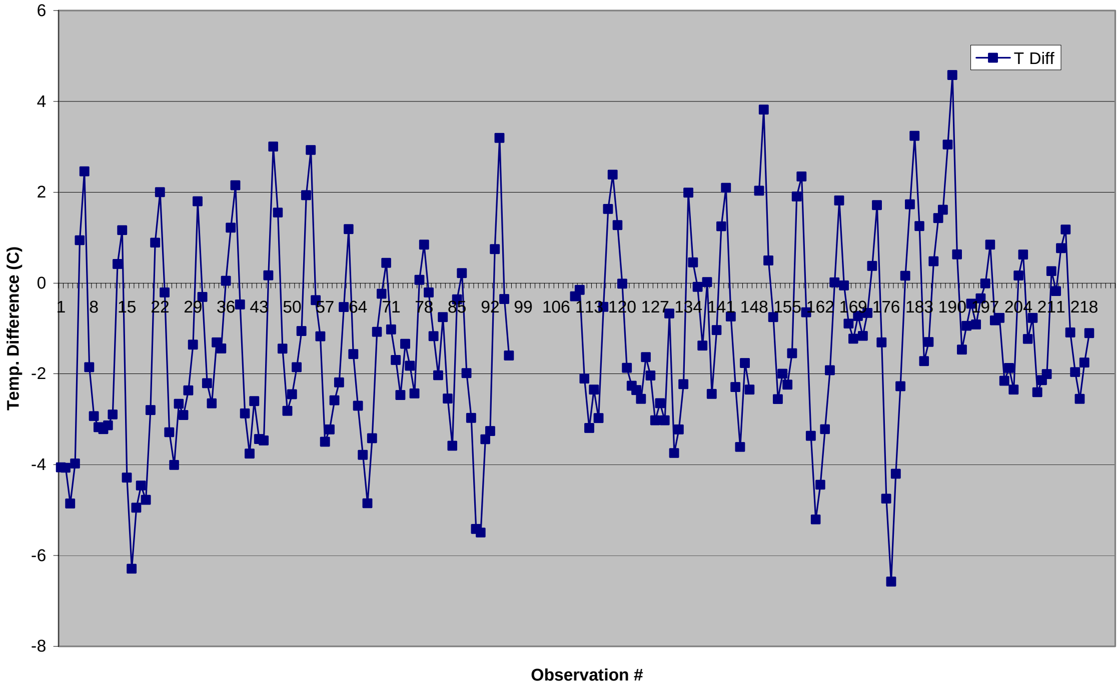
NARR - KMYP AWOS Temp Differences Dec. 2002

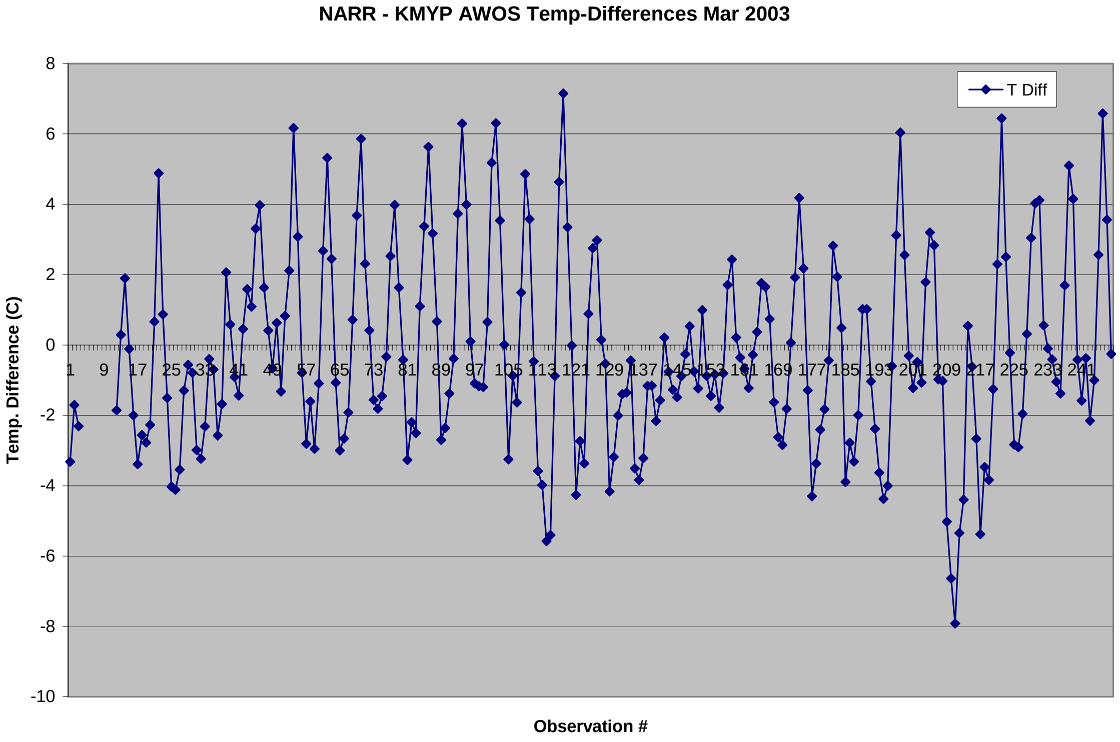


NARR-KMYP AWOS Temp. Differences Jan 2003

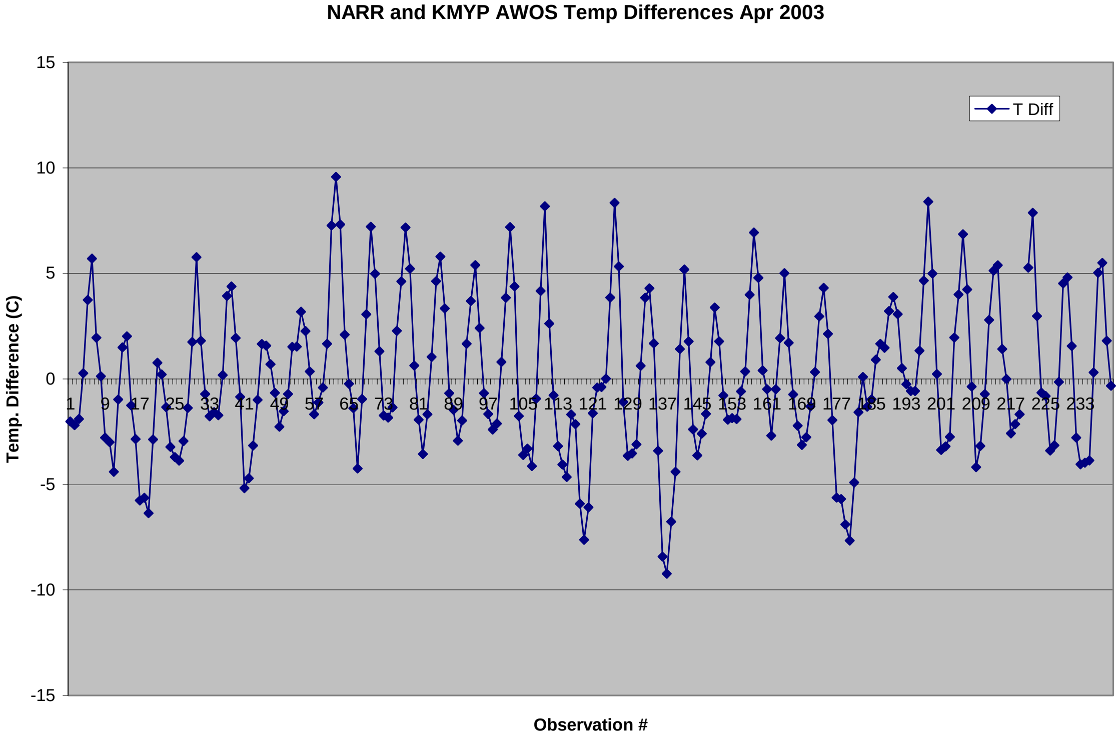


NARR and KMYP AWOS Temp. Differences Feb 2003



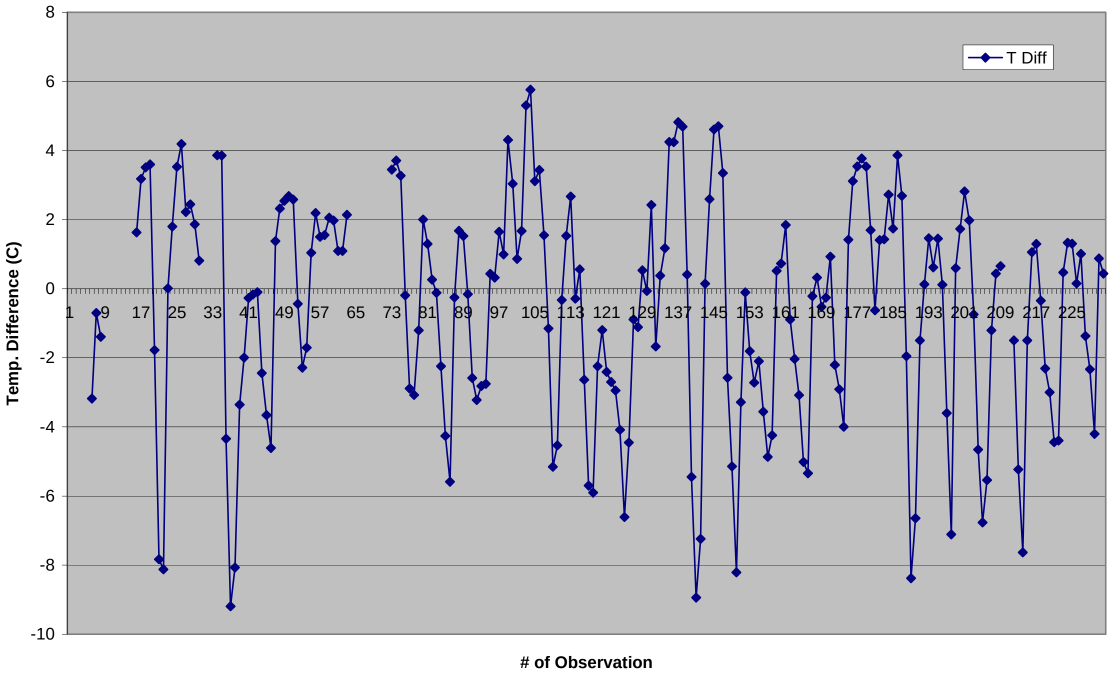


NARR - KMYP AWOS Temp-Differences Mar 2003

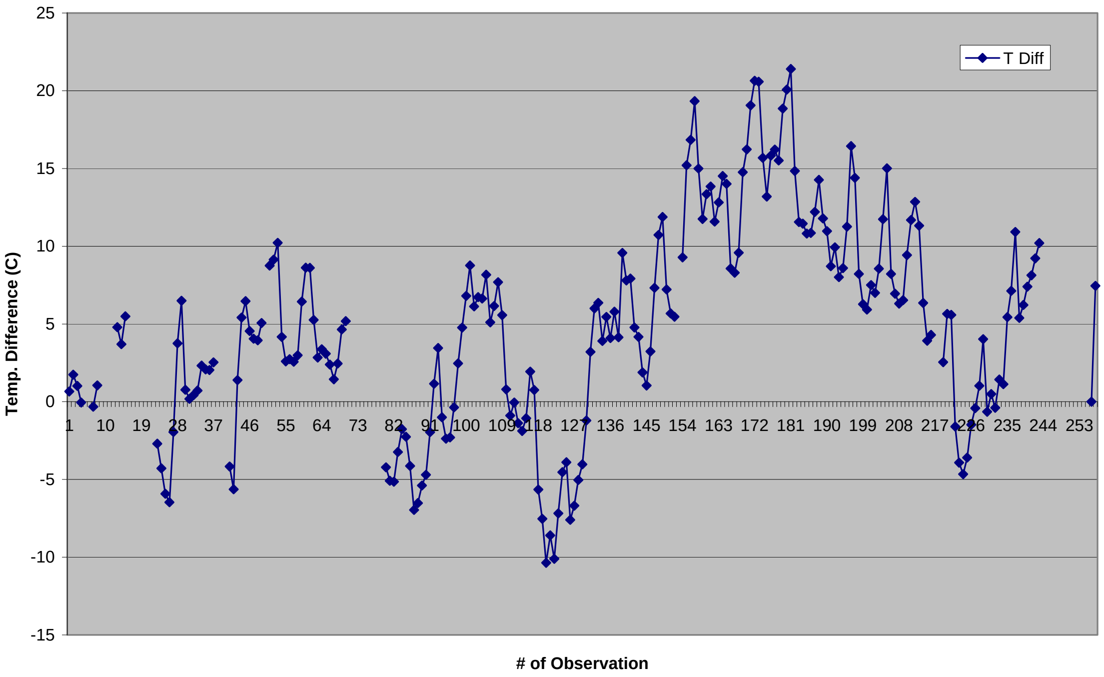


NARR and KMYP AWOS Temp Differences Apr 2003

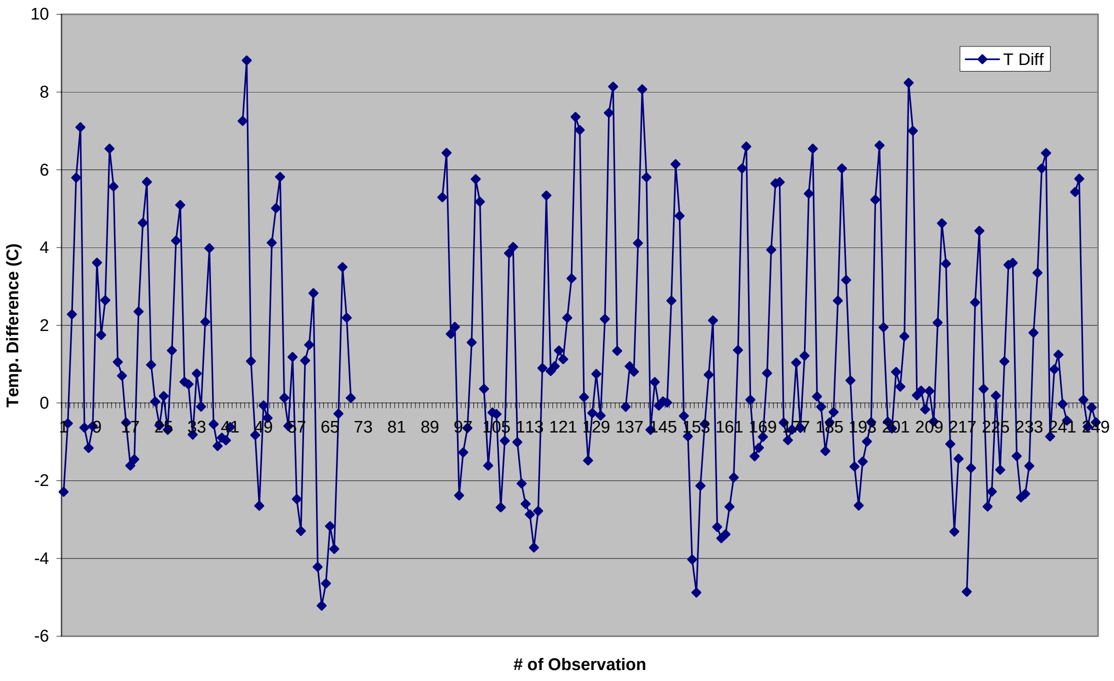
NARR and KCPW AWOS Temp Differences Nov. 2002



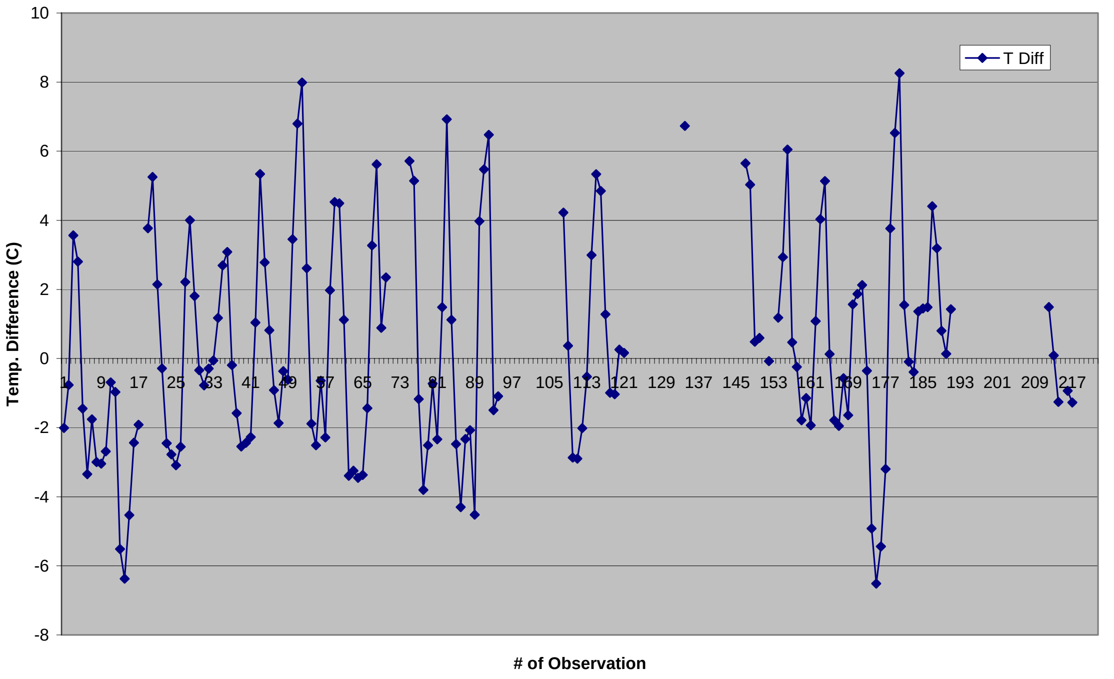
NARR and KCPW AWOS Temp Differences Dec. 2002



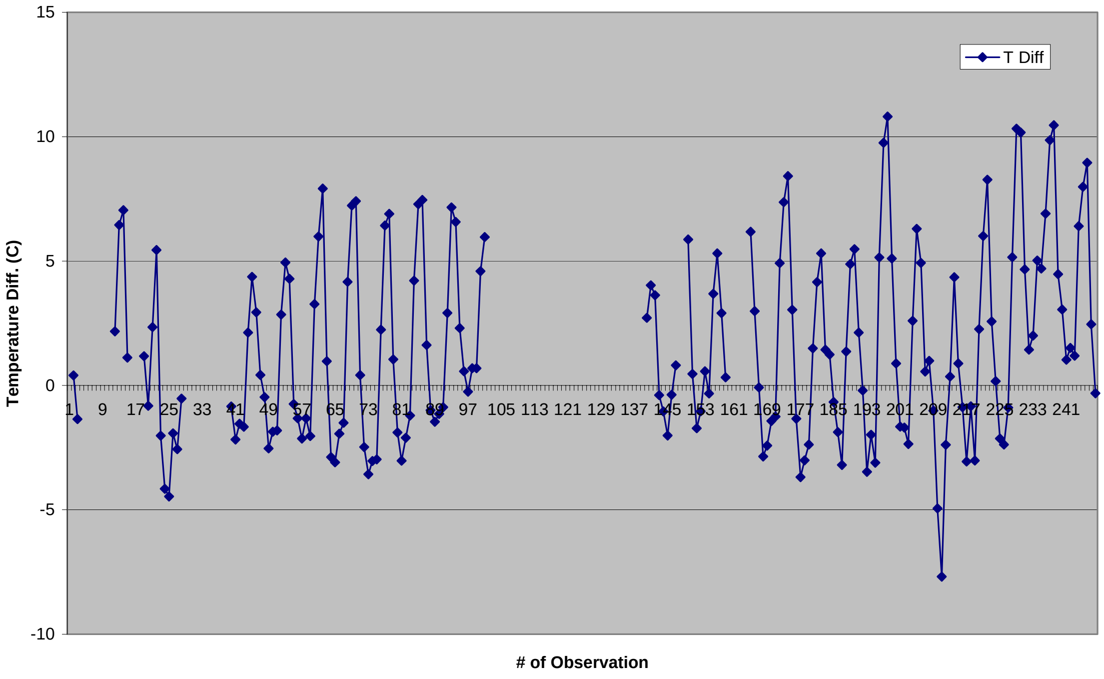
NARR and KCPW - AWOS Temp-Dewpoint DifferencesJan. 2003



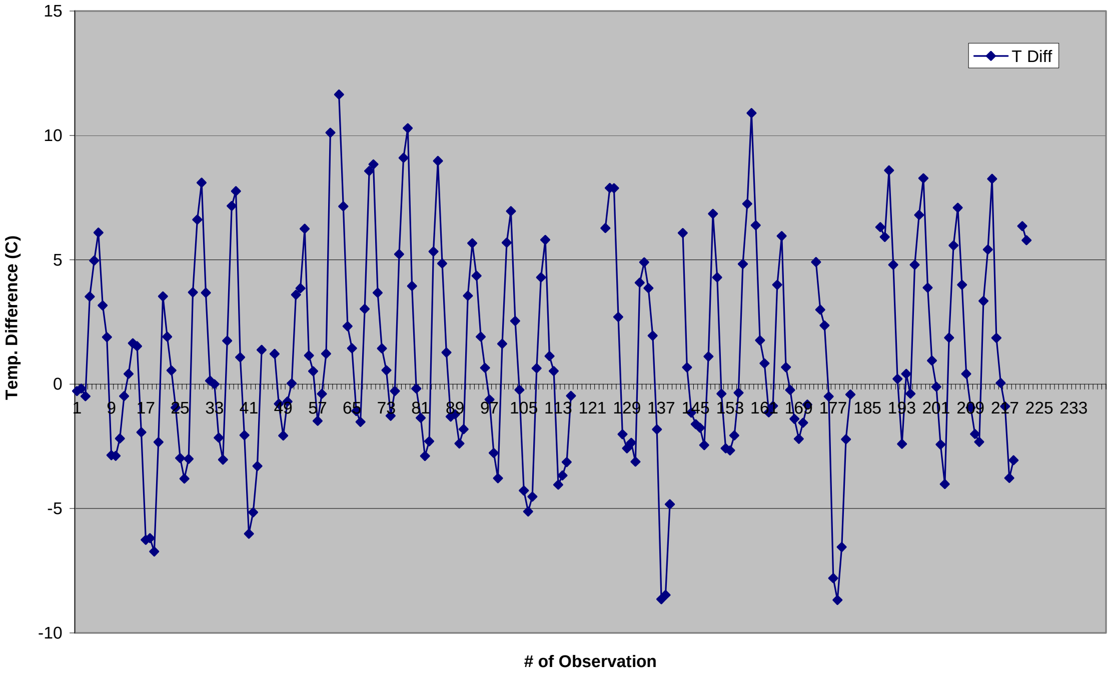
NARR and KCPW - AWOS Temp-Dewpoint Differences Feb. 2003



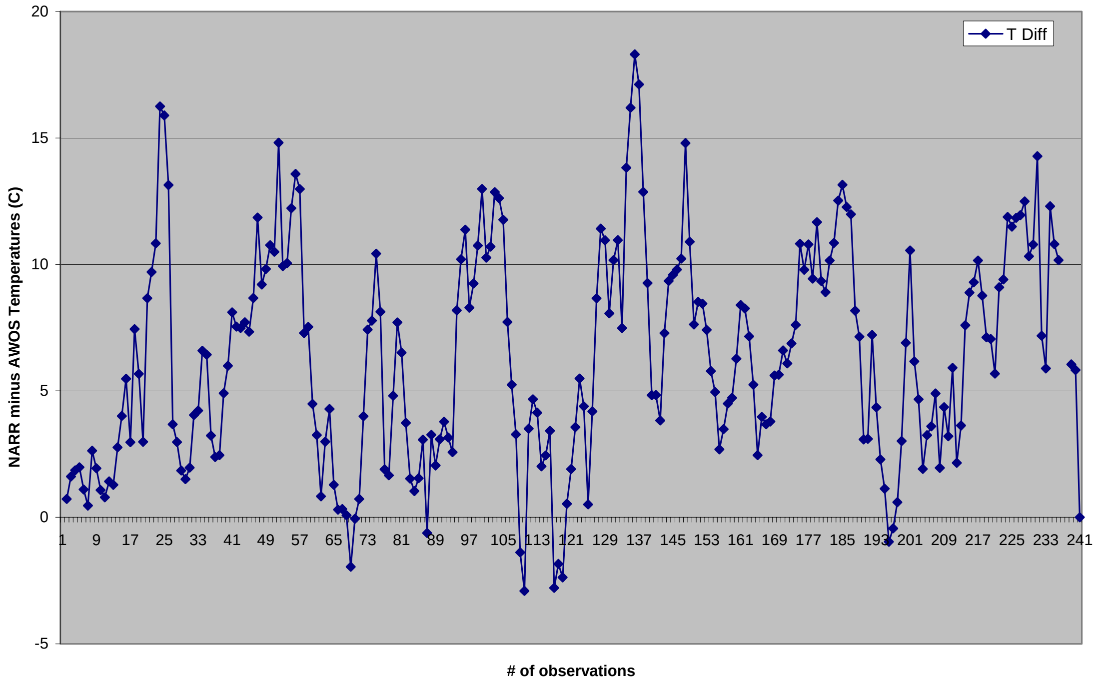
NARR and KCPW - AWOS Temp-Dewpoint Differences Mar. 2003



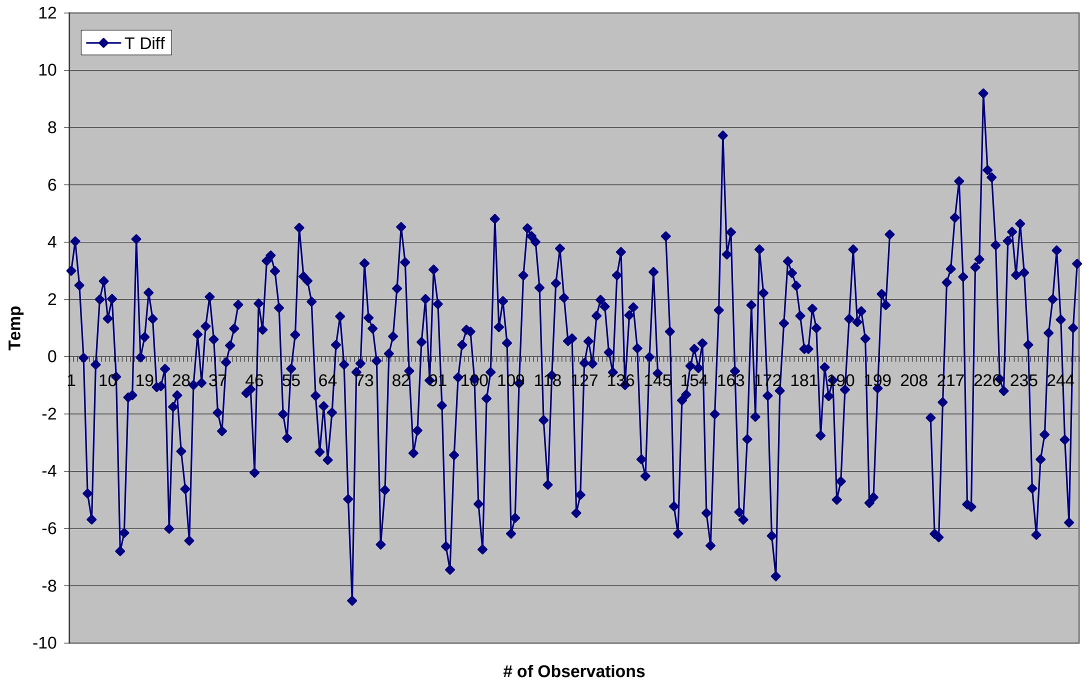
NARR and KCPW - AWOS Temp-Dewpoint Differences Apr. 2003



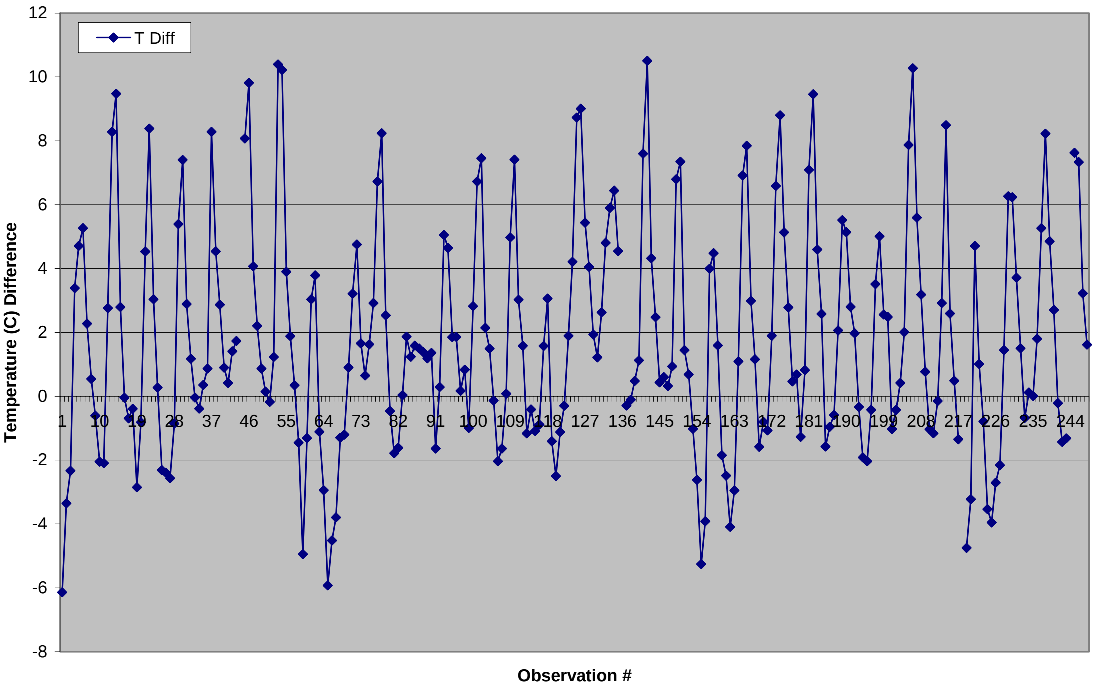
Interpolated NARR-AWOS Temperature Difference for KVTP for November 2002



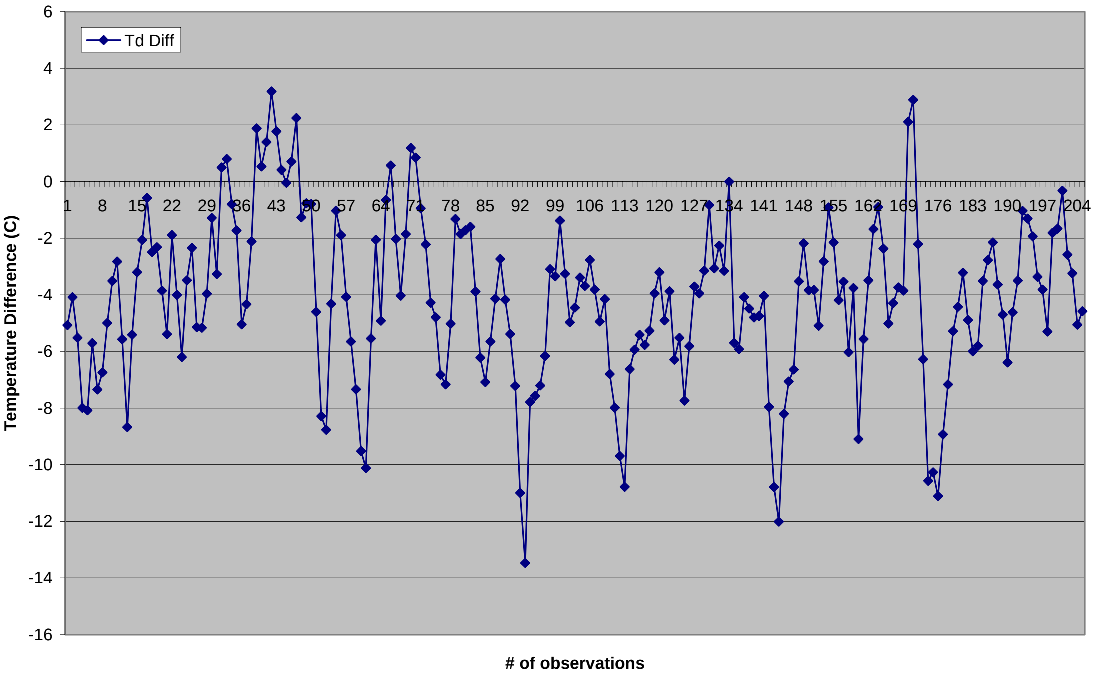
Interpolated NARR-AWOS Temperature Difference for KVTP for December 2003



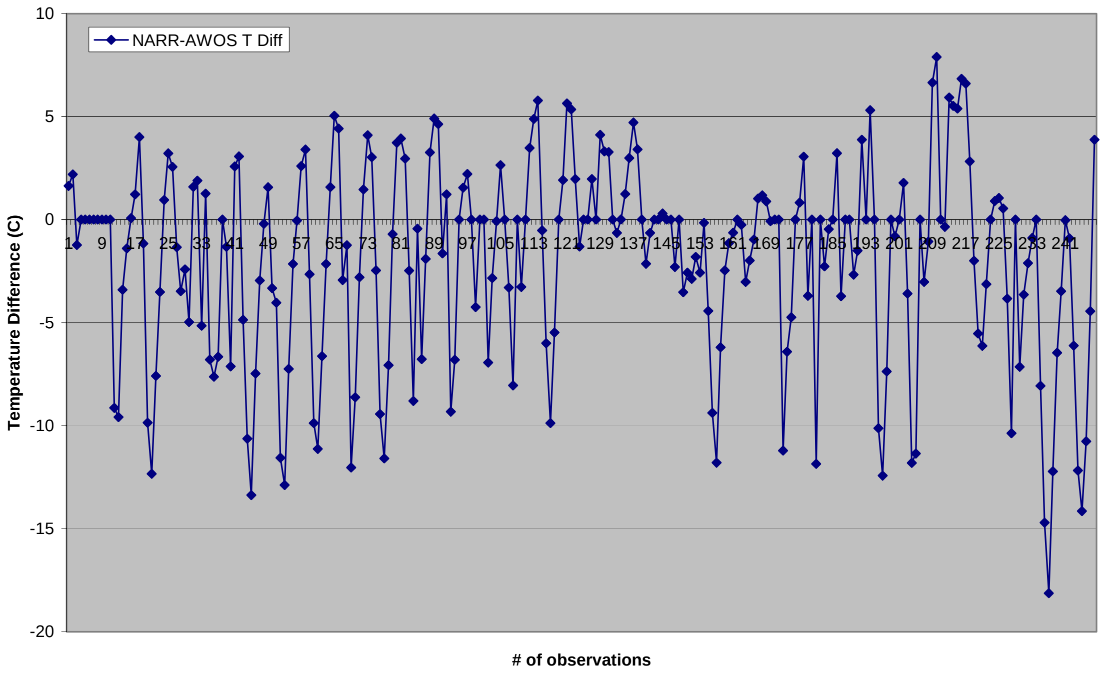
Temp. Diff. KVTP (NARR minus KVTP AWOS) - Jan 2003



Temperature Difference (NARR-AWOS) data at KVTP for Feb 2003



Interpolated NARR-AWOS Temperature Difference for KVTP for March 2003



Interpolated NARR minus AWOS Temperature Difference for KVTP for April 2003