Introduction

This online training was mandated in 2003 by NWS Director, Jack Kelly. The curriculum was developed by the National Weather Service Headquarters Climate Services Division.

The purpose of this training is to equip you with the knowledge needed to produce the most timely, accurate, and consistent climate observations possible in support of NOAA’s lead mission for climate in the federal government. In particular, this unit relates to the management and operation of in-situ surface weather and climate observing networks (Automated Surface Observing System (ASOS) & Cooperative Observer Program (COOP)). The basic principles presented here can also apply to other weather/climate networks, including the NWS upper air network, mesonets, state, and private networks, etc.

To meet the course objectives, this online tutorial covers:

1) Factors that can introduce unwanted uncertainty and discontinuities into the climate record, and,
2) Actions to be taken to minimize impacts resulting from these factors.
This lesson builds on information presented in PCU6 - Unit No. 1, “Applying the Ten Principles of Climate Monitoring to NWS Observing Systems.” Additionally, some of the materials contained here are covered in the NWS Training Center (TC) training course “CPM01- Cooperative Network Operations.” There is some overlap of content with both of these training activities. Completion of PCU6 – Unit No. 1 is encouraged before taking this training, but it is not a required prerequisite.

Climate records are based on meteorological data collected over a long period of time. Figures 1 through 3 illustrate the primary NOAA/NWS observing systems that produce climate data. They are the primary systems targeted for this training although the principles presented here are applicable to any climate/weather monitoring systems.

Figure 1 depicts a typical airport ASOS installation equipped with automated meteorological sensors. Figure 2 depicts a Cooperative Observer Program (COOP) site equipped with manual instruments. Figure 3 depicts a radiosonde in the upper air network.

Figure 1: An ASOS Airport Station.

Figure 2: A Farm COOP Station.
Figure 3: A Upper Air Station Radiosonde Launch.

**Background**

The NWS operates and maintains many of the nation’s weather and climate observing systems. Climate station standards are generally stricter than weather station standards because both data accuracy and long-term consistency are critical. It is not cost effective to have separate systems so we must ensure that all data needs are met with the existing networks.

Some climatologists argue that continuity is as important, if not more important, than absolute accuracy, for tracking the time-dependent behavior of climate, including trends and variability, and for assessment and analysis of extreme values and climatic risk factors. In any case, climate data form the basic building blocks for a multitude of applications, including the sciences of meteorology and climatology.

In recent decades, the observing systems were operated on the premise that the NWS’s primary mission of forecasts and warnings for the protection of life and property was the paramount driver. However, as the numerous applications of the data outside the NWS continue to grow and NOAA became the government’s lead agency for monitoring and assessing climate variability and change, it became mandatory that NWS refocus its management policies to include the somewhat forgotten climate needs of the systems.

The purpose of long-term (decades or longer) climate monitoring systems is to deliver continuous and reliable data and information. The data serve a great variety of climate services applications, including describing the climate, monitoring climate variability, climate change detection, national economic development, supporting climate research, modeling, and prediction, and mitigation of impacts.

Climate data are used in a multitude of socio-economic decision-making activities, ranging from sizing dam spillways and storm drains for runoff to the slope on highways to insure adequate water runoff, to the depth needed for structural foundations to ensure
long-term building stability. Industry uses weather and climate data in near real-time to understand business and sales trends (socio-economic indices). These applications all require measurements that are made in a consistent manner for long time periods.

Climate observations made under the oversight of the National Weather Service constitute the principal lasting legacy of the agency for future generations (NWS Director Jack Kelly, 2003). While forecasts and warnings have a short shelf life, climate data lasts centuries and longer. The data are as much a part of the national heritage as are material artifacts housed in the Smithsonian Museum in Washington D.C.

Climate observations will be examined repeatedly and in fine detail by advanced computers and algorithms for years, decades, and centuries to come. Diligent efforts must be made to insure that these observations are adequately and correctly documented and archived as they are meant to represent the true state of the atmosphere at the point of their measurement. In many ways, the NWS will be judged by the quality of the records it leaves to posterity.

NOAA/NWS is indeed viewed as the nation’s “neutral brokers” or stewards, for environmental data. For many legal applications such as contracts and litigation, NOAA data are the only source of information accepted for use.

In recent decades, another critical application of climate data has developed, its use in assessing global warming (greenhouse warming). Figure 4 illustrates the uncertainty (9 degrees F) associated with various greenhouse warming scenarios according to a recent Intergovernmental Panel on Climate Change (IPCC). Note that the projected changes are comparable to the error of a single observation, illustrating the importance of strict adherence to siting and sensor standards.

Figure 4: Temperature Uncertainty in Greenhouse Warming Scenarios.
NOAA is now the nation’s federal lead for climate services, including climate change research. We must recognize and respect the importance of NOAA’s climate monitoring mission, be aware of factors that can degrade the accuracy and continuity of that record, and exercise prudent judgment to minimize the unwanted uncertainty these factors introduce into our datasets. Doing so will increase the quality of our climate databases and support efforts to better understand what is happening to our climate.

Numerous factors can introduce uncertainty into the climate record. Some, such as instrument change, cannot be avoided. Sensors need replacement when they reach the end of their life cycle. Ongoing environmental change, also cannot be totally avoided. Trees grow and landscapes change. Under these circumstances, the best we can do is document the change through accurate metadata (data about data). To the many, the exposure changes that affect the measured climate may be invisible or appear subtle, dull and uninteresting as they happen but they nonetheless add some level of uncertainty to our climate record.

Figure 5 is the much publicized global temperature record. It illustrates the importance of accuracy in climate data and assessments. Note that climate trends are being evaluated to the nearest tenth of a degree Fahrenheit (F) over decades and centuries. The great global debate over the magnitude and causes of this warming are centered around potentially hundreds of billions of dollars of socio-economic action in just the U.S (United States Congress, Office of Technology and Assessments, 1991). The global implications are even greater.

Decision-makers need the most accurate data and assessments available to assist them in evaluating options for mitigation. Accurate, consistent, well understood data minimize the risk of making wrong, costly decisions and maximize the socio-economic benefit of action.
Importance of Accurate, Consistent Climate Observations

Figure 5: Annul Global Surface Temperature Over the Last 140 Years.

Importance of Climate Measurement Standards

Climate measurement standards ensure compatibility for observing methodology which in turn increases the quality data. Standards provide a critical level playing field….the same benchmark from which we can all measure so that data are collected consistently through the years and between stations.

In the real world, standards cannot be fully met all of the time (e.g., instrument exposure). Every site has factors which bias the measurements in some way or another. A good precipitation site is not necessarily a good temperature location is not necessarily a good wind location…etc. However, standards do provide a critical, compatible, framework for the collection of the measurements.

Adherence to standards increases the accuracy, continuity, comparability, and representativeness of data. On the flip side, a lack of adherence to standards increases the uncertainty in the data record and blurs our ability to confidently assess natural climate variability and trends. As uncertainty increases, so does the risk of making inaccurate assessments of what is happening to our climate.

In operating climate observing systems, we must do all we can reasonably do to comply with observing standards. Like our judicial system, the issue is not whether you agree with the standard (or law). The point is we must all apply the same principles across the table equitably for the system to work. In society, a lack of adherence to standards (laws) can led to anarchy (look at the lawless driving conditions today and the mess they create
if your skeptical!). In the climate world, the same situation leads to incompatible, inconsistent data (the current controversy over inconsistent methodology for snowfall measurements is a great example).

**Factors That Can Affect the Integrity of Climate Observations**

The magnitude of uncertainty in climate data that can blur the natural climate variability varies greatly with various factors that introduce biases. There are many factors that can impact the integrity of climate observations. Factors such as data assurance and quality control and maintenance are of great importance but are adequately covered under existing training curriculum of NWS TC. In the interest of containing this tutorial to the prescribed one hour session, we therefore focus our attention on the following:

1) Metadata
2) Instrumentation
3) Exposure
4) Changing Environments
5) Data Continuity
6) Observing Practices

Each factor is reviewed and then followed by recommended actions that can be taken to either minimize or document potential impacts.

Our goal in climate monitoring is to measure variability and change in natural environmental climate elements, not artificial ones such as those introduced by changing instruments, relocating stations, observing practices, etc.

Figure 5 illustrates our attempt to estimate of the relative importance of various factors that can impact the integrity of temperature observations. Other climate elements, such as precipitation (including snowfall), can also be similarly impacted.

As you review the chart, you see that artificially induced biases/discontinuities can be much greater in magnitude than the natural climate change/variability signals we desire to measure and track. If unaccounted for, artificial factors can totally overwhelm and blur the natural climate variability and change signals we so carefully strive to monitor and potentially mitigate.

**Factor 1: Station Metadata**

Station metadata are an essential part of climate information. Accurate metadata are paramount for data users in understanding observational data and artificial discontinuities that invariably occur as a result of events beyond our control. Simply stated, metadata are “data about data.”

Metadata provides the critical historical record of how and where
the data are collected over time. This includes such topics as the setup (exposure) of instruments, types of, and changes to instrumentation, changes in observing practices (time of observation, use of snow measurement boards), changes in the environmental site characteristics, dates of maintenance visits, changes in algorithms for processing and measuring the environment, and type of work performed, etc.

Metadata helps us understand and account for unwanted artificial discontinuities in the climate record.

What information should documented? Any factors that affects the data and/or the way we interpret the climate record. These include:

1) changes in the way measurements are made and recorded, and,
2) changes in the local physical environment.

Remember: Err on the side of over-documentation. There is no penalty for doing so, and once formed as a habit, it takes relatively little extra time to complete.

Recommended Metadata-Related Action:

The following actions are recommended to minimize unwanted discontinuities in the climate record:

1) Understand and honor the principle that metadata are as important a part of the data as the observations themselves. Keep a complete metadata record for each published climate station in compliance with Cooperative Station Service Accountability (CSSA) guidance and the “Ten Principles of Climate Monitoring (PCU6-1).”

2) Document any changes (sudden or slow) in site circumstances that can bias instrument measurements. Pay special attention to changes in the environment of the site such a forest cutting, changes in irrigation/fallow status of nearby crops, turf watering practices at the site, expansion or changes from gravel of asphalt driveways, roads and parking lots, encroachment of vegetation, new obstructions that affect wind flow, replaced or new sensors, changes in color or dirtiness of white shelter housing, vertical walls that provide additional infrared radiation at night, etc. Insure that the station’s metadata archive include digital photographs of the site for the eight points of the compass, updated annually with scheduled preventative maintenance visits.

3) Insure that observing changes and the date of occurrence, such as the implementation of new snow measurement boards, changing observation times, moved equipment, replaced or new instrumentation, changes in the environment within 200 feet of the station, different processing algorithms, etc. are recorded in the metadata.

4) Coordinate with your RCSPM and other climate services partners (NCDC, RCCs, SCs) on any related issues.

**Factor 2: Instrumentation**
Changes in observing instrumentation are a natural part of the maturing process for environmental monitoring that cannot easily be avoided. The instrumentation may be simple or complicated. It doesn’t really matter. In either case, it is a matter of time before it is replaced. The difference in how an instrument takes measurements and the materials used in the instrument can significantly affect the quantity measured (i.e., the data). These factors introduce biases into the climate record. Instruments can also slowly drift or deteriorate, and show discontinuities when swapped out.

To understand data, we must understand how the instrumentation works over the range of environmental conditions it is expected to be exposed to. Otherwise, we cannot be sure of the full range of its accuracy.

As we have seen, accuracy is important to the science of climate, especially with respect to extreme events, whose frequency and intensity are being monitored closely as a sign of climate change. Requirements for accuracy can be basically summarized as follows:

a) the instrument should have and maintain calibration under given conditions to within the desired precision, and,

b) The errors under other conditions should be known and constant in time within required limits.

Thus, one must understand instrumentation responses before we can determine whether a sensor meets climate requirements. Even though there are plenty of manufacturers producing quality instrumentation, if we have not seen validated test results, we do not understand which ones meet our requirements for climate data accuracy. And another consideration….don’t assume that advertised capabilities are 100 percent factual. We are all well aware of the limitations of advertising. The proof is in the observation itself.

The discussion of instrument accuracy brings us to the topic of installing non-approved instrumentation into the nation’s published climate network. Simply stated, this is not a wise choice. In fact, it’s a no-no (Figure 6). Refrain from the temptation. If you need to open a site with non-approved instrumentation for the less demanding accuracies of the public forecast and warning missions, and you can do so within policy and resource limitations, then that’s your call. But even here, it is prudent to understand the capabilities (and limitations) of the instrumentation you are using.
Figure 6: Install only Approved Instrumentation at Published Climate Stations

It is especially harmful to install non-approved equipment at a published climate station and not document that change in the station’s metadata. This only compounds the problem. Data users may discover significant discontinuities (inhomogenities) in the record at this point, but unknowingly, without any documentation of what happened, reach false conclusions regarding an “apparent” (false or artificial) climate change.

The good news is that a complete, detailed station metadata record allows data users to better understand discontinuities (note that the reasons for the discontinuities are shown on the illustration). Metadata information, combined with instrument performance specifications, allows users to adjust (or filter out) artificially-induced climate shifts so that the naturally occurring trends and variability are more accurately detected.

Another problem with the use of unapproved instrumentation is maintenance. Keep in mind we are in the climate monitoring game for the long run. This means network operation for decades and longer. We are responsible for long term maintenance and operation which is much more difficult with unapproved instrumentation that is not supported through the logistics pipeline.

A good example that illustrates the importance of instrument change on climate data is that associated with the implementation of wind shields on precipitation gauges (Figure 17). For example, researchers using precipitation data published in Monthly Climatic Data of the World, one of the primary sources of global climate data, must address the fact that by 1980, 44 percent of all the contiguous U.S. precipitation gages in the published set had shields installed around the orifice of the gage. Prior to 1948, shields were absent.

**Recommended Instrumentation-Related Actions:**

The following actions are recommended to minimize unwanted discontinuities in the climate record:
1) Use only approved instrumentation whose functional characteristics are understood for published climate stations. To do otherwise, increases the uncertainty in the quality, continuity, and comparability of the climate record.

2) Ensure that all instrumentation changes and the dates thereof, whether a new instrument, replacement or modification of existing stock, are documented in station metadata.

3) Coordinate with your RCSPM and other climate services partners (NCDC, RCCs, SCs) on any related issues.

**Factor 3: Station and Instrument Exposure**

We now give the subject of site and instrument exposure considerable attention as these factors can create great variability in the accuracy, continuity, and representativeness of measurements. They are also factors over which we can exert considerable control to minimize unwanted impacts.

Station exposure includes general siting characteristics (urban, suburban, rural, etc) and topographic setting, and instrument exposure. Instrument exposure relates to the specific placement of the sensors (height above ground, distance to surrounding objects, etc.)

The specific topographic and environmental setting of a station is an extremely important variable in determining the measured values of the climate data collected. In some situations, the topographic exposure of a station can result in much more variability in temperature and precipitation values than differences of say, 5 horizontal miles and 100 vertically feet (NWS policy for renumbering relocated stations). Changes of even a few feet (5 or 10) in elevation, or less than 50 feet horizontally, can affect readings. Relocating a station nearer to hills or hollows, in and out of nocturnal drainage channels, or near the influence of other subtle features, can change the climate record. This may sound unlikely, but it has been documented many times, even in apparently homogeneous “flat” land. Snow can have a major effect on temperature, and the way that snow accumulates and melts in the vicinity of the station can change with time. Also note that temperature may be affected significantly by a site change, and precipitation barely so, or vice versa. The impacting factors are typically element specific.

The type of topographic exposure of a location greatly influences spot climate. Figure 7 illustrates a classic example of the different types of topographic settings in the high Alleghenies of north-central West Virginia. They are:

- a) elevation (above sea level, and locally, small variations of a few feet),
- b) slope (north, south, east, west facing, or level), and,
- c) topographic setting (ridge top, valley, etc.).
We are all familiar with the important role that elevation plays in determining the climate and weather of a locale. Therefore we concentrate our discussion on the other two, less known factors of slope and topographic setting.

The slope orientation of a site changes the site’s exposure to solar radiation and therefore the basic energy balance that drives temperature. The north slope of a hill or building does not receive as much radiation as the sides facing south (in the northern hemisphere). Also, while the radiation exposure is highest to the south, the highest temperatures usually occur on southwest facing slopes. The point to make here is that extremes of any exposure are to be avoided in site selection whenever possible. If such exposures are unavoidable, it is again critical that the metadata (especially digital photography) reflect the specifics of the site’s orientation.

In addition to slope orientation, there are four basic topographic settings that can introduce significant variability into the spot climate of a site. These settings are:

- Crest (summit)
- Slope (sides of a hill or ridge)
- Valley bottom (frost hollows, flood plains, etc. surrounded by higher ground)
- Plain (level, flat surface without higher or lower ground close by)

Each of the settings, at similar elevations, can exhibit large differences in climate, including maximum and minimum temperatures, temperature range, shape of the diurnal temperature curve, etc. In general, elevation for elevation, crest, or hill tops, exhibit reduced temperature range (lower maximum and higher minimum) as compared to valley bottom locations. Slopes exhibit features in-between crests and valleys.

Topographic setting is extremely important factor in deciding where to install a station and with relocations, whether to determine if climate compatibility exists between the old (or current site) and the new location (section 5: data continuity contains a detailed discussion of station relocations).
Now let’s shift our focus to instrumentation exposure and its potential impact on the climate record. As discussed earlier, standards exist to insure compatibility and accuracy of measurements. Standards for how to set up instruments at climate stations are documented (NWS Observing Handbook No. 2: Cooperative Station Observations – July 1989—in process of being updated).

Temperature is often affected by factors which govern the local energy budget including:
- Sensible heat fluxes (type of surface)
- Latent heating (evaporative cooling from vegetation, water bodies, etc.)
- Radiative fluxes (solar and infrared, vertical & horizontal)
- Obstructions that restrict wind movement and ventilation
- Snow cover (which consumes heat in the melting process and reflects radiation)

Precipitation is most affected by factors that influence aerodynamics
- all precipitation gauges under catch
- shielded gages under catch less than non-shielded gages
- under catch is a much bigger factor when precipitation is frozen
- natural vegetation slows the wind and increases the catch
Figure 8 depicts a non-standard COOP MMTS exposure. To make matters worse, this is a Historical Climate Network station, which implies that the station is one of the best climatologically in the U.S. network. The rain gauge is situated only a couple of feet from a power-plant building, over a non-standard gravel surface (grassland is the surrounding environment) and within two feet of an exhaust vent and two metal stacks. Adherence to exposure standards decreases the risk of collecting data representative for only a very small local spot or micro-climate such as shown here.

Figure 8: Non-compliant Temperature Sensor at a Published HCN COOP Station.

In the real world, non-standard instrument exposures of one type or another are common. It is difficult to meet all instrument exposure guidelines in the natural environment. There are space, power, vegetation, topographic considerations, and aesthetic constraints, especially when private property and homes are involved. However, some non-compliant situations are worse than others.
Figure 9. Unrepresentative Temperature Siting in an Isolated Grove of Trees Without Adequate Instrument Exposure Metadata.

Figure 9 depicts another example of a non-standard instrument siting. Standards call for the sensor to be located over ground representative of the surrounding environment. These young trees have grown a great deal since this NWS MMTS system was installed at this cooperative station. The presence of the trees is not recorded in the metadata.

We can take measures to avoid or mitigate non-compliant exposure situations. Understanding the purpose of the data you are collecting is a big step in the correct direction. Is the goal to obtain data for a very localized spot climate (a mountain pass with a highway or a frost hollow for agricultural growing season applications)? Assessing “spot”, or extremely localized microclimatic and weather conditions are a valid need under certain circumstances (e.g., mountain pass data for transportation forecasts, research projects, etc.). Most frequently however, operational data are used for multiple purposes, many of which are not immediately known or understood and require that the station describe and represent the climate of a broader area. For these applications, you want to avoid locations that harbor non-representative spot mico-climates. Spot climates, by definition, are real and interesting, but may be representative for only a very limited locale. And indeed, on occasion they are justified, to help us understand the degree of fine-scale spatial variation.

Figure 10 illustrates an example of a poorly sited rain gauge. The gauge is situated only 2 feet from a 30 + foot high building. Siting guidelines call for obstructions to the gauge opening to be no more than half the height of the obstruction’s distance to the gauge. In this case, the gauge, optimally, should have been no closer than 60 feet from the structure.
Dinosaur National Park (that is a natural wall, of rock, and this is an artificial wall, of a house). In the Dinosaur case, the site tied or set four new all-time monthly records almost immediately. Both exposures are likely to yield data with a high degree of uncertainty in their accuracy, especially under certain synoptic conditions, and even more with snow swirling and drifting or blowing from the roof.

Figures 10: Extremely Poorly Situated Non-Compliant Rain Gauge Exposure.

There are many examples of stations that push the boundaries of non-compliance to the limit. In fact, many climate data users argue that bad data is worse than no data. Keep this thought in mind when locating climate stations! Are you be willing to defend the site you selected for a climate station (new or relocated) in front of an audience of climate data users, customers, and scientists? If the answer is yes chances are good it’s acceptable. If the answer is no, keep looking for another, more compliant location.

It is important to note that non-standard instrument exposures may not necessarily translate into bogus data with every single observation. Non-standard exposure means that data quality may vary, or put another way, the uncertainty in the quality and representativeness of the data increases. The validity of the data may vary with many meteorological variables such as wind speed and direction, amount of sunshine, time of year, etc. Some sites may produce high quality, representative data, while others may provide very poor quality, unrepresentative information.

Instrument exposure standards are really compromised with rooftop locations (Figure 11).
While the number of NOAA rooftop climate stations has remained at about 40 for the last decade, the number of private rooftop stations has grown during that period into the thousands. Rooftop exposures have an advantage of increased instrument security and good exposure for wind sensors (standard height is about 33 feet). However, there are also drawbacks. Access for maintenance can be difficult and exposure for precipitation and temperature instrumentation is clearly non-compliant, being elevated to high above the ground. Additionally, the instrument exposure is usually over environmentally non-representative surfaces (metal, black tar, shingle, stone etc.), while at the same time being close to a wide variety of roof surfaces which are subject to change.

The unrepresentative-ness of rooftop temperature and precipitation data was discovered long ago after studies quantified the biases. The late Professor Helmut Landsburg, considered the “father of climatology”, stated in his 1942 “bible of climatology” textbook, “Physical Climatology” that:

"Climate derived from records of roof stations may by no means be representative of those at the ground level."

In another published paper 28 years later, Professor Landsburg again reiterated his concern about rooftop exposures with respect to the urban warming issue:

"They [rooftop stations] are certainly of little value in a full assessment of the climatic changes brought about by urbanization."

Rooftops make good observation sites if you live work, play, or grow your food on a roof. Unfortunately, few people do any of the above. Rooftop exposures have been shown to exhibit biases towards warm temperatures (both maximum and minimum) and lower precipitation when compared to ground based stations. The warm temperature
biases likely result from extreme daytime heating of artificial rooftop surfaces, reduced cooling of the roof at night, and from heat flow from within the building, especially in winter. The biases can be substantial. One limited study indicates 5 to 10 degrees on summer days with bright sun and light winds. Biases have been found to vary significantly, depending on many factors (location on the roof, color of roof, type of roof surface (rock, metal, etc.) time of year, etc when compared to standard ground-based sensors.

On the flip side, if a station has been on a non-changing roof for decades, the site may have good continuity (value) for tracking climate change and variability. For some climate applications, consistency with a long record can be more important than accuracy with a shorter record. The best of both worlds is to have an exposure compliant, long-term station. Balancing these considerations for a long-established station requires some judgement and perhaps a difficult decision. In any case, proper metadata documentation will greatly assist future assessments of the station’s usefulness and quality.

Let’s review a summary of data from a recently relocated, published rooftop COOP climate station. There are still several dozen other rooftop COOP stations the NWS operates.

Figure 12 depicts the NOAA published COOP climate station on the roof of the Baltimore, Maryland Custom House in downtown Baltimore city.

<table>
<thead>
<tr>
<th>Station</th>
<th>Maxima &gt;100 F</th>
<th>Maxima &gt;90 F</th>
<th>Minima &gt; 80 F</th>
</tr>
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<tbody>
<tr>
<td>Balt (roof)</td>
<td>13</td>
<td>81</td>
<td>12</td>
</tr>
<tr>
<td>Balt. (gnd.)</td>
<td>0</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>BWI</td>
<td>0</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>IAD</td>
<td>0</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>DCA</td>
<td>0</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>10 COOPs</td>
<td>0</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 12: The old Baltimore, Maryland Custom House rooftop COOP and summary of comparison of overlapping data with surrounding ground-based stations.

The table to its right summarizes a comparison of 12 months of overlapping data that was collected on the rooftop and at the new relocated site (for data continuity), relocated several blocks away at ground level with other nearby standard, ground based stations.
A combination of the rooftop and downtown urban sitting explain the regular occurrence of extremely warm temperatures. Compared to nearby ground-level instruments and nearby airports and surrounding COOPs, it is clear that a strong warm bias exists, partially because of the rooftop location.

Maximum and minimum temperatures are elevated, especially in the summer. The number of 80 plus minimum temperatures during the one-year of data overlap was 13 on the roof and zero at three surrounding LCD airports, the close by ground-based inner Baltimore harbor site, and all 10 COOPs in the same NCDC climate zone. Eighty-degree minimum are luckily, an extremely rare occurrence in the mid-Atlantic region at standard ground-based stations, urban or otherwise.

Temperatures can be elevated on roofs due to the higher solar radiation absorption and re-radiation associated with many roof surfaces including black tar, shingles, stone, and metal. During the colder months, ongoing upward heat transfer through the roof from the heated interior of the building also can contribute to the warm bias although stronger winter winds tend to create better mixing and minimize this impact.

Let’s look at another example of the importance of instrument exposure on data representativeness and accuracy. It has long been understood that the height of a rain gauge above the ground affects the measured rainfall totals. Basically, studies show that the higher the gauge orifice, the lower the reported amount (Figure 13).
The quote below summarizes the results of an early study on this relationship:

“a rain gauge located on the top of a 30-foot tall house caught just 80 percent of the amount measured in a ground-level rain gauge. Similarly, a gauge on top of a 150 foot abbey tower caught just over 50 percent of the ground level catch.”

Can you guess the year of the study?

a) 1950  
b) 1971  
c) 1899  
d) 1815  
e) 1769

If you chose (e), 1769, you are correct! Much of what we know about observational bias has been known for a very long time … it’s more a matter of applying what we know.
Figure 14: Elevated Structures, Including Towers, Do Not Meet Basic Exposure Standards for Temperature and Precipitation Instrumentation.

We now look at one final example of the importance of instrument exposure on temperature data as a paper submitted in 2003 for publication in the Bulletin of the AMS (Microclimate Exposures of Surface-Based Weather Stations - Implications for the Assessment of Long-Term Temperature Trends, Davey et. Al. CSU) notes inconsistencies in the vertical placement of sensors at existing published COOP stations (differences of several feet in some instances).

Figure 15 depicts the importance of adherence to the standard height of 5 feet above the ground for the placement of the temperature sensor.

Figure 15: Hourly Surface Temperature Variability as a Function of Sensor Height.

Each curve denotes average hourly temperatures for 5 spring days at seven different heights are plotted for Seabrook, NJ (data from Thornthwaite, 1948). The sensor height differences are small, ranging from 0.3 feet above the ground to 21.3 feet.
There are two features to note in the graph: First, there is a difference of up to 5 degrees F at the time of the maximums and minimums between with only 21 feet difference in elevation. Second, the daily temperature range (difference between maximum and minimum) is different at each elevation. Differences of only a few feet in the sensor height can make a one degree F difference in extremes for the day. This difference is significant in relation to the magnitude of the tenths of a degree climate signal researchers look for. Therefore, it is important we adhere to the standard sensor height (1.5 meters above the ground) to maximize detection of the climate change signal over time.

Bottom-line…adhering to the standard temperature sensor height of about 5 feet reduces uncertainty in the measurements, increases our ability to make accurate comparisons between sites, and assures a level-playing field amongst observation sites, especially when relocations are involved.

In summary, non-standard instrument exposures minimally at best increase uncertainty in the accuracy and comparability of data. At worst, they pollute and blur information and result in poor assessments and costly, incorrect decision-making. The magnitude of the impacts on the record can be complex and difficult to quantify. That’s why adherence to standards is so important!

**Recommended Exposure-Related Action**

The following actions are recommended to minimize unwanted discontinuities in the climate record:

1) Do not operate climate stations in grossly non-standard exposures (rooftops, in close proximity to heat exchangers, etc.). If you cannot locate a station reasonably close to exposure standards, don’t install it there! The data could be misleading and do more harm that good when used for assessments of broader local or regional conditions where the users may not be familiar with the “small print” or spot climate of the station’s non-compliance. Consider other, more conforming locations.

2) Coordinate with your RCSPM and other climate services partners on any related issues (NCDC, RCCs, SCs).

**Factor 4: Changing Environments**

Changing environments are a fact of life that are not easily avoided. As our population grows, cities and towns creep ever outward (Figure 16), vegetation matures, and land use patterns evolve, the environments we monitor change. These changes impact the climate record. The question is not whether these changes impact climate, but how, and to what magnitude and geographic scale.
How do we deal with environmental change? To some degree, knowledge gained from environmental changes is useful. For example, understanding that urban climates are generally warmer than surrounding suburban and rural areas is useful for energy planning and landscaping activities.

In many cases our thermometer records are from airports. Figure 17 is an evening thermal picture (in the infrared, from ASTER) of Phoenix (at about 10 p.m. local time) and note how the warm runways are the brightest yellow area (warmest) in town. The official Phoenix climate observations are made at the airport on these runways. Phoenix has grown into a major metropolis with a very large and busy airport.

Regardless of data applications, in many cases, environmentally changing locations are unavoidable as measurement stations. Nonetheless, it is good practice, wherever feasible, to establish stations in environments expected to be as stable as possible over long periods of time unless special studies or research are the primary mission.
Let’s look at several examples of the impact environmental change can have on climate data. Figure 17 is a graph of the monthly temperatures departures from the multi-station NCDC-climate-zone average at Newark, New Jersey over a 17 month period (1991-92). A discontinuity is evident about 10-12 months into the record from this interval. Upon examination of the

![Newark, NJ Temperature Departures](image_url)

Figure 17: Temperature Discontinuity at Newark, New Jersey ASOS, Conincident with Parking Lot Expansion.

circumstances, it was found that:

1) the temperature sensor was within accuracy specifications, and,

2) a major black asphalt parking lot expansion had occurred during this time period in the immediate vicinity of the temperature sensor.

Figure 18 depicts a similar situation that occurred at a COOP station out west. A gravel parking lot was paved to within a few feet of the station. This change resulted in an average monthly temperature increase at the site of over 2 degrees (F) within several months with greater impacts seen on days with sun and light winds. There was no mention of the pavement change in the metadata, and a data user would have no knowledge of this important station change.
Another example of non-compliant temperature sensor is exhibited in Figure 19. Here, the environmental change is vegetation encroachment. This situation impacts the radiation balance of the site, and additionally, may reduce the natural aspiration of the sensor. What is the net resultant impact on temperature? Only a sophisticated statistical evaluation of the data might yield an answer and without this evaluation, incorrect conclusions about climate variation and trends will result.

Since, in many cases, environmental change may not be fully anticipated or avoided, the best mitigating practice is to fully document environmental changes in the station vicinity in the station record (metadata). By practicing this principle religiously, we increase our
chances of understanding the factors (both artificial and natural) driving changes and trends in the data.

**Recommended Environmental-Change Related Actions**

The following actions are recommended to minimize unwanted discontinuities in the climate record:

1) Correct non-compliant situations wherever possible. Keep vegetation in check. If non-compliance is severe and compromising data quality and remedial action is not an option, consider station relocation or closure of the station. Coordinate relocation/closure efforts with COOP modernization activities where possible. COOP modernization is now in the process of creating Regional Site Selection Teams that will be determining what existing sites will be modernized and where new stations need to be installed.

2) Ensure that the station metadata history contains reference to any situation that can bias measurements. Ensure compliance with the “ten principles of climate monitoring.” Yes, it may be embarrassing to admit that station circumstances are not ideal, but it remains important to report the facts for the historical record.

3) Coordinate with your RCSPM and other climate services partners (NCDC, RCCs, SCs) on any related issues.

**Factor 5: Observing Practices**

Another natural evolution of environmental measurement is changes in observation practices. These changes include variations in spatial and temporal sampling, processing algorithms and the tools used to take the measurements. Sometimes these changes can seriously affect the interpretation of data and products derived from the measurements, particularly climate variability and trend analysis.

These changes are frequently desired in the interest of improved data accuracy. However, it is imperative that the changes be documented in the interest of homogeneity of past, present, and future measurements. This practice cannot be accomplished without a sound data management system that includes documentation of all changes that can introduce data discontinuities.

Let us examine an example of how different observing practices can impact the continuity and accuracy of the climate record. Let’s first look at snowfall observations since this topic has been of great concern to scientists and customers alike in recent years.

NWS snowfall measurement guidelines have, for decades, promoted the use of snow measurement boards as the standard measurement surface for the measurement of fresh snowfall amounts. The spirit of the standard is to ensure compatible and consistent snowfall measurements (and data) nationwide.
Unfortunately, until the 2002 winter season, the agency did not provide users with the specified snow measurement boards. The result was data that was collected inaccurately and inconsistently from place to place. Amounts measured vary in the same location with which surface was being used, what the temperature was at observation time, etc.. Was the snowfall amount measured on the lawn (grass), the metal roof of the car, the driveway or sidewalk, the roof of a heated airport terminal building, or something else? In many cases, the metadata does not document this important aspect of the measurement procedure.

Another excellent example of the impact that different observing practices has on the climate record is the frequency with which snowfall measurements are taken. It has long been known that the amount of snowfall one measures is strongly correlated with the frequency of measurement. That is the case where the measurement surface is cleared with each observation.

In recent years, it became evident that the standard frequency of once each six hours (or once daily at COOP stations) was not being followed by all observers and that some were taking observations hourly and then summing the 24 values to produce a 24-hour total. The problem with this non-compliant methodology is that it inflates totals as compared to the standard frequency (Figure 23).

(Figure 20—Marina will create and insert bar chart from snowfall data I provided her with several months ago).

Snowfall, unlike rain, cannot simply be summed over varying time intervals to obtain a total. Snow settles, melts, and blows around and thus the total accumulation varies significantly with the frequency of the measurement. The more frequently that snow is measured, the snowier a location appears to become. The impacts of non-compliance with measurement standards on the data are 1) incompatibility between stations and 2) inhomogeneity with past data, depending on the methodology used historically.

A similar case can be made for changing the time of observation for temperature. NOAA researchers evaluating temperature trends in the U.S. during the 1950’s through 1970’s were aware that the NWS was requesting volunteer COOP observers to shift their 24-hour time of observation from afternoon. to morning readings to better support NWS hydrologic services needs. This change introduced a cold monthly bias of up to 2 degrees F into the climate record some parts of the country (Figure 21). It is now well-known that whatever time instruments are reset, those are preferred times for daily maximum and minimum temperatures to also occur, and especially so in frontal or advective (that is, non-solar-dominated) climatic regimes, such as winter and in northern latitudes). Conversely, it has been shown that if a single observation time is adhered to, no matter what the time the records can yield excellent tracking of the temporal variations in climate.

The apparent climate cooling introduced by the change in observing practices was many times greater than the magnitude of the natural climate change signal. In this case, good
metadata records allowed the National Climatic Data Center to develop and apply monthly time-of-observation bias corrections to create more homogeneous data sets for research.

Figure 21: Change in January Average Temperature Resulting from Changing the Time of Observation from 5 p.m.

Recommended Observing Practices Related Actions

The following actions are recommended to minimize unwanted discontinuities in the climate record:

1) Ensure that all changes in observing practices are entered into the station metadata record including the data of the change.

2) Ensure that observers understand the importance of compliance with standards for observing methodology with respect to the integrity of the climate record and that any changes they make in their practices need to be reported to the NWS representative and recorded in the station metadata immediately.

3) Coordinate with your RCSPM and other climate services partners (NCDC, RCCs, SCs) on any proposed observation change related issues before implementing the change so that impacts on the climate program and options can be considered.
Factors Impact on Data Continuity

Today, a primary concern of many climate scientists is the homogeneity of the data sets they use, especially relative to some long-term baseline such as 30-year decadal climate normals. Inhomogeneous data sets are the result of changes in the biases associated with data measurement (discontinuities).

Homogenized data sets have been adjusted for discontinuities and provide the means for data users to be confident that any changes and variations identified in the data are natural and not artificial. The adjustments are normally made so that the entire data set is based on the most recent observing system. This concept is an extremely important one to the climate community and requires a great deal of effort.

Inhomogeneous data sets can arise from a variety of factors, but in general, can be classified into three basic groups related to:

1) Changing the precision and/or accuracy of measurements,
2) Changes of temporal and/or spatial sampling and/or processing, and,
3) Micro-climatic changes of the local environment.

Changes in the accuracy and precision of the operational observing systems can lead to significant inhomogeneities. Discontinuities in precipitation measurements provide a good example.

Figure 22 illustrates numerous equipment and exposure-related precipitation discontinuities (Karl, et. Al. 1993). Note the apparent climate shifts (inhomogeneities or discontinuities) have been introduced as a result of changing precipitation gauges, adding or removing wind shields, changing the height of the gauge orifices, and changing observing practices (10 to 1 snow-to-liquid equivalent ratio used in Canada).

Many of the noted countries sport expensive, high quality precipitation gauges. These discontinuities also show up with climatological isoline precipitation analysis at international boundaries.

The ratio of 10:1 snowfall-to-liquid precipitation has dropped from about 30-40 percent of all U.S. snowfall observations at the turn of the century, to about 10 percent today (Figure 23). The frequency was derived for each individual station and then averaged for several hundred long-term U.S. stations.
Figure 23. Frequency of a Daily Ratio of 10:1 of Snowfall to Liquid Equivalent Precipitation. (prepared by Ken Kunkel at the Midwestern Regional Climate Center/Illinois State Water Survey).

An example of two types of other data continuity problems are shown in Figures 24a and 24b.
Reno Airport
(KRNO)

KRNO ASOS
(between runways)

Temporary ASOS
(“not windy enough”)

Temperature
differences can be 6-8
degrees F from one
end of runway to the
other, at night.

Figure 24a. Locations of Reno Runways, Urban Heat Bubble, Previous and Installed/Relocated and Re-relocated ASOS Instruments.

Reno Nevada Airport.
Mean Annual Minimum Temperature.
Figure 24b. Changes in Mean Annual Minimum Temperatures with ASOS Instrument Relocations at Reno, Nevada.

Reno’s busy urban airport has seen the growth of an urban heat bubble on its north end. The corresponding graph of mean annual minimum temperature (average of 365 nighttime minimums each year) has as a consequence been steadily rising. When the new ASOS sensor was installed, the site was moved to the much cooler south end of the runway. Nearby records indicate that the two cool post-ASOS years should have been warmer rather than cooler. When air traffic controllers asked for a location not so close to nearby trees (for better wind readings), the station was moved back. The first move was documented, the second was not. The climate record shows both the steady warming of the site, as well as the big difference in overnight temperature between one end of this flat and seemingly homogeneous setting, an observation borne out by automobile traverses around the airport at night.

Another bias can creep into the climate record simply by changing the sampling frequency or spatial averaging algorithms of the measuring and processing systems. This bias can be removed readily as long as it is quantified (by taking overlapping parallel observations between the old and new systems) and documented in time in the station’s history file (metadata).

Perhaps the most difficult biases to compensate for occur when local or micro-climatic changes around the instrumentation introduce non-representative (but physically accurate spot scale) changes in the data record. These inhomogenities can settle into the data quickly (a few days), as with parking lot expansions, or gradually (months or longer), as in the case of slowly maturing trees. The best known examples include the growth of big-city urban heat islands, changes of land use, and stations relocations (Figure 25). Any of these can blur or completely mask regional larger scale climate variations and/or change.
Figure 22: (Marina---I cropped this figure so please re-insert it as shown here) Discontinuities in international precipitation records (from Karl, et al.1993b).
Station relocations are unavoidable on occasion due to loss of an observer, property ownership transfers, poor data quality, etc. When this situation occurs, for whatever reason, the NWS field person is responsible for determining whether the new site is “climatologically compatible” with the old site and whether the data sets are thereafter treated as different time series.

A frequently asked question is how is climate compatibility determined? NWS policy (NWS Observing Handbook No. 6: Cooperative Program Operations) states that:

“compatibility is always determined by comparing the new to the original equipment location for the station as described on Rendition [original site, not last site] of the station’s WS Form B-44. With some exceptions, a move is considered compatible if the new equipment location is within 5 miles of the original equipment location and the difference in elevation is 100 feet or less. However, take great care to assure that moves made within these limits are not, for example, from a hilltop to a valley bottom or subject to other large magnitude influences such as large water bodies, pavements, etc.”

This somewhat arbitrary policy can result in the inappropriate continuation of long-term data sets at climate stations which in fact may be incompatible. Discontinuities such as these can then lead to serious misinterpretation of climate variability and trends at the locale by data users.

Figures 26 a and 26 b illustrate an example of a relocation that resulted in a large climate discontinuity although the station name remained the same. This COOP station was moved from about 400 yards from this 100 foot-high south-facing rock face to within about 100 feet of it. The original site was an open sagebrush exposure. That summer, the station set or tied four consecutive all time monthly extreme maxima.

This illustrates the importance of station exposure in determining climate continuity. In this case, although the station’s relocation fell well under guidelines that require renaming (5 miles, 100 feet), the new setting is completely incompatible with the original site and needs to be started over for climate purposes.
Figure 26a: Station Relocations are a Common Sources of Data Discontinuities and Non-homogenous Climate Records.
NWSH Climate Services Division plans to revisit this policy in the near future (FY05) to consider options for a more appropriate approach. However, at this time, we discuss the situation within the limitations of the existing policy.

Climate compatibility is best determined by running overlapping observations at both the existing and new site for a minimum of a year or so and then comparing differences. However, even when this approach is satisfied, a quantitative definition of climate compatibility does not exist. Thus, for the time being, it must be stated that climate continuity is subjectively determined. Traditionally, this determination has been made on the spot, on the day the station is moved, without benefit of analysis of actual data behavior. Evidence is now suggesting that a number of those determinations are in error and that many relocated stations should in fact be considered as separate stations.

**Recommended Station-Relocation Related Actions**

The following actions are recommended to minimize unwanted discontinuities in the climate record:

1) When considering station relocation climatological compatibility, strongly weight topographic characteristics of the old and new sites in addition to the 5 mile/100 feet policy. In some cases the relevant tolerance may be as low as 5-15 feet vertically and a few tens of feet horizontally. Understand that topographic setting differences (i.e., slope orientation and setting; crest, valley bottom, slope, plateau) can have a much greater impact on data continuity than, say, the relocation coordinates in the context of the 5-horizontal, 100-vertical feet rule. The chances are high that the two stations are climatologically incompatible if there are any significant topographic exposure differences.

2) Coordinate with your RCSPM and other climate services partners (NCDC, RCCs, SCs) before making the final determination on station relocation climate compatibility. Although current NWS policy gives you, the NWS representative, responsibility for determining climatological compatibility for station relocations, consultation and input from our climate partners will assist you in making the best call possible.

**Summary**

In our summary of the tutorial, we ask you to respond to questions related to each of the seven topics discussed. You are not being graded on your responses. The intent is to give you an opportunity to review the important points of the lesson, contemplate the information you have hopefully learned, and apply the concepts in real-world situations. The correct responses to some of the questions may include multiple choices.
Adherence to standards: Adherence to standards is important because it:

1) Helps create a level the playing field for the measurement and resulting comparability of data and increases data quality.
2) Increases unrepresentativeness of data.
3) Guarantees the collection of accurate data.

If you selected response one you are correct. Adherence to instrument and exposure standards increases the chances that we will collect valid data that meets ours and our customers’ needs. It also increases our ability to compare data between locations and make accurate assessments of climate variability and trends. Adherence to standards does not guarantee accurate data as there are many other factors that can affect data accuracy.

Metadata: Select the responses you believe should be entered into station metadata.

1) temperature sensor replaced with another of same manufacturer’s equipment
2) temperature sensor replaced with different manufacturer’s unit
3) removed tree limb overhanging precipitation gauge
4) observer began using snow measurement board for first time
5) changes in land use occurring within 200 feet of station
6) observer changed snowfall measurement frequency from once daily to 4 times a day

If you answered all of the above, you are correct. Remember that metadata is simply “data about data”. Also remember that metadata is as critical to understanding the data, and trends and variability in the data, as the data itself.

Document any event that you believe may enter a discontinuity into the climate record. This includes changes in the way measurements are made and recorded, and changes in the local physical environment. Err on the side of over-documentation. Coordinate with our climate services partners on issues.

Instrumentation

Select the responses below that you believe are TRUE regarding published climate stations:

1) In the interest of having some climate data versus no climate data, we should install any available equipment we can find.
2) Installation of unapproved instrumentation is acceptable as long as its kept secret and out of the metadata so NCDC and other data users don’t know about it.
3) Data continuity and related minimal instrumentation changes is of special consideration at Historical Climate Network (HCN) stations.
4) Off-the-shelf unapproved instrumentation can be assumed to be as accurate and reliable as the manufacturer’s advertised capabilities.
If you selected response three as TRUE, you are correct. The basic message regarding instrumentation at published climate stations is that we install only approved equipment. Approved equipment has been testing and validated for meeting climate needs across a wide range of environmental conditions.

**Station and Instrument Exposure**

This factor is one of the most important as it can contribute a great deal of uncertainty to the climate record and we can exert considerable influence to minimize the impacts. Look at the picture below and select the responses that you believe best fit the situation:

1) This temperature sensor is situated in a spot that will likely provide high quality readings representative of the surrounding environment.

2) The equipment is situated fine as it was put it here or nowhere.

3) I know being close to buildings can reduce the diurnal temperature range and that heat exchangers can artificially affect the readings but who cares? A couple of degrees error doesn’t really hurt anything.

4) The instrument is grossly non-standard in exposure and should be relocated farther away from the building and air exchanger or closed down.

If you selected answer number four above, congratulations! You are correct. The basic point to remember regarding the station and instrument exposure factor is that sensors
should be located as reasonably compliant with standard guidelines as prudent. Avoid grossly non-standard settings such as rooftops, under trees, etc. The argument that bad data is better than no data does not hold water in the climate community.

Also, understand and respect the fact that topographic setting can be much more important in determining whether a relocated station keeps the same name (has climate continuity with the previous site) or gets a new name (begins a new climate record) than the 5 horizontal mile/100 vertical feet rule. And when in doubt or just needing input on exposure issues, coordinate with our climate community partners.

**Changing Environments**

Changing environments are a fact of life that are difficult to totally avoid. In many cases, the best we can do is fully document any conditions in the local vicinity of the station which can introduce discontinuities into the climate record. This is best accomplished through keeping accurate and complete metadata.

When non-compliant situations are extreme, either correct the situation or consider closing the station down. Take digital photographs with each scheduled preventative maintenance visit per guidelines or as needed when change is apparent. And of course, don’t forget to coordinate issues with our climate community partners. They are ready and willing to assist with their climate expertise.

**Observing Practices**

Although the method in which we take environmental measurements may change over time to reflect changes in technology and needs, these changes, if not documented can seriously affect the accurate interpretation of data and derived products.

Snowfall measurements provide an excellent example. Consider an observer who, during a snowstorm, places 3 snow measurement boards side-by-side in his backyard. On board A, she takes a measurement of how much snow fell each hour, followed by sweeping the surface clean for the next measurement. On board B, she follows the same procedure, but measures the snowfall depth every six hours. On board C, the same as boards A and B but takes the measurement only once in 24 hours before cleaning the board.

Which snowfall measurement is the correct value to report? Without measurement frequency standards, even though each procedure and board results in a different amount, all three would be valid. However, since we do have a standard, which allows for up to four measurements no closer than 6 hours apart or optionally, once per 24-hours, either boards B or C are correct.

The morale of the story is that for comparability’s sake, and continuity in time and between stations, we must all adhere to standards of measurement to assure the highest quality data possible. And when the methodology changes, the date and procedural
changes must be documented in the metadata if data users are to be able to accurately assess climate trends and variability.