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TOWARD AN AUTOMATED TOOL FOR DETECTING RELATIONSHIP CHANGES WITHIN SERIES OF OBSERVATIONS

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1. INTRODUCTION

The U.S. Climate Reference Network (CRN) is being deployed to build a long-term homogeneous record of temperature and precipitation across the United States (Heim et al. 2001). Also, as the likelihood of a modernized cooperative observer (COOP) network increases, so too does the likelihood that only a subset of current COOP stations will be carried into the next generation of the network. These developments underscore the need for the climate community to be aware of the homogeneity of climate record of stations in the CRN (as an ongoing near-real-time assessment), and of the stations in the COOP network (to help identify and assess candidates for modernization).

Many traditional methods for examining and viewing long-term climate records can mask seemingly minor station moves, instrument replacements, and sensor drift. Additionally, as the number of independent networks and data sources increases, so too does the need for assessment tools to function in a robust manner, regardless of the origin of the data.

A set of tools is being developed through collaboration between scientists at the Western Regional Climate Center (WRCC) in Reno, NV and the Oklahoma Climatological Survey (OCS) in Norman, OK. These tools are designed to detect changes in relationship between one time series (e.g., a climate record) and one or more other time series. They are built on some tenets of double-mass analysis (Kohler 1949) and intended to help identify subtle changes that might be otherwise overwhelmed by the large cumulative values associated with long-term records.

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2. DESIGN CONSIDERATIONS

In order to be most universally useful, the tools are subject to several design considerations, with ultimate goal of the ability to provide a user-definable level of sensitivity to the smallest of changes in relationship between one station and one or more of its neighbors.

2.1 Mandatory Qualities

A. The tools must be able to work on datasets of any time scale and observation interval

The nation's climate records are composed of much more than just daily temperature and precipitation records. There is a distinct possibility, especially in the western U.S., that neighboring stations observe climate variables on significantly different time scales (e.g., hourly versus daily observations). Tools to assess the homogeneity of relationship between neighboring stations should be able to accommodate such differences in time resolution.

B. The tools must function properly regardless of variables being compared.

As the understanding of interrelationships between long-term indicators continues to evolve, the ability to compare traditional climatic data with non-traditional environmental data should be available. Moreover, the tools should be able to assess changes between different elements at a particular climate observing station.

C. The tools must be able to work on retrospective data and operational incoming data flows where the future values in the stream are not available

Meeting this requirement allows the tools to be useful in retro-active assessments of stationarity and in real-time (in a climate sense) operations of networks. This real-time assessment should be of value to networks, such as the CRN, that observe specific variables redundantly.

2.2 Other Desired Qualities

A. The tools should be accessible through a relatively-simple user interface.

Ideally, these tools should be available in real-time from a number of locations and for a number of target data sources. The world-wide web provides an excellent medium to deploy the tools.

B. The tools should be computationally inexpensive.

Many algorithms are available to assess changes in homogeneity (e.g., Tuomenvirta et al. (1997), Easterling et al. (1996), and many others). Those chosen for automation, particularly in a real-time assessment, should be computationally simple enough to allow a systematic reassessment of an ever-expanding volume of long-term climate and environmental data.

C. Assessment tools should be easily automated to alert a QA professional.

Many different factors can influence a station's homogeneity. An automated process should be able to detect a suspect change in relationship between a station and its neighbors, then notify a climate professional to prompt further investigation.

D. The tools should contain both a visual and a mathematical element.

Visual tools provide the opportunity for valuable human judgment and expertise. However, the number of graphics required to assess the health of the climate record of more than a few stations is staggering. Most desirable is a tool that can run in the "background" and objectively determine when the relationships between climate elements may have changed.

3. PRELIMINARY TOOLS

Initial collaboration between WRCC and OCS resulted in a set of tools meeting some of the criteria listed above. Full automation was not achieved, but some of the techniques proved promising.

Two families of tools emerged from the collaboration. Tools with a multiplicative nature, like double-mass analysis, are often used when comparing zero-based variables such as rainfall. However, it was soon apparent that, for climate records of significant length, an additive family of tools – one that looks at cumulative differences between a target station and a reference station – may be necessary to convey information with the amount of detail required to realize success.

3.1 Double-mass Analysis

Double-mass analysis is available between any of six common climate variables (maximum, minimum and average temperature, snowfall, snow depth and precipitation). Beginning and ending dates are user-definable, and up to six stations can be compared to the reference station. Results are provided in a standard double-mass plot (Fig. 1). In most long-term records, the accumulation of values becomes so large that a double-mass plot masks significant changes in relationship between climate elements.

3.2 Residual Analysis

The large cumulative values associated with double-mass analysis can mask subtle changes in relationship between two stations. Thus, it is often desirable to plot a running difference between two stations, with time along the abscissa. Even then, accumulation of large differences can dominate the graph and mask significant relationship changes. Therefore it is often desirable to display an accumulated departure from a line or curve that mathematically estimates the stations' relationship. The following options are currently available to set this estimate. Each provides an increasingly sophisticated method of magnifying seemingly small changes.

No estimate. The actual cumulative differences (remote station minus reference station) are plotted.

"Poor Man's Regression". Cumulative departures of the remote station's values from a line connecting any two user-defined dates (default are first and last points in the series).

Linear regression. Cumulative departures from a best-fit line beginning and ending with any two user-defined dates (default are first and last points in the series).

Exponential and polynomial regression techniques are also candidates for more sophisticated residual analysis.

In these residual analyses, a non-zero second derivative with respect to time represents a changing relationship between the climate elements. For example, consider a comparison of minimum and maximum temperature at a station, with minimum as the reference and maximum as the comparison time-series, and no regression estimate performed. A trace that curves to the right with time indicates that the maximum temperature is becoming increasingly warmer than the minimum temperature, i.e., that the diurnal temperature range is increasing. For the same comparison, with a regression estimate, a rightward-curving trace indicates an increase in diurnal range, *relative to the estimated relationship*.

3.3 Toward an Automated Tool

One candidate for automated analysis of changes in relationship has been identified. This method employs an army of “crawlers” that travel up and down the double-mass curve. These crawlers are equipped with feelers that reach a prescribed number of time units backward and forward to calculate the change in slope between the times (Fig. 2).

By deploying a set of crawlers with varying feeler lengths, sensitivity to multiple time scales can be accomplished, and cyclic patterns of distinct wavelengths (e.g., annual) can be accommodated. An inhomogeneity in a station’s record could be indicated when significant changes are detected with more than one neighbor by crawlers observing more than one timescale.

Well-chosen lengths of feeler arms will help smooth over systematic cycles in the relationships between climate elements. For example, annual cycles in daily observations can be filtered by selecting feeler lengths of 365 days (half-years will work as well).

4. PRELIMINARY RESULTS

The initial tools developed by WRCC and OCS have been applied to a limited data set composed of stations within the western United States. Even though these tools are far from mature, interesting changes in the relationships between these stations were found.

4.1 Evidence of Urban Heat Island Effect

The downtown and casino districts of Reno, NV have expanded rapidly, as the city’s population has increased by more than 300% since 1960 (Census Bureau, 2003). Reno/Tahoe International Airport is located about four miles southeast of Reno’s city center, and has become encroached by urbanization during the period.

Minimum temperature data from Reno, NV, taken at the airport were compared to that from Tahoe, CA located in a relatively rural setting approximately 20 miles southwest of Reno. Beginning in the early 1960’s, the rate of change of the cumulative residual (Tahoe minus Reno) has increased steadily over the following four decades (Fig. 3). This feature represents an increasing difference between minimum temperatures at the two sites, such that Reno’s have become relatively warmer than Tahoe’s over time.

This artifact seems to give evidence that the growth of Reno’s urban heat island may be increasing minimum temperatures at its airport. Deeper investigation of this phenomenon is desirable, as the ramifications of a local effect on a first-order station’s climate record can reach beyond the local scale.

4.2 Evidence of the Significance of Elevation Change

In July 1996, the Austin, NV COOP station was moved to a new observer's residence just 0.2 miles north-northwest of its previous location. While no documented change in elevation is associated with this move, a cursory survey of topographic maps indicates a high likelihood that the move was associated with an elevation change on the order of tens of feet. Indeed, a residual analysis when compared with nearby Snowball Ranch, NV indicates a significant change in relationship in mid-1996 (Fig. 4).

The “raw” residual analysis indicates that Austin's minimum temperatures are consistently warmer than those at Snowball Ranch throughout the period. Careful inspection reveals that the relationship between the two stations may have changed in mid-1996.

When the residual analysis is compared against the “background” relationship from 1966 through mid 1996, the station move becomes quite evident as an easily identifiable change in relationship between the two stations. Moreover, at this magnified level of detail, subtle shifts in the relationship between the two stations become apparent throughout 1980s and 1990s. The relationship seems to jump between two regimes, notably in 1982, 1985, 1990, 1993 and possibly 1995. The reason for the oscillation between these two “relationship regimes” is unknown at this time.

4.3 Evidence of Undocumented Station Moves

The dawn of the ASOS era at Reno in the 1990s brought several seemingly minor moves to the sensors at the Reno airport. Each move was just a few hundred yards along the north-south runways, with near-zero elevation change. These horizontal and vertical changes are well within established specifications to preserve the station’s identity as a singular climate observing point. However, the change in land use across those few hundred yards is remarkable. The north end of the runways sits in an urban concrete environment, while the south end rests farther from Reno’s central business district, with a considerably larger fraction of nearby land used as grassland.

The station is a long-term first-order station in the climate record. According to NCDC station documentation, the temperature and precipitation equipment were replaced in September 1993. This date appears as an inflection point in the residual analysis of Reno versus four neighboring stations (Fig. 5). Before this instrumentation change, the four stations accumulated negative differences in minimum temperature when compared to Reno (i.e., Reno's low temperatures were slightly warmer, on average, than all four neighboring stations. After the change, this relationship was amplified.

In September 1995, the station became part of the NWS Automated Surface Observing System (ASOS) network and the instrumentation was changed accordingly. Moreover, the station moved 0.6 miles to the south-southwest, according to NCDC documentation. This change, and move, shows up as a distinct inflection point in the residual analysis shown in Figure 5. The trend of accumulation reversed with these changes and Reno's minimums became relatively cooler than its dour nearest neighbors. The combination of ASOS instrumentation and a move to a much less urbanized environment just a few hundred yards away was enough to make Reno a “cooler” station.

In spring of 1998, the station moved again, this time back to the northern end of the runway, where it can be seen today. This move is not documented in the NCDC's online metadata. However, it can be seen clearly in the residual analysis. The sign of accumulation changed immediately upon the move to the more urbanized setting, and Reno became once again a “warmer” station than its neighbors.

These seemingly innocuous station moves show up dramatically in a residual analysis of the Reno minimum temperature record compared to its neighbors. Notably, the slope of the residuals between Reno and its neighbors adopted nearly the same values as those from 1993-1995, when the station was also located on the north end of the runway.

This method is most effective when the reference station is compared to several of its neighbors over the chosen time period. The simultaneous – and consistent – changes in *all of the traces* supports the concept that Reno is the station introducing inhomogeneities into the relationships.

5. SUMMARY

The use of double-mass analysis and associated residual analysis to assess the homogeneity of a station record has been demonstrated. While far from mature, tools developed by collaboration between WRCC and OCS have identified several documented and undocumented changes in the observational record of COOP stations in Nevada.

When mature, these tools may have use beyond assessing past climate records. The ability to automate some elements of these tools may provide an opportunity to provide day-to-day monitoring of the relationships between CRN stations, and even between the instruments within a CRN station.

6. REFERENCES

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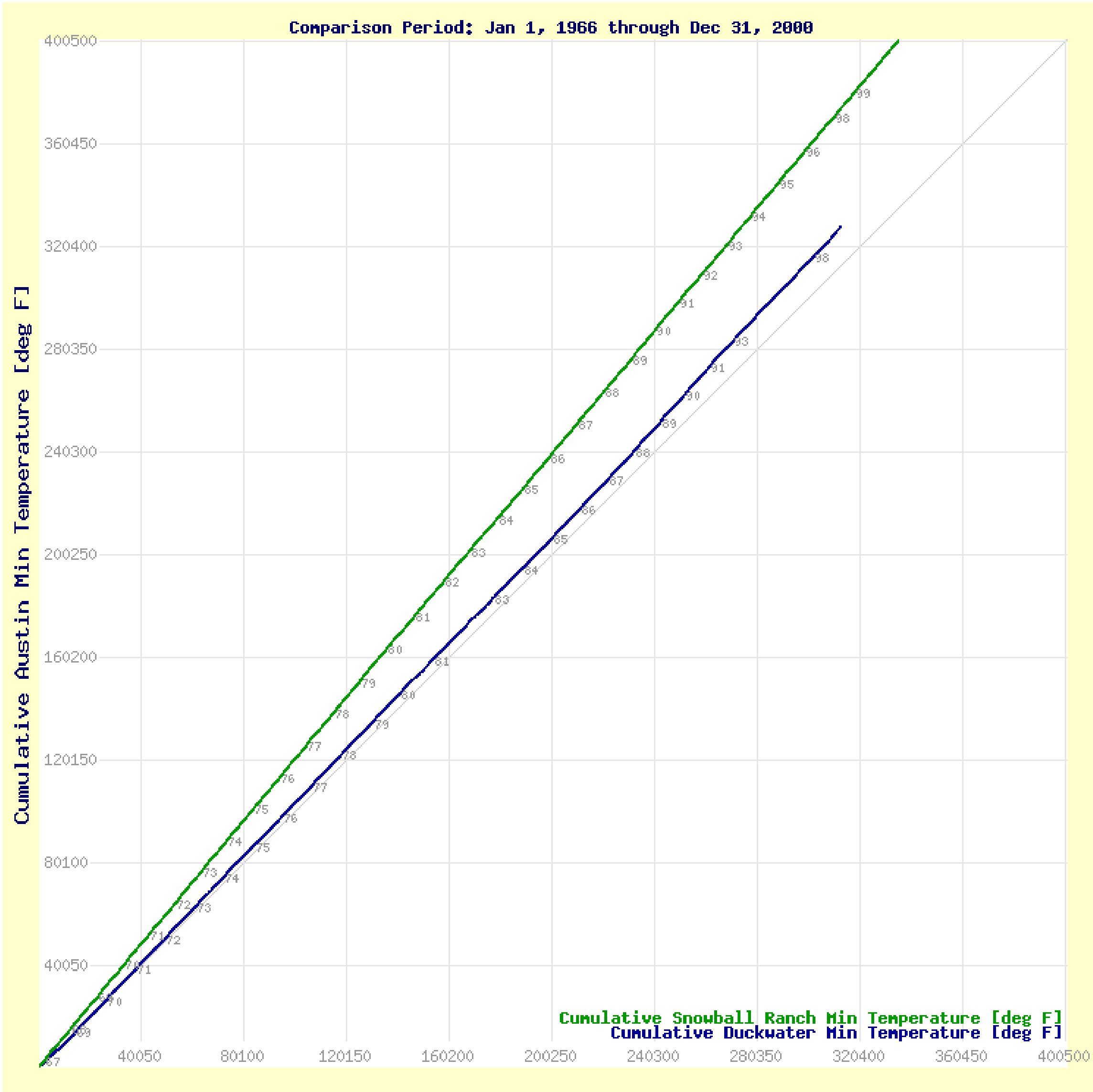

Figure 1. Double-mass analysis of minimum temperature at Austin, NV (the reference station) with two comparison stations: Duckwater, NV (blue) and Snowball Ranch, NV (green) from Jan. 1, 1966 through Dec. 31, 2000. The vertical axis represents cumulative minimum temperature at the reference station, and the horizontal axis marks that of the comparison stations. January 1st of each year is noted along the curves.

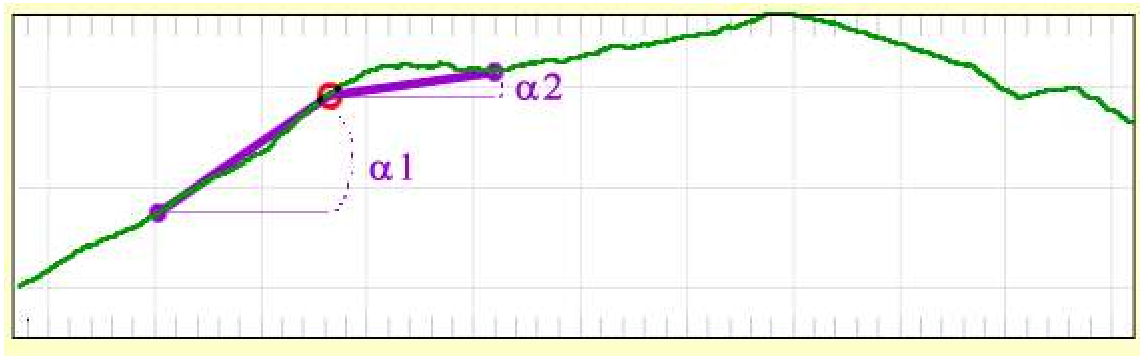

Figure 2. A schematic diagram of an automated "crawler" for determining changes in relationship in a time series record. The horizontal axis represents time, and the vertical axis indicates some accumulated value. The angular difference a2 minus a1 is recorded at each possible point along the series. The lengths of the "feeler" arms can be adjusted to record such differences at several time scales.

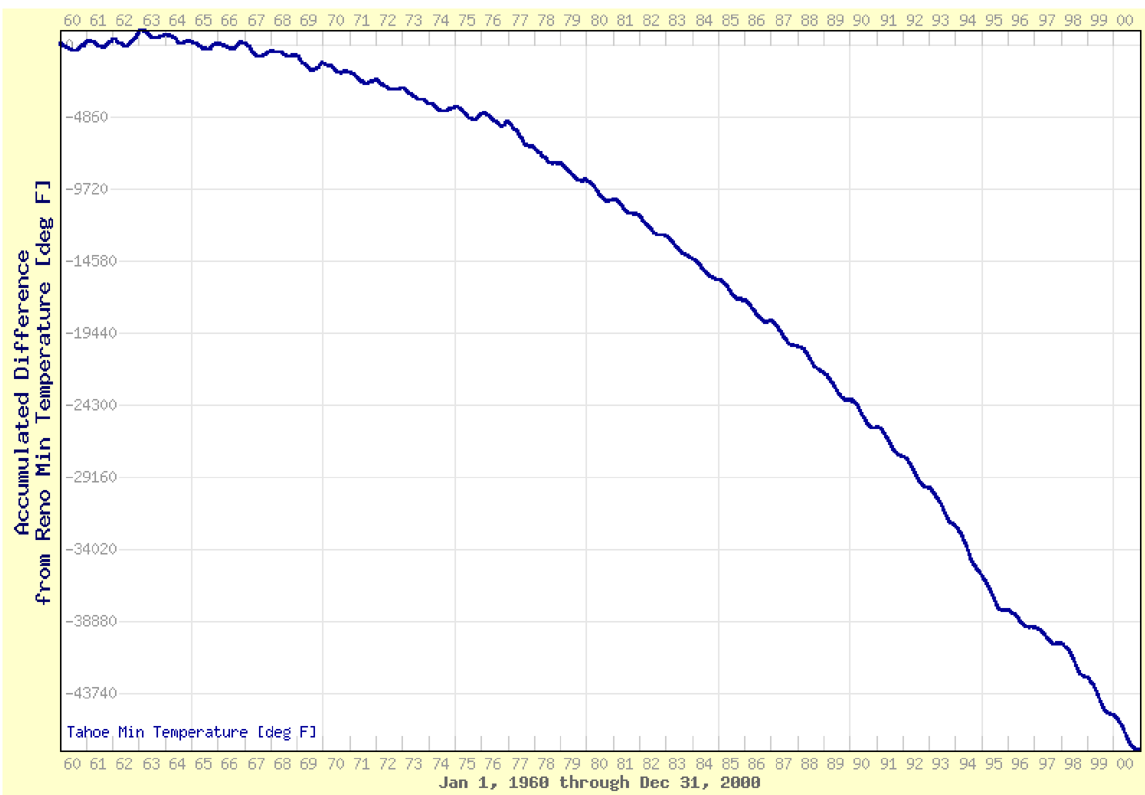

Figure 3. Residual analysis of minimum temperatures at Tahoe, CA and Reno, NV from Jan. 1, 1960 through Dec. 31, 2000. The horizontal axis is time, and the vertical axis represents the cumulative difference (Tahoe minus Reno). Segments with positive (negative) slope indicate that Tahoe minimum temperatures were less (greater) than Reno when averaged over the period. The rightward curve of the trace from the mid-1960s through the mid-1990s indicates that Reno's minimum temperatures were becoming increasingly warmer than those at Tahoe.

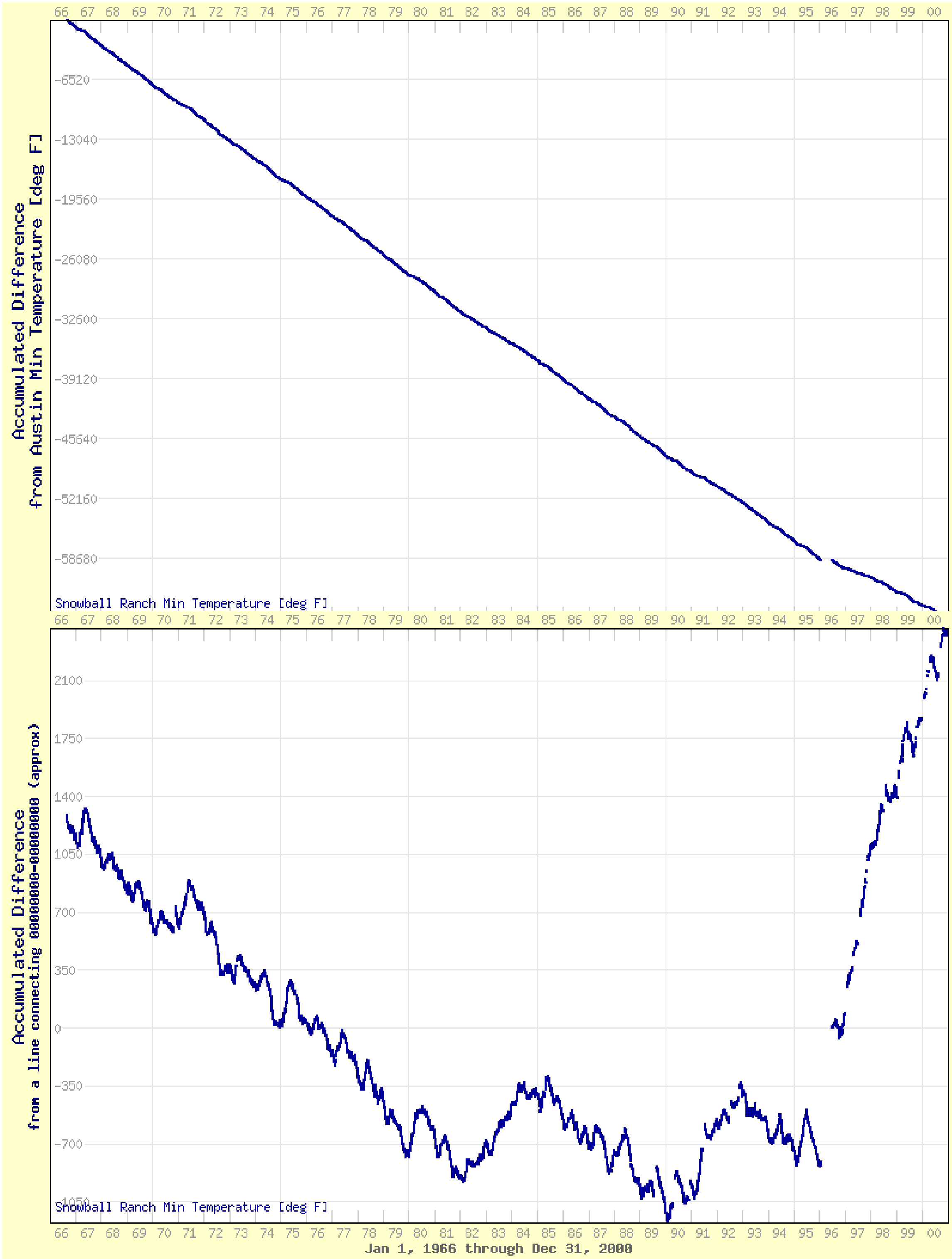

Figure 4. Residual analysis of minimum temperatures at Austin, NV and Snowball Ranch, NV from Jan. 1, 1966 through Dec. 31, 2000. The horizontal axis represents time. The vertical axis represents the cumulative difference in a) minimum temperature (Snowball Ranch minus Austin); and b) the residual from a line approximating the relationship from Jan. 1, 1966 through Jul. 1, 1996. A change in relationship associated with a 1996 station move is distinctly visible in the more detailed lower curve. Several subtle changes in relationship lasting 2-3 years each are visible during the 1980s and 1990s.

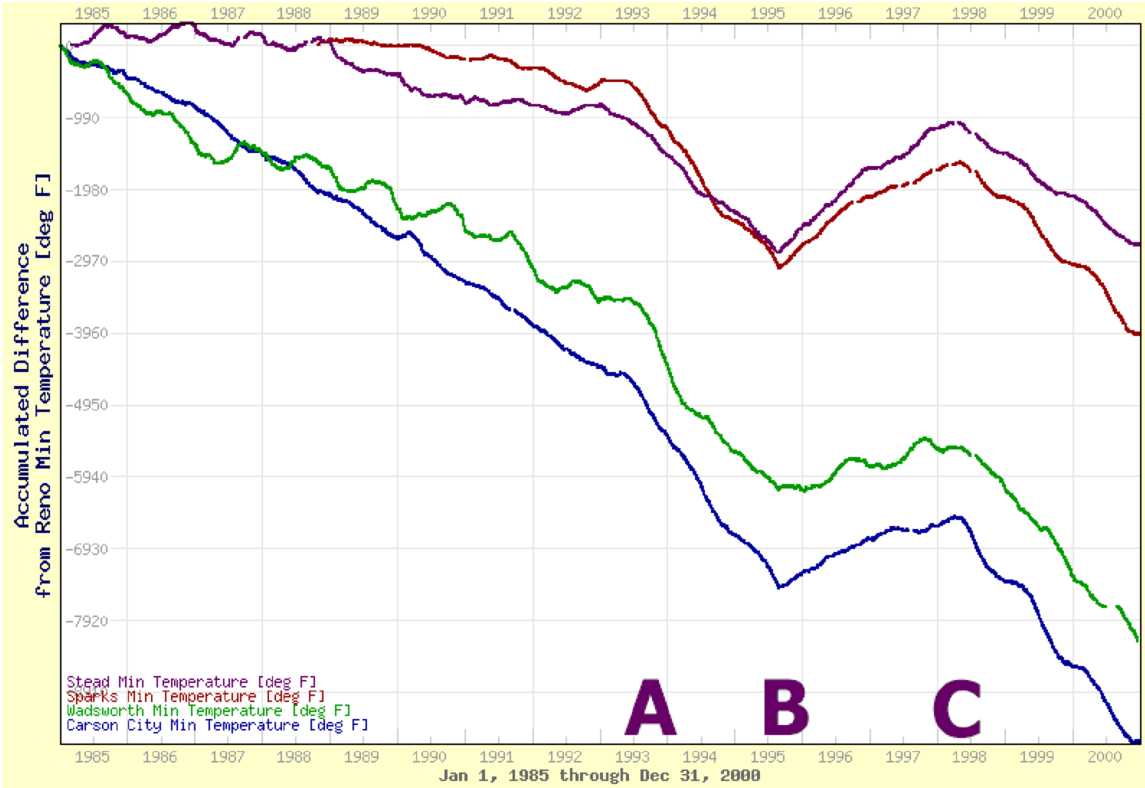

Figure 5. Residual analysis of minimum temperatures at Reno, NV and four neighboring stations from January 1, 1985 through December 31, 2000. The horizontal axis is time, with long tick marks indicating January 1 and short tick marks indicating July 1 of each year. The vertical axis represents the cumulative difference (comparison station minus Reno) with Stead, NV (purple), Sparks, NV (red), Wadsworth, NV (green) and Carson City, NV (blue). The approximate time of three known station changes are noted as: A – documented instrumentation replacement (Sep. 1993); B – documented station move of 0.6 mi to the south-southwest and conversion to ASOS platform (Sep. 1995); and C – undocumented station move of 0.6 mi to the north-northeast to its original location (spring 1998).