4.6B

A CLIMATE CONTINUITY STRATEGY FOR THE RADIOSONDE REPLACEMENT SYSTEM TRANSITION

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1. INTRODUCTION

1.1 *Heritage*

This paper builds on and borrows freely from:

The *Radiosonde Data Continuity Strategy* white paper version 4.0, September 3, 2002, prepared by Bill Murray (NOAA/OGP), Melissa Free (NOAA/ARL), Mel Gelman (NOAA/CPC), Chris Miller (NOAA/OGP), Tom Peterson (NOAA/NCDC), Chris Redder (NASA/GSFC/DAO), Dian Seidel (NOAA/ARL), Steve Sherwood (Yale) and Betsy Weatherhead (NOAA/ARL). 8 pages. This document was a result of work by an ad hoc group coordinated by Bill Murray.

The *OS4 Issue Paper: Options and Costs for Satisfying Climate Data Continuity Requirements in the NWS Upper Air Radiosonde Program* prepared November 1, 2001 from input provided by OST, OOS, NCEP, NCDC, and OAR. 6 pages.

It is also greatly indebted to the advice and guidance received at a *Radiosonde Replacement System Continuity Meeting,* held October 29, 2002 at NWS Headquarters, Silver Spring, MD. Meeting participants were:

Tom Peterson	NOAA/NESDIS/NCDC
Imke Durre	NOAA/NESDIS/NCDC
Bill Elliott	NOAA/OAR/ARL (retired)
Jim Angell	NOAA/OAR/ARL (contractor)
Dian Seidel	NOAA/OAR/ARL
Melissa Free	NOAA/OAR/ARL
John Lanzante	NOAA/OAR/GFDL
Frank Schmidlin	NASA/GSFC/Wallops Island
John Christy	University of Alabama in Huntsville
Bill Murray	NOAA/OAR/OGP
Rick Rosen	AER, Inc.
Dave Carlson	NCAR/ATD
Barry Lesht	Argonne National Lab
Larry McMillin	NOAA/NESDIS/ORA
Christopher Redder	NASA/GSFC/DAO - SAIC
Mel Gelman	NOAA/NWS/Climate Prediction Center
Carl Bower	NOAA/NWS/Observing Services Division
Raymond Downs	NOAA/NWS/Observing Services Division
Rainer Dombrowsky	NOAA/NWS/Observing Services Division
William Blackmore	NOAA/NWS/Office of Operational Systems
Joe Facundo	NOAA/NWS/Office of Operational Systems
Jiayu Zhou	NOAA/NWS/Office of Science and Technology
Tom Roberts	NOAA/NWS/Office of Science and Technology

Among the participants at the meeting, Jiayu Zhou, Carl Bower, Bill Blackmore, Rainer Dombrowsky and Joe Facundo continued to be significantly involved afterwards making contributions towards creating this document, particularly by providing important information and insights. The document was also shaped by the insightful comments from its many reviewers: Bill Blackmore, Joe Facundo, Melissa Free, Mel Gelman, Tom Karl, John Lanzante, Sharon LeDuc, Chris Miller, Bill Murray, Tom Roberts, Rick Rosen, Dian Seidel, Steve Sherwood, Russ Vose, and Jiayu Zhou.

1.2 *Background*

The climate community regularly uses and highly values observing systems and datasets originally developed to meet short-term weather forecasting requirements. Radiosonde systems are a prime example and represent one of the largest and most respected sources of upper air observations. These balloon borne instruments (see Figure 1) provide data on pressure, ambient temperature, relative humidity, and wind (speed and direction). As do many meteorological services all over the world, the National Weather Service (NWS) launches radiosondes twice a day, at 00 and 12 GMT. Over the last half-century of launches, radiosondes have created a wealth of data which are being used in attempts to answer some fundamental climate change questions. For example, they are key data in unraveling one of the controversial climate change concerns related to differences in recent warming rates between the surface in situ measurements and the satellite-derived measurements of the lower troposphere (National Research Council, 2000a).

The main obstacle to using radiosonde data in long-term climate change research is the effect of changing instrumentation and processing. This is true for most long-term climate change observations including sea surface temperatures (SST; Folland and Parker, 1995; Smith and Reynolds, 2002) and surface air temperatures (Peterson et al., 1998). However, homogenizing radiosonde data is evidently more difficult than other sources of data as the results from various radiosonde adjustment groups around the world do not converge the

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way SSTs and land surface temperature adjustments do (Free et al., 2002).

The NWS is now preparing to deploy a new set of radiosonde instruments as part of the Radiosonde Replacement System (RRS). But unlike radiosonde changes in the past, the NWS intends to address continuity concerns as it makes the changes. The purpose of this document is to provide guidance and recommendations to address continuity concerns. More specifically, its goal is to present metrics which can be used to determine the appropriate level of continuity effort. Review of the recommendations will be made by NOAA's Council on Long-term Climate Monitoring is a working group under the NOAA Science Advisory Board which is under the Administrator.

1.3 *The Radiosonde Replacement System*

The NWS currently operates upper air stations at 92 locations in the 50 United States, Puerto Rico and U.S. territories in the tropical west Pacific. See Figure 2 for a map of the sites and Table 1 for a list of stations. The antiquated Micro-ART ground system is used at all but three of these locations. Sixty locations fly the Vaisala RS-80 variety of radiosondes and 29 locations fly the Sippican VIZ B2 radiosonde. Three locations in the NWS network fly the Sippican Mark II LORAN-C "Microsonde" radiosonde associated with the Sippican W9000® ground system. The plan is to replace all the systems mentioned above with the Radiosonde Replacement System (RRS) comprised of a 1680-MHz GPS ground system and new state-of-the-art GPS radiosondes never flown before by any network.

The requirements for the RRS specify maximum errors in temperature (0.3°C); relative humidity (5% for pre-saturation and 10% for post-saturation); winds (1.0 ms^{-1}); and pressure (1.8 hPa below 400 hPa and 0.5 hPa above 400 hPa). However, it was never a primary program requirement to improve the performance of the meteorological sensors flown, though vendors are not restricted from making improvements. The requirements driving the RRS change are system obsolescence and loss of the operational radio frequency. Unfortunately, it appears that the RRS radiosondes will not be able to meet the stated humidity requirements, so deviations to the specification for the RH sensor have been authorized.

The radiosondes being produced for RRS are being provided by two companies, Sippican and Intermet. The NWS tests the radiosondes against specifications which the vendors must meet, with the requirement that 98.5% of the test results are within the listed accuracies (Wierenga, 2003). The main improvement anticipated is in the accuracy of the wind measurements. For temperature, the RRS specifications require adjustments or "corrections" for radiation induced errors (both long wave and short wave) be made by the vendor. Of the current sondes, only the Vaisala radiosondes have radiation adjustments applied on site. However, NCEP applies radiation adjustments to data from Sippican radiosondes when executing their numerical weather forecasting models. For humidity measurements, the RRS Intermet radiosonde uses a variable capacitance device, while the Sippican RRS radiosonde uses the less accurate carbon hygristor. Of the radiosondes currently flown, the Vaisala sonde uses a thin-film capacitor for humidity measurements (Wang et al., 2002), which has better sensitivity than the carbon hygristor used on the VIZ-B2 radiosonde. Therefore, NWS measurements of humidity, particularly upper tropospheric humidity, may deteriorate depending on the split of the sondes used.

After several decades of purchasing sondes from a single vendor, VIZ, it has been the recent practice of the NWS to maintain at least two qualified production sources on a 60/40 basis. This provides a measure of competition as well as protection against production issues that might cause a production shutdown of one of the vendors, a situation that has, in fact, occurred on several occasions in the past. Awarding the 60% share of the production to the lowest cost, qualified bidder is standard operating procedure with NWS qualified production lists (QPL). The NWS does not expect to decide which company will get the 60% share of the RRS contract until after it has received proposals for full production from the vendors next spring.

1.4 *Data Continuity Concerns*

In the context of this document, data continuity is defined as the compatibility of past, present, and future data such that the observational record is free of inhomogeneities caused by instrument changes, launch and sampling procedure changes, or data processing changes. Continuity is critical for constructing and using compatible data sets to accurately monitor and assess climate variability and change and to put the current conditions into accurate historical perspective. This continuity is at particular risk at times when observing systems are replaced because not all radiosondes are created equally (see Figure 3).

Temperatures in the free troposphere are increasingly being used for detecting climate change, and the radiosonde network offers the longest and highest vertical resolution records for analyzing past and future changes. For the radiosonde data to be of optimal use to climate researchers, it must represent a smooth continuation of observations (see Peterson et al. (1998) for a review of the issues associated with artificial inhomogeneities that can impact smooth continuation of observations in the climate record). Weatherhead et al. (1998) have shown that discontinuities or shifts in long-term data records can often double the period of record necessary to detect a change in an environmental parameter. Data continuity is therefore necessary for providing timely detection of trends of the order of hundredths to tenths of degrees per decade, the magnitudes discussed in the report entitled "Reconciling Observations of Global Temperature Change" (National Research Council, 2000a). Free et al. (2002) have demonstrated that, in the absence of overlapping observations, adjusting radiosonde station temperature data to remove inhomogeneities is a complex task and that different methods yield disparate results. Humidity data are even more challenging, since temperature and pressure adjustments need to be incorporated in the humidity adjustments. Given the large uncertainty associated with small expected magnitudes of change, the importance of maintaining high quality, continuous data becomes evident.

The NWS radiosonde network is the among the largest networks of its kind, and is recognized worldwide as a source of quality upper air observations. These data have greatly improved the understanding of atmospheric processes on short time-scales. However, changes in the network have limited the usefulness of the early data for documenting long-term atmospheric change. Without adequate oversight to assure some overlap and evaluation of the instrument changes, the long-term usefulness of the entire sonde record may be degraded. To support the RRS objective relating to NOAA's Strategic Goal of predicting and assessing decadal-to-centennial climate change (National Weather Service, 2001), attention should be focused on achieving radiosonde data continuity during the instrument transition.

Experiences with similar instrument changes, such as the introduction of the Automated Surface Observing System (ASOS), have often been characterized by the introduction of artificial, instrument-induced differences into the long-term climate data record. These differences can severely hamper the data's usefulness in analyses as real, long-term physical changes may be masked and biases either not identified or aggravated. Not only the mean values, but also data pertaining to the variance and to extreme events, are likely to be affected if biases occur. Multi-season, multi-location testing is necessary to understand all instrument-induced differences.

The risks associated with changing instruments were discussed in the specific context of radiosonde observations in National Research Council (2000a), which stated that:

"There have been many and widespread changes of radiosonde sensors during the history of the global radiosonde network. These changes often brought useful improvements in precision and accuracy, essential for weather analysis and forecasting, but they also prejudiced the homogeneity of the records from the perspective of climate change analysis (Gaffen, 1994)."

Although the NWS radiosonde network was established for short-term weather forecasting rather than long-term environmental monitoring, it has the potential to be an extremely useful tool for climate analysis. It remains the primary U.S. in situ measurement system for the troposphere and lower stratosphere. It forms a foundation for calibrating and validating many satellite measurements. Climate issues and concerns about human impacts on the atmosphere are currently subjects of much attention. The longevity of the sonde record, combined with its high time resolution and spatial coverage, provides an important data set for evaluating changes now and into the future.

Monitoring for long-term climate change or even variability on inter-annual time scales has historically been a secondary consideration in the operation of many of NOAA's environmental observing systems. Instruments, platforms, and exposures have been subject to frequent change for a variety of administrative, budgetary, and convenience reasons, as well as for scientific or technical reasons responding to concerns other than climate. These changes often introduce discontinuities and compromise the value of the data for longer-term assessment and trend analyses. In some cases, these discontinuities can be corrected, and in nearly all instances, with proper planning and oversight, they can be avoided.

1.5 *Principles for Preserving Data Continuity*

The risks to data continuity require that instrument changes be carefully monitored so they can be understood and ultimately corrected. The second of ten basic "climate monitoring principles" endorsed by the National Research Council (NRC) and United Nations Framework Convention on Climate Change (UNFCC) is of particular relevance. It reads:

Principle 2. <u>Parallel Testing:</u> Operate the old system simultaneously with the replacement system over a sufficiently long time period to observe the behavior of the two systems over the full range of variation of the climate variable observed. This testing should allow the derivation of a transfer function or homogeneity adjustment to convert between climatic data taken before and after the change. When the observing system is of sufficient scope and importance, the results of parallel testing should be documented in peer-reviewed literature.

Radiosondes, which unarguably meet the "sufficient scope" and "importance" criteria mentioned in the preceding Principle, are tested for accuracy and reproducibility in environmental chambers or factory tests, but natural exposure cannot be fully simulated in artificial or limited flight conditions. Instrument biases can vary with altitude, sensor, atmospheric conditions, sun angle, time of day, and other changes. Atmospheric quantities are continuously variable in time and space. Therefore, to address these data continuity concerns and to adhere to the climate monitoring principles, repeated measurements of the same quantities in a range of field environments will likely be required in order to determine differences between dissimilar radiosonde suites.

2. ANALYSIS

2.1 *Parameters Guiding the Analysis*

The transition to the new radiosondes will likely cause artificial discontinuities in time series of temperature, humidity and winds and the height in which they are assigned. As radiosonde data are assigned to pressure levels, a change in the pressure sensor could result in biases in observed temperature, humidity and winds. Wind data can be important in climate analyses that look at fluxes of energy. Most analyses of fluxes don't use radiosonde data directly. Instead they use reanalyses data which has assimilated the data into model dynamics. Humidity is of crucial importance to a wide range of climate interests including some central questions in the climate change debate such as the feedback role of upper tropospheric water vapor. However, humidity is a very difficult variable to deal with historically (Elliott and Gaffen, 1991). It is difficult to measure, difficult to quantify biases in as the biases can be highly non-linear, and it varies greatly in space and time. In sum, humidity continuity is an exceedingly difficult problem.

Temperature continuity is not an easy problem to solve but at least it is potentially tractable. Several groups around the world have been addressing radiosonde temperature continuity with varying degrees of success (Free et al., 2002). The current NOAA radiosonde temperature continuity effort is being undertaken by a group known as the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) team. Team members include John Lanzante and Steve Klein from GFDL/OAR, Dian Seidel, Jim Angell and Melissa Free from ARL/OAR, and Imke Durre, Tom Peterson and Jay Lawrimore from NCDC/NESDIS. Temperature is the sole variable currently being fully addressed by the climate community.

Therefore, temperature will be the sole parameter guiding the analysis presented in this report. However, any approach designed to address temperature continuity will attempt to preserve all available humidity, pressure/height and wind continuity data for potential future use, including evaluation of the impact of the changes on reanalyses.

2.2 *Environmental Factors Influencing Biases of Radiosonde Temperatures*

Radiosonde instrumentation has varied considerably over the years. One of the biggest changes is how the radiosonde responds to radiant energy. Different coatings on the thermistors have different responses to both solar and infrared radiation. Some, particularly older sondes, have sheltered the thermistors inside air ducts to limit exposure to solar radiation. But perhaps the biggest difference is that some radiosondes run their data through a radiation adjustment or “correction” algorithm in the ground receiving station to adjust the data to compensate for the effects of radiation. Of the currently flown NWS radiosondes, only the Vaisala radiosondes have radiation adjustments applied at the station so that the data released by the radiosonde station have these adjustments incorporated. NCEP applies radiation adjustments to the Sippican radiosonde data when executing their models. One requirement for the RRS is that the sondes have radiation adjustments.

Given the very different way in which radiosondes deal with radiation, the biggest environmental factor influencing radiosonde biases is solar radiation. As the sonde times are fixed, the solar elevation angle is usually quite different between the 00 GMT and the 12 GMT flights. For flights that take place during the day, the solar angle varies with the time of year as well as latitude, longitude and hour. Indeed some flights are daytime flights during only part of the year. And some launch in darkness but before the flight ends two hours later they are in bright daylight. The second greatest impact on radiation is due to clouds. Clouds impact not only the solar radiation load but the IR load as well. Anything else that can impact atmospheric radiation and therefore the radiation balance on the thermistors, such as aerosols and humidity, also plays a role in altering the biases or differences between the observations of two different radiosondes.

The absolute temperature of the atmosphere is not thought to significantly alter the differences between radiosondes, which is good considering that the radiosondes can go through a huge range of temperatures from the surface to 5 hPa. However, the radiation effects do vary greatly between the surface and the upper air. Much of this is caused by the relative effect of radiant versus sensible heat transfer. Sensible heat is much more easily transferred at 1000 hPa than where the air is only half of one percent as thick. Therefore, biases can change significantly with height.

In sum, biases need to be stratified by location, time of day, time of year and pressure. The recommendation from the October 2002 meeting was that for a given location and for a specific pressure level, the biases at 00 and 12 GMT should be calculated separately for each season.

2.3 *Guidance from Neighboring Stations*

Historically, groups calculating adjustments to station data to account for inhomogeneities were forced to rely heavily on information from neighboring stations. Determining the variability of the bias between two stations can provide one with a measure of the error in estimating this bias. Each station in the U.S. network (except San Juan, Puerto Rico) was compared with its closest neighbor. The analysis used data for December, January, February, June, July and August 2000. To stratify the data by time of year and time of day, each month’s data were processed separately as was each observing hour. The mean difference for each month/time was determined and the variability of the approximately 30 data points for each month/time was calculated. The results are shown in Figures 4 (Alaska), 5 (Contiguous United States, CONUS), and 6 (tropical Pacific). Only the standard deviation of the difference is shown as the magnitude of the actual differences isn’t relevant to analyses of the errors.

Examination of these figures reveals, unsurprisingly given the distance between stations and the variability of the weather, that Alaska has the greatest variability and the tropical Pacific the least. In the CONUS, the variability remains fairly similar going up all the way from 1000 to 10 hPa. However, in Alaska there is less variability between neighbors in the stratosphere than near the surface while it is exactly opposite in the tropical Pacific.

Unfortunately, analysis of neighboring stations reveals not only the differences between radiosondes but also the large variability in the gradients of temperature between stations. The gradients of temperature at, say, 500 hPa varies day by day, month by month and even year by year. Therefore, continuity analysis using neighboring station data can not be reliably applied in near real time. Rather it takes several years of data on both sides of a discontinuity to dampen or average through the noise of the variability in the gradient of temperature to determine the change in bias due to changing radiosondes. But it is still useful to be able to compare the variability of neighboring station data to that of dual sonde data in order to determine if dual sonde data is a significant improvement for continuity purposes.

2.4 *Guidance from Dual Sonde Data*

How many dual sonde flights are needed to accurately assess the bias between two different radiosondes at a particular location? To answer this question, all available dual sonde data that could be located were obtained. This resulted in data acquisition from 13 different sources. Of those 13, only six were deemed useable for in this analysis. A few of the sources were rejected due to data quality or processing problems, but most were not useful because they did not have enough dual flights to provide an adequate comparison. The six data sets used were:

WMO Phase I, Beaufort Park, England, June – July 1984, 196 flights (Hooper, 1986).

WMO Phase II, Wallops Island, VA, USA, February – March 1985, 102 flights (Schmidlin, 1988).

WMO Phase III, Dzhambul, Kazakhstan, August 1989, 66 flights (Ivanov et al., 1991).

WMO Phase IV, Tsukuba, Japan, February – March 1993, 59 flights (Yagi et al., 1996).

WMO Phase V, Wallops Island, VA, USA, September 1995, 61 flights (Schmidlin and Ivanov, 1998).

Atmospheric Radiation Measurement (ARM) Program, Department of Energy, September – October 2000, 26 dual flights (Lesht, 1998; Turner et al., 2002; Revercomb et al., 2002).

The question at hand is not "What is the bias between different radiosondes?" The RRS radiosondes will not be identical to any previously tested. But rather the question is "What is the variability in the dual sonde data that would be used in determining the bias between any two sondes?" From that assessment of variability in determining biases, one can assess what the errors would be in bias assessments.

Time-of-day is one of the stratification variables. It has already been mentioned that one of the biggest factors influencing radiosonde biases is different responses to solar radiation. While each experiment only took place over the course of a month or two, balloons were often launched at different times of the day or night which brought in a variety of solar angles. Therefore, the results were stratified by time of day. Specifically, the most common launch hour was determined for all flights in an experiment that match two particular radiosondes. Then data from all flights within 3 hours of that time were examined to determine the mean bias and the variability around the mean bias. Ignoring data counts that were used in that first analysis, the second most common hour was determined and the assessment was repeated. Therefore, the next most common hour selected had to be at least 4 hours from the first one. If the two selected times were less than 7 hours apart, some of the dual flight observations would be used in both analyses. Typically, though, test times were not randomly chosen but rather concentrated at certain times of the day so that where there were two peak times, the times were often quite far apart.

The data from the 510 intercomparison flights provided analyses of 79 pairs of radiosonde types, as many of the flights would have five sondes on a single balloon. Thanks to the analysis being performed on different groups of hours, they provided 114 assessments. Each assessment used here was based on a minimum of 10 pairs of dual sonde data points at a pressure level. The temperature from sonde A was subtracted from sonde B's temperature at that level. The mean of this difference series (the bias) was not calculated as the magnitude of the bias in these historical radiosondes was not of interest to this study. Evaluation of many of these series indicated that an assumption of normal distribution was appropriate. The only number calculated from each set of dual sonde data was the standard deviation of the difference series at each pressure level. The results of this variability analysis are shown in Figure 7. The mean standard deviation of the intercomparison flights was less than 0.5°C in the troposphere. This is significantly less than the neighboring station analyses. However, the intercomparison data standard deviation increased dramatically above 100 hPa, with the highest level, 10 hPa, approaching values of neighbor analyses.

One of the assumptions in using these intercomparison data to provide guidance for RRS continuity decisions is that the results from this comparison are appropriate estimates for future changes. Can results from mid-1980s radiosonde data really be relevant to the radiosondes of 2003? This is a legitimate question. Radiosonde technology has improved over the last two decades. As radiosondes become more accurate, one would expect a narrowing of the variance between two different sondes flown on the same balloon. On the other hand, one of the most significant causes for differences in radiosonde data is the adjustment applied to "correct" for radiation induced errors. Also, it may be possible to "over-correct" temperatures at high altitudes if the radiation adjustments are not applied properly. Some of the currently flown radiosondes do not have radiation adjustments applied on site while all of the RRS sondes will. Given the opposite effects of these two influences, the mean results from these intercomparison data are probably fairly appropriate to use as a guide.

The data from the dual sonde RRS flights will be used to calculate the mean difference ($\bar{x}$) between the old and new sondes. This mean difference will be the adjustment applied to the earlier data to make them homogeneous with the new data. How accurate will the adjustments be? The formula for the standard error of the mean is given by:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

where $\sigma_{\bar{x}}$ is the standard error of the mean, σ is the standard deviation of the data going into the calculation of the mean, and *n* is the number of observations used to calculate the mean (White, 1985).

The implications of this formula are clear: the more dual sonde flights, the more accurately the mean bias can be determined and therefore the more accurate the continuity adjustments will be. Using the mean standard deviation from the intercomparison data (shown in Figure 7) in this formula, the standard error in an assessment of the bias stratified by the number of dual sonde flights flown in the course of a year was determined (Figure 8). The assumption going into this stratification is that 00 GMT and 12 GMT will have separate bias calculations as will each season. Therefore, the 40 dual sonde flights per year shown in Figure 8 represents 5 dual sonde flights per bias calculation. The incremental change shown in Figure 8 goes up by 5 until 30 dual sonde flights per season per time (240 per year), jumps up to 50 (400 per year) and lastly to 90 (720) which is basically every flight for a year being a dual sonde flight.

The standard error in the assessment of the bias (Figure 8) follows a pattern in the vertical similar to the mean standard deviation (Figure 7). The best one year of dual sonde flights can do is a standard error of around 0.04°C below 250 hPa. The incremental decrease in the error associated with adding 5 additional sondes per season per time is, of course, larger when the total number of dual sonde flights is small. For example, at 500 hPa, going from 5 to 10 dual flights per season per hour decreases the error by 0.046°C while going from 25 to 30 decreases it by only 0.006°C. These estimates of error in assessing the bias between sondes will be used to determine the impact on area averaged time series, which is presented in section 3.

2.5 *Interpolation of Biases to Other Stations*

Several different opinions were voiced at the October meeting as to how biases can or can not be interpolated in space. Basically, there were three points of view:

1. Using information from dual flight data, the biases should be modeled. The model could then be used at each station with that transition (e.g., VIZ B2 to Intermet or Vaisala to Intermet). This is an appealing vision: To launch enough dual flight data that a model could be created that would properly account for the differences between the radiosondes at all stations. This minority view was rejected by the group for several reasons. Some of the factors that would need to go into such a model are unavailable, particularly in pre-RRS data. These can include balloon rise rate, cloud data - both amount and layers, aerosol information, etc. Also, not only is there no history that such an approach could work, the one group that did attempt to model the differences between radiosondes (Luers and Eskridge, 1995) were unable to adequately remove the biases using the model (Durre et al., 2002).

2. An alternate approach would be to perform dual flights for each transition at a representative station in a region and then spatially interpolate the bias assessments to all the other radiosonde station in that region that underwent the same transition. This is basically the plan presented by Bill Murray's ad hoc group. Supporting this approach are the results in Elliott et al. (2002) that indicate stations in Alaska as a whole had quite different transitions than tropical Pacific island stations. Going against this point of view was careful analysis of the Elliott et al. (2002) results that showed considerable variation within each region despite some basic similarities. Of additional concern were results that Frank Schmidlin presented at the meeting indicating that the radiation and other characteristics at each location could be radiatively unique, making spatial interpolation of the dual sonde results extremely difficult. It may turn out that some spatial interpolation may be possible, but that can not be determined *a priori*. Hence, no information is available that could scientifically support an assessment of the number of regions that would be required for adequate spatial interpolation.

3. Therefore, the third option, performing dual flight analyses only at selected climate stations was deemed the best option by the group meeting in October. The advantages to this approach are that (a) no spatial interpolation will be necessary, (b) yet the potential for future spatial interpolation of the bias analyses to additional stations remains possible, (c) the best stations from a climate perspective will be given careful continuity analyses, (d) stations and/or transitions that aren't needed for regional or large-scale climate averages won't be addressed at all, thereby saving considerable resources, and (e) the number and distribution of NWS radiosonde stations used for climate purposes is likely to be similar to the number of test sites for a plan that called for spatial interpolation, as far fewer upper air stations are needed for climate purposes than for weather forecasting purposes.

There are several clear downsides to this third option, however. If continuity is only assessed of a limited number of specific stations, the potential for analysis of features with high spatial variability such as the boundary layer may be lost. Also, the potential for additional climate stations will likely be lost. And there is no guarantee that these few stations will be able to be maintained to climate standards. So focusing now on a limited number of stations implies that the future network will never be any larger and may, indeed, become smaller. This may be particularly true because the vast majority of the stations used for climate purposes are those that maintained their VIZ radiosonde. Therefore, there will be few evaluations of the transition from Vaisala to RRS sondes. This may impact future assessment of water vapor in particular because the work at NCAR by David Carlson and June Wang has shown the Vaisala humidity measurements to be far superior to the current VIZ.

Also, some of the selected stations may have little available space for an additional radome. This may or may not be a serious problem. It is one example of the larger concern that selection of only certain climate stations for homogeneity will result in other options being limited. The NWS was going to survey the Regions and provide information on which stations can easily handle dual sondes and which can not. The results of this survey are not yet available. However, like many problems, if the need is great enough a solution can be found. Ergo, it is recommend that the NWS do its best at finding workable solutions to launching dual sonde flights at each selected site. For example, since the GPS receivers will not be using azimuth and elevation angles to determine winds, the GPS radome does not need to be close to the balloon release site. Therefore, the NWS should seek innovative ways to make dual flights possible at climate stations, perhaps by siting the GPS radome atop a building some distance from the launch site.

2.6 *Selecting Stations*

Different groups of global and U.S. radiosonde stations have been used over the years for climate purposes. For example, for determining error estimates of MSU/AMSU bulk atmospheric temperatures, Christy et al. (2003) used all NWS stations that have continued to use the VIZ radiosonde. However, three specific networks of stations have been selected specifically for use in climate change detection:

1. The first network is known as the Angell network. Jim Angell has been using radiosondes to determine temperature changes in the free atmosphere since 1975 (Angell and Korshover, 1975, 1983; Angell 1988). The Angell Network consists of about 63 radiosonde stations well distributed around the world. These are enough stations to monitor large scale changes. In response to this climate use of selected radiosonde stations, the NWS made a concerted effort to preserve the homogeneity, wherever possible, of the stations Angell was using for climate purposes. As a result, many of the Angell stations did not change from VIZ to Vaisala radiosondes in the 1990s. However, they did change from VIZ to the VIZ B2 which has a different pressure sensor. This resulted in a small discontinuity in temperature as temperature data are fixed at specific pressure levels (Christy et al., 2003). Stations in the Angell network are listed with an A in Table 1.

2. The second network builds on the work by Jim Angell and is a product of NOAA's current effort to produce homogeneous upper air time series. These stations were selected by the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) team from GFDL/OAR, ARL/OAR and NCDC/NESDIS. The first part of the team's work was adjusting selected historic radiosonde station data to account for changes in instruments and observing practices and was accomplished primarily by Lanzante, Klein and Seidel (2003a, 2003b; hereafter LKS). This involved a great deal of detailed work. They selected 87 stations around the world for their network based on data quantity and quality, station location and likely homogeneity with a clear preference to those stations that had the fewest inhomogeneities in their climate records. NWS stations that have already been homogeneity adjusted by LKS are listed in the station tables with an R1. Plans are being developed to expand the network. NWS stations that are currently actively being considered for future inclusion in the RATPAC data set are designated with an R2 in the tables.

3. The third climate network is the Global Climate Observing System (GCOS) Upper Air Network (GUAN; Daan 2002). The principal aims of the GUAN are to ensure a relatively homogenous distribution of upper air stations that meet specific record length and homogeneity requirements outlined by GCOS and to develop, and make available, their current and historical data. This is a network of stations with reliable prior records and which are expected continue to provide data in the future. The selection process subjectively considered the following in order of importance:

- position of the station in its contribution to a spatially homogenous network;
- performance of the site in producing consistently high quality data; and
- existence of a historical record of reasonable length.

A total of 150 sites have been selected. The Met Office, Hadley Centre and NOAA/NCDC serve as joint data analysis centers for GUAN. Additional information on the GUAN can be found on www.metoffice.gov.uk/research/hadleycentre/guan from which Figure 9, map of the GUAN stations has been taken. GUAN stations are listed in the station tables with a G. When a country agrees that a particular station can be part of the GCOS Upper Air Network, the country is expected to follow best practices guidelines for that station's observations. As a review of Table 2, GCOS Climate Monitoring Principles, indicates, many of the GUAN concerns are related to climate continuity.

Preparing to conduct expensive dual sonde continuity flights is a good time to reassess climate networks. Of particular relevance is the GUAN because maintaining climate continuity is a significant part of what is expected at GCOS stations as per the GCOS Climate Monitoring Principles (Table 2). If the GUAN stations truly are the best long-term climate stations, then U.S. climatologists would likely be using them. However, there are four exceptions to that expectation: 72261 Del Rio, TX; 72403 Sterling, VA; 72764 Bismarck, ND; and 91765 Pago Pago are GUAN stations that aren't used by climatologists and are discussed below.

Modifying the GUAN station list is a fairly straightforward process. The international body with oversight of the GUAN is the Atmospheric Observation Panel for Climate (AOPC). Within the AOPC, there is a small Advisory Group for GSN (GCOS Surface Network) and GUAN. This small group evaluates potential changes, usually in response to requests from countries, and makes recommendations for changes to the network to the full AOPC. Tom Peterson, the lead author of this report, serves on both the AOPC and the Advisory Group for GSN and GUAN. Upon reviewing a map of the GUAN (Figure 9), it became clear that all the GUAN stations in CONUS were around the edges which left a large area in the middle unsampled. In 2001, the AOPC made a recommendation that the GUAN should be expanded to include a station in the central U.S. and Tom Peterson passed that request on to the U.S. GCOS representative, Howard Diamond. Howard Diamond discussed it with NWS personnel, such as Bill Blackmore, who recommended Dodge City as the best central U.S. station for climate purposes.

There are five changes to the U.S. GCOS Upper Air network that are appropriate. They are:

1. Add Dodge City, KS to the GUAN. Dodge City is a high quality station in the center of the CONUS where the AOPC is seeking another GUAN site. It is also a RATPAC station.

2. Remove 72261 Del Rio, Texas and replace it with 72250 Brownsville, Texas. Del Rio used a poor quality Space Data Sonde for 5 years, which presents a problem with the climate record during those years. Brownsville is in both the Angell and the RATPAC networks. The nearest Mexican GUAN stations are far enough away that changing from Del Rio to Brownsville does not present a problem with having GUAN stations too close together.

3. Remove 72403 Sterling, VA from the GUAN and replace it with 72520 Pittsburgh, PA. Sterling has a history of poor performance and changed to the Vaisala radiosonde while Pittsburgh has an excellent performance record and has remained a VIZ station. Pittsburgh has been identified as a RATPAC expansion station.

4. Remove 72764 Bismarck, ND from the GUAN. Bismarck used the Space Data Corporation sonde for 4 years which created problems with its climate record. As the nearest Canadian GUAN is quite far from the U.S. border, another one or two northern CONUS GUAN sites would be appropriate. Based on the previously identified climate stations, the choice for additional U.S. GUAN stations would be either (a) 72768 Glasgow, MT, (b) 72768 Glasgow, MT and 72645 Green Bay, WI, (c) 72776 Great Falls, MT and 72645 Green Bay, WI, or (d) 72776 Great Falls, MT. Depending on which option of stations is used for the final RRS continuity work, the best solution would be (d) for the minimum option or preferably (c) for the expanded option.

5. Remove 91212 Guam from the GUAN. While Guam is both a GUAN station and an Angell station, it has had problems with its climate record. Specifically, despite recommendations from NWS headquarters and against the guidance of the GCOS Climate Monitoring Principles (see Table 2), the Pacific Region switched Guam over to the poor quality Microsonde for two years. The significant problems with Microsonde data essentially create a 2 year gap in the climate record.

The only remaining U.S. GUAN station not used by Angell or RATPAC is Pago Pago in American Samoa. This station is in a remote area of the Pacific and is therefore appropriate to maintain as a GUAN site.

The list of climate stations totals 26. If the Sterling, Bismarck and Guam sites mentioned above are removed, the list totals 23: three Alaskan, 11 in the CONUS, 1 station in the Caribbean, and 8 in the tropical Pacific. The selection of climate stations was based partly on their data quality and homogeneity and partly on the location. For example, there is a long distance between Pittsburgh and Key West. Yet, no climate stations were selected in this region because there are no long-term VIZ stations along the southeast coast. The nearest other VIZ station is Nashville. The same is true for Alaska: all Alaskan VIZ stations have been selected. Are these three Alaskan stations adequate?

To partly address this question, Figure 11, taken from Wallis (1998), shows the areas of influence of the Angell and Korshover (1983) stations. "To ascertain the area of representativeness, time series of ECMWF monthly gridpoint 850–300- and 300–100-hPa thickness data were used, with boundaries drawn where correlation coefficients decay to less than the inverse of *e*, the natural base of logarithms (1/*e* = 0.3679)" (Wallis, 1998). However, for climate monitoring purposes, one would lose considerable signal if the stations were spaced so far apart that correlation (r) of the signal dropped to 0.37. Therefore, a goal should be to have considerable overlap of the ellipses. A quick examination of Figure 11 reveals that 3 stations do not adequately cover Alaska, 8 or 9 stations would provide good coverage over the CONUS, and with the much larger ellipses in the tropics, 8 tropical Pacific stations are more than would be needed for that region.

Another way to examine appropriate station density for climate change analyses is to examine area averaging approaches. Angell (1988) averages seasonal deviations at each of his 63 stations into 7 large zonal bands. These zonal bands were then area averaged to produce global values but no values were calculated for regions smaller than these zonal bands (60˚-90˚ N, 30˚-60˚N, 10˚-30˚ N, 10˚–10˚ S, 10˚-30˚ S, 30˚-60˚ S, 60˚-90˚ S). However, it is unlikely that analyses limited to such large zonal bands will be considered adequate for future climate change research. Instead, the NWS climate network should be expected to able to support analyses at least on the half continental-scale (e.g., CONUS).

Rosen et al. (2002) examined the radiosonde station requirements for detecting trends in North America and the CONUS. They used reanalysis data interpolated to radiosonde station locations to evaluate 50-year trends in 500-hPa temperatures. Their conclusion was that cutting down the network size from the full radiosonde network to the much smaller GCOS network produced trends for CONUS or North America that were not significantly different from those based on the full network. The largest difference between sampling from all 78 CONUS radiosonde sites and the six GCOS sites was less than 0.05 K per decade for winter trends. However, it should be noted that these results depended on the large spatial scale of the underlying 50 year 500-hPa tropospheric trend field. Other quantities of interest for climate monitoring or other periods of time might be more sensitive to the number and distribution of upper-air stations. Also, the Rosen et al. study only considered one mid-tropospheric parameter and did not take into account effects of missing data on the time series.

Performing an objective analysis to quantitatively assess other periods of record and/or other fields would likely give additional guidance. But the guidance would be a direct response to the specific question being asked. Which questions should be assessed is a subjective matter, so rather than ask a subjective question, the information presented here will be used to make a subjective assessment of the stations. Another factor to weigh into this assessment is the climatological importance of a region. Alaska, for example, is in a region that has experienced considerable surface warming over the last several decades. Also, the tropics and especially the tropical Pacific is an area with considerable interest from a climate change point of view (e.g., Gaffen et al., 2000). It is an area directly impacted by ENSO, deep convection in the tropical Pacific transports considerable amount of water vapor into the upper atmosphere, and the tropics is a region with significant divergence between the surface and tropospheric temperature trends.

There is no magic number of climate radiosonde stations needed. It is important to keep in mind that since the radiosonde network is, by necessity, going down the path of a two-tiered network, it is prudent to err on the side of including some extra stations rather than limiting the climate network to the barest of minimum now and forever. But a general assessment to balance out the numbers and locations was made which indicates that a reasonable minimum number of stations would be:

Alaska: Three stations. All three climate stations are needed. In fact, looking at the areas of influence (Figure 11), it is clear that these three stations really wouldn't provide adequate coverage.

```
70026 BARROW, AK              71.289 -156.783
      VIZ-B2      G A  R1
70308 ST. PAUL ISLAND, AK 57.150 -170.217
      VIZ-B2      G A  R1
70398 ANNETTE, AK             55.039 -131.578
      VIZ-B2      G A  R1
```

CONUS: Minimum of 8 stations. Rosen et al. (2002) indicated that 6 would provide adequate coverage for CONUS-wide 50 year trends, but analyses of shorter periods and smaller regions would likely require more stations. Some are easy to select. Brownsville, TX; San Diego, CA; Medford, OR; Key West, FL, and Caribou, ME are all good stations that cover the corners of the CONUS. In the middle of the CONUS there is Dodge City, KS. In the north or western north Great Falls, MT makes sense. And Pittsburgh, PA is the only option to fill in the large distance along the eastern seaboard between Caribou and Key West.

```
72201 KEY WEST, FL          24.552  -81.758
      VIZ-B2      G          R2
72250 BROWNSVILLE, TX       25.917  -97.419
      VIZ-B2        A  R1
72293 SAN DIEGO, CA         32.833 -117.117
      VIZ-B2      G A  R1
72451 DODGE CITY, KS        37.761  -99.969
      VIZ-B2           R1
72520 PITTSBURGH, PA        40.532  -80.217
      VIZ-B2                 R2
72597 MEDFORD, OR           42.383 -122.883
      VIZ-B2      G          R2
72712 CARIBOU, ME           46.868  -68.013
      VIZ-B2                 R2
72776 GREAT FALLS, MT       47.461 -111.385
      VIZ-B2        A  R1
```

Caribbean: One station. There is only one NWS run station in this region. Fortunately, it is a good climate station.

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78526 SAN JUAN, PR          18.432  -65.992
      VIZ-B2      G A  R1
```

Pacific: Five stations. Hilo and Pago Pago are distant from the others so they need to be selected. The other six stations form an east to west line. The western most and the eastern most, Majuro and Koror are both GUAN and RATPAC stations. While the ellipses of the fields of influence are quite large in the tropical Pacific, it should be noted that ENSO plays an important role in causing the large spatial cohesiveness of the signal and that the boundaries of the ellipses are quite low correlations (r = 0.37). Couple this information with the importance of this region to climate change analyses and the conclusion is that for climate purposes, Majuro and Koror are too far apart for completely adequate coverage. Therefore, the station situated closest to half way between Majuro and Koror, namely Chuuk, is added. Chuuk is also a GUAN and a RATPAC station. Guam is not selected for reasons already mentioned.

```
91285 HILO, HI              19.718 -155.058
      VIZ-B2      G A  R1
91334 CHUUK, ECI             7.454  151.843
      Vaisala     G    R1
91376 MAJURO                 7.086  171.391
      VIZ-B2      G    R1
91408 KOROR, PALAU WCI       7.340  134.489
      Vaisala     G    R1
91765 PAGO PAGO            -14.338 -170.719
      Vaisala     G
```

This provides us with a minimum of 17 stations for dual flight data. More stations would definitely provide better coverage and better potential for future analyses. There are two good choices for additions. The first choice would be adding an Alaska station as equidistant from the 3 current stations as possible. An assessment of the ellipses of station representativeness (Figure 11) clearly indicates another station is needed in Alaska. Also, qualitative support for a fourth station in Alaska comes from analysis the map of 500-hPa March-April-May 1959-1996 trends in Rosen et al. (2002). According to this map, Alaska is the portion of the continent with the strongest gradient in temperature trend during MAM, and one could infer by inspection that a regionally-averaged trend would be poorly estimated by only three stations. The best additional station is Anchorage (see Figure 12). Anchorage switched to Vaisala sondes during the 1990s, but so did all Alaskan stations except for the three already designated. Several Alaskan stations also had the poorer quality Space Data Corporation sonde for a period, but Anchorage was not one of those.

```
70273 ANCHORAGE, AK         61.156 -149.984
      Vaisala
```

The second choice would be adding another station in the northern CONUS east of the Bismarck, ND GUAN station which was not selected. Unfortunately, as a quick review of Figure 2 reveals, the only northern station east of Bismarck and west of Pittsburgh that has remained a VIZ station is Green Bay, WI. It is fairly close to

Pittsburgh, PA but it helps fill in the long distance along the northern CONUS between Great Falls, MT and Pittsburgh, PA.

```
72645 GREEN BAY, WI          44.491  -88.110
       VIZ-B2                 R2
```

More additions could, of course, be considered. Indeed, a case could be made for much greater emphasis on continuity in all weather observations. But these 19 stations would be expected to provide adequate coverage for most anticipated climate monitoring activities. A review of Figure 12, a map showing the location of these selected stations, indicates a fairly well distributed network. The spatial distribution would be improved if International Falls, Minnesota had been selected instead of Green Bay, Wisconsin but the historical record of Green Bay is far more homogeneous than the data from International Falls which currently flies the Vaisala sonde.

One factor that did not go into the station selection process was any information on the ease in which a site could accommodate dual sonde capabilities. This is partly because this factor has not yet been determined for each site, but it is primarily because in no case did the existing station history indicate that two nearby radiosonde stations were equally good from a climate perspective. In most cases it is clear which are the good long-term climate stations needed for a good climate network. Substituting a nearby low quality (from a climate perspective) station because of increased ease of accommodating dual sonde capabilities would serious degrade the quality of the climate network.

2.7 *Stratification at These Specific Stations*

As mentioned earlier, the biases are likely to be quite different in January than in July and at 00Z than 12Z. These differences are a response to the changing radiation loads on the sensors and the radiation "corrections" or adjustments that are or are not being applied to data from those radiosondes. Also impacting the biases will be the radiative effect of different cloud amounts. Therefore, the recommendations from the October meeting were to consider the assessment of biases separately for 00GMT and 12GMT for of the four seasons. However, one recommendation from the October meeting was to examine the question of seasons for the tropical stations where the solar angle doesn't change a great deal yet the cloud cover may. But the cloud cover may not change according to the standard 4 seasons. Decisions on which seasons were appropriate to consider were made subjectively by considering the solar angle and the ISCCP derived cloud amounts as shown in Figure 13. Based on examination of this information, two seasons, listed below, are recommended to be considered for the three stations closest to the equator:

```
91334 CHUUK, ECI               7.454  151.843
       June-Oct, Nov.-May
91376 MAJURO                   7.086  171.391
       June-Nov, Dec-May
91408 KOROR, PALAU WCI         7.340  134.489
       Oct-May, June-Sept.
```

3. RESULTS

3.1 *Area Averages*

The reason attention is being given to the climate continuity of radiosondes is because of the improvement it will make in their end use. Specifically, how continuity efforts will decrease the errors and uncertainties in the final use of radiosonde data. The primary use of radiosonde data in climate analyses is to determine long-term changes in area-averaged temperatures. The size of the region averaged has varied in the past and will likely continue to vary. For purposes of this analysis, the CONUS will serve as the region. It is likely that attempts will be made in the future to assess long-term changes in upper air temperatures on smaller regions, but if a reliable job on this ~ ½ continental-scale region is possible, the majority of the probable future questions regarding U.S. climate radiosonde data will likely be able to be answered.

The network of selected radiosonde stations are quite evenly distributed across the CONUS. Therefore, for area-averaging purposes, equal weighting will be considered appropriate. For this analysis, the concern is not about the underlying climate trend in the region. Rather, the only concern is the errors that would arise in assessing the trend. Therefore, it doesn't matter whether the upper air temperature in the region is increasing or decreasing, or whether it is increasing in one part and decreasing in another. Those influences would be contained in the underlying data (subtracting the error). So only the RRS change induced errors that would be in future analyses of the data need to be assessed.

Towards that end, Monte Carlo simulations were performed (Rubinstein, 1981). The first step was creating normally distributed random data with a standard deviation equal to the standard error at that level of the atmosphere (based on results shown in Figure 8). Since 9 climate stations were recommended for CONUS and 8 was considered the minimum, a CONUS area averaged time series would simply be the average of 9 (or 8) radiosonde time series. To assess the errors in bias assessments, 9 (and 8) random error data points were averaged together to determine the impact on an area averaged CONUS time series. The advantage of a Monte Carlo simulation is that the magnitude of the 95% confidence interval can be assessed. Often the errors at one station will counteract the effect of errors at another station but other times they will have a cumulative effect on an area average. The results presented in the following two sections will be the 95% confidence level. That is, 95 percent of the time, the absolute value of the error in a CONUS averaged time series would be less than this amount.

3.2 *Impact on Jumps in Time Series*

The most direct climate impact of changing instrumentation is simply that of a jump in the time series. All the RRS changes won't take place at exactly the same date. But they will be fairly close to each other. For this assessment, it was assumed the change date was the same and asked what the 95% confidence level would be for an artificial jump in a CONUS time series. The results are shown in Figure 14. Note that the actual magnitude of the discontinuity caused by going from one type of radiosonde to another doesn't matter. What matters is the error in the assessment of the discontinuity as the discontinuity (within the error bounds) will be removed by adjusting the data. With only 5 dual sonde flights per season per hour, the 95% confidence level on assessing a CONUS area averaged discontinuity exceeds 0.1°C throughout the atmosphere. However, 30 flights cuts that down to less than 0.05°C below 250 hPa.

3.3 *Impact on Trends*

The differences between time series are often assessed by comparing differences in trends. In this case, the effect on CONUS area averaged 10, 20 and 30 year trends was examined. Again the effect of the magnitude of the discontinuity due to going from one radiosonde type to another isn't included as the adjustments (with error bounds) will take care of the discontinuity. The question is the effect of the errors in assessing the discontinuity. Also the underlying trend in the CONUS area doesn't matter as we are only assessing how much an assessment of the trend would could change due to errors in assessing the RRS induced discontinuity. Since the RRS deployment is expected to take several years, in the simulations were made with the reasonable assumption that one-third of the CONUS stations change in each of three consecutive years. Also the unrealistic assumptions were made that this one discontinuity was the only discontinuity in the time series and that it occurred in the middle of the 10 and 20 year periods and two-thirds of the way along in the 30 year period. The potential impact of the errors on trends, shown in Figures 15, 16 and 17, are, naturally, quite a bit larger for 10 year trends than 20 or 30 year trends. Again one can see the pattern that was revealed in the assessment of standard error of the mean but quantified according to a parameter, namely impact on trends, that is often evaluated in other climate change analyses.

4. COST OF DUAL SONDE FLIGHTS

4.1 *Fixed Costs Per Station*

In order to receive data from both the current radiosonde and the RRS GPS radiosonde at the same time, a radiosonde station will need to have two different sets of receivers. While the receiver for the current system is already in place and the receiver for the new system would need to be purchased as part of the modernization of the network, the housing for the new system is an additional expense. One key feature of the new expense is a radome. This is the fiberglass dome that protects the tracking equipment from the weather yet allows clear transmission of the frequency transmitted by the radiosonde. Along with the dome comes the expense of setting it up, installing wires, etc.

Table 3 provides detailed cost break downs on a per station basis from hardware to training. The bottom line is that the estimated costs are from $80K to $130K per station. The range of expenses is due largely to the question of how one should factor in the cost of the $55K radome: $130K assumes a cost of $55K per station. The $80K uses only $5K for a radome expense as (a) used radomes are in the process of being acquired from the Air Force, (b) radomes may be moved from station to another after a year of dual sonde flights so that one dome may serve 3 stations and (c) after the radomes are no longer needed for dual sonde flights they will not be thrown away but rather reused in the network somewhere when the current domes need replacing.

The cost for radomes and related expenses was estimated in the 2001 OS4 issue paper at $70,000 "based on recent purchases and include contractor installation, AC power, and conduit and wiring, moving the radome two times during the rotation process, and decommissioning/storage after parallel testing is completed." As the OS4 paper listed 6 radomes needed for 18 dual flight stations, the estimated cost per site was only $23,300. These new estimates therefore represent a 340% to 650% increase in the estimated fixed site expenses associated with dual sonde flights. Since the GPS receivers will not be using azimuth and elevation angles to determine winds, the GPS radome does not need to be close to the balloon release site. Therefore, it is recommend that the NWS continue to seek innovative ways to trim fixed costs, perhaps by siting the GPS radome atop a building some distance from the launch site.

4.2 *Expendables*

The second aspect of the cost is the extra cost for larger balloons, more labor, an additional sonde, and all the other costs associated with dual radiosonde flights. These costs have been calculated two different ways. As the old style radiosonde is less expensive than the new GPS sonde, it makes a difference whether the dual flights are made at stations with the current sondes (so the more expensive sondes are part of the cost of dual sonde flights) or at a station after it has changed to the new sonde. See Tables 4 and 5 for details. The extra cost of a dual sonde flight is estimated at either $145.72 per flight or $225.72 per flight depending on the deployment strategy (compared to the $120 per flight estimate from the 2001 OS4 issue paper).

There are pluses and minuses for both approaches. In addition to the obvious cost benefit of flying the dual sondes after the change the added benefit is that the presumably higher quality new radiosonde data would be the official radiosonde data for that station. The main advantage of flying dual flights before the change over is that the homogeneity transfer functions can be calculated prior to the transition. Otherwise, if the stations were used in real-time monitoring of upper air temperatures, the dual sonde data would have to be processed and homogeneity adjustments calculated right away in order to use the data from that station in current analyses. Given the straightforward nature of calculating the homogeneity adjustment or transfer function from dual sonde data, changing to the RRS prior to completion of a year of dual sonde flights should not present a significant obstacle to climate monitoring, would decrease the continuity costs, and would not require the RRS to remain in a "non-commissioned" status until the continuity testing is complete.

4.3 *Analysis of the Data*

The costs of analyzing the dual sonde data can be considered in three aspects. The first is the necessary preliminary work of setting up the appropriate data ingest capabilities. This is estimated to take one ZP-III level meteorologist/programmer two weeks at a cost, including overhead, of $3.5K. The second part involves real-time evaluation of the dual sonde data to make sure it is arriving in good shape, makes sense, and is coming in from the expected stations in the expected quantities. This would involve a ZP-III level meteorologist devoting approximately a week to writing software for this assessment and then approximately one tenth of the person's time monitoring the results of the assessment on a regular basis for each of the four years of the RRS transition. The cost for this aspect is estimated at $40K. The final aspect is the actual homogeneity adjustment calculations. These should be fairly straightforward. But because of the importance of this step, it would include a thorough and time consuming evaluation of the adjustments to insure that they are robust. This is estimated at 3 months of a ZP-IV's time which would cost $30K. The total cost estimate for analysis of the dual sonde data is $73.5K

4.4 *Archiving the Dual Sonde Data*

There are three aspects to the cost of archiving the data. The first and least expensive is the cost of storage media and the computer time to write the data to the archival media. For the data volumes associated with the recommended number of dual sonde flights, this cost is estimated at $0.5K. The second archival cost is associated with preparing the scripts not only for archiving the data but also for retrieving the data. This includes extensive checking to make sure the retrieved data matches the original data prior. The total expense of this part is estimated at $2,500. The last and, at $5K, the most expensive part of archiving is preparing the data set documentation in the Federal Geographic Data Committee (FGDC) standard and entering the data set into the National Virtual Data System (NVDS). The total archival costs, therefore, are expected to be about $8K.

4.5 *Putting Costs into Perspective*

Continuity testing is expensive. The climate community owes a debt of gratitude to NWS upper management for deciding to take on a significant effort to ensure the climate continuity of weather observations. Everyone knows that money spent on continuity will mean less money for other worthwhile purposes for there is no surplus pool of money waiting for this project. However, it is important to put the cost of a radiosonde continuity effort into the context of the total radiosonde effort. Tables 4 and 5, in addition to showing the cost delta for dual flights, provide information on how much ordinary radiosonde flights cost. Today's ordinary radiosonde flight costs $200.95 and one flight of the new GPS sonde will cost $280.95. This means that the current network of 92 stations taking twice a day observations costs $13.5 million. Once the RRS is fully operational, the costs will increase to $18.9 million per year. Because the new sondes are significantly more expensive than the old sondes, delaying the installation of the RRS network by one month would result in a savings of $450K and a delay of one year would save $5.4 million. The point here is not to recommend delaying the RRS as a way of funding continuity but rather to put the cost of the continuity effort into a tangible perspective.

5. DEPLOYMENT STRATEGY

5.1 *RRS Deployment Strategy*

At the October meeting, someone from NWS headquarters indicated that their most cost efficient deployment strategy for the RRS was to install them at all the sites in one region and then move on to the next. The regions, however, preferred having only one or two installed at a time so that they could gain experience on the new system that could aid later deployments. As indicated by someone who has had experience adjusting radiosonde data, deploying new systems at all stations in a region at approximately the same time is the worst possible strategy from a climate continuity standpoint. After some discussion at the meeting, there was widespread agreement that the NWS use a deployment strategy that would maximize the potential for neighboring station data to be used to evaluate adjustments and to potentially aid adjusting of additional stations should that be deemed appropriate at some future date. Therefore, it is recommended that change over to the RRS be commenced at widely spaced stations and continue in a manner that preserves some stations with their current sounding technology in all regions until the very end of the change over.

5.2 *Dual Sonde Flight Strategy*

The previous sections discussed dual sonde flights as a certain number per season (per 00 GMT and 12 GMT). What the optimal seasons are may vary from site to site depending on mixes of changes in clouds and changes in solar angle, including, for example, the dates when a flight at 12 GMT is in sunlight versus at night. These can be determined after the dual data have been collected. Therefore, dual sonde flights should be made at fairly evenly spaced intervals throughout the year. This approach would provide the most options for analyzing the data and would allow the data to help define the appropriate seasons.

The National Research Council (2002b) wrote: "When instrument packages change, simultaneous launches of the old and new instruments, at regionally representative sites in the field, should be performed. These simultaneous launches should take place under a range of conditions, over at least one annual cycle, and at both day and night. The objective should be to determine instrument biases to a sufficient level to allow adjustment of the data for continued long-term climate monitoring." The implications for the appropriate dual sonde flight strategy is for the flights to take place over the course of "at least" one annual cycle. If very unusual conditions exist during a particular year, perhaps because of a strong el Niño, the conditions might not allow for a bias assessment that would be sufficiently accurate for normal years. Therefore, it is preferable to have the dual sonde flights take place over the course of two years rather than one.

5.3 *Monitoring and Managing the Dual-flight Data Flow*

The dual sonde data needs to be monitored in near real time. These continuity evaluation flights are costly and therefore any problems with the data should be addressed immediately, not two years down the road. The group at the October meeting recommended that a climate group be involved in monitoring these data. Specifically, they thought NCDC was the appropriate location for this activity.

An interesting round of discussion ensued when the question was asked whether the person monitoring the data and performing preliminary analysis of the data should recommend changes in the continuity plan. For example, if the data come in showing far less (more) variance than expected, should the number of dual sonde test flights be decreased (increased)? The overwhelming recommendation was no. Part of the reason is related to how plans are made and followed through in the NWS. Agreements are negotiated in advance and the culture seems to value reliability and follow through more than flexibility. The point of view voiced by someone from the research community was that if the plans are carefully thought out in advance, changes made to them in the middle of an experiment may seem appropriate at the time but seldom seem that way once the experiment is over and all the data are being analyzed.

Therefore, the dual sonde data should be sent to NCDC in real time. They should be evaluated for quality problems immediately and on-going preliminary analyses should be performed in a timely fashion such as once a month on all new data. This latter step could be considered a form of high level post-production quality assurance. The results of the preliminary analysis, however, should not be used to recommend changes in the dual sonde flight plans other than for specific quality related issues.

5.4 *Dual Sonde Data Comparisons: Pressure Levels or Elapsed Time*

One interesting subject of discussion at the October meeting was the question of how the data from the dual sondes should be compared. Specifically, should the temperature be compared at pressure levels or at elapsed time. Christy et al. (2003) showed that a discontinuity in temperature observations arose as a result of changing the pressure sensor even when there was no change in the thermometer (i.e., the change from VIZ-B to VIZ-B2 in 1997). In order to understand the causes of the differences between one type of radiosonde and another, synchronization of the two radiosonde clocks can be important because that will allow data taken at the same point in space to be compared directly. However, all long-term climate analyses use data tagged to pressure levels. For homogeneity adjustments based on the differences in the data between the two sondes, the physics behind the differences does not need to be known: only the sign and magnitude of the transfer function needs to be known. So while synchronization of the dual radiosonde clocks would make the data more useful for some specific purposes, it is not necessary for climate continuity analyses.

6. BEYOND THE RRS

6.1 *Caribbean Stations Supported by the NWS*

NWS supports 10 Caribbean Hurricane Upper Air Stations (CHUAS) through bilateral agreements with various countries in the Caribbean. The NWS provides these stations/countries with expendables as well as the ground stations. Three CHUAS locations (Barbados, Belize City, and Grand Cayman) have Micro-ART and fly the Sippican VIZ B2 radiosonde. Two CHUAS sites fly the Sippican Mark II LORAN-C "Microsonde" radiosonde associated with the Sippican W9000® ground system and five fly the Mark II "Microsonde" with the Intermet Systems CV-700® ground system. All of the stations will be given new ground equipment, the Intermet Systems IMS-1500C which is a Radio Direction Finding System rather than GPS. And all will be converted over to fly the VIZ B2. This means that three of the 10 stations will not change radiosondes. The replacement work is scheduled to start in December 2002 and finish by May 2003. The 10 CHUAS stations are:

78073	Nassau, Bahamas	25.05	-77.47	03/03	
78384	Grand Cayman, Cayman	19.28	-81.35	04/03	R2
78397	Kingston, Jamaica	17.93	-76.78	02/03	G
78486	Santo Domingo, Dominican Republic	18.43	-69.88	05/03	
78583	Belize City, Belize	17.53	-88.30	03/03	G
78866	Prinses Juliana, St. Maarten	18.05	-63.12	01/03	
78954	Grantley Adams Airport, Barbados	13.07	-59.48	02/03	G
78970	Piarco Intl.Airport, Trinidad	10.62	-61.35	12/02	
78988	Curacao, Netherlands Antilles	12.20	-68.97	01/03	
80001	San Andres Is., Colombia	12.58	-81.70	05/03	R2

Three of these stations are GUAN stations. None of the stations are Angell stations. None of the stations are current RATPAC stations, however, two have been targeted for possible inclusion in future RATPAC analyses. Barbados and Belize City, two of the three GUAN stations, are already flying VIZ B2. As of yet, no plans have been made for any continuity analyses. Not even for the GUAN stations which have continuity as part of the GCOS climate monitoring principles (see Table 2).

Deciding what is the most appropriate continuity approach for this effort is not necessarily straightforward. The data quality and historic continuity is not always as high as one might want for climate analyses. For example, John Christy has used Barbados and Grand Cayman data directly (Christy et al., 2003) but was not able to use Belize due to too much missing data. Discussions with various people working on hurricane research did not reveal a strong need for continuity studies because when a hurricane is close, dropwindsondes are used fairly extensively and when evaluating the background conditions there is a heavy reliance on satellite data in this data sparse region. However, surface data indicates that the climate of the Caribbean has been changing over the last several decades (Peterson et al., 2002). So it is not a region where upper air climate continuity should be ignored.

Options include:

1) Ignoring the continuity issue as three of the stations will continue to fly VIZ-B2 and two of those stations are GUAN stations.

2) Performing dual sonde flights at one or more selected Caribbean stations, such as the Kingston, Jamaica GUAN station. This may or may not be problematical as the NWS does not take the observations. At a January 2001 Caribbean Climate Change workshop held at the University of the West Indies near Kingston, Jamaica it was clear that there is considerable meteorological expertise in the region. Indeed representatives of 8 of the 10 countries with NWS supported radiosonde flights are co-authors on the climate extremes paper that came out of the workshop (Peterson et al., 2002). However, whether a high level of expertise is involved in taking the radiosonde observations is a relevant concern. One approach to providing additional expertise would be through contracting with the University of the West Indies (UWI) in Mona, Jamaica (suburban Kingston). For example, Michael Taylor (Ph.D., 1999, University of Maryland, Department of Meteorology) and other UWI faculty have considerable meteorological expertise that could be utilized to provide additional training and guidance to those taking dual sonde observations in Jamaica.

3) Take dual sonde flights at the NWS station in San Juan. The NWS station in San Juan is a VIZ B2 climate station that is targeted for dual sonde flights. Perhaps in addition to flying the old VIZ B2 with the new GPS sonde the site could also fly the Microsonde to provide an estimation of the homogeneity adjustment for those Caribbean stations changing from Microsondes to VIZ B2s. This approach assumes an ability to spatially interpolate the biases determined by dual sonde flights. As noted earlier, the October meeting participants agreed that this was not an assumption that was appropriate to make for reasons already explained. However, some continuity information is likely to be far better than no continuity information.

Figure 18 shows the location of the CHUAS stations as well as the two NWS stations, Key West, Florida and San Juan, Puerto Rico. Given the distribution of the stations and the GCOS Climate Monitoring Principles associated with GUAN stations (see Table 2), Kingston, Jamaica should have dual sonde continuity testing. This would provide continuity at all three CHUAS GUAN stations. Treating the CHUAS GUAN stations differently for continuity purposes is important not just for today but on into the future as well because the current changes are just the initial changes planned for the CHUAS network.

6.2 *The More Distant Future*

As noted, the Caribbean deployment is actually part of a phased in approach. Initially the equipment will be changed as indicated. However, the NWS already anticipates replacing the CHUAS VIZ B2 sondes and will be issuing contracts for radiosondes every several years as conditions warrant. For the U.S. network, the NWS intends to initiate another Qualified Products List (QPL) in April of 2003 in an effort to introduce additional competition and reduce radiosonde recurring costs. This could result in another company, such as Vaisala, beating out either InterMet or Sippican. If this does happen, we're told, it is unlikely that Vaisala sondes would be introduced before FY05. Since the deployment strategy of the RRS won't see it fully deployed until FY06, the implication of this new QPL is that another potential transition may occur immediately on the heels of the RRS transition or, worse yet, perhaps even take place before the full RRS transition is complete!

In sum, plans are underway that are likely to present future continuity problems. Perhaps, one might better describe it as continuing continuity problems. The climate community has made recommendations regarding such changes before. For example, the National Research Council (2000b) writes: "NOAA should attempt to minimize the number and frequency of changes in instruments and observing methods in its radiosonde and other in situ systems. Although future technologies may offer improved operational observation capabilities, a major factor in evaluating instrument changes should be the continuity of the climate record."

Essentially, the problem is that the climate community wants to hold on to the past while the weather community wants to take advantage of possible cost savings and quality improving steps into the future. This is, indeed, what each community's outlook should be. The question is, how can the two groups meet when routine weather observations are needed for climate analyses? How can the NWS and its partners better manage change without stifling it? One way is for the NWS to quantify and factor in the costs on continuity testing when considering any instrument or processing change. This would change the cost benefit analysis to help support continuing use of the old instrumentation at climate stations and help support the cost of continuity testing when changes are needed. The climate community applauds the NWS's commitment to pursuing continuity in the change over to the RRS. It is clear that this effort is an additional burden that was not adequately factored in to the original planning for the RRS. Probably if it had been part of the initial planning of an instrumentation change, it could be accommodated more easily. Therefore, continuity should be factored into the planning for all future observing system changes right from the beginning.

How continuity testing should be done in the future deserves serious discussion beyond this document. One part of future assessments should involve chamber testing. A chamber that could simulate the environment a radiosonde experiences in a flight from the surface to 5 hPa would be very useful in determining if vendor expendables meet the stated requirements. Such a chamber might also provide enough dual sonde comparisons to be able to assess the environmental factors that impact a transfer function and perhaps reduce the number of required real world dual sonde flights. An earlier radiosonde test chamber was damaged during a move so the NWS no longer has adequate chamber testing capabilities. Also, better techniques for on site testing may be able to be developed. For example, one technique might use the spare channel on RRS-type radiosondes to perform a three thermistor evaluation. A three thermistor approach might be associated with a future reference standard. If the different sondes could be compared to a reference standard, they wouldn't need to be directly compared to each other. The advantages of this approach are that it would involve minimal training and the comparisons could be done at any station with only a one person release. Unfortunately, the differences in radiosonde data are not due just to a particular sensor which could be tested on an RRS-type radiosonde but to the whole package: sensors, housing, data processing, etc. Therefore, it is uncertain whether such an approach could eventually eliminate the need for dual sonde flights.

7. DISCUSSION AND PRIMARY RECOMMENDATIONS

7.1 *Site Preparation Implications*

Two separate pieces of information presented earlier, when examined together, lead to the first logical recommendation. The first piece of information is that the cost of setting up a site for making dual sonde flights and collecting the data is high. Given the high set up costs, the savings gained by taking down the radome after 1 year of dual flights and moving it to another station is fairly minor. The second piece of information is that the NWS is firmly committed to continuing technological improvements in radiosondes. In fact, they intend to take the first steps towards changing the RRS radiosondes used by initiating a new QPL even before the first of the RRS sondes are deployed.

It does not make much sense to go through the major expense of setting up a station to take dual sonde flights only to go through all this again in a few years. It is doubtful that the concern about climate continuity for radiosonde data will disappear in four years. It is also doubtful that the potential for chamber testing and three thermistor evaluations can be adequately developed to provide climate continuity of all meteorological parameters prior to the next radiosonde transition. So it is appropriate to make concrete plans for the future beyond the RRS deployment. Therefore, dual sonde capabilities that are put in place at the selected stations should be permanent.

7.2 *Stations Selected*

If the dual sonde flight capabilities at the climate stations are permanent there will be two effects. The first is that changes at these select stations will always be made with continuity in mind. The second is that continuity will likely be ignored at all the other stations. This will clearly make for a two tiered network consisting of stations with excellent continuity and those with poor climate continuity. Therefore, as time moves on it will be increasingly difficult to turn any other radiosonde station into a climate station.

The implication of creating a two-tiered network is that great care should be taken in the decisions about which stations should be included in the climate network to make sure that the coverage is adequate for all anticipated future climate needs. Towards this end, a minimum 17 station network was selected (see section 2.6). Two additional stations were also identified. The first choice was Anchorage to fill in a large hole in Alaskan climate coverage. The second was Green Bay, Wisconsin to provide better coverage along the northern CONUS border after the GUAN station in North Dakota was found to be unworthy of that designation and a station farther west, Great Falls, Montana was deemed the best substitute. Green Bay, Wisconsin is fairly close to the climate radiosonde station of Pittsburgh, PA, so it may not absolutely be needed to provide robust CONUS time series. However, should the need arise for analyses of regions smaller than CONUS, Green Bay would be expected to play an important role.

Different approaches to station selection could have been used. For example, an objective EOF analysis could have been performed to identify how many and which sites were necessary to capture various aspects of climate variability and change. However, these approaches would still have to incorporate both the reality of station histories and unknown potential future modes of climate variability and change. For example, it doesn't matter if an objective assessment determines that Charleston, South Carolina is an important location for stratospheric observations because, as indicated in Figure 3, the Charleston data are not of high enough quality to use to examine long-term changes in stratospheric temperatures. The sites of the six current CONUS GUAN stations may have been able to adequately capture the CONUS upper air climate change signal for the last 50 years (Rosen et al., 2002) but if in the future there are strong gradients of upper air climate change over New England, where we don't currently have a GUAN station, that signal would not be observed by the climate network.

While maximizing the CONUS signal is a good metric, it should not be the sole goal in CONUS station selection. The goal should be to get the best climate change information for the largest area. Consider Key West, Florida and Caribou, Maine. A large part of the signal they capture represents areas extending beyond the CONUS borders. If one was only concerned with maximizing the CONUS signal rather than capturing the largest possible part of the global climate change signal, one would want stations farther inland such as Tampa Bay, Florida or Gray, Maine. The subjective station selection approach described in this document was able to combine both climate change information and station history information to come up with a recommendation that all of these 19 U.S. upper-air stations be designated as climate stations for continuity study purposes. Since for global climate change purposes, good climate data are sought from remote locations, such as St. Paul Island, Alaska, providing dual flight capabilities at some of the selected stations may prove difficult and require extra time.

7.3 *Obligations to GCOS Upper Air Network Stations*

Considerable interest in supporting the GCOS networks has been expressed at the highest levels of NOAA and the U.S. government. For example, Dr. Harlan Watson, senior climate change negotiator and special representative at the State Department, recalled President Bush's commitment to improving climate observing systems, particularly in developing countries, and said, "We are pleased to work closely with NOAA to implement the president's initiative" (Hopkins, 2002). Also Vice Admiral Conrad C. Lautenbacher, Jr., U.S. Navy (Ret.) Undersecretary of Commerce for Oceans and Atmosphere said, "The Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS), working with the Integrated Global Observing Strategy (IGOS) Partners and others, have developed international consensus on overall needs. There is, however, much work still to be done. This challenge lies in our ability to provide one coherent plan which integrates space and in-situ observations across those three elements" (Diamond, 2003). The NOAA Administrator also said that "this new funding for the GCOS global observing effort further demonstrates the administration's commitment to working with our international partners to build a sound base of scientific knowledge for future global climate change policy decisions. Expanding global climate observation will require cooperation and coordination from the international community in realizing our collective end goal of having the tools we need to take the pulse of mother earth" (Hopkins, 2002).

The implications of these comments are that obligations to the Global Climate Observing System Upper Air Network (GUAN) stations should be taken seriously. As indicated in Table 2, continuity is a prime concern of the GUAN. Therefore, continuity testing at all U.S. GUAN stations and all CHUAS GUAN stations that the U.S. supports seems to be required in order to have the approach to addressing radiosonde continuity be compatible with the stated U.S. support of the Global Climate Observing System goals.

7.3.1 *U.S. GUAN Stations*

In order to adequately address these concerns for U.S. stations, the GUAN station list should be modified to be in line with the 17 to 19 climate stations that will be given special continuity consideration. As discussed in section 2.6 this specifically means:

1. Remove Del Rio, Texas from the GUAN and replace it with Brownsville, Texas.

2. Remove Sterling, Virginia from the GUAN and replace it with Pittsburgh, Pennsylvania.

3. Remove Bismarck, North Dakota from the GUAN and replace it with either Great Falls, Montana or, preferably, with both Great Falls, Montana and Green Bay, Wisconsin.

4. Remove Guam from the GUAN but don't replace it with any other station on the assessment that the other U.S. climate stations in the tropical Pacific, which are all GUAN stations already, provide adequate coverage (see Figures 9 and 11).

5. Add Dodge City, Kansas to the GUAN. This is in response to a request in 2001 from the Atmospheric Observation Panel for Climate to have a GUAN station in the middle of the CONUS and is in keeping with the designated climate stations.

7.3.2 *CHUAS GUAN Stations*

Giving GUAN stations special treatment also has implications for the Caribbean CHUAS stations which the NWS supports. Three of the 10 CHUAS stations are GUAN. Only one of these three, Kingston, Jamaica will have a change in radiosondes in the near future, though for changes being considered for several years from now, all 3 GUAN stations should get special continuity consideration. Dual flights should be supported at the Kingston GUAN station. Should the Meteorological Service of Jamaica not readily have the technical expertise to take dual sonde observations, the NWS could consider contracting with the University of the West Indies (UWI) in Mona, Jamaica (suburban Kingston). For example, Michael Taylor (Ph.D., 1999, University of Maryland, Department of Meteorology) and other UWI faculty have considerable meteorological expertise that could be utilized to provide additional training and guidance to those taking dual sonde observations in Jamaica.

7.4 *How Many Dual Flights are Enough?*

The more dual sonde flights, the lower the error will be in the calculations of continuity adjustments. But also the more dual sonde flights, the higher the costs will be. How many dual sonde flights are enough? There is no magic threshold. But comparisons to some of the existing climate change controversies can provide insights.

The U.S. Climate Change Science Program (2002) reports that one satellite-derived record of tropospheric temperatures indicates warming during the 23 year period 1979-2001 "of more than 0.1°C per decade" while another group found "only a small statistically insignificant positive trend." So difference in tropospheric trends of 0.1°C per decade is significant and controversial. The report also states that 65% of this difference is due to adjustments applied to the NOAA-9 satellite which provided data for 1985 and 1986. Over the couple of years of NOAA-9 data, the time series of the two groups diverged by 0.15°C. Therefore, discontinuities in the data caused by changes in the observing system are significant and controversial when they are as large as 0.15°C.

Both of the examples cited above are for global numbers. Can these numbers be used as a guide when dealing with CONUS averages? The CONUS is only a small region of the globe being monitored by a limited number of climate radiosonde stations, so the errors would be expected to be larger for an 8 or 9 station CONUS average than an average of all 19 of the proposed U.S. climate radiosonde stations. This argues for accepting larger errors over the CONUS than for the globe as a whole. However, a case could be made that the trend in tropospheric temperatures should be measured as accurately over the U.S. as it is for the globe. Also, when one examines the CONUS averages in Figures 14-17 it is clear that the improvement due to additional stations (both 9 station and 8 station averages are provided) decreases as the accuracy of the transition due to more dual sonde flights per station increases.

The bottom line is that one can use these global values as a guide, particularly as upper bounds. If a global discontinuity of 0.15°C is controversial, one would want to be confident that adjustments for RRS induced discontinuities for the CONUS are well below 0.15°C with half of that (0.075°C) being a bare minimum, one third of that (0.05°C) being a reasonable goal and lower being even better. The same should be true of 20 year trends. Half of the controversial 0.1°C per decade trend (0.05°C per decade) would be considered a minimum target for an error in the trend and one third of that (0.033°C per decade) would be a goal.

Examination of Figure 14, the CONUS 95% confidence value for a discontinuity and Figure 16, the 20 year trend 95% confidence values for CONUS averages reveals fairly similar results. For discontinuities, 100 dual sonde flights per year would be below the 0.075°C minimum and 200 per year gives a tropospheric average of about 0.05°C. For 20 year trends (Figure 16), 120 dual sonde flights brings the 95% confidence value down to just below 0.05°C per decade and 240 dual sonde flights brings the 95% confidence value averaged from the surface up to 300 hPa to just below 0.033°C. Because trend results are dependent on factors other than the discontinuity caused by changing radiosondes such as the number of years going into the trend calculations and where in the time series the discontinuity takes place, the most directly comparable result would be the 95% confidence limit on CONUS area averaged tropospheric discontinuities using the 9 station averages. These are presented in Table 6.

Reasonable people can look at the information presented and come to different recommendations based on both budgetary and scientific concerns. An example from the budgetary side could be that the relationship between the small incremental cost of additional dual sonde flights and the major fixed costs per site might imply that this should be an opportunity to perform an exceedingly accurate continuity study. An example from the scientific side could be that there are different views as to how important the accuracy in radiosonde continuity adjustments will be in the climate change debate in 10 years. Radiosondes are just one of many pieces of information. Yet the information they provide will be used to address one of the most controversial topics in climate change: the different rates of warming observed at the surface compared to the troposphere. If the expanded selection of 19 stations is chosen, then at total of 200 dual sonde flights at a station is an appropriate target number. This represents 25 flights per bias assessment which means per season per hour. Should only 18 stations be selected (that is, Green Bay, Wisconsin is not slated for dual sonde continuity flights), 224 dual sonde flights per station is deemed appropriate. Both of these options will give us a 95% confidence limit of the magnitude of the error in assessing CONUS average discontinuity caused by changing to the RRS that is less than 0.05°C.

7.5 *Scheduling the Dual Sonde Flights*

The best flight schedule from a climate perspective is to take all the dual sonde flight observations prior to the change in radiosonde. Furthermore, if the dual sonde capability is going to remain in place at the station, it would better to take the dual sonde observations over the course of two or more years. The reason is that it is quite possible, due to, for example, a strong el Niño, that the first year or potentially only year of the dual sonde data might not be typical for the climate of the region. Adjustments calculated during an unusually cloudy or dry year will not be as accurate when applied to other years as might be preferred.

However, the extra cost associated with taking the dual sonde data prior to the commissioning of the RRS may not be justified. Given that routine climate monitoring with radiosonde data is likely to be addressed first on an annual or seasonal basis, it is possible to determine an appropriate adjustment immediately after the end of a season if all the dual sonde data at a station are collected in one year rather than two. Therefore, changing the sonde over to the new instrumentation and then taking dual sonde data would be acceptable as long as each season and observation time receives an equal share of dual sonde flights and that these flights sample the full range of weather conditions. Therefore, it should not be necessary to have the RRS in a “non-commissioned” status awaiting the determination of the transfer function.

7.6 *Managing Dual Sonde Data*

It is important to monitor dual sonde data in near real time to make sure there are no problems with the data. Preventing the possibility of finding a fatal flaw in the data two years after they were taken (rather than two weeks) needs to be part of the continuity program. This is particularly true if the observations are made after the change over to the new sonde rather than before the change. The task of managing and assessing incoming dual sonde data should be undertaken by an institution and team that is committed to climate continuity. This means that probably the best candidate for this role is the NCDC wing of RATPAC. The agreement and support for this activity should be scheduled and confirmed prior to the start of dual sonde flights.

The role in monitoring the dual sonde data flow should be very narrow. Problems with the data need to be reported to the NWS immediately and the NWS will need to take immediate action to rectify the situation. But unexpected findings from preliminary analysis of the data should not be used to alter the planned series of dual sonde flights.

7.7 *RRS Deployment Strategy*

The planned RRS deployment takes place over the course of FY 03–06. For continuity purposes, the deployment should take the full time period currently expected and be planned in such a way that, as much as possible within practical constraints, neighboring stations have very different deployment dates. As the ellipses shown in Figure 11 tend to have a greater east/west extent than north/south, it would be more advantageous for the neighbors with the very different deployment dates to be east/west neighbors rather than north/south neighbors. This would maximize the potential use of neighboring station information in homogeneity assessments.

7.8 *Cost estimates*

7.8.1 *Fixed Costs Per Station*

The final estimates of the fixed cost per station are based on Table 3 with the following modifications based on the assumption that the dual sonde capabilities will be permanent fixtures at these stations. It is estimated that six used radomes will be available from the Air Force for a cost of $5K each and all other radomes will cost $55K. Installation costs are not included as the new system would have to be installed whether the site took dual observations or not. This cost was included in Table 3 on the assumption that the site would have to be reinstalled after the continuity test period is over. The total per site fixed cost for the minimum 17 recommended sites is $1,742K. For 18 sites it would be $1,862K. And for the full complement of 19 locations, the best fixed site total cost estimate is $1,981K, which represents an incremental cost at each additional station of $119K.

7.8.2 *Expendable Costs*

The total cost of dual sonde flights will depend on several factors. The first is how many stations will be selected. The results will be provided for 17 (minimum), 18 and 19 (recommended) stations. Three of the stations in the equatorial Pacific will deal with only two seasons and therefore will have half as many dual flights as the rest of the stations. The cost of the expendables depends on whether the stations are changed to the RRS sonde before or after the dual sonde flights are commenced. For performing 200 dual sonde flights per station prior to the RRS change, the estimated costs for 17, 18 and 19 stations are: $700K, $745K, and $790K respectively. If the dual sonde flights take place after the transition, the costs would be: $452K, $480K and $510K. The costs for more or fewer dual sonde flights can easily be determined as a percentage of the 200 flight costs.

7.8.3 *Continuity Costs at Caribbean Hurricane Upper Air Stations*

Continuity for the CHUAS stations, as discussed previously, would be only for the single CHUAS GUAN station changing sonde types. While the cost of labor isn't being covered by the NWS additional costs for undertaking dual sonde flights in a foreign country may compensate for the savings. So the estimated the costs for CHUAS should be equivalent of adding one additional station to both the fixed costs of $119K and the dual sonde costs of, for 200 dual sonde flights of $29K. The expendable cost is the same if done before or after the transition because the CHUAS stations will continue to use the lower cost non-GPS sondes.

7.8.4 *Analyzing the Dual Sonde Data*

The costs of analyzing the dual sonde data, including ingesting the data, monitoring the data receipt in near real time over the four year expected life of the continuity study, and calculating the transfer function or homogeneity adjustment to be applied to historical data at each station to make them comparable to RRS data is estimated to be $73.5K.

7.8.5 *Archiving the Dual Sonde Data*

The cost of archiving the data, including storage media, writing and evaluating archive and retrieval scripts, and preparing data set documentation, is estimated at $8K.

7.8.6 *Total Costs*

Our best estimate of costs for radiosonde continuity, including installing dual sonde flight capabilities at 19 NWS stations and one CHUAS station, 200 dual sonde flights per station (with three exceptions) and analysis and archiving of the dual sonde data, is $2.7 to $3.0 million depending on whether the dual sonde flights were made before or after the RRS transition.

7.9 *Beyond the RRS*

Even with permanent dual sonde capability at the selected stations, the sonde technology at these select stations should not be changed without significant need. This is not a new recommendation as it has been voiced many times before (e.g., National Research Council, 2000b). Even very accurately assessed biases bring in error compared to having no transition at all. However, when changes in sondes do need to be made in the future, the NWS should factor in the cost of dual sonde flights at these climate stations, including all three CHUAS GUAN stations, when performing cost benefit analyses. The recommended policy of maintaining dual sonde capabilities at climate stations should insure that future transition costs are kept to a minimum. As even with a new test chamber, which would also be valuable in determining if new sondes meet the specifications, and an extra channel on the RRS sondes, the need for dual sonde continuity flights is likely to remain for the foreseeable future.

8. EPILOGUE

The above material was prepared for and presented to NOAA's *Council on Long-term Climate Monitoring*, 15 January 2003. The Council largely endorsed the continuity strategy presented here. However, the Council also made a significant related recommendation. This study only addressed the relative continuity of the old radiosonde to the new radiosonde. It did not address the new radiosonde to truth. Towards that end, the Council also recommended that the NWS move forward with reference radiosondes as well. Reference radiosondes are very high quality sondes that are far too expensive for twice daily use at all the NWS stations. However, a moderate number of reference radiosonde flights could help build transfer functions between the RRS sondes and the true temperature and humidity. If they were flown to correspond with satellite overpasses they would greatly assist in satellite calibration. And they would provide insights into important climate factors, such as upper tropospheric water vapor, that are not monitored very well with the current observing system.

The NWS has also largely embraced the continuity strategy. Towards that end they have been developing innovative ways to cut down on the cost, such as using a mobile second sonde system for dual sonde flights, which can be moved from one station to another after the year-long continuity flights at a station have ended. For additional updates on the Radiosonde Replacement System, there are four other relevant papers in the Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans and Land Surface: 3.1 National Weather Service in situ radiation temperature correction for Radiosonde Replacement System GPS radiosondes by Carl Bower and J. J. Fitzgibbon; 3.2 Update on the implementation of the National Weather Service's Radiosonde Replacement System, by Joseph Facundo; 3.3 Testing the Radiosonde Replacement System (RRS) Radiosondes by James Fitzgibbon and Carl Bower; and 3.5 Verifying radiosonde solar radiation correction algorithms for the RRS by James Fitzgibbon and J. Facundo.

9. REFERENCES

Angell, J. K., 1988: Variations and trends in tropospheric and stratospheric global temperatures, 1958-87. *J. Climate*, **1**, 1296-1313.

Angell., J. K., and J. Korshover, 1975: Estimate of the global change in tropospheric temperatures between 1958 and 1973. *Mon. Wea. Rev.*, **103**, 1007-1012.

Angell, J. K., and J. Korshover, 1983: Global temperature variations in the troposphere and stratosphere, 1958-82. *Mon. Wea. Rev.*, **111**, 901-921.

Christy, J. R., R. W. Spencer, W. B. Norris, W. D. Braswell, and D. E. Parker, 2003: Error estimates of version 5.0 of MSU/AMSU bulk atmospheric temperatures*. J. Atmos. Oceanic Tech*., submitted.

Daan, H., 2002: Guide to the GCOS Surface and Upper-Air Networks: GSN and GUAN. GCOS - 73, WMO/TD. No. 1106, World Meteorological Organization, Geneva. 37 pp.

Diamond, H., 2003: The U.S. Global Climate Observing System (GCOS) Program Office's involvement in the international GCOS effort. *The 19th International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology,* Long Beach, February 10-13.

Durre, I., T. C. Peterson, and R. S. Vose, 2002: Evaluation of the effect of the Luers-Eskridge radiation adjustments on radiosonde temperature homogeneity. *J. Climate*, **15**, 1335-1347.

Elliott W. P. and D. J. Gaffen, 1991: On the Utility of Radiosonde Humidity Archives for Climate Studies, *Bull. Amer. Meteorol. Soc.*, **72**, 1507-1520.

Elliott, W., R. Ross and W. Blackmore, 2002: Recent Changes in NWS Upper-Air Observations with Emphasis on Changes from VIZ to Vaisala Radiosondes, *Bull. Amer. Meterol. Soc.*, **83**, 1003–1017.

Folland, C. K., and D. E. Parker, 1995: Corrections of instrumental biases in historical sea surface temperature data. *Quart. J. Roy. Meteor. Soc.,* **121**, 319-367.

Free, M., I. Durre, E. Aguilar, D. Seidel, T. C. Peterson, R. E. Eskridge, J. K. Luers, D. Parker, M. Gordon, J. Lanzante, S. Klein, J. Christy, S. Schroeder, B. Soden, L. M. McMillin and E. Weatherhead, 2002: Creating Climate Reference Datasets: CARDS Workshop on Adjusting Radiosonde Temperature Data for Climate Monitoring, *Bull. Amer. Meteorol. Soc.*, **83**, 891-899.

Gaffen, D. J., 1994: Temporal inhomogeneities in radiosonde temperature records, *J. Geophys. Res.,* **99**, 3667-3676.

Gaffen, D. J., B. D. Santer, J. S. Boyle, J. R. Christy, N. E. Graham, and R. J. Ross, 2000: Multi- decadal changes in the vertical temperature structure of the tropical troposphere. *Science*, **287**, 1239-1241.

Hooper, A. H., 1986: WMO international radiosonde comparison - Phase I, Beaufort Park, U.K., *WMO/TD-No. 174,* 118 pp.

Hopkins, R., 2002: *NOAA Chief Announces New U.S. Funding for Global Climate Observing Efforts*. NOAA press release 2002-072.

Ivanov, A., A. Kats, S. Karnosenko, N. Nash, and N. Zaitseva, 1991: WMO International Radiosonde Comparison - Phase III, Dzhambul, USSR, *WMO/TD-No. 451*, 135 pp.

Lanzante, J. R., S. A. Klein, and D. J. Seidel, 2003a: Temporal homogenization of monthly radiosonde temperature data. Part I: Methodology. *J. Climate*, **16**, 224-240.

Lanzante, J. R., S. A. Klein, and D. J. Seidel, 2003b: Temporal homogenization of monthly radiosonde temperature data. Part II: Trends, sensitivities, and MSU comparison. *J. Climate*, **16**, 241-262.

Lesht, B. M., 1998: Uncertainty in radiosonde measurements of temperature and relative humidity estimated from dual-sonde soundings made during the September 1996 ARM water vapor IOP. *Proceedings of the Tenth Symposium on Meteorological Observations and Instrumentation*, 11-16 January 1998, Phoenix, AZ, American Meteorological Society, pp. 80-83.

Luers, J. K. and R. Eskridge, 1995: Temperature corrections for the VIZ and Vaisala radiosondes, *J. Appl. Meteor.*, **34**, 1241-1253.

National Research Council, 2000a: *Reconciling Observations of Global Temperature Change,* National Academy Press, Washington, D.C. 85 pp.

National Research Council, 2000b: Improving Atmospheric Temperature Monitoring Capabilities: Letter Report, National Academy Press, Washington, D.C., 17 pp.

National Weather Service, 2001: *Radiosonde Replacement System (RRS) Implementation Plan*, Office of Science and Technology, Silver Spring, MD.

Peterson, T. C., D. R. Easterling, T. R. Karl, P. Ya. Groisman, N. Nicholls, N. Plummer, S. Torok, I. Auer, R. Boehm, D. Gullett, L. Vincent, R. Heino, H. Tuomenvirta, O. Mestre, T. Szentimre, J. Salinger, E. Førland, I. Hanssen-Bauer, H. Alexandersson, P. Jones, D. Parker, 1998: Homogeneity adjustments of in situ atmospheric climate data: A review. *Internat. J. Climatol.*, **18**, 1493-1517.

Peterson, T. C., M. A. Taylor, R. Demeritte, D. L. Duncombe, S. Burton, F. Thompson, A. Porter, M. Mercedes, E. Villegas, R. Semexant Fils, A. Klein Tank, A. Martis, R. Warner, A. Joyette, W. Mills, L. Alexander, and B. Gleason, 2002: Recent Changes in Climate Extremes in the Caribbean Region. *J. Geophys. Res.*, **107**, 4601, doi: 10.1029/2002JD002251.

Revercomb, H. E., D. D. Turner, D. C. Tobin, R. O. Knuteson, W. F. Feltz, B. Balsley, J. Barnard, J. Boesenberg, S. Clough, D. Cook, R. Ferrare, J. Goldsmith, S. Gutman, R. Halthore, B. Lesht, J. Liljegren, H. Linne, J. Michalsky, V. Morris, W. Porch, S. Richardson, B. Schmid, M. Splitt, T. Van Hove, E. Westwater, and D. Whiteman, 2002: The Atmospheric Radiation Measurement (ARM) program's water vapor intensive observation periods: Overview, accomplishments, and future challenges. *Bull. Amer. Meteorol. Soc.*, in press.

Rosen, R. D., J. M. Henderson and D. A. Salstein, 2002: Sensitivity of continental-scale climate trend estimates to the distribution of radiosondes over North America. *J. Atmos. Oceanic Tech.*, in press.

Rubinstein, R. Y., 1981: *Simulation and the Monte Carlo Method*. John Wiley & Sons, Inc., New York, 278 pp.

Schmidlin, F. J., 1988: WMO international radiosonde intercomparison – Phase II, Wallops Island, Virginia USA, *WMO/TD-No. 312.*

Schmidlin, F. J., and A. Ivanov, 1998: Radiosonde relative humidity sensor performance: The WMO intercomparison-Sept. 1995. Preprint volume. *10th Symposium on Meteorological Observations and Instrumentation*, American Meteor. Soc., 68-71.

Smith, T. M. and R. W. Reynolds, 2002: Bias corrections for historical sea surface temperatures based on marine air temperatures. *J. Climate*, **15**, 73-87.

Turner, D. D., B. M. Lesht, S. A. Clough, J. C. Liljegren, H. E. Revercomb, and D. C. Tobin, 2002. Dry bias and variability in Vaisala RS80-H radiosondes: The ARM experience. *J. Atmos. Oceanic Technol.*, in press.

U. S. Climate Change Science Program, 2002: *Draft white paper: Understanding recent atmospheric temperature trends and reducing uncertainties*, in support of chapter 3 of the Strategic Plan for the Climate Change Science Program. 25 pp.

Wallis, T. W. R., 1988: A subset of core stations from the Comprehensive Aerological Reference Dataset (CARDS). *J. Climate*, **11**, 272-282.

Wang, J., H. L. Cole, D. J. Carlson, E. R. Miller, K. Beierle, A. Paukkunen and T. K. Laine, 2002: Corrections of humidity measurement errors from the Vaisala RS80 radiosonde – application to TOGA COARE data. *J. Atmos. Oceanic Tech.*, **19**, 981-1002.

Weatherhead, E. C., G. C. Reinsel, G. C. Tiao, X.-L. Meng, D. Choi, W.-K. Cheang, T. Keller, J. DeLuisi, D. J. Wuebbles, J. B. Kerr, A. J. Miller, S. J. Oltmans, and J. E. Frederick, 1998: Factors affecting the detection of trends: Statistical considerations and applications to environmental data, *J. Geophys. Res.*, **103**, 17149-17161, 1998.

White, R. S., 1985: *Statistics*, CBS College Publishing, New York, 394 pp.

Wierenga, R. D., 2003: 1680 MHz radiosonde. *Preprint of the Seventh Symposium on the Integrated Observing System: Water Cycle*, Long Beach, CA. Paper 1.3.

Yagi, S., A. Mita, and N. Inoue, 1996: WMO international radiosonde comparison-Phase IV Tsukuba, Japan, *WMO/TD-No. 742*, 129 pp.

Table 1. List of all 92 NWS radiosonde stations. Columns are: WMO station number, name, latitude, longitude (in thousandths of degrees), type of radiosonde currently flown, G=GUAN, A=Angell network, R1=current RATPAC station, R2=proposed new RATPAC station.

70026	BARROW, AK	71.289	-156.783	VIZ-B2	G	A	R1	
70133	KOTZEBUE, AK	66.886	-162.613	Vaisala				
70200	NOME, AK	64.507	-165.438	Vaisala				
70219	BETHEL, AK	60.778	-161.844	Vaisala				
70231	MCGRATH	62.958	-155.598	Vaisala				
70261	FAIRBANKS, AK	64.816	-147.877	Vaisala				
70273	ANCHORAGE, AK	61.156	-149.984	Vaisala				
70308	ST. PAUL ISLAND, AK	57.150	-170.217	VIZ-B2	G	A	R1	
70316	COLD BAY, AK	55.201	-162.716	Vaisala				
70326	KING SALMON, AK	58.681	-156.665	Vaisala				
70350	KODIAK, AK	57.746	-152.493	Vaisala				
70361	YAKUTAT, AK	59.517	-139.667	Vaisala				
70398	ANNETTE, AK	55.039	-131.578	VIZ-B2	G	A	R1	
72201	KEY WEST, FL	24.552	-81.758	VIZ-B2	G			R2
72202	MIAMI, FL	25.755	-80.384	Vaisala				
72206	JACKSONVILLE, FL	30.484	-81.702	Vaisala				
72208	CHARLESTON, SC	32.896	-80.028	Microsonde				
72210	TAMPA BAY, FL	27.705	-82.401	Vaisala				
72214	TALLAHASSEE, FL	30.446	-84.300	Vaisala				
72215	PEACHTREE, GA	33.363	-84.566	Vaisala				
72230	BIRMINGHAM, AL	33.179	-86.783	Vaisala				
72233	SLIDELL, LA	30.337	-89.825	Vaisala				
72235	JACKSON, MS	32.319	-90.080	VIZ-B2				R2
72240	LAKE CHARLES, LA	30.125	-93.216	Vaisala				
72248	SHREVEPORT, LA	32.451	-93.841	Vaisala				
72249	FORT WORTH, TX	32.838	-97.303	Vaisala				
72250	BROWNSVILLE, TX	25.917	-97.419	VIZ-B2		A	R1	
72251	CORPUS CHRISTI, TX	27.779	-97.506	VIZ-B2				
72261	DEL RIO, TX	29.377	-100.944	VIZ-B2	G			
72265	MIDLAND, TX	31.943	-102.189	Vaisala				
72274	TUCSON, AZ	32.124	-110.941	Vaisala				
72293	SAN DIEGO, CA	32.833	-117.117	VIZ-B2	G	A	R1	
72305	MOREHEAD CITY, NC	34.777	-76.877	Vaisala				
72317	GREENSBORO, NC	36.098	-79.943	Vaisala				
72318	BLACKSBURG, VA	37.204	-80.414	Vaisala				
72327	NASHVILLE, TN	36.247	-86.562	VIZ-B2				
72340	LITTLE ROCK, AR	34.836	-92.267	Vaisala				
72357	NORMAN, OK	35.237	-97.461	Vaisala				
72363	AMARILLO, TX	35.226	-101.717	Vaisala				
72364	SANTA TERESA, NM	31.873	-106.698	Vaisala				
72365	ALBUQUERQUE, NM	35.034	-106.622	VIZ-B2				
72376	FLAGSTAFF, AZ	35.230	-111.821	Vaisala				
72387	DESERT ROCK, NV	36.617	-116.017	VIZ-B2				
72402	WALLOPS IS., VA	37.933	-75.483	Microsonde				
72403	STERLING, VA	38.974	-77.478	Vaisala	G			
72426	WILMINGTON, OH	39.421	-83.822	Vaisala				
72440	SPRINGFIELD, MO	37.235	-93.402	Vaisala				
72451	DODGE CITY, KS	37.761	-99.969	VIZ-B2			R1	
72456	TOPEKA, KS	39.073	-95.631	Vaisala				

72469	DENVER, CO	39.763	-104.869	Vaisala				
72476	GRAND JUNCTION, CO	39.120	-108.525	Vaisala				
72489	RENO, NV	39.567	-119.783	Vaisala				
72493	OAKLAND, CA	37.750	-122.217	VIZ-B2				
72501	UPTON, NY	40.865	-72.863	Vaisala				
72518	ALBANY, NY	42.693	-73.832	Microsonde				
72520	PITTSBURGH, PA	40.532	-80.217	VIZ-B2				R2
72528	BUFFALO, NY	42.939	-78.724	Vaisala				
72558	VALLEY, NE	41.321	-96.366	Vaisala				
72562	NORTH PLATTE, NE	41.133	-100.700	Vaisala				
72572	SALT LAKE CTY, UT	40.783	-111.950	Vaisala				
72582	ELKO, NV	40.860	-115.742	VIZ-B2				
72597	MEDFORD, OR	42.383	-122.883	VIZ-B2	G			R2
72632	WHITE LAKE, MI	42.698	-83.472	Vaisala				
72634	GAYLORD, MI	44.907	-84.718	Vaisala				
72645	GREEN BAY, WI	44.491	-88.110	VIZ-B2				R2
72649	CHANHASSEN, MN	44.851	-93.565	Vaisala				
72659	ABERDEEN, SD	45.456	-98.414	Vaisala				
72662	RAPID CITY, SD	44.073	-103.212	Vaisala				
72672	RIVERTON, WY	43.065	-108.477	Vaisala				
72681	BOISE, ID	43.567	-116.217	Vaisala				
72694	SALEM, OR	44.917	-123.017	VIZ-B2				
72712	CARIBOU, ME	46.868	-68.013	VIZ-B2				R2
72747	INT'L FALLS, MN	48.565	-93.398	Vaisala				
72764	BISMARCK, ND	46.773	-100.760	VIZ-B2	G			
72768	GLASGOW, MT	48.200	-106.617	VIZ-B2				R2
72776	GREAT FALLS, MT	47.461	-111.385	VIZ-B2		A	R1	
72786	SPOKANE, WA	47.681	-117.628	VIZ-B2				
72797	QUILLAYUTE, WA	47.950	-124.550	VIZ-B2				
74389	GRAY, ME	43.893	-70.253	Vaisala				
74455	QUAD CITIES, IA	41.612	-90.582	Vaisala				
74494	CHATHAM, MA	41.667	-69.967	Vaisala				
74560	LINCOLN, IL	40.152	-89.338	Vaisala				
78526	SAN JUAN, PR	18.432	-65.992	VIZ-B2	G	A	R1	
91165	LIHUE, HI	21.985	-159.340	Vaisala				
91212	GUAM	13.477	144.794	VIZ-B2	G	A		
91285	HILO, HI	19.718	-155.058	VIZ-B2	G	A	R1	
91334	CHUUK, ECI	7.454	151.843	Vaisala	G		R1	
91348	PONAPE, ECI	6.975	158.223	Vaisala				R2
91376	MAJURO	7.086	171.391	VIZ-B2	G		R1	
91408	KOROR, PALAU WCI	7.340	134.489	Vaisala	G		R1	
91413	YAP, WCI	9.494	138.091	Vaisala				R2
91765	PAGO PAGO	-14.338	-170.719	Vaisala	G			

Table 2. GCOS Climate Monitoring Principles. Excerpted from the Report of the Eighth Session of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC), Wokingham, UK, 20 – 24 May 2002.

Effective monitoring systems for climate should adhere to the following principles:*

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.

2. A suitable period of overlap for new and old observing systems is required.

3. The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.

4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.

5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.

6. Operation of historically-uninterrupted stations and observing systems should be maintained.

7. High priority for additional observations should be focussed on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.

8. Long-term requirements should be specified to network designers, operators and instrument engineers at the outset of system design and implementation.

9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.

10. Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

Furthermore, satellite systems for monitoring climate should adhere to the following specific principles:

11. Rigorous station-keeping should be maintained to minimize orbital drift.

12. Overlapping observations should be ensured for a period sufficient to determine inter-satellite biases.

13. Satellites should be replaced within their projected operational lifetime (rather than on failure) to ensure continuity (or in-orbit replacements should be maintained).

14. Rigorous pre-launch instrument characterization and calibration should be ensured.

15. Adequate on-board calibration and means to monitor instrument characteristics in space should be ensured.

16. Development and operational production of priority climate products should be ensured.

17. Systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.

18. Continuing use of still-functioning baseline instruments on otherwise de-commissioned satellites should be considered.

19. The need for complementary in situ baseline observations for satellite measurements should be appropriately recognized.

20. Network performance monitoring systems to identify both random errors and time-dependent biases in satellite observations should be established.

** The ten basic principles were adopted (in paraphrased form) by the Conference of the Parties to the UN Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November, 1999.*

Table 3. Per station cost estimate for hardware and set up associated with taking dual flight data. This is primarily cost associated with installing an additional Telemetry Receiving System (TRS) near an existing Upper Air site. These cost estimates have been provided by the Engineering and Acquisition Branch, Office of Operational Systems, NWS.

Part I. Site survey. The site needs to be surveyed to determine the appropriate location for the second receiver. This includes analysis of prevailing wind, open land between TRS and GMD/WBRT, sky obstructions for Radiosonde Surface Observing Instrument System (RSOIS) and differential GPS site, room or shack to install Radiosonde Work Station (RWS; a PC), room for extra supplies, electrical power in conduit, signal cable in conduit, and placing the pads. The product of this survey will be agreements and drawings. The final cost is estimated at $18,300 for the first survey but as the team gains experience the cost would drop to $10,980 for each additional site.

Team	Per	Hours	Labor	Travel	Sub-Total
Region SFT	$36	96	$3,456	$ 700	$4,356
Site MIC/ET	$27	64	$1,728	$ 50	$1,778
COTR - DM	$42	120	$5,040	$1,800	$6,800
OPS2-Coord	$36	64	$2,304	$1,200	$3,504
Draftsman	$27	40	$1,080	$ 0	$1,080
Material					$900

Total First Site $18,300

```
                                            Each Add. Site   $10,980
On site -5 workdays, -2 travel days,
Agreements and Drawings -10 workdays

Subtotal:                               Average of $11.4K per site
```

Part II. Groundwork and material. The ground work involves ground leveling, a pad for TRS tower and dome, lease/buy and erect tower, lease/buy and erect dome, pad for RWS shack if not in Weather Forecast Office, cement barrel for differential GPS antenna, and run out the power and signal conduit. There are several factors that need to be considered which will vary from site to site. For example, can the new radome be located on the roof of a nearby building, be placed on a concrete pad near the existing radome, or will it have to be located on a tower?

```
Signal Conduit
   Upper Air to WFO/Upper Air to RWS shack
   TRS Dome to Upper Air/TRS Dome to RWS shock
   RSIOS to Upper Air/RSIOS to WFO

Grading - Machine rental   per day          $ 0.6K
Pads   -20' X 20' X 6' triangle
             elect., bolts, and anchors     $10K
          -4'X4'X4' bolts, and anchors      $ 2K
          -cement barrel
Structures
          -Dome   4 meter (16 ft)           $55K
          -RWS shack, Rent and place        $ 2K
             Monthly at $.5 per             $ 6K/yr.
             Cinder blocks                  $  .3K

Trencher - Machine rental $400 per          $ 2K
Power Conduit and Cable  $14 per ft
          -UAB to TRS Dome 200 ft           $ 2.8K*
             or WFO to TRS Dome 1200 ft     $16.4K*
          -UAB to RWS shack 200 ft          $ 2.8K**
             or WFO to RWS shack 1000 ft    $14.0K**
             or RWS in WFO 25ft cable only  $ 0.3K**
*  Must pick one of two choices
** Must pick one of three choices
Signal conduit and Cable   $10 per ft
          -UAB to TRS Dome 200 ft           $ 2.0K*
             or WFO to TRS Dome 1200 ft     $12.0K*
          -UAB to RWS shack 200 ft          $ 2.0K**
             or WFO to RWS shack 1000 ft    $10.0K**
             or RWS in WFO 25ft cable only  $ 0.3K**
*  Must pick one of two choices
** Must pick one of three choices

Subtotal:                     $79.3K to $122.5K plus $6K per year
Average subtotal:                                $100.9K + $6K/year
```

Part III. Installation. Installation is actually a difficult quantity to factor in as installing a new Signal Processing System (SPS), GPS receiver, etc. would be part of the RRS network installation anyway. The main expense associated with this is $27K for transportation of the receiver and a crane to lift it into place. Other expenses are listed below. These expenses would be associated with moving the GPS from the dual sonde location to the final location.

```
Safety Equipment                            $ 2.4K
SPS, Diff GPS, GPS repeater, RSIOS          $ 4.8K
PDB, crew 2 Techs 1 Week
Gen Elect and Inspection   10@$400/day      $ 4.0K

Subtotal                                    $11.2K
```

Part IV. Final preparation and testing. This reflects the time and expense of getting the crew ready and able to fly dual sonde flights.

```
Integration, training, site data
```

```
development, and test flights           $ 4.8K
crew (2 mets, 1 engr 2 weeks)

Subtotal                                $ 4.8K
```

Part V. Adjustments to the numbers based on alternate options and final total.

```
Subtotal from parts I-IV:               $128.3K + $6K/year
```

The shack to house the Radiosonde Work Station (RWS) will not be needed at all sites as many of the existing sites have room to fit in one more PC. So the estimate of the cost for the shack is factored in as if 50% of the sites required space to house an additional PC.
`Savings: $1.2K + $3K per year.`

Assuming that the dual sonde flights are conducted over a one year period at each station, the $3K/year shack rental is incorporated into the final cost per site as $3K.

The radome costs $55K new. Efforts are underway to pick up 6-7 used radomes from the Air Force. If continuity tests only take one year so the radome is used at 3 stations, this would cut the expense down to one third on a per station basis. If, after three years, the radomes were stored for potential future use where they are needed (e.g., Alaska has requested some replacement radomes), then the full $55K cost of a dome should not be considered part of continuity expenses. Based on these factors, the cost of a dome will be figured as somewhere between $5K and $55K, depending on deployment strategy and other factors.
`Savings: $0-$50K.`

```
Total estimated cost:                   $80.1K to $130.1K
```

Table 4. Cost basis for dual sonde flights if the flights were flown at a station that had already changed to the RRS GPS sonde.

Labor Cost in 2002	Ordinary GPS	Dual-Flight DELTA COST
Observer’s Labor GS-10	3.00 hrs = $66.60	+ 0.75 hrs = $16.65
E1 Tech’s Labor GS-11.5	0.214 hrs = $5.27	+ 0.214 hrs = $5.27
Total Labor 2002	3.24 hrs = $71.87	+ 0.96 hrs = $21.92
Expendable Costs	Ordinary GPS	Dual-Flight DELTA COST
Radiosonde	$150	+ $70 (weighted sonde FY04)
Balloon	$34	+ $26 (1,000 g)
Inflation Gas	$10	+ $10 (2,400g or 900 cu ft)
Parachute	$4.10	+ $4.10
Train Regulator	$0.57	No Change
Twine	$0.28	+ $0.07 + $3.50 Separator Bar
Data Print-out & Repro	$2.53	+ $2.53
Transport of Things	$2.60	+ $2.60
Risk of 2nd Release	$5.00	+ $5.00
Total Material 2002	$209.08	+ $123.80
Grand Total Costs	Ordinary GPS = $280.95	Dual-Flight DELTA + $145.72

Table 5. Cost basis for dual sonde flights if the flights were flown at a station that has not yet changed to the RRS GPS sonde.

Labor Cost in 2002	Ordinary RDF	Dual-Flight DELTA COST
Observer’s Labor GS-10	3.00 hrs = $66.60	+ 0.75 hrs = $16.65
El Tech’s Labor GS-11.5	0.214 hrs = $5.27	+ 0.214 hrs = $5.27
Total Labor 2002	3.24 hrs = $71.87	+ 0.96 hrs = $21.92
Expendable Costs	Ordinary RDF	Dual-Flight DELTA COST
Radiosonde	$ 70	+ $150 (weighted sonde FY04)
Balloon	$ 34	+ $26 (1,000g)
Inflation Gas	$ 10	+ $10 (2,400g or 900 cu ft)
Parachute	$ 4.10	+ $4.10
Train Regulator	$ 0.57	No Change
Twine	$ 0.28	+ $0.07 + $3.50 Separator Bar
Data Print-out & Repro	$ 2.53	+ $2.53
Transport of Things	$ 2.60	+ $2.60
Risk of 2nd Release	$ 5.00	+ $5.00
Total Materiel 2002	$129.08	+ $203.80
Grand Total Costs	Ordinary RDF = $200.95	Dual-Flight DELTA = $225.72

Table 6. The 95% confidence level in the absolute value of the error in CONUS discontinuity analysis in degrees C based on the number of dual radiosonde flights. The analysis going into this table is the same as that going into Figure 14. The main difference is that this table only shows the mean value for the surface to 300 hPa of the 6 mandatory levels. Note that 730 flights represents two dual sonde flights per day for a year so values greater than 730 would require more than one year of dual sonde flights.

# of flights	9 station avg	8 station avg
40	0.1102	0.1166
80	0.0780	0.0825
120	0.0636	0.0673
160	0.0551	0.0583
200	0.0493	0.0522
240	0.0450	0.0476
280	0.0416	0.0440
320	0.0390	0.0413
360	0.0367	0.0388
400	0.0347	0.0367
440	0.0332	0.0351
480	0.0318	0.0336
520	0.0304	0.0322
560	0.0295	0.0312
600	0.0284	0.0300
640	0.0275	0.0291
680	0.0266	0.0282
720	0.0260	0.0275
760	0.0253	0.0268
800	0.0246	0.0261

Figure 1 a-d. Photos of radiosondes. Top left, radiosonde being prepared for release. Top right, radiosonde being released. Bottom left, radiosonde flight underway with, in foreground, the balloon inflation shelter with radome above it that houses the radiosonde tracking equipment. Bottom right, radiosonde in full flight. By the time the balloon bursts two hours and approximately 35 vertical kilometers later the balloon will be 6 meters in diameter. Photos courtesy of the Upper-air Observations Program, Observing Systems Branch (OSB), NWS.

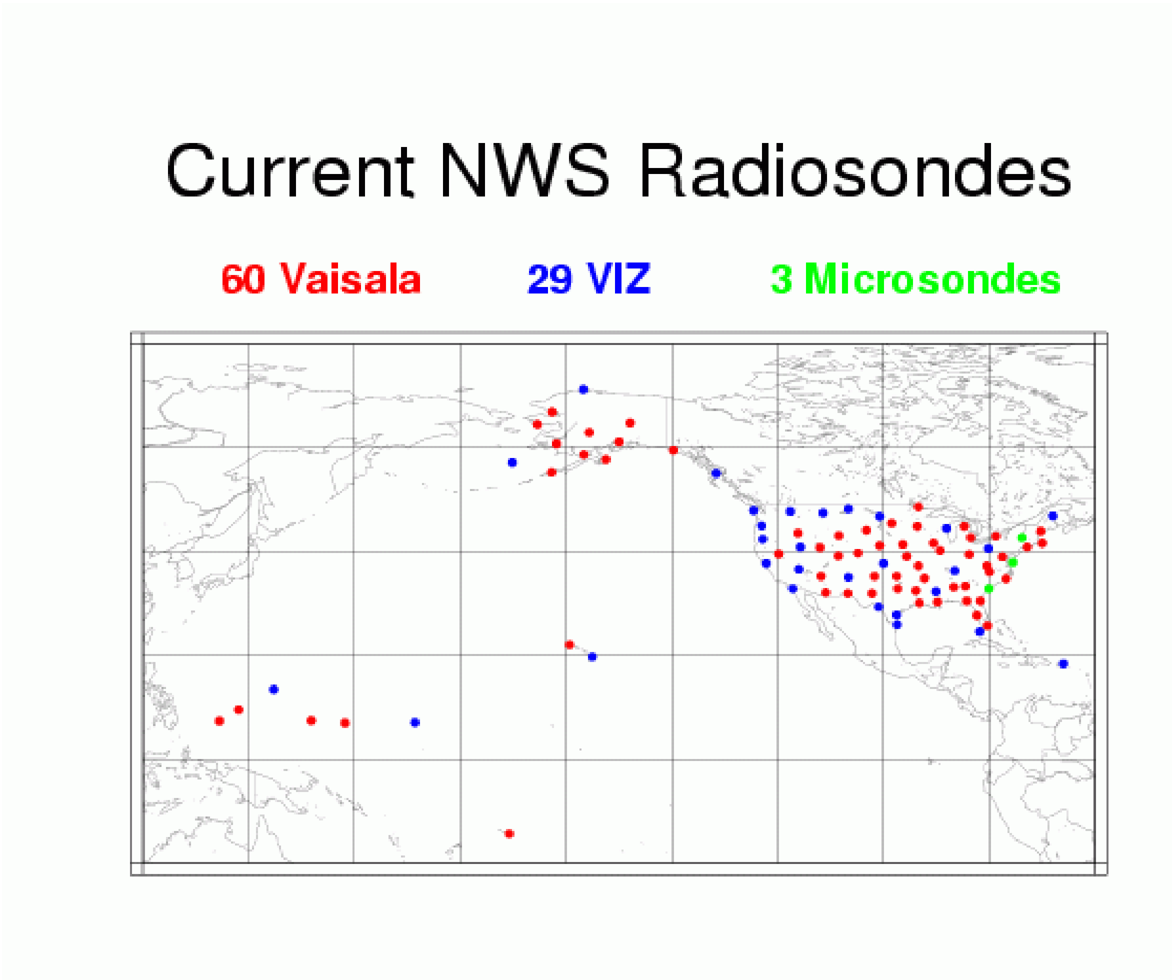

Figure 2. Map of NWS' 92 current radiosonde stations showing the type of radiosonde currently being flown at the stations.

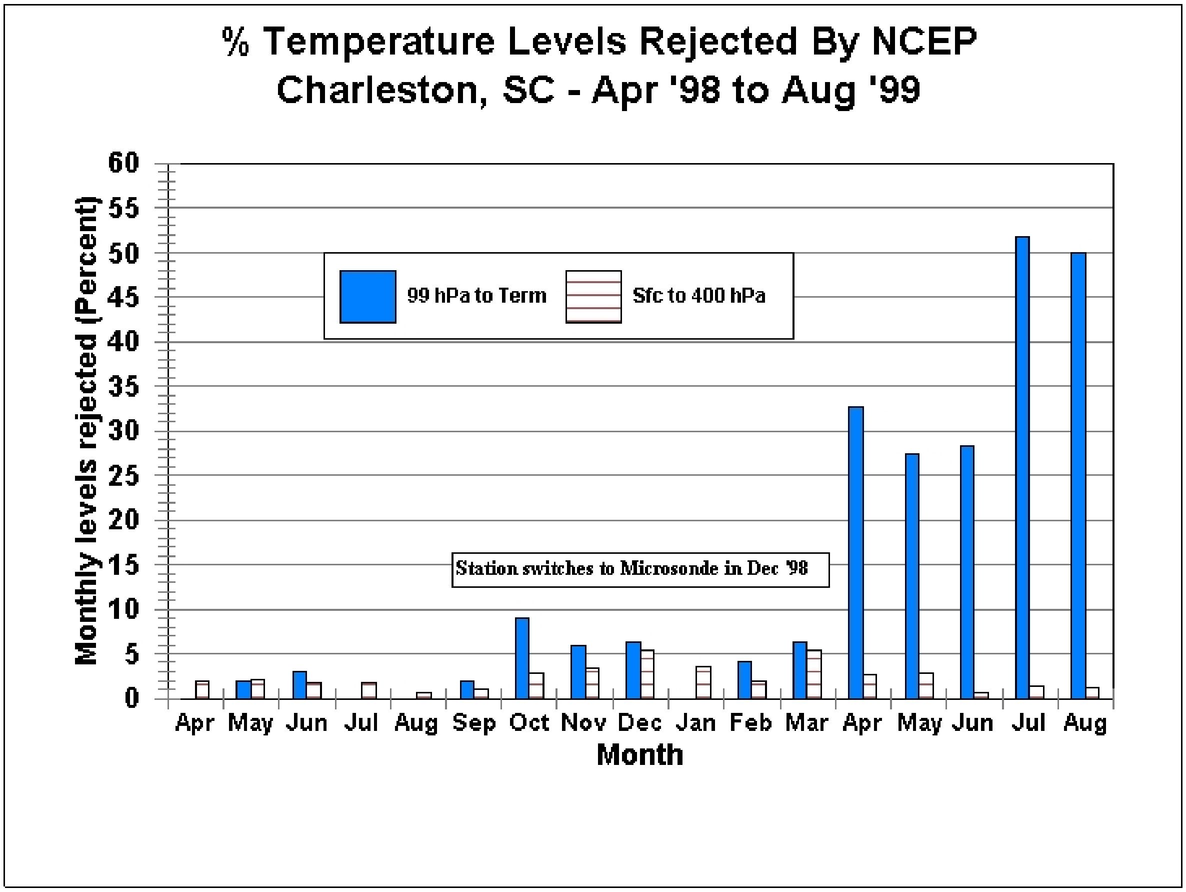

Figure 3. Percent of levels of the Charleston radiosonde data rejected by NCEP prior to use in their weather forecasting model. This station switched to the Microsonde radiosonde in December 1998. The problem did not show up until April because it is related to the impact of solar radiation on the thermistor. In winter months both 00 and 12 GMT flights from Charleston are at night. In the summer they are both under the influence of short wave solar radiation. A radiation adjustment scheme is now applied to data from this station and has essentially halved the rejection rate. But the rejection rate is still much greater than that of the previous sonde. Figure courtesy of Bill Blackmore, Office of Operational Systems/NWS/NOAA.

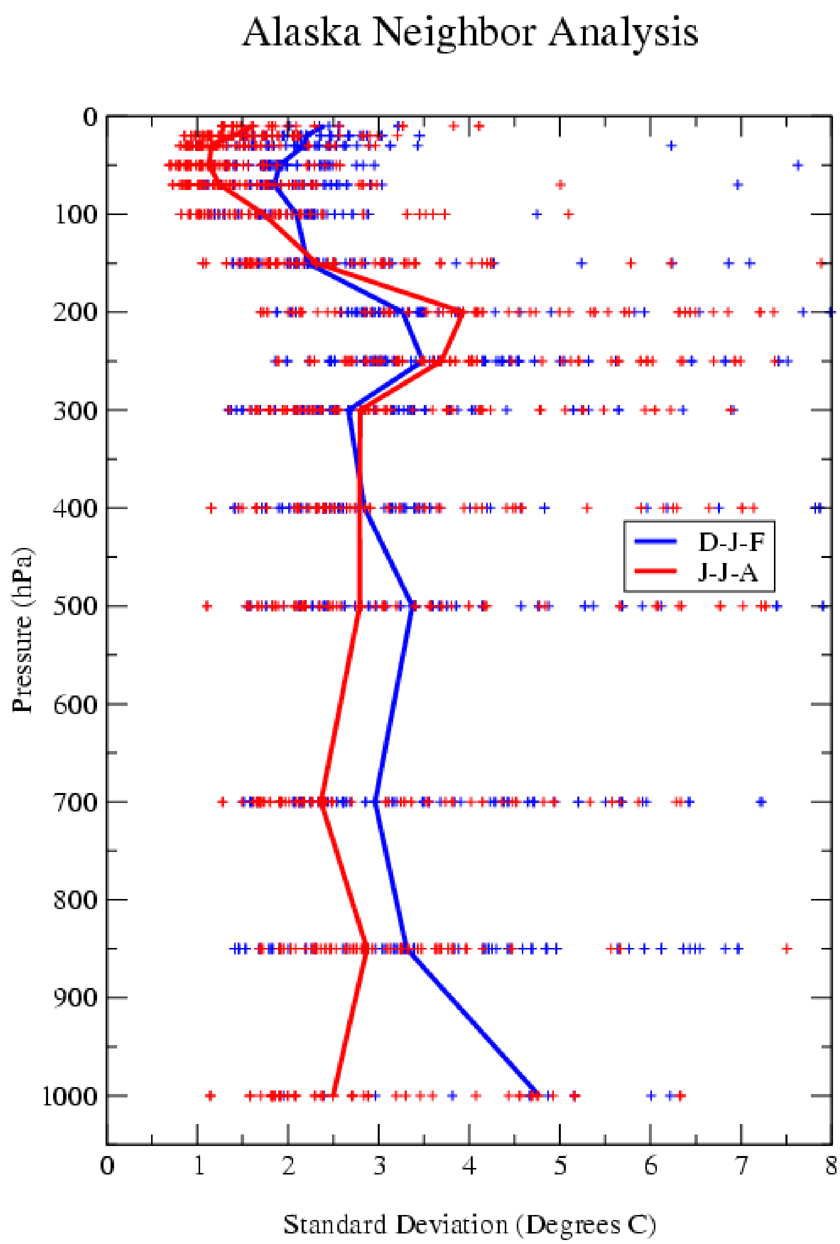

Figure 4. Standard deviation of the bias between Alaskan NWS stations and their nearest neighbor. Each data point represents on month of paired comparisons. The solid lines are median values for the two seasons.

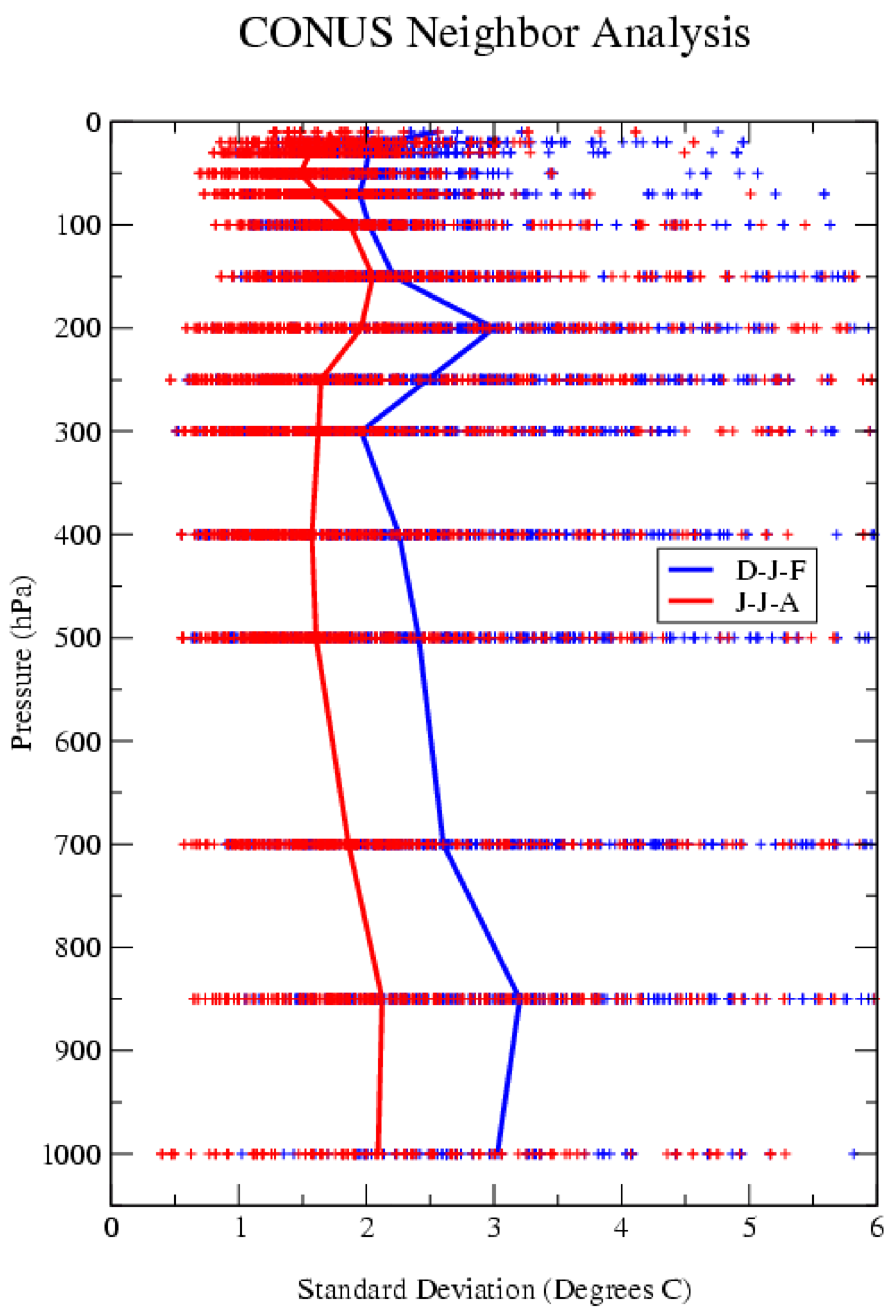

Figure 5. Same as Figure 4 but for the contiguous U.S.

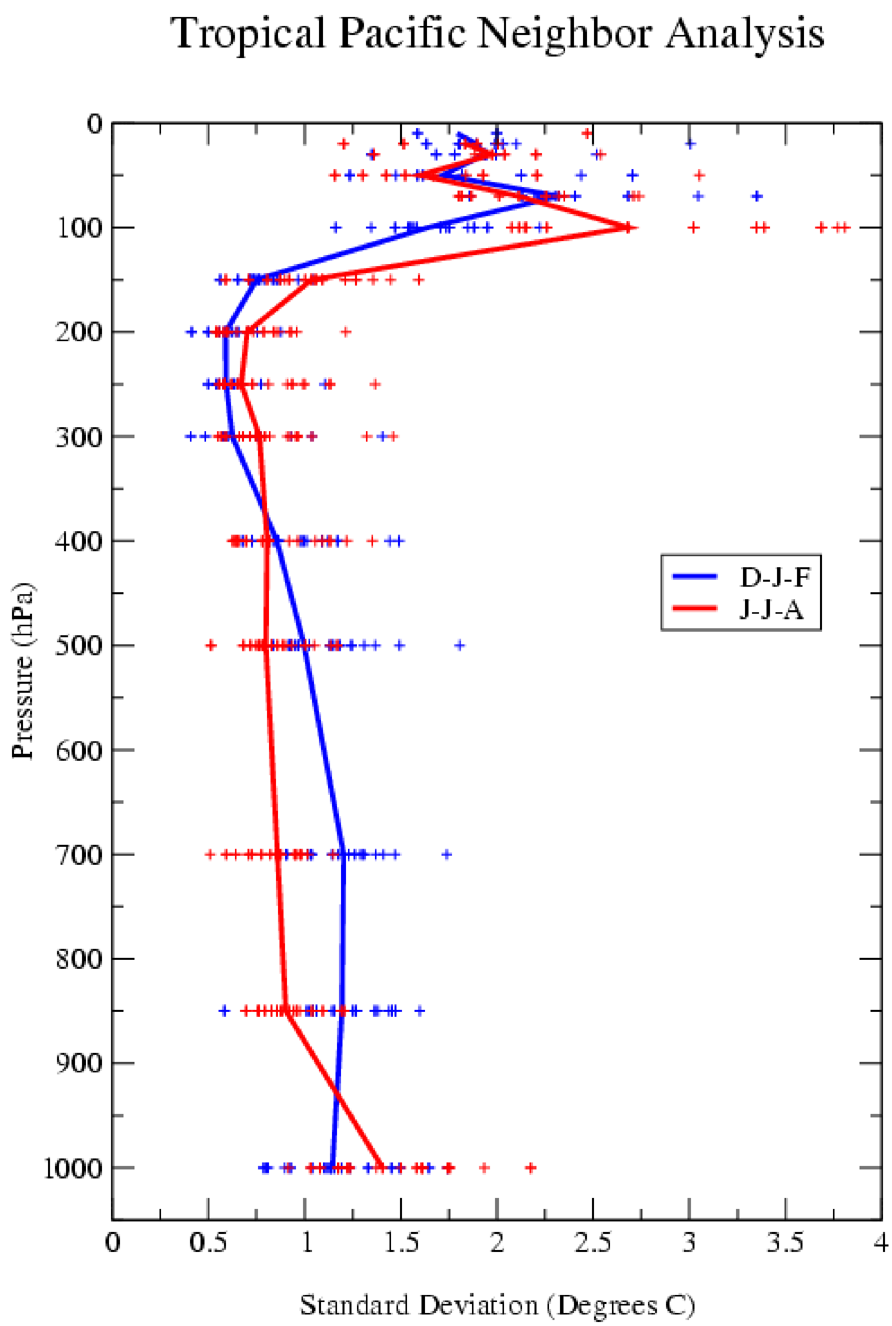

Figure 6. Same as Figure 4 but for the tropical Pacific island stations.

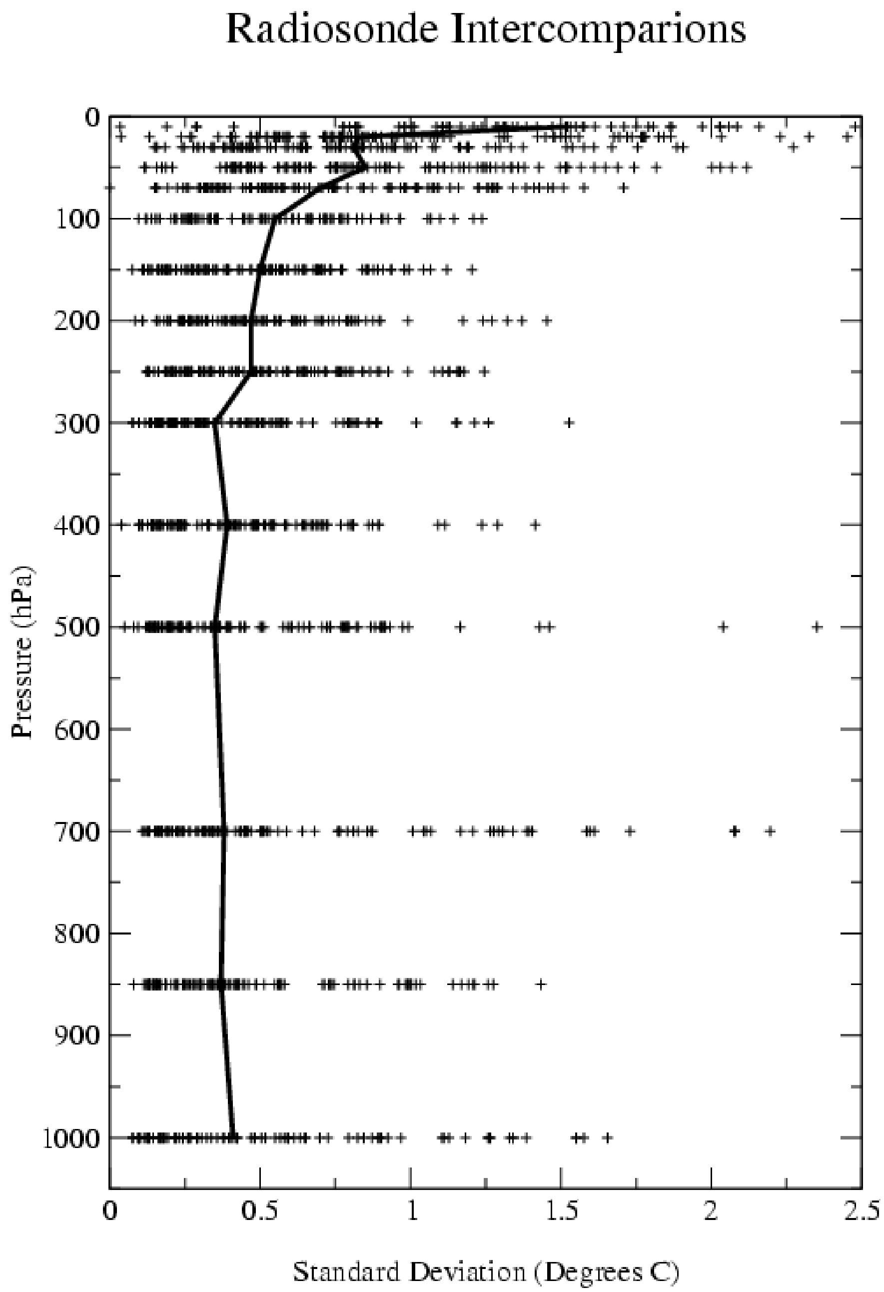

Figure 7. The standard deviation between two different radiosondes flown on the same balloon. Data going into each data point are were from launches from similar times of the day. The vertical line is the mean standard deviation.

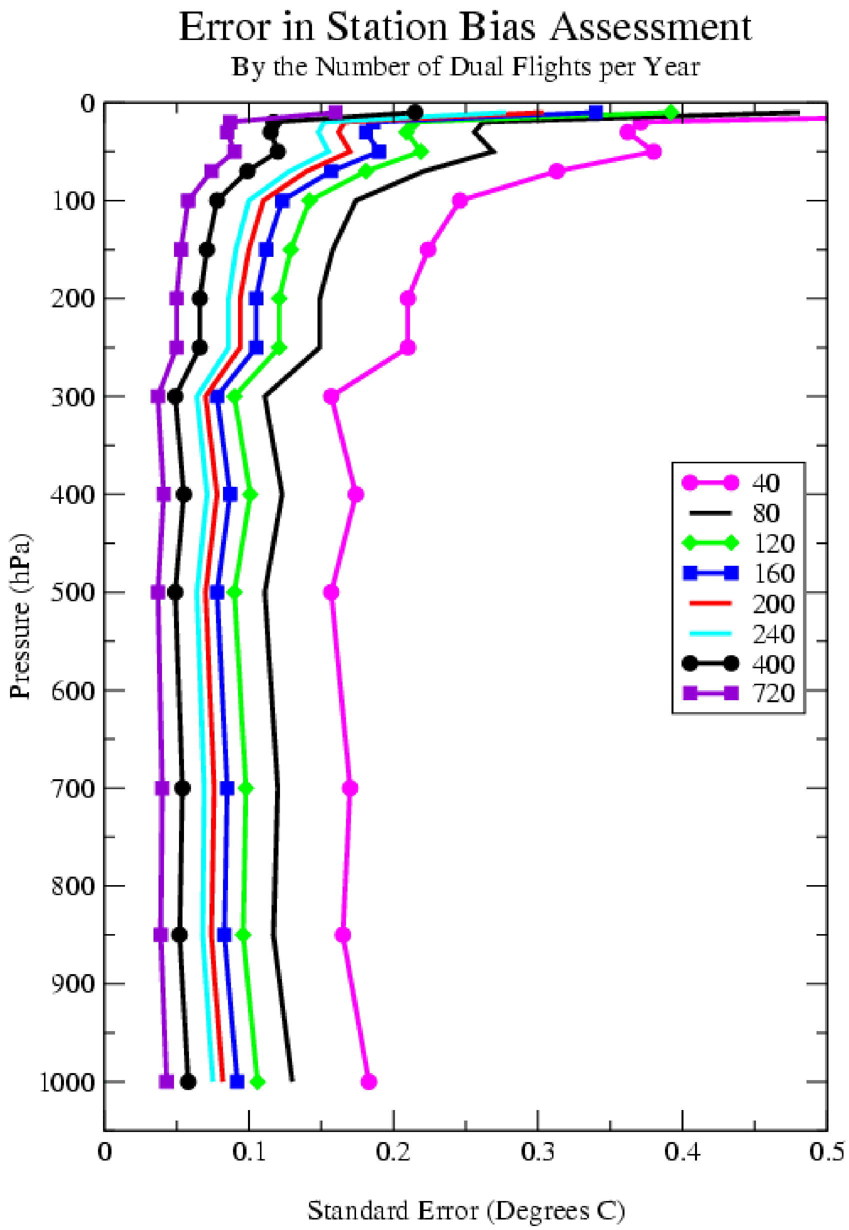

Figure 8. Using the mean standard deviation indicated in Figure 7, the standard error in an assessment of the mean bias between two different types of radiosondes was calculated based on the number of dual radiosonde flights. The number of flights listed in the figure are the number of flights per year based on the assumption that the bias at 00 and 12 GMT and each of the 4 seasons must be calculated separately. Therefore, 40 dual sonde flights over the course of a year represents 5 dual sonde flights per hour per season.

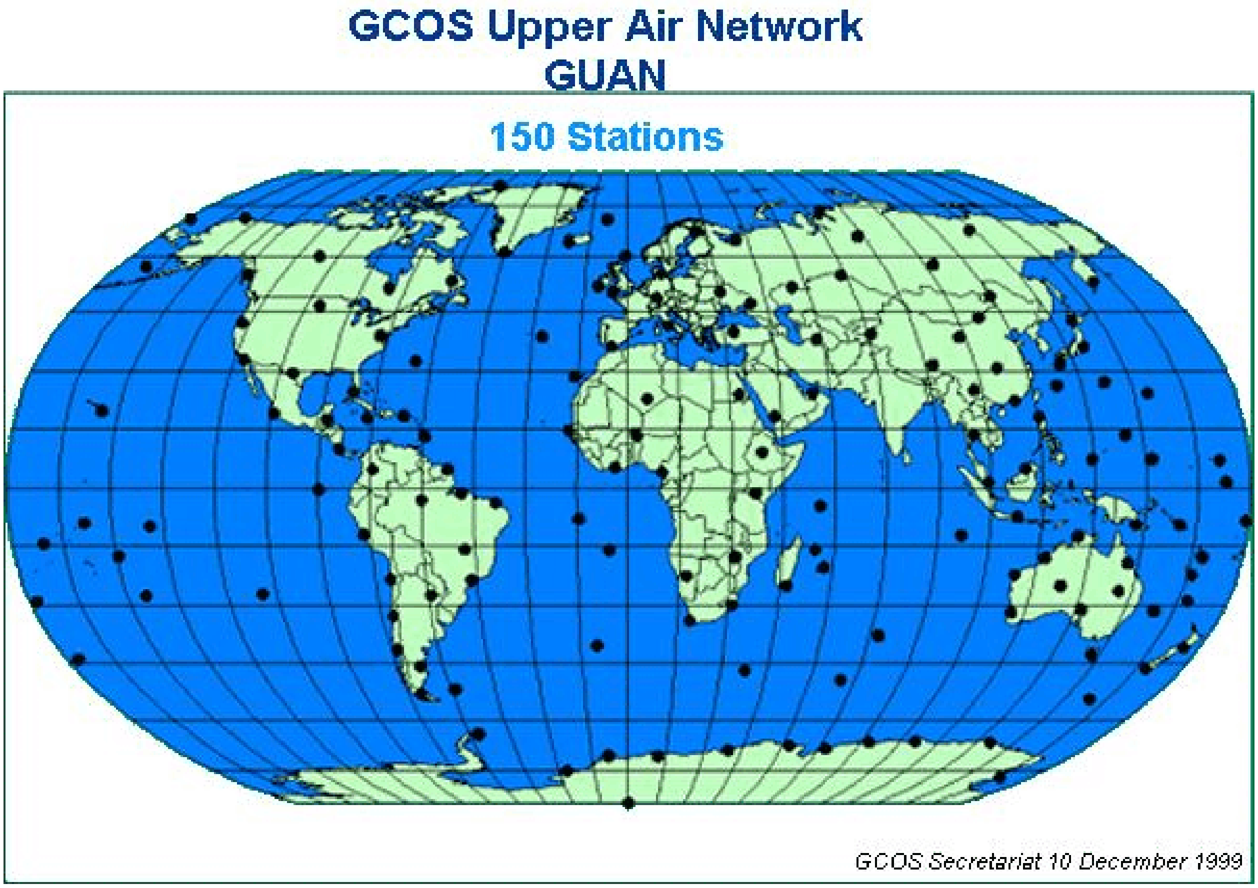

Figure 9. The location of the Global Climate Observing System (GCOS) Upper Air Network (GUAN) stations. Figure is courtesy of the Hadley Centre, UK Met Office.

Climate Radiosondes

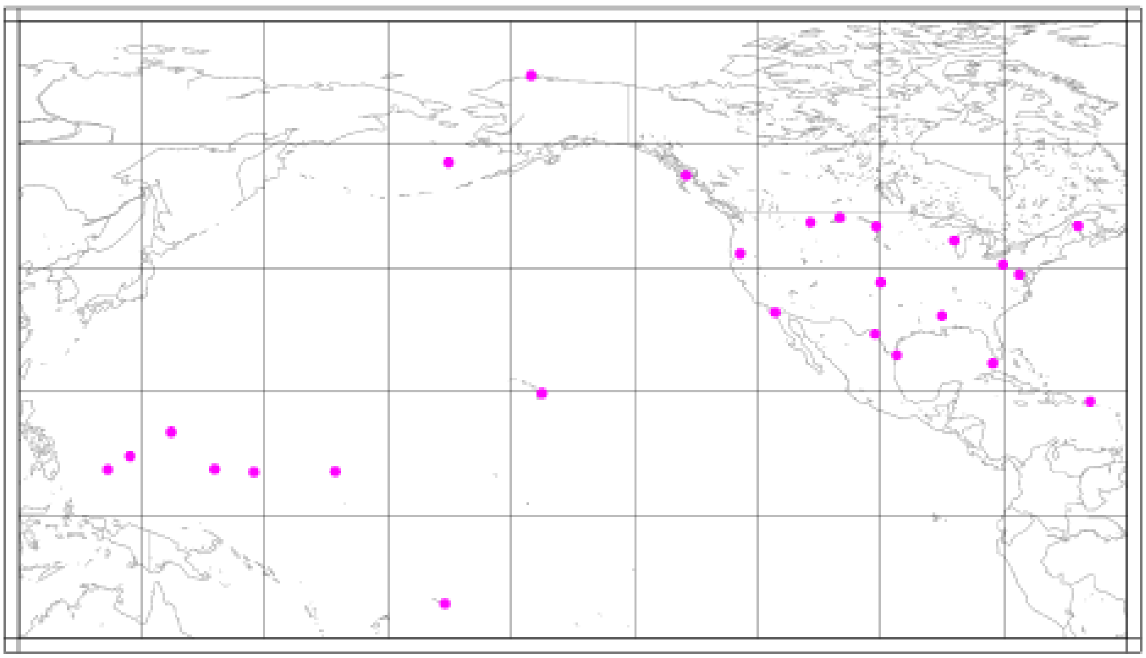

Figure 10. Map of all the NWS radiosondes that have a special designation for climate purposes. Specifically, these are the GUAN stations, the stations used for climate monitoring by Jim Angell ("the Angell Network"), stations currently used by RATPAC and stations targeted for use as potential RATPAC extensions. Some of the stations, like the two stations in Texas, are quite close to each other.

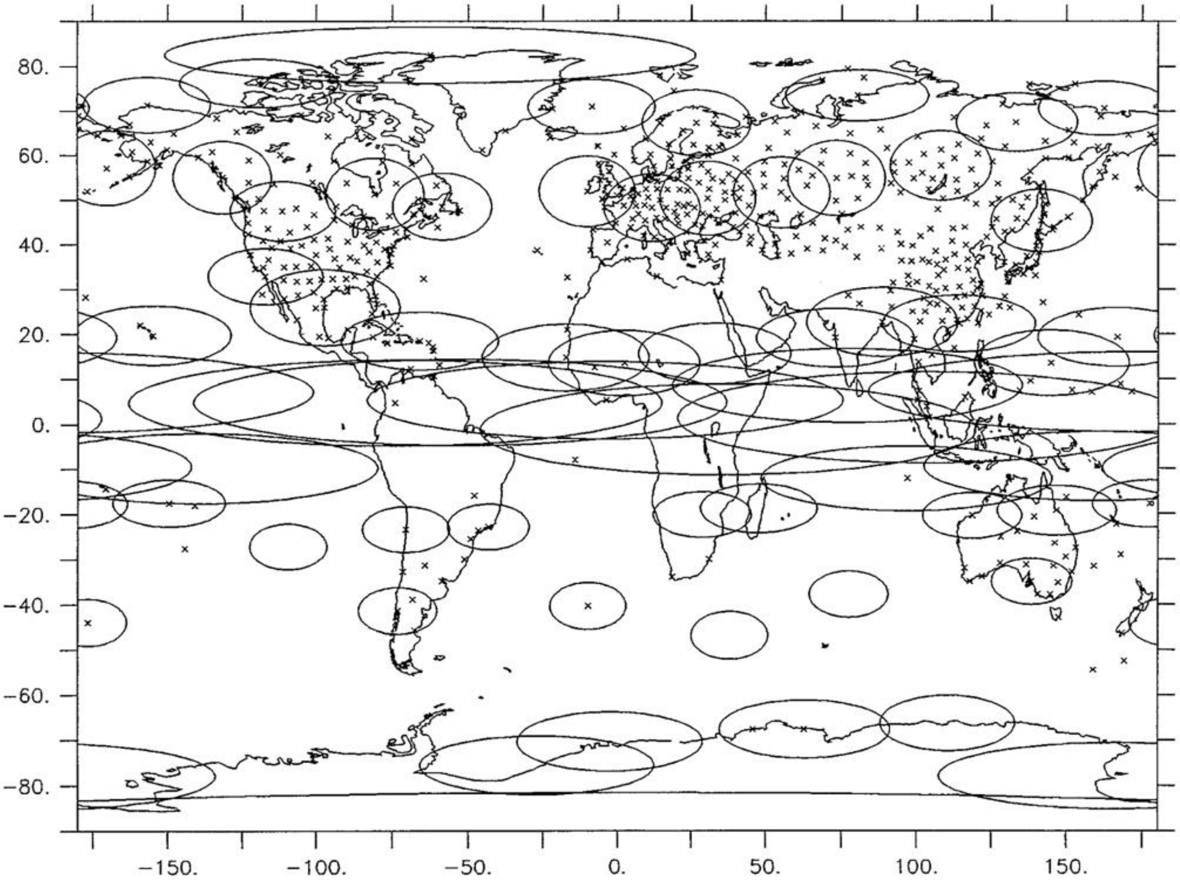

Figure 11. The ellipses in this figure represent the “areas of influence” around radiosonde stations. The boundaries are where the time series correlation coefficients decay to less than the inverse of *e*, the natural base of logarithms (1/*e* = 0.3679), based on ECMWF monthly gridpoint 850–300 and 300–100 hPa data (figure from Wallis, 1998). The actual stations with ellipses are those used by Angell and Korshover (1983) with locations of additional “good” stations shown by “x” with no ellipse around them.

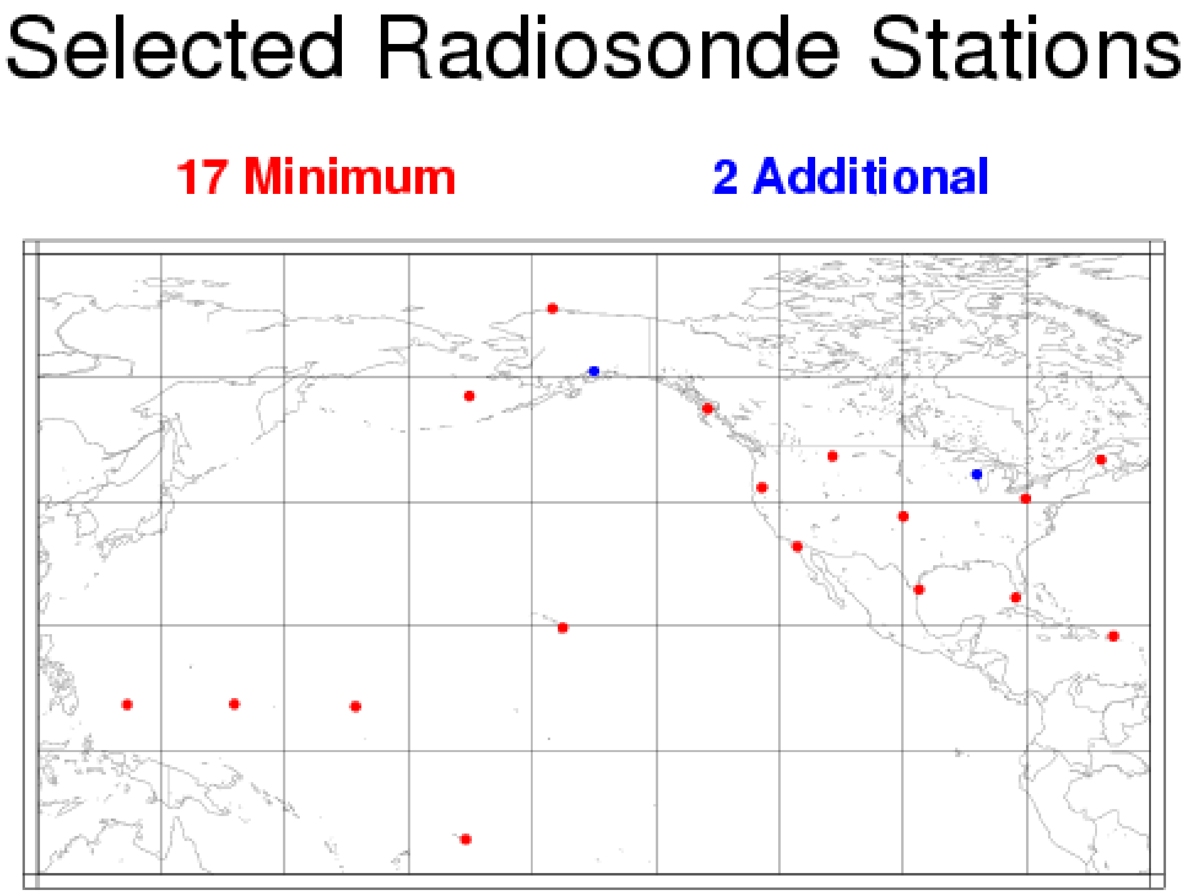

Figure 12. Selected climate stations. A minimum of 17 stations climate stations are shown in red with two additional stations that would significantly improve the coverage shown in blue.

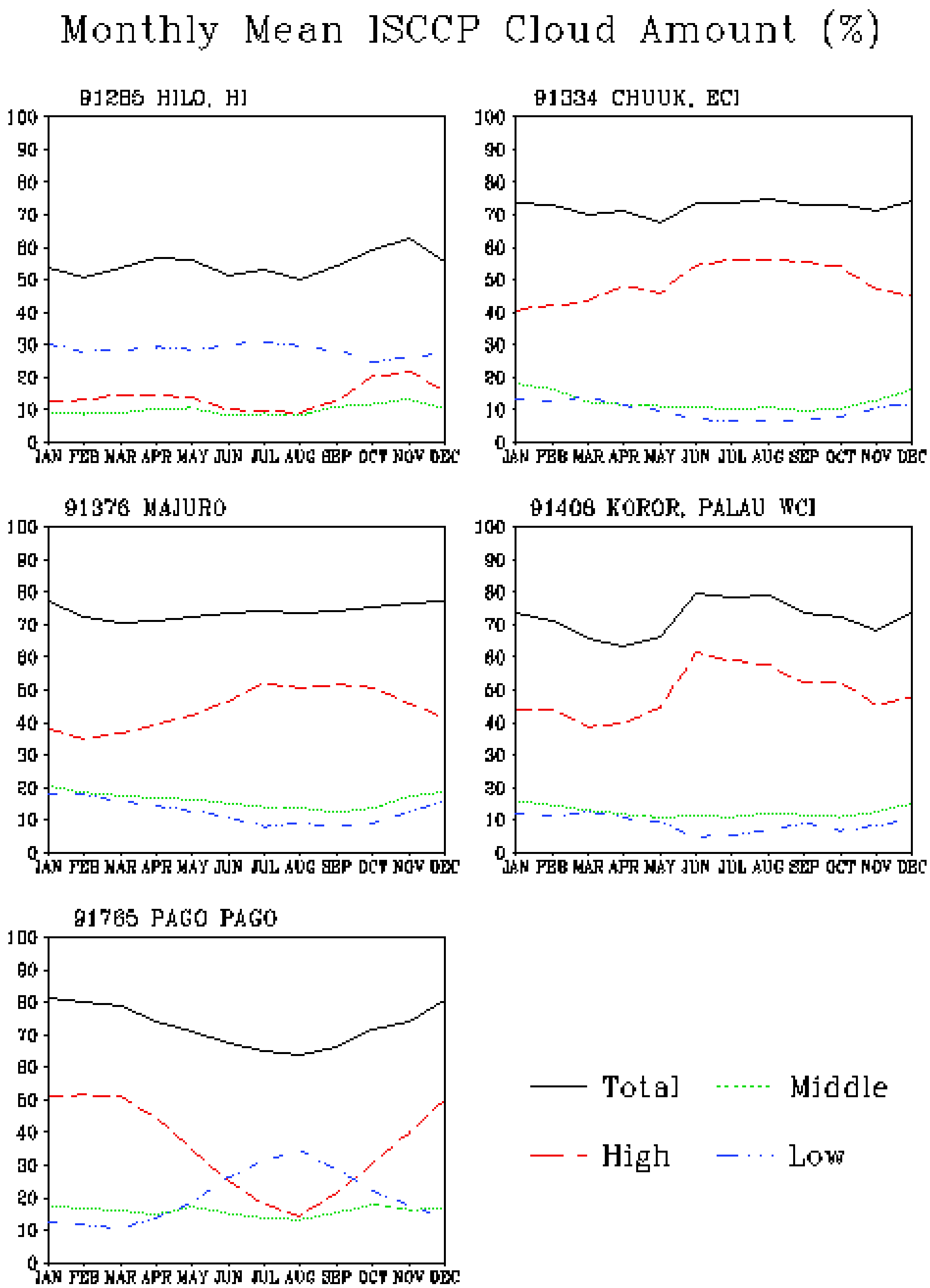

Figure 13. ISCCP monthly mean cloud amounts at the five selected Pacific Island stations. The three stations closest to the equator (Chuuk, Majuro, and Koror) were subjectively determined to have limited enough changes in solar angle and cloud amount that dual sonde radiosonde continuity flight continuity analyses should be divided into two seasons rather than four. This reduces the total number of dual sonde flights required at these stations by 50%.

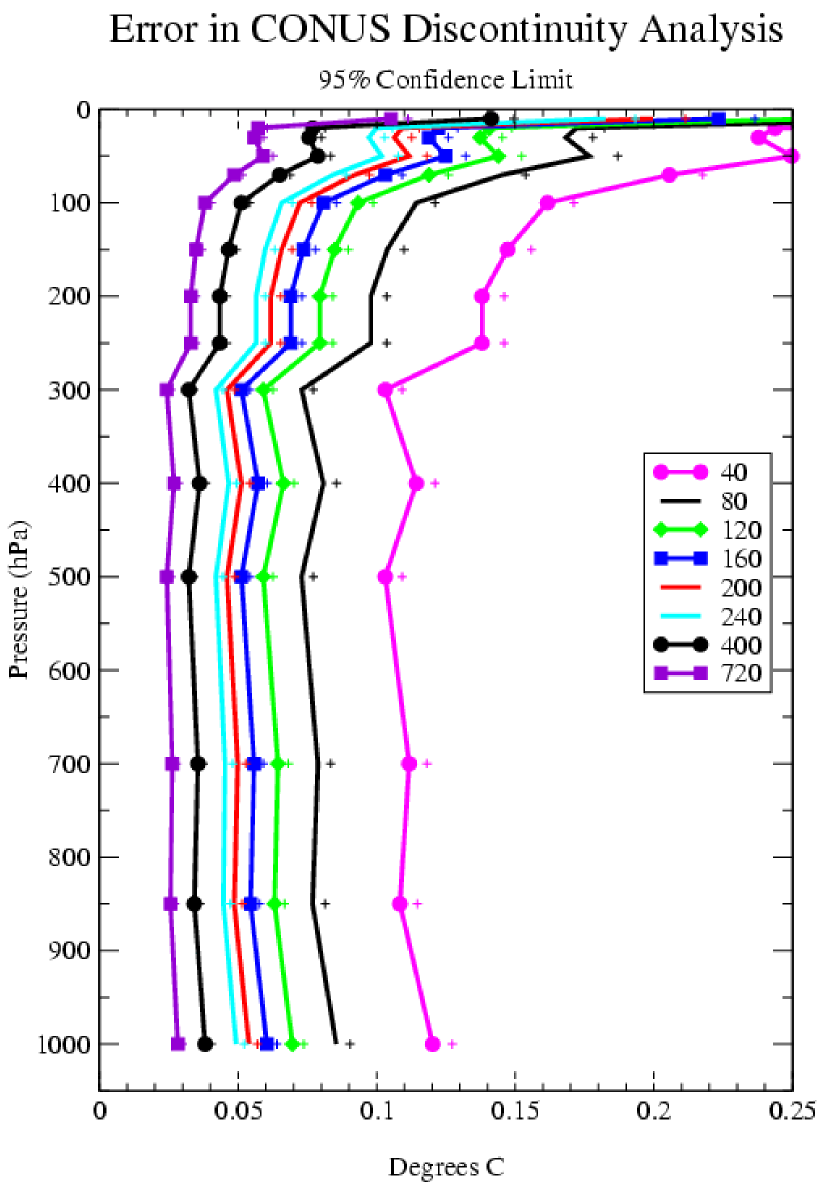

Figure 14. For CONUS area averaging purposes, the fairly even distribution of the climate stations allow them to be averaged with equal weight. The lines represent values for the 9 recommended stations averaged together. The + symbols just to the right represent the values from 8 stations, the minimum number of stations recommended. Using Monte Carlo simulations of averaging 8 or 9 stations together where each station had an error in the determination of the bias as indicated in Figure 8, the 95% confidence value is determined. The lines indicate that 95% of the time, the error in assessing the biases at these station would result in a jump in the time series whose absolute value would be less than the values indicated.

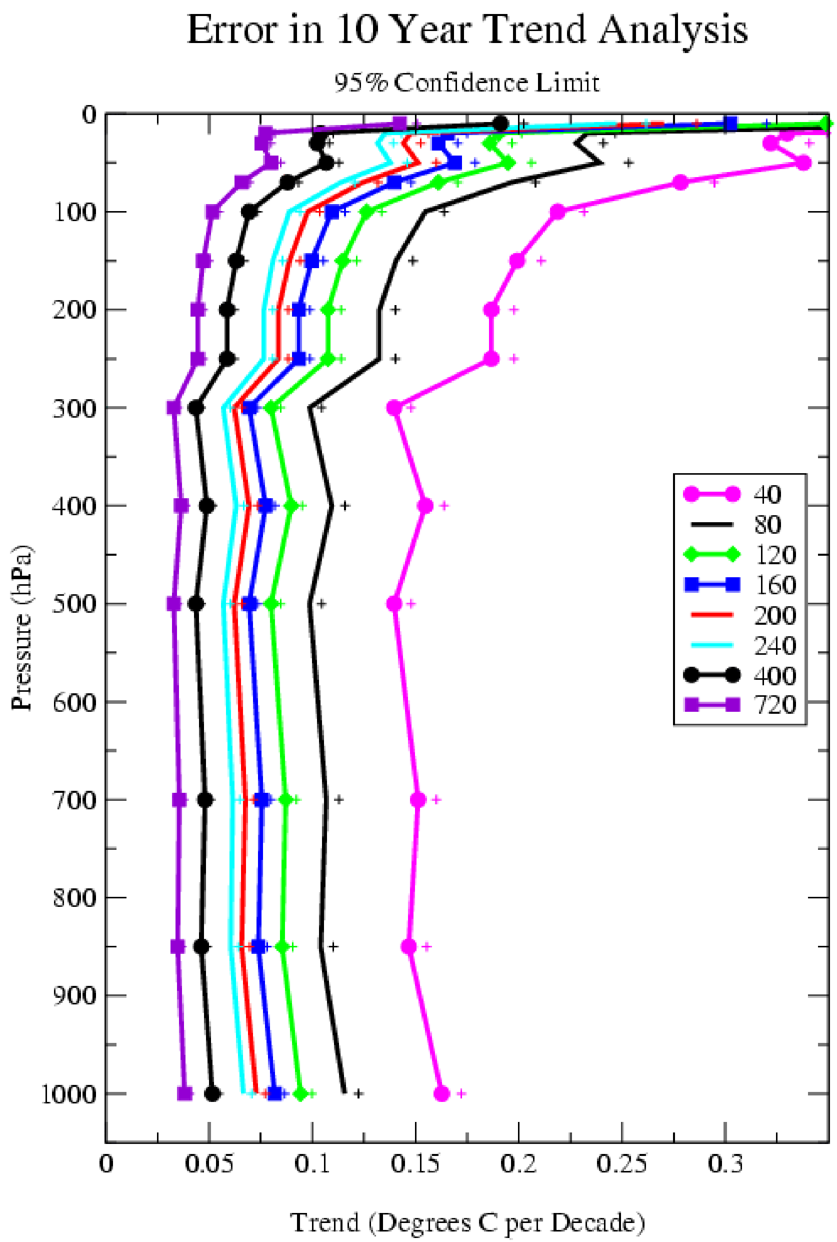

Figure 15. Same as Figure 14 but in this case the impact on a 10 year area averaged trend is determined. The 10 year trend assumes this one discontinuity will be the only discontinuity in the time series and it occurs in the middle of the 10 years.

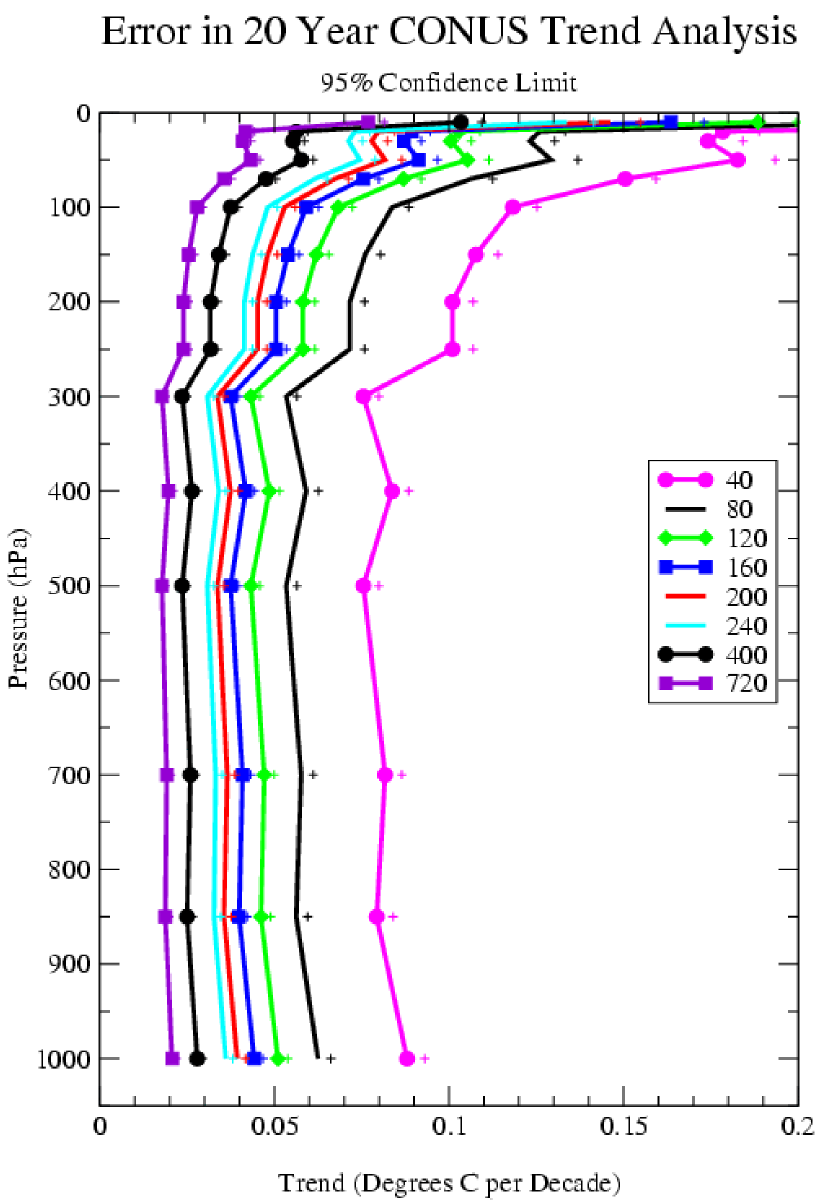

Figure 16. Same as Figure 15, but for 20 year area averaged trends.

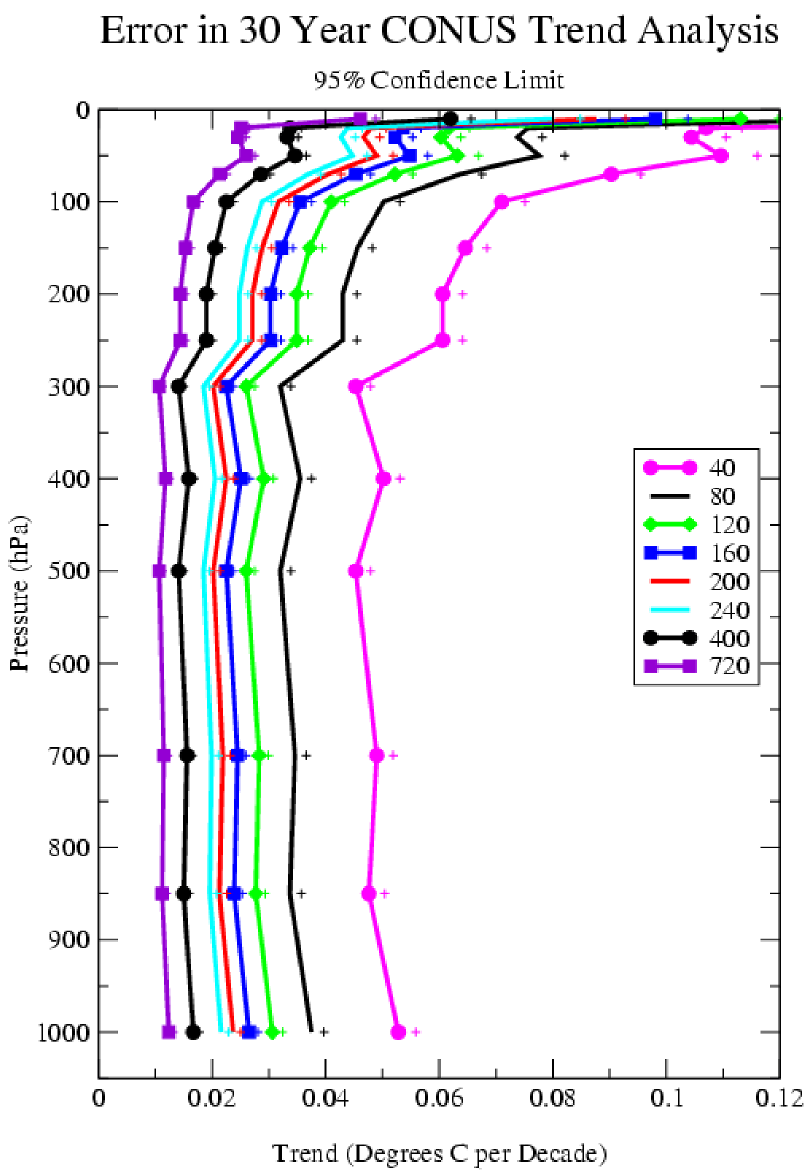

Figure 17. Same as Figure 15, but for 30 year area averaged trends where the discontinuity in the time series was centered at year 20.

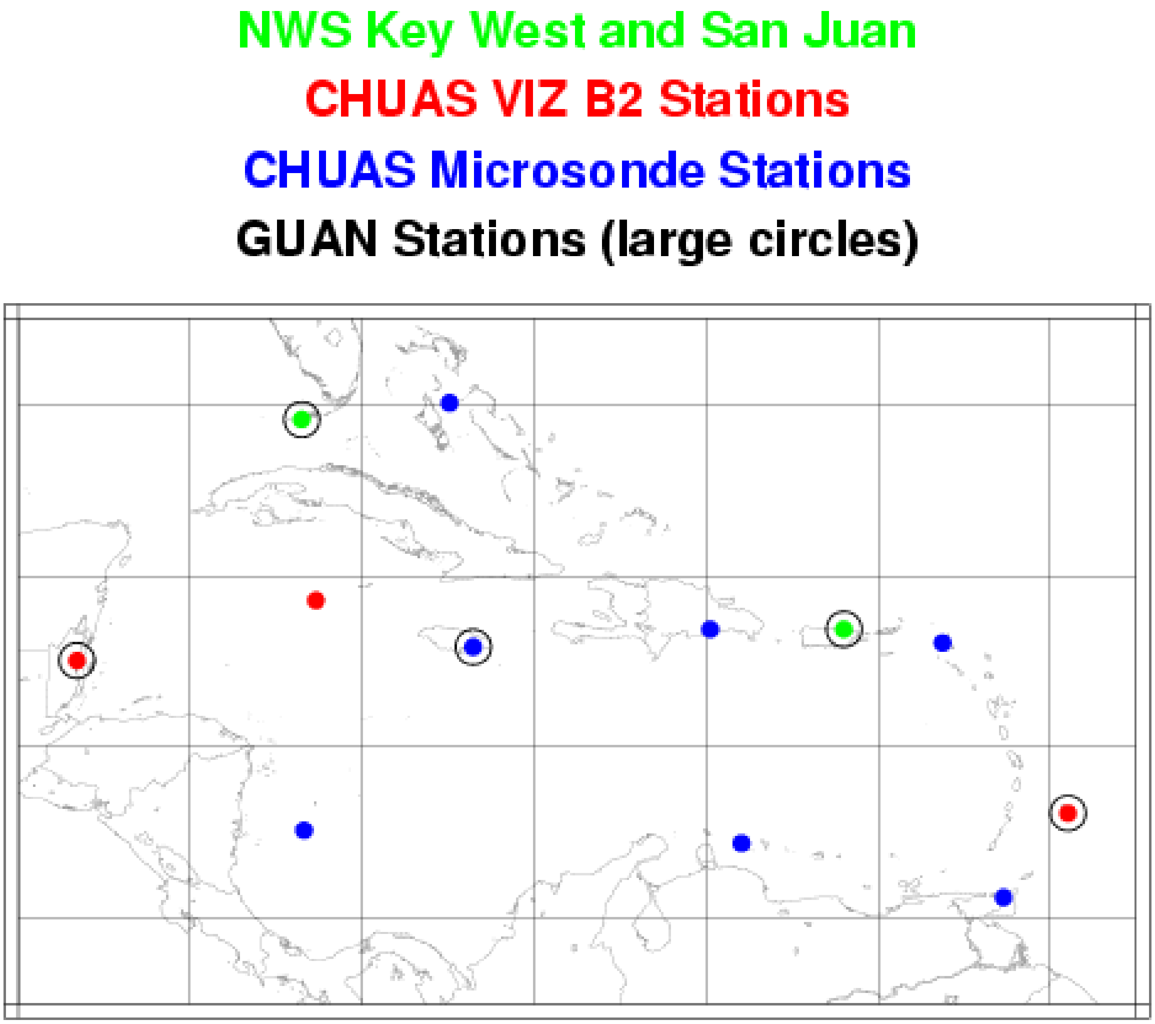

Figure 18. NWS supported stations in the Caribbean. The two stations in green are the NWS stations at Key West, Florida and San Juan, Puerto Rico. All the other stations are Caribbean Hurricane Upper Air Stations (CHUAS). The CHUAS stations have hardware and software provided by the NWS. Currently the 10 CHUAS stations fly two different radiosondes, the VIZ B2 (red) and the Microsonde (blue). Starting in December 2002, the NWS will be converting all the stations over to the VIZ B2. Stations with large black circles around them are designated GCOS Upper Air Network (GUAN) stations.