A New Possible Plan for a More Cost-Effective Adaptive Radiosonde Observing Strategy for the United States

Lauryn Gonzalez, Leah Kos and Sara Lavas

Dr. Michael Douglas, NSSL

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ABSTRACT

Budgetary pressures are threatening the future the U.S. radiosonde network, prompting the need to research adaptive radiosonde strategies. Cost-effectiveness is detrimental to the continuation of the current network and to the promotion of any adaptations. This project analyzes SUMO and TAMDAR as viable system variants and THORPEX as a radiosonde research activity. Research and surveys to the National Weather Service (NWS) and private sector companies suggested that forecasts and model outputs heavily rely on upper-air data from soundings. Most of these outlets depend on the use of special soundings, in addition to the twice-daily sounding data, for severe weather forecasts. This project proposes two adaptations to the radiosonde network:

1. Quit launching radiosondes during fair-weather days. These changes promote the increase of special soundings to help aid severe weather forecasts. TAMDAR will help to maintain upper-air data between radiosonde launches. This solution allows for a timely adaptation to the current network and helps diminish prior spatial limitations.

2. Relinquish TAMDAR as a source of upper-air data and reallocate these funds to supplementary special soundings. This solution maintains the current network's automatic measurements and increases the use of special soundings.

More reliance on special soundings will help aid forecasts during severe weather. Overall, both solutions resolve the budgetary pressures because they increase flexibility and network response to budget cuts.

INTRODUCTION

The optimization of the current radiosonde network by all U.S. meteorological services is a challenge. Common to any type of sounding network, it is important to make accurate observations for the lowest cost possible. This network is still in place across the United States but is potentially losing funding. Many different types of adaptive strategies have been evaluated in the past to find a more beneficial network. Most research has not focused on a cost-effective solution to this challenge, prompting the need for our project.

Research for an adaptive network is motivated by many factors, including the current budgetary pressure in all governmental areas, including in the National Oceanic and Atmospheric Administration's (NOAA) budget. These cuts continue to increase each fiscal year. NOAA's budget currently includes the funding for the current radiosonde network. Unfortunately, the trend of decreasing funds is something that cannot be changed without an increase in taxes, which with the current economy, is not a viable option.

An additional factor includes the need for improved observations. This corresponds with a need for increased radiosonde accuracy. The accuracy of the radiosonde data is directly related to the physical representation of the single sounding. In other words, this representation refers to the physical geographic area in which the sounding covers, which certainly can be improved. Currently the network has many holes, or areas that do not have sounding data. Adding observations to these areas would increase the accuracy of the network, thus improving forecasts and model output that rely on this twice-daily data. Also, with the heavy reliance on this data for severe weather, or high-impact weather forecasting, improved accuracy could lead to better forecast lead time.

Severe weather motivates the need for special soundings. These high-impact days frequently benefit the most from these asynoptic soundings, which potentially justifies their use and extra cost. It is important to determine if special soundings are necessary or unnecessary in a more cost-effective adaptive network.

Our project researches and evaluates the cost-effectiveness of the current radiosonde observing strategy for the U.S. and addresses how it could be improved through the adoption of an adaptive observation strategy. It also determines the potential benefits of a partial adaptation of the current network. Cost-effectiveness is defined as a balance between the cost and accuracy. In order for there to be a better option to the current radiosonde network, the benefits must balance, if not outweigh, the costs.

BACKGROUND

Our goal is to seek a more cost-effective adaptive observation strategy that is less costly than the current radiosonde network and has a better physical representation. Radiosonde cost efficiency and alternative, cost-efficient ways of data gathering are researched in various outlets including: scientific investigations, published works, surveys and personal interviews. Conclusions based on such works that are suited best for our project motivation, or goals, are summarized below.

(A) Current Radiosonde Network

The current radiosonde network spans across the entire United States. There are currently 92 National Weather Service (NWS) Weather Forecasting Offices (WFO), shown in Figure 1, that launch these radiosondes twice daily. These launches are at synoptic times, 00Z and 12Z and cost 325 dollars per launch (B. Blackmore 2012, personal communication). This amount includes the cost of the radiosonde itself, the balloon and labor. Using the 325 dollars per sounding:

Equation 1: 325 dollars per sounding x 2 per day x 92 locations x 365 days in a year = 21,827,000 dollars

Based on Equation 1, the annual budget for the current radiosonde network totals to nearly 22 million dollars. However, this amount depends on the number of special soundings launched. A survey (Appendix B) was sent to all the WFOs Meteorologist-In-Charge and Science Operations Officer. It was used to gain information on how often they use special sounds, what weather events they are launched for and how important they are to forecasting. This will be discussed further in the following sections.

The NWS currently uses three types of Lockheed Martin Sippican radiosondes at its launch sites. They include the Lockheed Martin Sippican (LMS) Mark IIA GPS radiosonde shown in Figure 2, the LMS B2 radiosonde and LMS-9 radiosonde (only used at Wallops Island) (NWS FAQ, cited 2012). The LMS Mark IIA, most commonly used, has accuracy specifications show in Table 1 below.

Table 1: Accuracy Specifications of the LMS Mark IIA Radiosonde

Sensor	**Accuracy**
Pressure	± 0.5 mb
Temperature	± 0.2°C
Humidity	± 2%

Many different groups of people use radiosonde data. The typical weather community users are the NWS, the private sector and more specifically the Storm

Prediction Center (SPC), Hydrometeorological Prediction Center (HPC) and the climate sectors. Also, a good amount of the general public uses the data as well. Radiosonde data does not have to necessarily be used raw, it is used in models and interpreted into forecasts. It is also a representation of the upper-air “climate” and gives a vertical wind and temperature profile.

Although radiosonde data is widely used and has good sensor accuracy as shown in Table 1, there are still many limitations to the current radiosonde network. First, it is designed as a non-recoverable system. After the 325 dollars is spent to launch the radiosonde, it is rarely found and returned after it descends. Figure 1 also shows the physical representation challenge of the current network. Many large areas are not included. But spatial restrictions are not the only problem. Studies such as “Multifunctional Mesoscale Observing Networks” conducted by Dabberdt el al (2005), acknowledge the limitations of radiosondes only being released twice a day across the United States. Their study concluded that quality relative humidity sensors deployed on radiosondes are essential to nowcasting in mesoscale events. Consequently, if the radiosondes need to cut costs somewhere Dabberdt et al (2005) states that the NWS should not reduce the quality of the relative humidity data nor cut back on the number of radiosonde sites.

(B) Adaptive Strategies and Projects

These limitations could possibly be lessened or avoided with the use of an adaptive measurement strategy, or adaptive network, and thus provide further motivation for our project. By definition, an adaptive measurement strategy is a strategy that varies its spatial or temporal measurements to maximize its benefit-to-cost ratio. An adaptive strategy delivers the possibility of lower costs and benefits. Adaptations can be tailored by need. In other words, a radiosonde can be launched at a certain time and location, relinquishing the requirement for set locations. This could also contribute to the problem of launching radiosondes when they are not needed (i.e. non high-impact weather days) and launching them more frequently (more than twice a day) when they are needed (i.e. high-impact weather days). Many of these adaptive measurement strategies have been researched in the past in relation to the challenge and limitations presented by the current radiosonde observing network.

i. SUMO

Reuder et al (2009) analyzed an adaptive measurement strategy of gathering upper air data via the Small Unmanned Meteorological Observer also known as SUMO. Here the idea was to create a way to gather meteorological information in a cost-efficient manner in between radiosonde and tower/mast measurement stations. This strategy was deemed cost-efficient because it was designed and referred to as a “recoverable radiosonde”. While SUMO is simply a Styrofoam model airplane, it has successfully reported measurements for temperature, humidity, wind speed, and wind direction up to 3500 m above the ground. In fact, through a direct comparison with a Vaisala RS92 radiosonde, SUMO proved to be an effective method of measurement. Both instruments were simultaneously released from the same environment. The findings (Figure 3) showed a good agreement between the two with less than a 0.5 K variation in temperature throughout the sounding.

There were more variations between humidity as well as wind speed and direction possibly because the SUMO ascended vertically while the radiosonde drifted in the horizontal with height. Although the SUMO is being further developed to overcome its limitations, it has proven to be an effective and efficient tool for atmospheric boundary layer analysis. Each SUMO airframe with propulsion and autopilot system, including the meteorological sensors, costs roughly 1200 Euro (~1600 U.S. dollars). The key advantages of SUMO over radiosondes are that it handles easily and maintains a cost-efficient performance.

ii. TAMDAR

TAMDAR (Tropospheric Airborne Meteorological Data Reports) is another current upper-air adaptive measurements strategy. It is currently predominantly operated by Mesaba airlines and provides upper-air data by placing temperature and humidity sensors on many different commercial aircraft. Turbulence and icing data can also be taken from these sensors. As of late 2009, around 239,000 aircraft observations were measured each day (Moninger 2010). The data collected by these sensors has been shown to improve both short and long term weather forecasting and help fill in the spatial and time gaps of the current radiosonde network. Limitations include the absence of data below 20,000 feet between major airline hubs and almost complete absence of water vapor data at any altitude (Moninger 2010). The sensors for each aircraft cost around 15,000 dollars and installation per aircraft is around 5,000 dollars (R. Curtis 2012, personal communication). Although this data is useful for gathering upper-air data in locations that otherwise would not get measured, it is unclear if the NWS is going to continue these services or not.

iii. THORPEX

Durre et al (2005) recognized the vital applications of the radiosonde network for climate monitoring, satellite data analysis, and weather prediction. Their study analyzed how spatial sampling over remote areas, such as oceans, creates problems for all users by causing poor analyses. They suggested that continuous radiosonde observations are not only needed on a national scale, but also on a global one.

On the international level there is research related to radiosondes and improving forecasts. Majumdar et al (2011) discuss the THORPEX, which began in 2003 and is a ten year international research program focusing on improving the ability to forecast high-impact weather events. The program is working with academic institutions, operational forecast centers and forecast products to achieve satisfying results (Rabier 2007). The study is devoting a good amount of its research worldwide effort to observations over the oceans to increase forecast accuracy. The largest increased accuracy thus far is seen in forecasting hurricane tracks and in short-term forecasting. A rough cost estimate for THORPEX is between 50,000 dollars and 100,000 dollars over the research thus far (D. Parsons 2012, personal communication).

This being said, economic concerns may influence the NWS's decision and possibly result in radiosonde reduction due to a lack of funding. The NWS budget is dependent on how much money the government gives to NOAA. Of NOAA's budget for the fiscal year (FY) of 2012, the NWS requested 988,000,000 dollars (NWS FY2012, cited 2012). Of this, 5,000,000 dollars went to GPS upgrades for radiosondes. For FY 2013, the NWS has requested less, 972,200,000 million dollars**,** and consequently has to reduce some programs (NWS FY2013, cited 2012). With the budget cuts continuing, the amount of funding for the radiosonde program is in jeopardy.

(C) Cost-Effectiveness

Relating the cost efficiency to the effectiveness of the current radiosonde network itself and comparing it to alternative methods requires knowledge in both the economic and meteorological fields. In terms of relating the radiosonde network to economics Morss et al (2004) states it best:

> When applied to a particular arena, such as weather forecasting, economic efficiency requires that the most valuable forecasting activities are undertaken first, and that the resources expended on each activity are such that no reallocation of resources—either among forecasting activities or between forecast production and activities in other sectors—could increase net societal benefit.

This research analyzed not only if soundings helped improve forecast skill, but also if they were worth the cost to the country and concluded that increasing the number of released soundings would be economically efficient by benefitting society. From this, one can conclude that economic costs ultimately drive the completion of an adaptive radiosonde network strategy or improvements of the current system.

METHODS

We first evaluated the current U.S. radiosonde strategy, including its budget, to determine the cost-effectiveness of the radiosonde network and the data it collects. We then narrowed down our research to two possible adaptive radiosonde observing strategies and one research activity. For these three main areas, we researched background information as well as their overall cost and accuracy to. For the adaptive strategy to be applicable, the accuracy needs to balance, and preferably outweigh, the cost.

Another one of our objectives was to evaluate the special soundings that are launched during high impact weather days. We wanted to evaluate how effective these soundings are during this type of weather and how important they are to NWS forecasters. We distributed a survey to NWS forecasters, which is shown in Appendix B, to determine the benefits and needs of special soundings. The survey assessed the number of events that use these additional upper-air measurements. It also asked if there were weather situations that would have benefitted from special observations (that were not made). Since these soundings are expensive (325 dollars each) and paid for by local NWS offices, we attempted to determine if they were an essential supplement for local weather forecasting.

First we conducted our research with the current radiosonde network. This included researching related studies, articles and books in the National Weather Center library as well as online through scholarly sources. From these sources, we learned the current costs of the equipment and labor to launch and maintain the network. From the same survey shown in Appendix B, we asked NWS forecasters for their opinion on the cost-effectiveness of radiosondes as well as its performance in relation to accuracy.

Next, we focused on adaptive radiosonde observing strategies. We looked into two alternatives, which are SUMO-type recoverable systems and TAMDAR. Also, we investigated the global radiosonde research activity, THORPEX. We gathered the background information through many similar techniques as for before. However, due to the lack of available cost information, we received additional counsel from individuals, who are involved in evaluating alternative observation strategies.

Lastly, we focused on the topic of special soundings. We evaluated the use of these soundings as well as their cost-effectiveness. We started with research on how often they are used, how many are launched on average each year and how much impact they have on forecasts. In order to gather this information, we sent a survey to send to all the National Weather Service Forecasting Offices across the country. The survey (Appendix B) collected information on how useful the special soundings are to forecasting and what type of weather conditions require, or should require, special soundings.

The survey also asked for ideas on adaptive networks. In conjunction, we gathered information from private sector companies in order to do a direct comparison between them and the NWS. We were interested in how private sector uses radiosonde data and if it is essential to their businesses and clients. We contacted different companies by phone and asked them specific questions about radiosondes (Appendix A).

Once we finished with the research stated above and analyzed all of our information, we attempted to calculate the cost-effectiveness of the current network, the different adaptive strategies and the research project. As further discussed below, the cost-effectiveness became difficult to calculate because it is hard to quantify the cost-to-benefit ratio for radiosondes. However, we still determined the best solution for the radiosonde network issue presented here.

RESULTS

(A) Adaptive Strategies and Projects

Our research tries to compare the cost and accuracy of SUMO, TAMDAR and THORPEX to the current radiosonde network. Each individual adaptation has different instrument specifications and equipment costs. This information is analyzed below.

First, the overall price for the SUMO system was 1200 EUROS (1,584 dollars) (Reduer 2009). Research showed that each airplane averaged one hundred flights; however, the maximum number of flights possible was unclear. SUMO is comparable to the current radiosonde network in several ways, as discovered in the background section. While the longevity of the sensors onboard SUMO model aircraft is unknown, the accuracy specifications are as follows.

Table 2: Accuracy Specifications of SUMO

Sensor	**Accuracy**
Pressure	± 0.5 mb
Temperature	± 0.5 K (absolute)
Humidity	± 1.8%

In general, the accuracy of SUMO is similar to the current radiosonde network. Here, one of the main discrepancies lies with the temperature sensor. The temperature readings have a warm bias during ascent and a cold bias during descent, which alters the measurements. In addition, SUMO is limited by cloud coverage, especially when clouds are low. Besides these limitations, the main problem that we discovered with SUMO comes from the Federal Aviation Administration (FAA). Airspace restrictions limit SUMO to a ceiling height of 1000 meters for ascent (Reuder 2009) which ultimately limits the entire SUMO system altogether in the U.S.

Next, we have the TAMDAR adaptive network. Again it was very difficult to find cost reports. The information that was received from Southwest Airlines Chief Meteorologist, Rick Curtis, indicated that the sensors alone cost around 15,000 dollars, and that an additional 5,000 dollars is needed for installation onto the actually aircraft (the labor). The sensors specifications are indicated in Table 3.

Table 3: Accuracy Specifications of TAMDAR

Sensor	Accuracy
Pressure	± 3 mb
Temperature	± 0.5°C (absolute)
Humidity	± 5%

Again, like SUMO, the accuracy of the adaptive strategy seems comparable to the current radiosonde network. The TAMDAR data stream has grown over the years. However, the NWS never purchased the full data stream. We directly communicated with Dr. William Moninger about TAMDAR. He informed us that the NWS purchased a tiny subset, roughly 2-3%, of TAMDAR for an approximate 300,000 dollars per year. Beyond this, TAMDAR details are strictly confidential.

Lastly, was the research activity, THORPEX. This system's monetary figures were determined by personal contact as well. After consulting with Dr. David Parsons from the OU School of Meteorology, we received an average estimated cost of 75,000 dollars for land measurements. As THORPEX is research based, there were several conclusions on how it influences forecasts. Rabier et al (2007) found that mid-latitude targeted observations are twice as effective as random observations. Here it was also concluded that targeting alone is unlikely to significantly improve the accuracy of forecasts one to fourteen days out. While we found various results from THORPEX studies, the accuracy specifications were harder to evaluate than the costs. Due to the complexity of the project, we could not find the actual accuracy values of the pressure, temperature and relative humidity sensors that THORPEX employs. It is interesting that the costs and accuracies of THORPEX were so difficult to find because the researchers claim that the global strategy is a cost-effective one.

Overall, evaluating the cost-effectiveness for SUMO, TAMDAR and THORPEX is difficult because costs are not available to the public and the benefits are hard to judge. Different observations have different impacts and consequently, different accuracies. There is no way to make direct comparisons between SUMO, TAMDAR and THORPEX for this very reason. Therefore, the cost-efficiency for our project is one based off qualitative results instead of quantitative ones. Our project attempts to evaluate a situation that has been problematic for several decades, owing to the fact that the U.S. radiosonde network has not changed in over 50 years. With such an ‘old’ system in place, there certainly remains areas of improvement. In order to assess which areas of the radiosonde network should or should not be changed in conjunction with the parts that are most beneficial to the NWS and private sector, we analyzed the following survey information.

(B) Surveys

The private sector survey (Appendix A) responses had many common results. All of the companies said that they directly or indirectly used radiosonde data. Several of these companies used the data after it was processed into another forecasting product, such as a weather map. Also, they all welcomed the idea of having more data and filling the gaps in the network. This would help the companies make better decisions for their customers by supplementing their forecast accuracy. The radiosonde data helped hindcast as well to recreate a past weather events for forensic purposes. A few agreed that network budget cuts and less launches would negatively impact their business and in turn, their customers. Overall, the survey concluded that all the private sector businesses heavily rely on the radiosonde network.

The NWS survey (Appendix B) responses were similar to the private sector ones, but this survey was more detailed and catered to special soundings. The sample size of the survey included 86 NWS forecasters. The breakdown of the representation by NWS regions are shown in Figure 4. Each of the responses indicated how many special soundings were launched on an average year at each station (Figure 5). It was found that the most launches were made in the central region. This could be related to the high number of launches during severe weather.

The survey showed that severe weather was the number one reason to launch the soundings for a majority of the regions, not just the central one. The only region that had another high-impact weather event was in the eastern region due to tropical weather. In general, this result helped us to understand where the need for observations is during certain types of weather events.

The last two topics on the survey requested the thoughts of the NWS WFO employees on the creation of an adaptive network and if they had any suggestions for it. Their main thoughts included:

- It would be beneficial to fill the real-time gaps in the current radiosonde network
- An adaptive network is a good idea, yet there is not a budget to support it
- They want to see asynoptic times and no set locations
- The adaptive network would need to be integrated into their AWIPS/AWIPS II system.
- Only launch radiosondes if they are needed (high-impact weather vs. non high-impact weather)
- Possibly use alternative observation networks (i.e. GPSMet Sites provided by ESL)
- Collect the data as the radiosonde descends to gather more data from one launch

It was very interesting because these main thoughts ran almost parallel to the motivations behind this research project. These results helped guide our conclusions.

CONCLUSION

Ultimately, we needed to determine the most cost-effective way to spend the fixed NWS budget. Of the two adaptive strategies that we analyzed, SUMO appears to have the most potential in terms of cheaper costs and maintained accuracy. Although SUMO is a viable solution to the radiosonde network problem, there remain several limitations to this strategy. Until the hindered airspace restriction is removed, SUMO cannot be used in the U.S. as a radiosonde replacement. Further work to enhance the accuracy (capability) of SUMO is unmotivated until the FAA will allow the equipment to fly above 1000 meters.

Until SUMO can be enacted, we have two possible solutions. First, we conclude that the current radiosonde network needs to be adapted. To adequately use the radiosonde resources and balance the budget, we suggest the following adaptations:

1. Discontinue fair-weather observations
2. Incorporate additional special soundings for severe weather
3. Keep TAMDAR

The U.S. should no longer automatically take 00Z and 12Z observations twice a day at the 92 locations during fair-weather. (We define fair-weather to be mostly clear skies, no precipitation, calm winds and consistent temperatures and humidity.) Instead, there should only be launches when there is active weather at, near or impinging upon the launch location. This aspect of our solution will help minimize unnecessary costs. Each preserved sounding saves 325 dollars. We realize that automatic launches are important for climatology and as such, any automatic launches should come from the climate budget, which will not be discussed in our project.

By withdrawing the fair-weather observations we have additional funds for extra special soundings. These special soundings are relevant because they can be launched at any location at any time. Also, if needed, the special soundings can be launched in places that are not radiosonde observation sites. This added flexibility is not only an adaptable way to spend the taxpayers' dollars, but it also helps aid severe weather forecasts, which ultimately improves forecast lead time and protects life and property. To supplement upper-air data, especially during fair-weather instances when measurements are not being taken, we suggest that TAMDAR continue. TAMDAR will help fill in the spatial limitations. It is a beneficial and efficient way to collect measurements because it relies on aircraft travel.

Overall, our conclusion is imperative to the ongoing budget problems and radiosonde concerns. Our solution tackles the budget concerns because it takes away unnecessary costs used for fair-weather days and relocates these funds in more important areas to help improve forecasts.

We realize that not everyone will agree with not launching radiosondes during fair-weather, and as such we propose our other solution. Our second conclusion still enhances the use of special soundings, but relinquishes TAMDAR. As previously stated, TAMDAR costs the NWS around 300,000 dollars per year. We determined that each sounding costs 325 dollars. Based on these dollar amounts, the NWS can launch almost 1000 special soundings for the price of TAMDAR. This solution allows the current radiosonde network to continue gathering data automatically during any type of weather while still employing special soundings.

While both of these are viable solutions, we realize that there remains room for continued research in this area. We present two cost-efficient plans to the radiosonde network. In order for future research to assess the cost-efficiency of radiosondes and resolve the budgetary pressures, the costs of the adaptive strategies need to become more available. In conclusion, the U.S. radiosonde network is beneficial in several ways even though it is difficult to quantify.

FIGURES

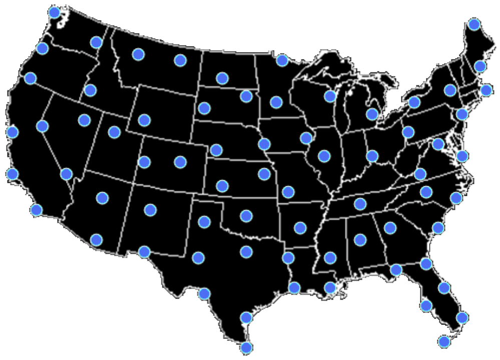

Figure 1: NWS radiosonde sites marked by blue dots.

Figure 2: LMS Mark II2 GPS radiosonde

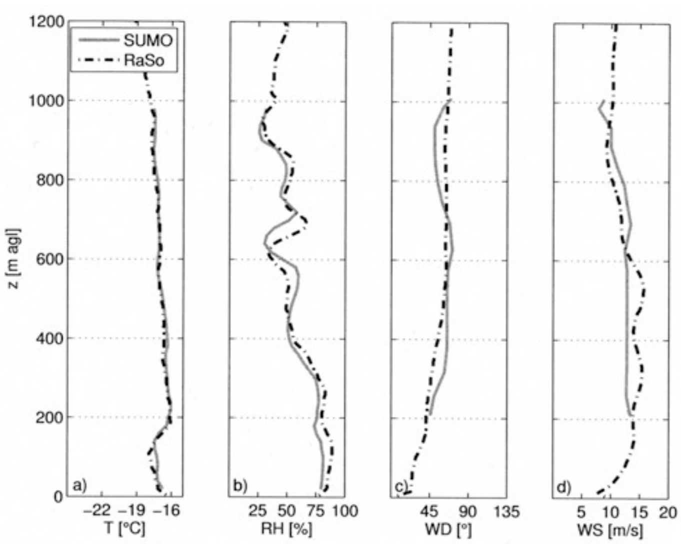

Figure 3: Direct comparison between the SUMO and RS- 92 radiosonde measurements (Figure 6 in Reuder et al (2009)).

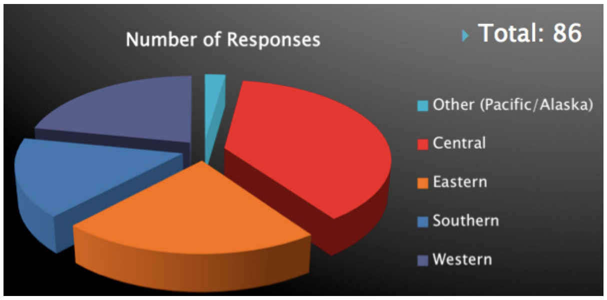

Figure 4: Number of NWS survey responses by region

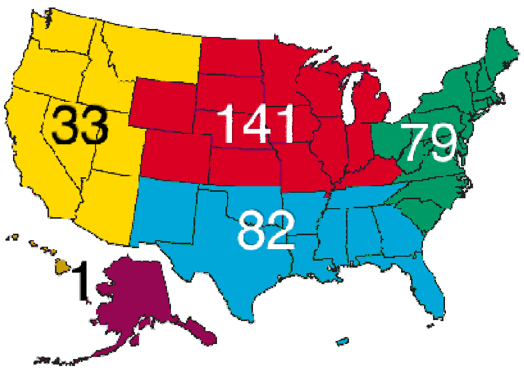

Figure 5: Number of special soundings launched per year in each region

APPENDIX A: Private Sector Survey

Questions:

1. Does your company use Radiosonde data?

2. Would more sounding data lead to better forecasts? How?

3. If less sounding data were given, how would that impact your profession?

Companies Surveyed:

1. Air Quality and Sea Conditions, Inc.: Specialize in reconstructing what weather conditions were at a certain time and place. They reconstruct the event and then do data analyses for legal and insurance claims.

2. Meteorological Solutions, Inc.: Forecast for the government and the private sector.

3. AECOM: Work is mainly in air quality compliance studies for regulated industrial sources. They do work for only the private sector and do not work with the government.

4. Climatological Consulting Corporation: Focus is in forensic meteorology.

5. North American Weather Consultants: Concentrate on weather modification such as cloud seeding for an example.

APPENDIX B: NWS Survey

Questions:

1. What is your name?

2. What forecast office are you employed at?

3. What is your position at the forecasting office?

4. How many times per year does your office launch special soundings?

5. What synoptic or mesoscale conditions are most often responsible for your launch of a special sounding?

6. Do you coordinate your special radiosonde observation soundings with other forecast offices? (Was a Yes/No/Unsure format question)

7. Would it be valuable to make occasional special soundings in locations different from the current NWS Radiosonde Observation Sites? Where might you like such soundings to be made that would likely add to your forecast area's short-range forecast skill?

8. Any comments of the possible benefits (or problems with forecaster use) of special radiosonde observations on-demand at non-NWS sites? Any other thoughts related to possible adaptive observations would be welcomed.

All weather forecasting offices received this survey to their Meteorologist in Charge (MIC) and Science Operations Officer (SOO). Some offices forwarded it to other members in their office so a few were not of those two titles.

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