Adaptive sounding arrays for tropical regions

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Abstract

The advent of low-initial cost radiosonde systems (relative to previous systems available on the market) affords the possibility to establish radiosonde networks that can be operated on-demand. This paper describes the essential requirements to affordably operate such sounding networks, with particular application to the region of the western Atlantic. Key to the effectiveness of such adaptive networks are 1) low initial cost of the sounding system which permits many sites to be established, 2) relatively infrequent need for observations (saving on sounding costs), 3) availability of personnel that are paid by observation rather than full-time staff, and 4) suitable locations that exist for additional sounding sites. Two-way communications with the stations is critical, since the observations would be on-demand. The greatest challenge is likely to be in deciding when to make observations – which observations are likely to have the greatest impact and over what time frame? A comparison will be made between the current hurricane season "enhanced" sounding network in the Caribbean Sea region and what might be possible for the same budget via an adaptive strategy.

1. Introduction and Motivation

Radiosonde measurements remain one of the more costly activities for most meteorological services that continue to make them. In many developing countries the cost of operating one radiosonde station, making once-daily observations, can equal the salary outlay for the entire forecast staff. Yet the perceived benefit of the observations may not always be apparent to the meteorological service when compared with other activities.

The recurring cost of radiosonde observations, their requirement for human intervention (reduced, but not eliminated in some automated versions), and the need for moderate infrastructure (balloon shelters, gas supplies and receiving and processing equipment) has led to calls for their reduction or elimination in favor of other observations, or blend of observations. To date this has not yet happened because no combination of remote sensing systems can reproduce the high vertical resolution of radiosondes under all-weather conditions. Observing system sensitivity tests have continued to show that radiosonde observations are the most important single component of the upper-air observing network over the northern hemisphere.

Nonetheless, the budgetary burden of operating radiosonde networks is real and many parts of the world cannot maintain dense sounding networks comparable to those in developing countries. The costs of a routine radiosonde station can be broken down into a few main components. These are as follows:

1) Radiosondes, which for GPS sondes are near $200/each, though this depends on the quantity purchased and the vendor.

2) The radiosonde receiver/processor (ground station), which has in past decades cost on the order of ~$50-$100K, again depending greatly on the vendor and the software and hardware options.

3) The gas supply – most commonly a hydrogen gas generator, using electricity and pure water. These generators, are most cost effective for larger balloons and frequent (at least daily) observations. However they can cost ~ $50-100K each, with recent figures closer to the upper value. They require special electrical, plumbing and safety considerations as well as careful maintenance.

4) A balloon inflation shelter. A permanent building - sufficiently large to inflate a large balloon and with large doors is usually required. This can be a considerable expense, depending on the country. Let us say $50-$100K for discussion.

5) Communications equipment to transmit the data. To reduce labor costs most radiosonde

stations are located near other meteorological facilities, often international airports.

6) Observers trained to carry out the radiosonde observations.

Taken together, items 2)-6) must be in place before the first operational radiosonde can be launched. This implies an initial outlay of from $150K - $300K - using the above numbers and excluding communications infrastructure, power lines, observer training etc. These costs should be compared against the labor costs of many developing country met services, where an observer may make only a few hundred dollars a month and a forecaster less than $1000/mo.

The relatively large initial outlay required to establish a conventional radiosonde station has in part contributed to the relatively small number of stations in many parts of the world. The problem is compounded because the large initial outlay forces a meteorological service to fully utilize their substantial investment. This requires frequent radiosonde observations (at least daily) that the NMS's annual operating budget may not be able to sustain. Even where foreign donations have covered the initial establishment of a sounding site, the consumables are rarely completely covered by donations, and often the station goes "silent" when stocks of radiosondes are depleted.

2. Impact of New Technology

Several relatively simple, low technology developments have in the last few years improved the possibilities for expanding radiosonde coverage in many regions. Some of these are a consequence of commercial developments independent of meteorology, while several are an outgrowth of meteorological activities.

The increasing availability and reliability of the internet as a means of communicating data has now allowed remote locations to communicate observations without the need for dedicated communications networks and for observations to bypass problematic communications nodes. Personal computers can now process and display data locally at the observing site for (potentially) improved quality control. And for truly remote locations there is more-affordable satellite communications that a decade or two ago.

Unfortunately, the improvements in internet availability, personal computers and satellite communications can only slightly reduce the actual cost of radiosonde observations, and have little effect on either reducing the initial cost of establishing a station or on its annual operating costs.

Fortunately, two developments in meteorology technology have occurred to potentially reduce the cost associated with establishing radiosonde stations. The most important is probably the marketing of low-cost radiosonde ground stations. That is, a number of manufacturers have reduced the purchase price of certain versions of their ground stations, in some cases by almost an order of magnitude relative to costs a decade earlier. Fully-functional systems can now be obtained for $6 - $10K from several vendors, with more companies offering systems only moderately higher. A second item that can be important, especially for remote locations, is that hydrogen gas for balloon inflation can be more easily obtained with the aid of new portable generation units**.** Finally, the evolution of radiosondes in recent years towards lower-weight units (most are now near 200-300 gm) means that smaller balloons and less gas can be used for tropospheric soundings. This in turn means that smaller balloon-inflation shelters are needed and low-cost portable shelters are commercially available.

Taken together, the developments in radiosonde- and gas generation-related technology mean that establishing radiosonde stations is now considerably more affordable than in previous years.

Unfortunately, all of this is not enough to convince most met services to increase their radiosonde station density, since the actual daily cost of operation remains high, and has not decreased much over the years. To operate denser radiosonde networks a further step is required – *they must be operated adaptively*.

3. Adaptive radiosonde networks and requirements for their economical operation

Adaptive observations are not new. On-demand, "special" radiosonde observations have been made by the US NWS for decades, usually for severe weather or hurricane-related forecast concerns. More spatially-flexible observations include the dropsonde soundings made by hurricane reconnaissance aircraft, either for research or forecasting objectives. Such observations are also made over the Pacific Ocean for winter storm forecasting.

To justify establishing additional radiosonde stations to improve the spatial-density of sounding observations a number of factors must be considered. The key requirements for a radiosonde network to be spatially-dense:

1) an adaptive network *must be adaptive* – that is the priority days when observations are needed should be a small fraction of the total number of days in the year. Otherwise the annual cost of operation per station will be high. A single radiosonde observation, for discussion here, costs about $300 for a developed country Met Service. This includes $150 for the GPS-radiosonde (some volume discounts to get this number, otherwise near $200), $25 for the balloon (typically 300gm or 600gm), $25 for the gas and $100 for the labor and miscellaneous costs. These numbers vary from country to country but $250 would be near a minimum even in a developing country and volume discounts might not apply to relatively small radiosonde purchases.

Applying these numbers to estimate the cost of a routine radiosonde station we find that for once-daily observations (~400 observations per year assuming ~ 10% extra launches to account for radiosonde in-flight failures and some special off-time observations) the annual cost is $120K, and $240K for twice-daily observations. *These are enormous numbers for most NMS's, and the operating cost for one radiosonde station can easily exceed the budget for the entire forecasting staff.*

2) *observers should be paid per-observation*. This is important if new observing sites are to be established. If relatively few observations are made per year it is not efficient to have full-time staff to make the observations. It is more cost-effective to train individuals at a new site to make the observations and pay a motivational fee per observation than to underutilize full-time staff. Even at $50/per observation (a substantial amount for ~2 hours work) the cost of 100 observations per year is only $5K.

3) *two-way communication between forecast centers and observation sites is essential*. Since the observer would have to be notified of a required launch some hours (perhaps 12) in advance, reliable two-way communication (most likely internet) would be required between the network operations center and the observing site. Only for a relative few island stations would this require satellite communications.

4) *important forecast conditions must be identifiable*. This is probably the most essential requirement for any adaptive observing system, of any kind. For any forecast system / meteorological service to continue to exist, the value of its services must exceed the cost of providing them. Every day presents a forecasting challenges and potential value from a good forecast. But conditions on some days require more accurate predictions so that greater economic impacts can be realized. The most apparent example of this is hurricane forecasting, where an accurate 3-day track forecast allows ships to move out of the storms path, aircraft to be evacuated from airports, or coastal residents to evacuate or prepare for the storm's arrival. Many of these actions require more than a day's notice, and the longer the lead-time the more the potential savings. Conversely, a poor forecast would lead to an over-warned area and much needless expense.

To have a positive impact on numerical weather prediction adaptive observations need to be made in advance of the phenomena to be predicted, so that effective action can be taken. In the example, a strong tropical wave or tropical storm crossing over the Lesser Antilles would be a clear signal than special observations would likely be required over the western Caribbean Sea region in following days.

This paper focuses on the use of adaptive radiosonde networks for improving hurricane prediction precisely because it is probably the most important meteorological event that can benefit from improved prediction days in advance and the conditions requiring adaptive observations can be relatively easily determined. The less-strong the economic impact of a particular event, the more effort will be required to justify the cost of additional observations.

5) *station establishment costs must be low*. The cost of different components of a radiosonde station mentioned earlier are critical in establishing a new radiosonde station. If the initial costs can be made small enough then there is no dis-incentive to establishing more stations. To this end, the use of a) low-cost radiosonde systems with b) smaller balloons (100-200gm), inflated with hydrogen gas from cylinders or gas-

on-demand systems, allows for c) small inflation shelters. With these conditions, an adaptive GPS-radioosnde station can be established for less than $25K, fully one order of magnitude less than possible several decades ago.

One cannot over-emphasize the importance of a low set-up cost for an adaptive sounding station. Currently, a meteorological service choosing to invest possibly $250K in a "top-of-the line" new upper-air site, has pressure to fully utilize the new resource. This implies another $120K or more annually for daily observations. Eventually the initial cost becomes a small fraction of the total operational cost of the station over the station's lifetime. But for an adaptive site, with few observations per year, the initial cost will be a much larger fraction of the overall cost of the station. There will be reluctance to spend large sums on a system that operates only sporadically, thus the need for adaptive sites to have low set-up costs.

4. Revamping the Western Atlantic/ Caribbean Basin Hurricane sounding network

Currently the US NWS supports special 00Z radiosonde measurements during the hurricane season, in addition to the regular 12Z observations. This involves supplying additional expendables to a number of sites (~10) in the Caribbean Sea region to make a second-observation per day (00Z) during a period from roughly June through September. The total 00Z observations is approximately 800, from information available from the US NWS:
http://www.nws.noaa.gov/iao/ia/hom/IAOChuas.php

Could there be a more effective use of equivalent resources? Suppose that there are 30 days each hurricane season when hurricanes, tropical storms or developing depressions are present in the Caribbean Sea region. This might be an underestimate some years and an overestimate other years but is a plausible number. Now suppose there are 10 additional adaptive radiosonde stations in addition to the 10 NWS-supported routine network sites. Twice-daily soundings for the 30 days would require an additional 900 soundings. This is only slightly higher than the 780 soundings currently supported, and would double the number of soundings available on the priority hurricane days.

Adaptive observations could be further optimized by making only 12Z observations, when all other stations are also generally making observations. This would permit twice as many stations to be operated adaptively (see Fig. 1 for an example of possible networks). Further optimization could be obtained by selecting the geographical region for the adaptive soundings on a daily basis. Forecasts of a tropical storm developing in the southwest Caribbean would benefit from additional sounding over Central America and the western Caribbean but might benefit little from an additional observations in the eastern Caribbean. Or a landfalling hurricane in Texas might not benefit much from additional observations in the Bahamas. An efficient adaptive network requires that the network's observations be optimized for the forecast challenge at hand. *Like any meteorological observation used for forecasting, the observation's value must exceed the cost.*

5. Adaptive networks for weather forecasting, climate monitoring, and research

Adaptive radiosonde networks need not only be used for high-impact weather forecasting, though that application might be the easiest to justify. Spatially-dense soundings could be used to monitor climate in a systematic manner, providing more detailed "snapshots" at lower time-resolution than the routine sounding network. Such observations could detect systematic problems with routine data assimilation of less-dense observations, or could reduce model drift in regions with few in-situ observations. Some island sites, well removed from land areas, could help with over-ocean satellite calibrations.

Fig. 1. Example of a hypothetical radiosonde network over the Caribbean Sea region including both routine (red) and adaptive (yellow) stations.

Adaptive stations could be used for on-demand observations to aid in research studies. A strictly hurricane-focused network would not permit, for example, studies of cold surges and their impact along the Caribbean coast of Central America. A research effort to study such features could use an adaptive network to provide observations just when needed over the course of one or more cool seasons. Innumerable such research applications are possible, which could be funded independently by the particular research project.

Thus, it may be that the most effective adaptive network for a given region includes components that are funded for climate monitoring, high-impact weather forecasting, and specific research programs. An example of such a sounding network (similar to Fig. 1) might be developed for the Intra-American Seas region as part of the upcoming Intra-Americas Climate Study Program (IASCLIP) program. This program will have a climate research focus that might include monitoring and process studies (yet undefined). Yet such a network, if developed, would also have a high-impact weather capability. Critical to such a capability is the ability to make the on-demand observations at short notice, this is discussed next.

6. Coordination of an adaptive network

Operating an adaptive network would present challenges not found in routine radiosonde networks. Adaptive stations must be notified in advance of a required observation – 12 hr might be a reasonable expectation. While this would be easiest via email, satellite phone calls might be needed for island sites, requiring a coordinator for the responsible site.

The main difficulty in operating an adaptive network is deciding when to request observations and what stations to involve. For a network as shown in Fig. 1, extending from western Mexico to the eastern Caribbean, it would be necessary to specify both the stations to operate and the duration of their observations (and perhaps also whether they should be 00Z and 12Z or both). Such decisions would most likely need to be made by a committee of forecasters selected to represent the region's economic and forecasting interests, as well as the National Hurricane Center staff. A daily conference call during the summer or a default plan of the day initiated by the NHC and then subject to comment by the committee might be effective.

Although there are objective procedures to identify regions of sensitivity in the initial analysis and the best regions for targeted observations, the lack of mobility of the adaptive stations (compared with aircraft for example) reduces options for precise placement of observations. However, for the hypothetical network of 22 sites shown in Fig 1, not all sites would make observations on every adaptive-observation day.

7. Economic aspects of adaptive networks

There is a fundamental premise to the adaptive network – that additional observations will have a greater economic impact on high-priority forecast days and that the positive impact will be larger than the cost of making the observations. This premise is rarely verified for even routine observing networks, as the quantification of forecast benefit for incremental improvements in any observing network is rarely done.

For a "go-day" for a 20-station adaptive network the direct costs would on the order of $6K, using the numbers in Section 3. For a tropical depression intensifying in the SW Caribbean Sea (Fig. 4) or a hurricane crossing the central Caribbean this is a small investment for an incremental increase in forecast confidence. But for events of less-clear importance and economic impact the call for a "go-day" may be more difficult and would need prior discussion. In fact it is reasonable to expect that different events in different parts of the basin should be stratified in advance, with different stations designated to make observations when such events occur.

To avoid the situation where one country in a multi-national adaptive network such as shown in Fig. 1 decides to opt-out because of difficulty in justifying the observational costs, such networks should really be collaboratively-funded and operated. The current US-supported Hurricane Network across the Caribbean Basin is one such example. Another is the ASECNA upper-air network in parts of Africa (Fig. 2). Such a network would need a dedicated coordinator for improved operation, capable of solving issues as they arise.

Geography will ultimately determine the density of stations possible in an adaptive network, with oceanic regions without islands being devoid of observations while land areas can be sampled without limit if so desired. At some spatial density the asymmetries between oceanic areas and land areas will limit further forecast skill, at least for plausible investments in sounding infrastructure.

By themselves adaptive radiosonde stations cannot cover the entire forecast domain, which is mostly oceanic. However, they can provide peripheral observations that can free the aircraft resources needed for oceanic synoptic reconnaissance such as provided by the NOAA G-4 or USAF C-130 aircraft. Together, both the adaptive sounding sites and the aircraft dropsonde missions can cover a larger region more effectively than either alone. A single aircraft synoptic reconnaissance mission (~8 hrs + 20 or more dropsondes) may cost ~$50K, this is similar to a 20-station adaptive radiosonde network making measurements at 8 synoptic times. Thus, an adaptive array can help provide the time continuity over the synoptic scale that aircraft missions cannot affordably do.

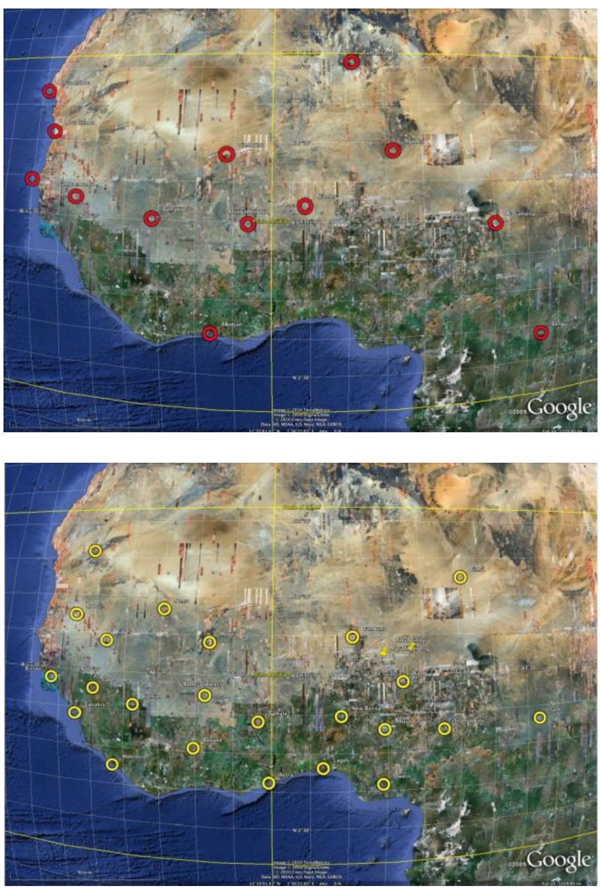

Fig. 2. Example of West African routine radiosonde network (top) and possible adaptive sites (below) designed to complement the routine sites.

By way of example, suppose that an adaptive Intra-Americas radiosonde network makes operational hurricane-related observations at all 20 sites on 40 days (800 obs). Then 5 observations per month are made throughout the year at all sites, for climate-monitoring (1200 obs). And finally, 30-observations times per year for research projects (600 obs). At $300/ob, this totals $780K. Substantial, but comparable to a major research project by a university faculty member. Modest variations in the above numbers would be expected from year-to-year, based on hurricane activity and research project activity.

8. Other regions suited for adaptive networks

The examples above have focused on the Caribbean basin region, since adaptive observations there have the greatest potential for economic impacts on the US. However, most regions can benefit from adaptive sounding strategies. What is required is a clear perception of the important weather events that need to be forecast better and that such events be somewhat uncommon and the initial conditions for their occurrence need to be somewhat predictable. For example, in West Africa it might be important to predict the rainfall associated with African easterly waves. Rainfall with such waves generally occurs from June through September. Thus an adaptive radiosonde network dedicated to improving such forecasts might operate only 4 months per year. And within those 4 months it might be possible to make observations only every other day, providing better initial conditions every 48 hr. In this manner such a network would make only 16% the number of observations made by a year-round, daily sounding network. Put another way, six such adaptive stations could be operated for the cost of one routine station.

The western Pacific is another potential region for adaptive observations, thought the island distribution is not ideal for improving tropical cyclone prediction in the NW Pacific. Many islands already have routinely operating radiosonde stations. The main opportunity for adaptive sites appears to be in the Marshall Islands and in the Philippines (Fig. 3), which has a very limited sounding network.

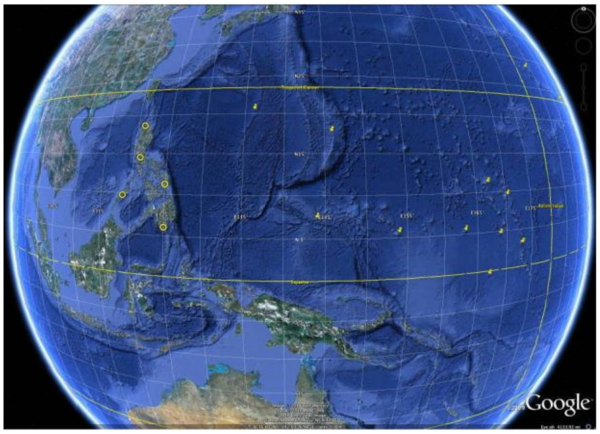

Fig. 3. Potential adaptive sounding sites on inhabited islands with reasonable infrastructure in Western Pacific. Sites in Philippines are shown in yellow circles.

9. Final thoughts

With recent improvements in radiosonde technology, gas availability, and internet and satellite communications, adaptive radiosonde networks can be established today. To fund and operate such networks will require good coordination between diverse interests and supervision at the international level by both the operational and research sectors. And, like all other aspects of weather forecasting, the issue of cost versus benefit needs to be addressed, as it should be with all other observing systems.