ON DETECTING LONG-TERM CHANGES IN ATMOSPHERIC MOISTURE

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Abstract. Long-term temperature changes are expected to give rise to changes in the water vapor content of the atmosphere, which in turn would accentuate the temperature change. It is thus important to monitor water vapor in the troposphere and lower stratosphere. This paper reviews existing data for such an endeavor and the prospects for improvement in monitoring.

In general, radiosondes provide the longest record but the data are fraught with problems, some arising from the distribution of stations and some from data continuity questions arising from the use of different measuring devices over both time at one place and over space at any one time. Satellite records are now of limited duration but they will soon be useful in detecting changes. Satellite water vapor observations have their own limitations; there is no one system capable of measuring water vapor over all surfaces in all varieties of weather. Among the needs are careful analysis of existing records, the collection of metadata about the measuring systems, the development of a transfer standard radiosonde system, and the commitment to maintaining an observing system dedicated to describing any climate changes worldwide.

1. Introduction

Water vapor plays a major role in the dynamics of the atmosphere's circulation as well as in radiation exchange within the atmosphere. A large portion of the energy transferred between the surface and the free atmosphere is in the form of latent heat. The redistribution of this latent heat and its realization through condensation and precipitation is a main energy source for the general circulation. Water vapor is also the most important of the greenhouse gases in the overall control of climate, and its condensate, clouds, modulate the radiative energy transfer. Thus changes in water vapor concentration have major effects on climate.

Models estimating effects of greenhouse gas increases portray an increasing water vapor concentration as the atmosphere warms, 20% to 30% as CO_2 doubles in various models (Meehl and Washington, 1990; Hansen *et al.*, 1984). Some such result would be expected if only because the saturation vapor pressure increases with temperature. The increased moisture content in turn would increase the warming. This positive feedback of water vapor is one of the largest factors calculated to amplify the effects of increased greenhouse gas concentrations.

It is not only the total quantity of water or its geographical distribution that is of interest; the vertical distribution is also important. Despite the small absolute amount of water possible in the cold of the upper troposphere and stratosphere, water vapor changes there have a disproportionate effect on radiation exchange and surface temperature. It is, approximately, the fractional change in water vapor

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rather than the absolute change that is important (Shine and Sinha, 1991). Thus not only total water vapor should be monitored but its vertical distribution as well, both for long-term changes and for understanding the dynamics of the atmosphere. How well we can monitor water vapor now and the prospects for the future are the topics of this paper.

This note stresses long-term monitoring. Only brief mention will be made of measuring systems that are not now, or apt to be, widely deployed. Stress will also be placed on sources of bias in observations and possible changes in bias. For detecting long-term climate changes, no matter what their cause, homogeneous records are necessary. Indeed, homogeneity is more important than absolute accuracy, given a reasonable level of the latter. Thus observations that have large random errors may still be useful for detecting change and introducing more accurate instruments, if they produce an offset in the time series, introduce analysis problems which have to receive attention.

The next part will review some of the water vapor variables, both measured and calculated, and what we know of their distribution. Then will follow a review of the available observations, and their current limitations, focusing on routine surface and upper-air radiosonde measurements made by the world's weather services as well as data routinely collected from space-borne instruments. Next, the outlook for the next few years will be discussed, and finally some thoughts on what might be done to improve monitoring.

2. Background

2.1. VARIABLES AND ALGORITHMS

There are a number of quantities used to express the amount of water vapor in the air. As most depend in one fashion or another on the temperature of the parcel being considered, almost any measurement of a water vapor variable is accompanied by a measurement of temperature. The usual reported variable is the dewpoint temperature, T_d, but this is not always measured directly. Rather, it is often calculated from measurements of temperature and either wet-bulb temperature, T_w, or relative humidity, RH. The latter is taken as the ratio of the actual vapor pressure to the vapor pressure that would saturate the air at its present temperautre, the saturation vapor pressure or s.v.p.

The specific humidity, q, and its close relative, the mixing ratio, are often calculated. (These quantities are, respectively, the ratio of the mass of water vapor in a given volume to the total mass in the volume, the specific humidity, or to the mass of dry air, the mixing ratio.) The integral of q between pressure surfaces gives the precipitable water, PW, (or column integrated water vapor) between the pressure levels or in the entire column. Values of PW can also be estimated from remotely sensed radiances either from satellites, aircraft or from the ground. There are additional remote measuring techniques, including active ones such as the various lidars, that are quite useful as research tools. Their cost will likely restrict their use to research for some time and they are not discussed further here.

The relationship that is basic to all calculations of water vapor quantities is that between temperature and the saturated vapor pressure, a function only of temperature. This relationship, the Clausius-Claperyon equation, is non-linear and cannot be integrated analytically. Furthermore, laboratory measurements of saturated water vapor (over a plain surface of pure water) are not made at temperatures below freezing (although relative humidity is usually expressed as the ratio of vapor pressure to s.v.p. over water at all temperatures). There are a number of approximations to the s.v.p.-temperature relation (see, e.g., Gueymard, 1993), ultimately based on laboratory measurements and extrapolated to below-freezing temperatures.

2.2. WATER VAPOR DISTRIBUTION

The source and the sink for almost all water in the atmosphere is the earth's surface, through evaporation and precipitation. Oxidation of methane appears to be an important additional source of stratospheric water, and this probably contributes to the slight increase with height of water vapor concentration in the stratosphere. As methane emissions appear to be increasing at the ground (Steele *et al.*, 1992; Khalil and Rasmussen, 1993), they could contribute to an increase in water in the stratosphere. Additions from volcanoes and other geologic activity, while probably important over vast time scales, have not been shown to affect significantly the present distribution or its changes.

If the water vapor in the air were all condensed, the average depth of the condensate would be about 2.5 cm. Above polar regions the mean *PW* is about 0.5 cm and near the equator it averages about 5 cm. Globally, about half of all the moisture in the atmosphere is between sea level and 850 mb and only about 5–7% is above 500 mb. The amount in the stratosphere is probably less than 1% of the total.

In the stratosphere the volume mixing ratio is only a few parts per million (ppmv) with frost-point tempertures as low as –90 to –100 °C. Near the surface in the tropics, on the other hand, the mixing ratio can be over 20,000 ppmv. This range of at least 4 orders-of-magnitude makes extreme demands on sensors, demands which few can meet, and so different techniques are called for at different heights. Furthermore, because precipitation rapidly removes water from the atmosphere, the residence time of water vapor in the atmosphere is only about 10 days, and its horizontal distribution is quite variable. Thus observations at many locations over a substantial period of time are required to establish its distribution.

3. Long-Term Records

A few records of surface temperature extend for several centuries, and some estimates of global surface temperatures extend over a century. The same is not true of humidity records, either because the records were not maintained or the quantity was not measured. In addition, the technology of routine humidity measuring has changed a good bit over the years, more so than of temperature. This is partly because there are several humidity quantities that can be measured directly: RH, T_d, and T_w, for instance. Changes in instrumentation and recording practices require care to identify because changes they can inject into the records can be confused with changes in climate.

Another prominent issue in the evaluation of humidity records is the algorithms used both to convert electro-mechanical signals to meteorological variables and to convert these variables to one another can and have changed. The introduction of computers into data handling and processing allowed more accurate computational methods to replace less accurate, but less cumbersome, ones. However, changes in processing algorithms can lead to subtle differences in calculated values which could then appear as apparent climate changes (Elliott and Gaffen, 1993; Wade, 1994).

3.1. SURFACE OBSERVATIONS

There are some records of surface humidity extending back into the last century in the U.S. and likely in some other countries, at least in the Northern Hemisphere. In the U.S. the early observations were of wet- and dry-bulb temperatures. The thermodynamics of wet-bulb thermometers is complicated; conversion to relative humidity and dewpoint was accomplished with tables and slide-rules. After about 1960, the Weather Service installed hygrothermometers which give dewpoint directly, using absorption of water by lithium chloride crystals which changes their electrical properties. In 1984 the Weather Service adopted dewpoint hygrometers. Currently the Weather Service is replacing these with newer versions in the ASOS (Automatic Surface Observing System) program. Other nations have likely undergone similar changes over the years. The Historical Climate Network of the U.S. does not make humidity measurements so this network does not offer an alternative to the normal weather stations.

As with estimating surface temperature trends, station histories need to be considered in evaluating water vapor records. Moves of the station, instrument replacement and changes in the surroundings would affect the records. The effect of urbanization, the urban heat island, leads to rural-urban differences in humidity as well as temperature (Lee, 1991). Increases in humidity could also come about from increased irrigation or the construction of a nearby reservoir. Such local changes could obscure a regional or global signal, as is true with temperature.

A source of long-term humidity data over the oceans is the Comprehensive Ocean-Atmosphere Data Set (COADS; Woodruff *et al.*, 1987). There are humidity data taken from research vessels and merchant ships but how widespread these are needs investigation. There has been no attempt known to the author to estimate global or even regional long-term surface moisture changes. Brazel and Balling (1986) examined the 1896–1984 humidity record for Phoenix, AZ, to seek local influences and they did find a decrease in RH accompanying the urban warming in Phoenix, but little change in dewpoint.

The whole topic of examining moisture changes at the surface over the globe, or a substantial part of it, would first require a search of the meteorological archives to determine what would be feasible.

3.2. UPPER AIR (RADIOSONDES)

Most of our knowledge of tropospheric water vapor (see e.g. Peixoto and Oort, 1992) comes from routine radiosonde observations taken for weather forecasts. Observations have been made globally since World War II but the bulk of useful humidity data begin in 1958 when the present observing times of 00 and 12 UTC were adopted. The main purpose of these observations is weather forecasts so maintaining long-term homogeneity of the observational record has not been a primary concern. Because frequent improvements in technology have been introduced, separating true long-term trends or variations from the effects of differing observation techniques is difficult.

There are about 700–800 regularly reporting radiosonde stations reporting once or twice a day, although there are additional stations that send reports irregularly. The distribution of these stations leaves large gaps in coverage, Figure 1. The stations shown are those from which useful data can be obtained over part of the period since 1973. Some are no longer operating, particularly the Ocean Weather Stations in the North Pacific and North Atlantic. Since the almost complete demise of these OWS we are at the mercy of the distribution of islands for observations in remote parts of the oceans, so that the Southern Ocean, the Eastern Pacific and the South Atlantic are particularly under-sampled. (Several nations are making radiosonde observations from moving merchant vessels following particular tracks, which provide augmentation of observations along these routes.) Even some continental areas are not well covered; Africa and South America in particular.

The expendable nature of the instruments and the number used daily means the instruments cannot be expensive or need highly trained scientists to operate them. These constraints limit the quality of the instrumentation. The current humidity sensors respond more slowly at the low temperatures of the upper troposphere and stratosphere and are generally less reliable under these conditions. (This is why, until recently, the U.S. did not report humidity values when the temperature was below –40 °C.) Above about 500 mb the reliability of radiosonde moisture

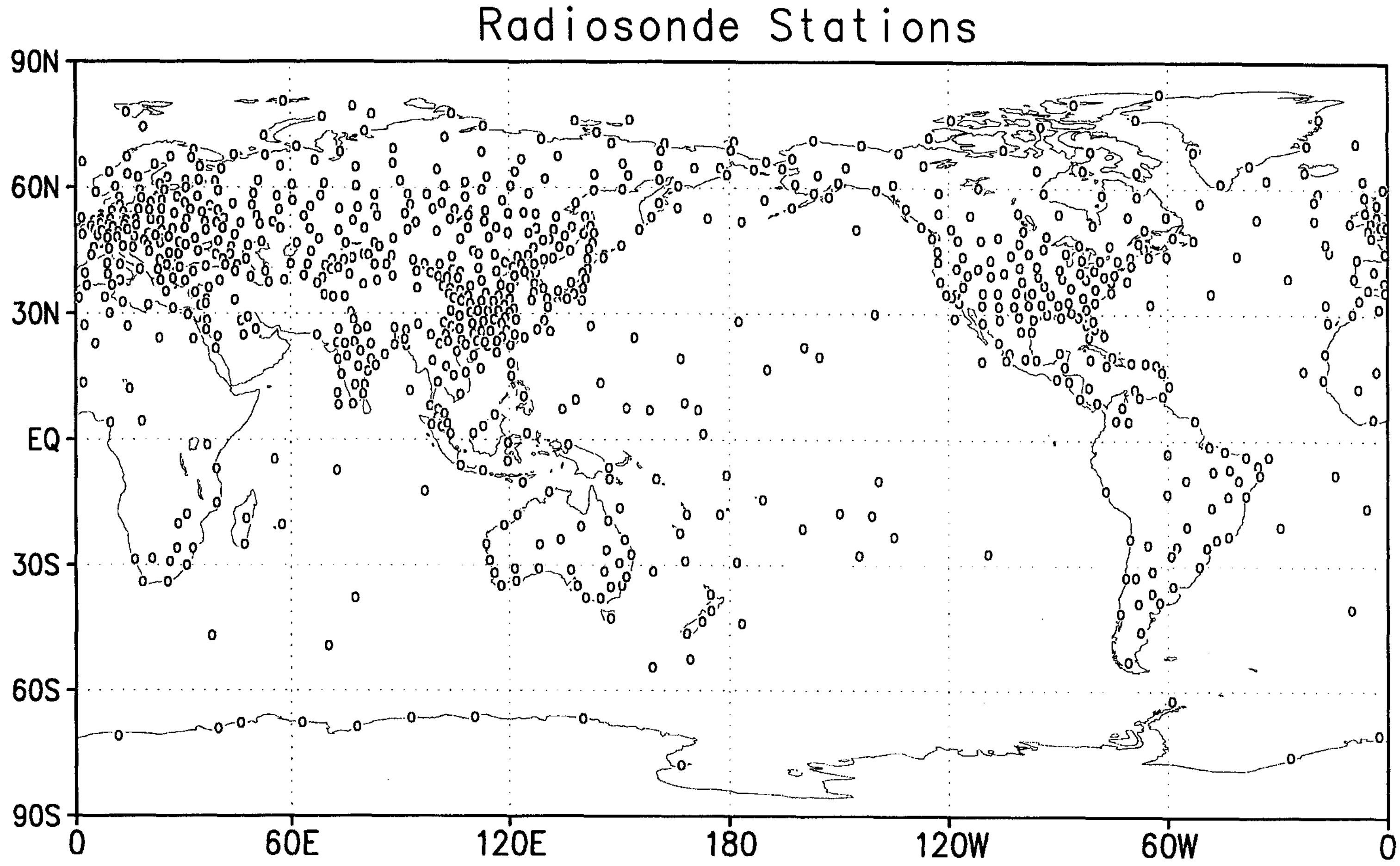

Fig. 1. Location of land-based radiosonde stations that have relatively long records during the 1973–94 period. Also included are some Ocean Weather Stations, most of which are no longer active.

data diminishes although in the tropics the temperatures remain warm enough for reasonable estimates up to about 300 mb.

A more serious problem with radiosonde data stems from the variety of instruments and reporting practices that are now or have been in use. About ten different manufacturers supply radiosondes to the world's weather services. Some of these use quite different sensors to measure relative humidity. The most widely used sonde, that manufactured by Väisälä Oy, uses a device that changes capacitance with changes in humidity. The sonde most widely used in the U.S., as well as throughout much of the north Pacific and Latin America, is made by VIZ Corp. and uses a carbon-based element whose resistance changes with humidity. Others use other elements whose resistnace or physical dimensions change with humidity, such as goldbeater's skin.

There have been and continue to be intercomparisons of some of these instruments (Nash and Schmidlin, 1987) but it is difficult to adjust the data to a common standard. Schmidlin (personal communication) states that most tested instruments give comparable values at humidities between 20% and 80% but outside this range differences can become significant. Some of the differences result from different reactions to wetting in clouds. Also some come about from the algorithms used in data reduction, as discussed below.

Furthermore, most nations have changed humidity sensors and other radiosonde components over the decades, in addition to changing suppliers. A particular example (Gaffen, 1992) comes from Adelaide, Australia, Figure 2, where there have been frequent changes of sonde supplier. Gaffen (1993) has assembled a useful summary of some changes in world-wide radiosonde in use since World War II.

Changes in the design of the enclosure and even changes in the length of the attachment to the balloon can have noticeable effects. In 1965, when the U.S. changed from a lithium chloride sensor to the carbon hygristor, a new design of the sonde's case was introduced. This led to the notorious situation shown by Elliott and Gaffen (1991), where the data at Hilo HI demonstrate the dramatic effect of allowing sunlight into the humidity sensor housing. Despite the fact that the problem was recognized early (Morrissey and Brousaides, 1970), a redesigned housing was not introduced until 1973.

Changes are not confined solely to measuring instruments. There have been changes in data processing algorithms and algorithms for converting from one moisture variable to another. Two sets of algorithms are needed. The first converts the electrical signals from the sonde to meteorological quantities and the second converts these quantities to others that are desired. Wade (1994) gives a description of the changes in the U.S. calcultion of low humidities from the sonde's electrical signals, where an apparent error has been carried through for years. He further notes that currently the calculations still require improvement (which is now under consideration). What is sobering about Wade's discussion is the realization that many of the problems he describes have been known for some time but making the corrections seems to present inordinate bureaucratic difficulties.

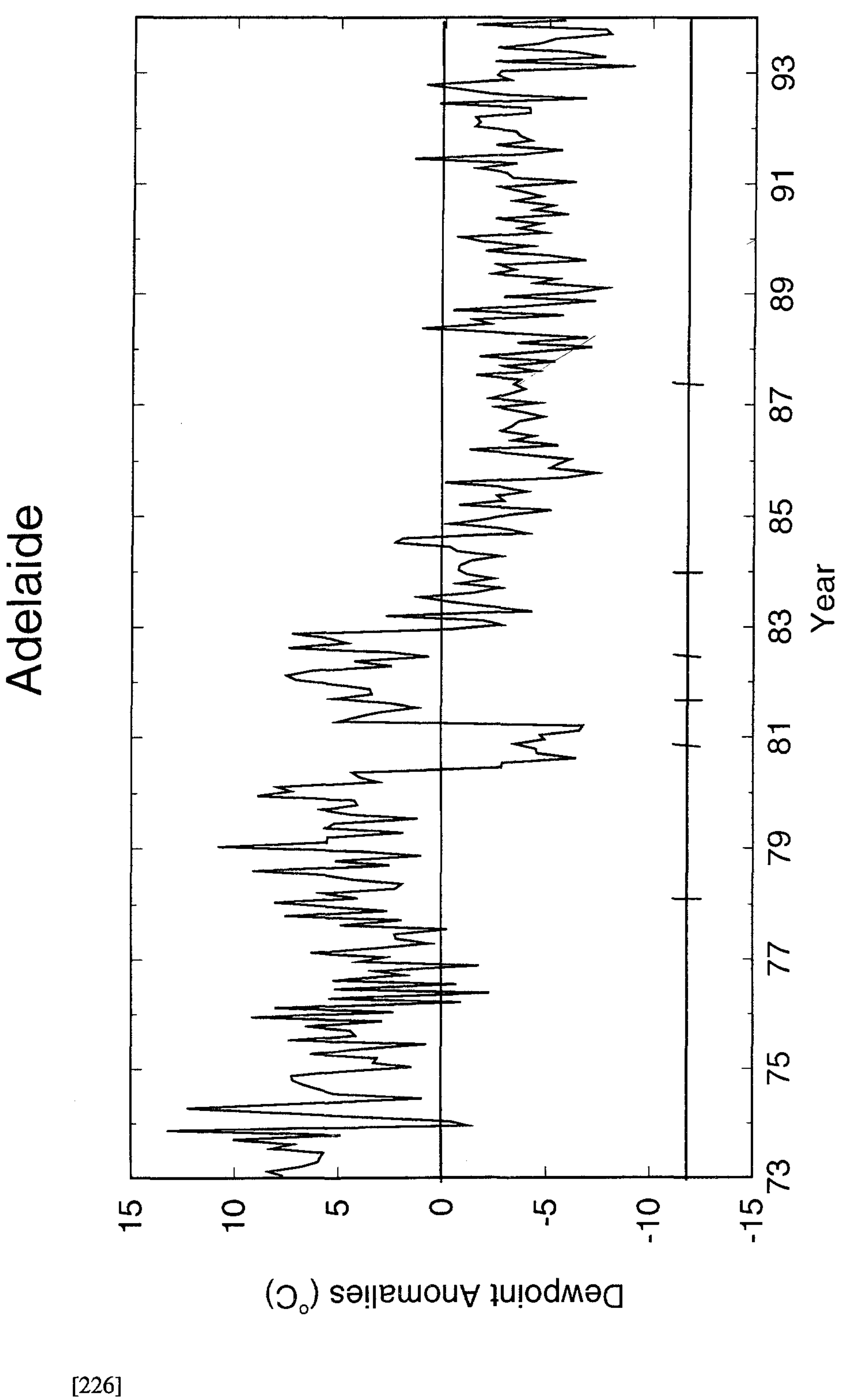

Fig. 2. Time series of 500 mb dewpoint anomalies at Adelaide, Australia. The vertical bars along the x-axis indicate dates when changes in radiosonde types occurred.

Another source of potential problems is related to the use of different algorithms to convert relative humidity, to which the sonde's sensor responds, to dewpoint depression which is the quantity reported. Elliott and Gaffen (1993) show that this can be a source of small inhomogeneities in both horizontal moisture fields, as different nations use different conversions, and in time when new algorithms are adopted.

Not all nations report similar observed values in the same way. Until recently, the U.S. practice was to report humidity data at temperatures below −40 °C as 'missing' and all relative humidities less than 20% as 19%, (or dewpoint depression as '30', which is not the same RH value). These practices were dropped in Oct. 1993 by the U.S. and this will create a small discontinuity in records of monthly mean values. Some other nations have used similar rules and they could change also.

Most (but not all) of these changes represent improvements in sensors or other practices and so are to be welcomed. Nevertheless they make it difficult to separate climate changes from changes in the measurement programs. In the 1940s untreated human hair was the humidity sensor on most sondes but values were virtually useless at temperatures below freezing because the lag time at these temperatures was so large. Since then, there have been several generations of sensors and now sensors have much faster response times. Whatever the improvements for weather forecasting, they do leave the climatologist with problems. Because relative humidity generally decreases with height slower sensors would indicate a higher humidity at a given height than today's versions (Elliott *et al.*, 1994). This effect would be particularly noticeable at low temperatures where the differences in lag are greatest. A study by Soden and Lanzante (submitted) finds a moist bias in upper troposphere radiosondes using slower responding humidity sensors relative to more rapid sensors, which supports this conjecture. Such improvements would lead the unwary to conclude that somepart of the atmosphere had dried over the years.

Despite these problems there have been attempts to estimate changes in tropospheric water vapor from radiosonde observations. Hense *et al.* (1988) report an upward trend of moisture in the 700–500 mb layer in the western Pacific from 1965 to 1986 but there are questions from the '65–'72 period because the U.S. changed instrumentation in 1973. Elliott *et al.* (1991) document a moisture increase in the equatorial Pacific from 1973–86 and Gaffen *et al.* (1991) using more stations and an empirical orthogonal function analysis also found an increase in moisture in the tropics, a finding supported by Gutzler (1992) in a study of 4 tropical island stations. He found an increase in precipitable water of about 6% per decade for the period 1973–1988. Gaffen *et al.* (1992) computed trends for some 35 stations with reasonably homogeneous records around the globe. Most of these stations showed an increase in precipitable water during the period 1973–1990, with the largest and most statistically significant trends again at tropical stations, where increases as large as 13% per decade were found. In a forthcoming study, Ross and Elliott (in preparation) find statistically significant increases in PW, of 3 to 7% per decade, over most of North America, except for north and east Canada.

There has been one series of observations of stratospheric moisture of sufficient length to begin examining trends. Oltmans and Hofmann (1995) report data from balloon-borne frost-point hygrometers from Boulder, Colorado for 1981–1994 which show increases in stratospheric water vapor concentration at heights between 9 and 27 km with the most statistically significant values, which are between 0.5% and 1% per year, between 16 and 22 km. The increases are large enough that they may not be entirely caused by increased oxidation of methane.

Thus there is some observational evidence for increases in moisture content in the troposphere and perhaps in the stratosphere over the last 2 decades. Because of limitations of the data sources and the relatively short record length, further observations and careful treatment of existing data will be needed to confirm a global increase.

3.3. UPPER AIR (SATELLITES)

Most water vapor observations from satellites are too recent to give much help in estimating past changes in moisture. Techniques for extracting moisture information from satellite-observed radiances are rapidly improving, however, and can be applied to observations collected in the past. Unfortunately, there is no system in present operation which is able to measure total column water vapor in all conditions; that is, over both ocean and land in both clear and cloudy regions. Furthermore, only rough estimates of the vertical distribution of water vapor are now possible. A useful summary of remote sensing techniques, including satellite and ground-based observations, can be found in Starr and Melfi, 1991.

The longest record, since 1979, is from the Tiros Operational Vertical Sounder (TOVS) system. The system employs several of the High-resolution Infrared Radiation Sounder (HIRS) channels for water vapor (Smith *et al.*, 1979; Wu *et al.*, 1993). As the observed radiances are affected by temperature, temperature must also be retrieved. Moisture retrievals are not produced in overcast areas or with cloud cover greater than about 75%. In partly cloudy scenes (up to about 75% cloud cover) the measurements are valid only in the cloud-free areas. The channels of the HIRS-2 sounding system can resolve the precipitable water into three layers, approximately the 1000–700, 700–500, and 500–300 mb layers.

At first, radiosonde data were used to produce the temperature and moisture profiles from the HIRS observations through statistical regressions. Physically based techniques are now being used that reduce the reliance on nearby radiosondes. Some of these use Numerical Weather Prediction runs for the first-guess. Accuracy is believed to be within about ±20% of the radiosonde values for total PW; less is known of the accuracy in the upper layers, partly because of the uncertainties of the radiosonde data there.

The Stratospheric Aerosol and Gas Experiment (SAGE II) instrument on board the Earth Radiation Budget Satellite has provided measurements of water vapor in the stratosphere since late 1984. The technique depends on solar occultation and allows water vapor to be calculated with 1-km vertical resolution from the mid-troposphere to 45 km. It has the best precision of any of the current instruments aboard satellites. The spatial and temporal sampling is somewhat limited and the method does not permit measurements below cloud tops and reaches down to about 5 km only one-half the time. It has provided the best estimates of the global climatology of water vapor in the stratosphere (McCormick *et al.*, 1993).

Other observations of total column water have been provided by microwave instruments (SSMR, SSM/I) aboard several satellites (Liu *et al.*, 1992). While these instruments can 'see' through most clouds, except in heavy precipitation, they do not provide vertical resolution and their use for water vapor is limited to over-water regions. (The microwave emissions from land surfaces are too irregular to separate them from the atmospheric emissions.) SSMR observations were made from 1978–1984 while SSM/I began in 1987. SSM/I will continue to be used on future satellites.

The water vapor IR channels on the GOES/VAS and METEOSAT give good spatial descriptions of moisture features. The vertical resolution is relatively coarse, being comparable to that of TOVS and it requires a large effort to quantify the accuracy of the moisture retrievals. Nevertheless, strides are being made in this regard and information on water vapor over the regions viewed by these satellites may be forthcoming.

Much of the original data from many of the satellites have been archieved. This makes it quite possible that the ongoing work on improving the moisture-retrieval algorithms will allow these 'old' data to be reworked to obtain better estimates of water vapor from the periods of operation. However, when new satellites replace older ones, even those launched with the same types of instruments, care is necessary to ensure data continuity. Changes in Equator-crossing times and deterioration of calibration in space are other potential problems. Satellite observations do not escape data homogeneity questions.

3.4. ANALYZED DATA FIELDS

It has been suggested that the four-dimensional data assimilation systems used to initialize models for forecasts could provide a physically consistent data set for analyzing trends of several quantities, including moisture. However, this attractive idea has problems similar to the measurements, namely, that there have been changes over the years in the models used to assimilate the data (Trenberth and Olson, 1988) which produces changes in the fields that can mimic true changes in climate. Some hope lies in the so-called Reanalysis Project (Kalnay and Jenne, 1991) whose goal is to produce consistent analyses using the same data assimilation procedures on the archived data sets. This project will still have to cope with changes in the instruments that produced the original values if climate change is to be monitored by this procedure.

3.5. METADATA

If all observations were taken with the same unchanging instruments and recorded with the same procedures there would be little use for details about them for climate change purposes. Such is not the case, of course, and so knowledge of the changes and how they might affect the record are necessary. Unfortunately, such information is often buried in the archives of the respective weather services or not available at all. Elliott and Gaffen (1991) give some history of the changes in U.S. radiosondes as they affect the moisture record and Gaffen (1993) summarizes some information on radiosonde changes world-wide. Neither of these compilations is complete; a number of nations did not respond to Gaffen's requests for information and there have been recent changes in the U.S. practices, see e.g. Wade (1994).

Metadata about satellite observations and also changes in data assimilation procedures have presumably been recorded but the information is scattered. Individual data sets are usually accompanied by some information about the observing techniques. Whether a systematic record is being kept, including information about cross calibrations among the satellites, and whether research workers in the future will know how to obtain it is not known to this author.

3.6. SUMMARY

All reasonably lengthy records of water vapor that could be examined for trends present problems. The surface data are subject to the same problems as the surface temperature data; station moves and changes in surroundings. In addition, changes in humidity sensors have been even more frequent than those of temperature sensors. Surface humidity records have not been examined save at a few locations, so their utility for trend detection is not known.

Radiosondes are the source of the longest records of upper-air moisture but their global distribution has large gaps and their ability to provide reliable data above 500 mb (about 6 km) is suspect. In addition the frequent changes in nations's observing programs makes identifying climate changes difficult.

Besides the relative brevity of their records, satellite observations of moisture cannot be made over all surfaces in all conditions. At present the vertical resolution of the observations is not as good as desired. They, too, suffer from changes in sensors as newer satellites replace those whose useful life ends. Nevertheless satellites provide data at heights where radiosonde moisture measurements are inadequate and in locations where radiosondes are not available.

In addition to being subject to all the problems with continuity of the underlying observation, analyzed NWP fields experience changes in analysis and data assimilation procedures.

Information about changes in instrumentation and procedures is useful for identifying potential discontinuities in climate records. However this information is lacking in many places and incomplete or even erroneous in some instances.

4. Near-Term Trends in Observations

There have been substantial changes in all the observing systems in the past decade and this is likely to continue for the next decade and beyond. The brief survey of anticipated changes emphasizes U.S. plans as these are best known to the author. The U.S. is unlikely to be the only nation making changes and those anlayzing data records must be alert for future changes.

4.1. SURFACE OBSERVATIONS

In the U.S. replacement of manual surface observations by ASOS is going on now and scheduled for completion in 1996. This activity is creating turmoil with climate records of surface quantities. The wholesale substitution of instruments, designed to operate unattended and with minimal maintenance, has already caused some recorded surface temperatures to be 1–2 °C too high at some locations (Kessler *et al.*, 1993). One can expect similar problems exist with the humidity records there, not only because the temperature records are compromised and so conversions to other humidity variables questionable, but the exposure problems of the temperature sensors may also be found with the humidity sensors. Additionally, the possibility exists that some of the new sensors will be at different heights than the older ones.

4.2. RADIOSONDES

The U.S. is also changing its radiosonde network as part of its Modernization Program. When it is finished somewhere between 1/3 and 1/2 of the radiosonde stations will have been moved from their locations of a few years ago (or disappeared). In addition there have been, and likely will be more, changes in the radiosonde supplier. For many years the sondes were manufactured by the VIZ Corp. which used a carbon-based hygristor. Between 1989 and 1995 sondes of another vendor were used at some locations, mainly in the western U.S. Although these used the same humidity sensor, there were differences in their reported humidity values. These have now been replaced with VIZ sondes. It is now planned to replace VIZ sondes with Väisälä sondes at some locations later in 1995. Also the VIZ sondes themselves are in some cases newer versions. Some of these changes will be accompanied by algorithm changes, as mentioned earlier. The U.S. is also developing a next generation of radiosondes, whose introduction into the network could occur in this decade.

Overseas the situation is a bit less tumultuous but changes are also taking place. Sondes from Väisälä are slowly replacing those manufactured in other countries, particularly in Europe. Both Japan and China, which make their own sondes, are experimenting with different humidity sensors (Schmidlin, personal communication). Some nations newly formed from the former Soviet Union are changing supplier; others may follow.

At the same time, the major suppliers of radiosondes continue to improve their products. Humidity sensors are receiving attention and we can hope for better performance at high altitudes and at low humidities. Some attention is being paid to improving data handling algorithms, also.

A problem that could result in fewer observations in the future arises from potential costs, particularly to the less-developed nations. There may be requirements for narrower band-widths for radiosonde transmitters because the part of the frequency spectrum available to radiosondes could be curtailed to make room for commercial broadcasts. This could increase the cost of sondes and ground stations which might reduce the number of observations. Furthermore, the use of GPS equipment for wind calculations would be another additional expense.

4.3. SATELLITES

Improved sensors have recently been launched or are scheduled in the near future. Advanced Microwave Sounding Units (AMSU A and B) should produce better water vapor profiles as will the SSM/T-2 aboard the DMSP satellites. There are also improvements in the moisture sensing of the geostationary satellites being launched for NOAA. Beyond these, there are plans for improvements in the EOS series. It is difficult to say when, with the budget restrictions now prevailing, the EOS satellites will be in orbit or what instruments they will carry.

We can also expect improvements in satellite retrieval of water vapor data. This is an on-going effort and, while not without cost, much more can be reasonably hoped for, both in processing the newer observations and in gleaning more from the older ones. In the latter effort the NOAA-NASA Pathfinder program (Ohring and Booth, 1995) should be particularly useful. Archived operational satellite observations, as far back as 1978, are being reprocessed with the best available calibrations and community consensus algorithms to produce a research quality data set.

5. What More Needs To Be Done?

The focus of this discussion is long-term changes in moisture, i.e. changes over several decades. This means observations and their analysis will have to cope with shorter term changes, such as those associated with ENSO phenomena and occasional volcanic eruptions, as well as instrumental noise and the vagaries of weather. The magnitude of these signals may well be greater than the signal from greenhouse gas increases or other long-term climate adjustments. It will require sustained observations over several decades to detect long-term moisture increases so there is real importance to extracting what one can from existing records. To discard the past data, with all their imperfections, would condemn us to begin anew the recording of climate changes. A perceived lack of data might well be used to delay any policy decisions beyond the time when they could be effective, or, if fears about climate warming ultimately prove to be exaggerated, lead prematurely to unnecessary restrictions.

There will be improvements in measuring techniques in the coming decades and there may be now-unthought-of developments. Continuity of data records as the old gives way to the new should be a major concern. Climatologists should not reject improvements on the grounds that the record will be compromised, but they should insist that the consequences of the introduction of new devices and procedures be well understood and ways be established to blend new data into the time series before the 'old' methods are abandoned.

The discussion in the preceding two paragraphs, and some of what follows, applies equally well to all climate data, not just moisture. Changes in surface temperature and precipitation receive the most attention as these affect the public and are the most widely measured. Water vapor content is not of direct public concern except as it occasionally affects comfort. From the standpoint of monitoring climate change, however, moisture may be better monitored above the surface rather than at the surface. Changes aloft should more readily reflect broad scale changes rather than reflect changes in local conditions.

Radiosondes and recently satellites provide almost all our knowledge of moisture changes. They now complement each other and will continue to be the main sources of data. To extract the most information from past radiosonde and satellite observations we need more information on the histories of changes in equipment and procedures. As noted above, Gaffen's (1993) summary of what we know about radiosondes is not complete and she is continuing to collect information. Some nations did not heed the original WMO request for information; their contributions are still needed. Furthermore, changes in radiosondes and satellite observations and data handling procedures will continue. There should be one repository of such metadata for scientists to consult and it should be kept up-to-date. This requires the active participation of all concerned. Perhaps the WMO should consider undertaking this function.

Wade (1994) shows how examining the algorithms used in transforming the electrical signals from radiosondes into humidity data can result in substantial improvement in the data without touching the instruments themselves. This shows that better data can be acquired in the upper troposphere and lower stratosphere, a region of particular interest and one where the need for better data is particularly acute. In addition, work on improving satellite water vapor retrieval algorithms also should continue. These will not only provide improved data in the future, they will add value to past observations. Improving all data handling algorithms is a relatively low-cost way of gaining additional observational power.

Because we are not likely to see nations adopt one radiosonde type any time soon, there is great need for some means of comparing them, a transfer standard against which all could be compared. This would allow one to adjust data from differing sources to a common reference, although that reference may not be absolutely accurate. It would also assist in ensuring continuity of data over time. Development of such a system is going on at the National Center for Atmospheric Research (Dabberdt, personal communication) and should be encouraged. When this or some other system is available, careful thought must be given to how it is operated, in what conditions and locations, etc.

A promising method of acquiring information on global distribution of total column water vapor (and possibly some vertical resolution) can be found in analyses of signals from satellites in the Global Positioning System (GPS; Rocken *et al.*, 1993). The effect of moisture on the refractive index of the air can be extracted from signal delays. This technique should be explored further as it could provide a relatively inexpensive network of observations because the satellites will be in place for navigational purposes.

A useful effort would be a comparison of a number of water vapor measuring devices in the field. These would include ground-based and aircraft lidars (e.g. Differential absorption and Raman scattering lidars) and other sensors not necessarily appropriate for deployment in a monitoring mode but valuable for calibrating those that are. Accompanied by many ancillary measurements and in such a way that satellites could be overhead at times, such a program would contribute to the development of improved water vapor retrieval algorithms and help evaluate a variety of measuring techniques. Such a program is a goal of GVaP (GEWEX Water Vapor Project). GVaP is, at present, a loose confederation of scientists working on monitoring, as well as understanding, water vapor and climate (Starr and Melfi, 1992).

It would be desirable if one space-borne instrument or technique could be developed that would allow water vapor to be calculated in all weather conditions and above all surfaces. Barring that, combinations of data from microwave and infrared instruments, blended with radiosonde observations, will be needed. These must consider the shortcomings of each data source in the analysis. Such an undertaking is discussed by Vonder Haar *et al.* in the August, 1994 issue of the GEWEX News (and is available from Vonder Haar at Colorado State Univ. or the GEWEX Project Office (IGPO) Suite 203, 409 Third St. SW, Washington DC 20024).

One approach to monitoring low frequency, global changes in the upper air is the establishment of selected climatological sites around the world using high quality radiosonde instruments and other sensing systems. Their function would be as climate monitors and not primarily to serve as additional sites for the global weather observing network. They could, of course, be co-located with such stations. Because climate monitoring is their function they would not be tied to the 00 and

12 UTC schedule; observations at local noon and midnight might be considered. Observations might also be coordinated with satellite observations.

In any event, considerable planning would need to go into such an enterprise and this is not the place to try to lay out such a network. Deciding how many stations and where they should go could be helped by modeling studies designed to address the question. An order-of-magnitude estimate of the number can be found in Angell's (1988) 63-station network. The estimates of temperature trends from this group of stations compares well with results using all the 700–800 radiosonde stations (Oort and Liu, 1993). Trenberth and Olson (1991) note that this network did a reasonable job of picking up the low frequency fluctuations in temperature over a 9-year period.

In summary then, the recommendations are: (1) collect in one location as much metadata as possible about both radiosonde and satellite observations (surface metadata could be included, as well); (2) continue to improve humidity sensors for both radiosondes and satellites, and data reduction algorithms, but give equally serious attention to continuity of the long-term record; (3) develop a reference radiosonde system to be a transfer standard for both present sondes and new ones as they are developed; (4) plan for a small network of upper-air climate stations, committed to be maintained for decades, perhaps with no determined end.

Probably the strongest recommendations is for the world's weather services to recognize the importance of climate, as distinct from weather forecasting, and to assume responsibility for detecting any changes in it.

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