MEASUREMENT OF UPPER-AIR PRESSURE, TEMPERATURE AND HUMIDITY

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Measurement of upper-air pressure, temperature and humidity

Foreword

In 2011, the WMO’s Commission for Instruments and Methods of Observation (CIMO) published the report on the WMO Intercomparison of High Quality Radiosondes, Yangjiang, China, 12 July to 3 August 2010, (WMO IOM Report 107, WMO/TD-No. 1580, 2011). Soon after, I requested Dr John Nash to use the increased knowledge and understanding of radiosondes provided by the Yangjiang intercomparison to update the relevant chapters of the so-called CIMO Guide (Guide to Meteorological Instruments and Methods of Observation, WMO No 8). I asked Dr Nash to do this because he is generally recognized as the world’s leading expert on radiosondes, he took the scientific lead in the Yangjiang intercomparison, he was primary author of the intercomparison report and he had recently retired from his lengthy and distinguished career with the UK Meteorological Office. Dr Nash kindly agreed to take the task on.

The result of his efforts over the following months was a comprehensive document containing an extraordinary amount of highly detailed information on all aspects of surface-based upper air measurements, with a strong focus on radiosondes, of particular use to radiosonde experts. When submitted to the CIMO Guide Editorial Board for its approval to include the material in the 2014 edition of the CIMO Guide, the Board agreed that the level of detail exceeded the more general requirements of the CIMO Guide, and it requested Dr Nash to provide a condensed version for publication in the Guide that would be reachable by a wider and less specialized audience. The Board noted, however, that Dr Nash’s original document comprised an invaluable reference for radiosonde specialists and should be preserved by separate publication as an IOM Report.

This report is that document, as authored by Dr Nash, in all its original detail. Starting with the existing version of the CIMO Guide (2010 update) Dr Nash revised that information, primarily to include the additional understanding gained from the Yangjiang intercomparison. At the same time, though, he added a wealth of further specialist knowledge, gained from his protracted involvement in WMO CIMO activities over more than thirty years, and in particular from his participation in all eight CIMO international radiosonde intercomparisons, commencing with the first, held at Bracknell in 1983.

This report comprises a treasure trove of information on radiosondes and other upper air measurement technologies and techniques. It contains the distilled knowledge and understanding gained by Dr Nash over the thirty years of his experience in testing and operating radiosondes. It is essential reading for anyone with a specialized interest in radiosondes.

I wish to express my sincere gratitude and that of the Commission for Instruments and Methods of Observation to Dr Nash for this extraordinary contribution to the CIMO literature. I also wish to thank the CIMO experts who gave their time to review an earlier draft of the report.

(Prof. B. Calpini)
President
Commission for Instruments and Methods of Observation
CONTENTS

Foreword .......................................................................................................................... 1
1 General ........................................................................................................................ 5
  1.1 Definitions ............................................................................................................... 5
1.2 Units used in upper-air measurements .................................................................. 6
1.3 Meteorological requirements .................................................................................. 6
  1.3.1 Radiosonde data for meteorological operations ............................................ 6
  1.3.2 Relationships between satellite and radiosonde upper-air measurements ....... 9
  1.3.3 Maximum height of radiosonde observations ................................................. 10
1.4 Uncertainty requirements [always stated in terms of k=2, see chapter 1, Part 1 of the CIMO Guide] ................................................................. 10
  1.4.1 Geopotential Height: Requirements and performance ............................... 11
  1.4.2 Temperature: Requirements and performance .............................................. 11
  1.4.3 Relative humidity: Requirements and performance .................................... 11
1.5 Measurement methods ........................................................................................... 12
  1.5.1 Constraints on radiosonde design ................................................................. 12
  1.5.2 Radio frequency used by radiosondes ......................................................... 13
1.6 Radiosonde errors, General considerations ........................................................... 14
  1.6.1 Types of error ................................................................................................ 14
  1.6.2 Potential references ....................................................................................... 14
  1.6.3 Sources of additional error during radiosonde operations .......................... 15
2 Radiosonde electronics ................................................................................................. 15
  2.1 General features .................................................................................................. 15
  2.2 Power supply for radiosondes ............................................................................ 16
  2.3 Methods of data transmission ............................................................................. 16
    2.3.1 Radio transmitter ......................................................................................... 16
3 Pressure sensors (including height measurements) .................................................... 16
  3.1 General aspects .................................................................................................... 16
  3.2 Aneroid capsules ............................................................................................... 17
  3.3 Aneroid capsule (capacitive) .............................................................................. 17
  3.4 Silicon sensors ................................................................................................... 18
  3.5 Pressure sensor errors ....................................................................................... 18
    3.5.1 Relationship of geopotential height errors with pressure errors ............... 20
  3.6 Use of geometric height observations instead of pressure sensor observations ... 21
Measurement of upper-air pressure, temperature and humidity

3.6.1 General ................................................................................................................. 21
3.6.2 Method of calculation .......................................................................................... 22
3.7 Sources of errors in direct height measurements .................................................. 24
    3.7.1 Sources of error in GPS geometric height measurements ............................... 24
    3.7.2 Radar height measurements .......................................................................... 25
4 Temperature sensors .................................................................................................. 25
    4.1 General requirements ......................................................................................... 25
    4.2 Thermistors .......................................................................................................... 27
    4.3 Thermocapacitors ............................................................................................... 27
    4.4 Thermocouples ..................................................................................................... 28
    4.5 Scientific Sounding Instruments ......................................................................... 28
    4.6 Exposure ................................................................................................................ 28
    4.7 Temperature errors .............................................................................................. 29
        4.7.1 Calibration ...................................................................................................... 29
        4.7.2 Thermal lag ..................................................................................................... 31
        4.7.3 Radiative heat exchange in the infrared .......................................................... 31
        4.7.4 Heating by solar radiation ............................................................................ 33
        4.7.5Deposition of ice or water on the sensor .......................................................... 37
        4.7.6 Representativeness issues ............................................................................. 37
5 Relative humidity sensors .......................................................................................... 39
    5.1 General aspects ..................................................................................................... 39
    5.2 Thin-film capacitors .............................................................................................. 43
    5.3 Carbon hygristors ................................................................................................. 44
    5.4 Goldbeater’s skin sensors .................................................................................... 44
    5.5 Scientific Sounding Instruments ......................................................................... 45
    5.6 Exposure ................................................................................................................ 46
    5.7 Relative humidity errors ...................................................................................... 47
        5.7.1 General considerations .................................................................................... 47
        5.7.2 Relative humidity, night, temperatures higher than -20°C .............................. 48
        5.7.3 Relative humidity, day, temperatures above -20°C ........................................ 51
        5.7.4 Relative humidity, night, temperatures between -20°C and -50°C ................. 54
        5.7.5 Relative humidity, day, temperatures between -20 °C and -50 °C .................. 55
        5.7.6 Night, temperatures between -50°C and -70°C ............................................. 56
        5.7.7 Day, temperatures between -50°C and -70°C ................................................ 58
        5.7.8 Wetting or icing in cloud ............................................................................... 60
        5.7.9 Representativeness errors ............................................................................. 60
6 Ground station equipment .......................................................................................... 62
Measurement of upper-air pressure, temperature and humidity

6.1 General features ................................................................. 62
6.2 Software for data processing .............................................. 63
7 Radiosonde operations ........................................................... 64
7.1 Control corrections immediately before use .......................... 64
7.2 Deployment methods ....................................................... 64
7.3 Radiosonde launch procedures ........................................... 65
7.4 Radiosonde suspension during flight .................................. 66
7.5 Public safety ................................................................. 66
8 Comparison, calibration and maintenance .............................. 67
8.1 Comparisons ..................................................................... 67
  8.1.1 Quality evaluation using short-term forecasts .................... 67
  8.1.2 Quality evaluation using atmospheric time series ............... 67
  8.1.3 Comparison of water vapour measurements with remote sensing ..... 68
  8.1.4 Radiosonde comparison tests ....................................... 68
8.2 Calibration ......................................................................... 69
8.3 Maintenance ....................................................................... 70
9 Computations and reporting .................................................. 70
9.1 Radiosonde computations and reporting procedures ............ 70
9.2 Corrections ........................................................................ 71
10 Procurement Issues ............................................................ 72
  10.1 Use of results from WMO Intercomparison of High Quality radiosondes, and update of these results. ......................................................... 72
  10.2 Some issues to be considered in procurement ..................... 72
Annex A Breakthrough and optimum uncertainty requirements
(standard error, k=2) for radiosonde measurements for synoptic and climate meteorology . 74
Annex B Estimates of goal, breakthrough and threshold limits for upper wind, upper air temperature, relative humidity and geopotential height ................................................. 75
Annex C Guidelines for organizing radiosonde intercomparisons and for the establishment of test site .......................................................... 79
References and further reading .................................................. 85
Measurement of upper-air pressure, temperature and humidity

Introduction

This paper is a detailed application of the results from the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, WMO (2011) into the format of chapter 12, Part I of WMO Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8 (2008, updated in 2010, hereafter called CIMO Guide). This is intended for use by radiosonde manufacturers, and those scientists interested in the development of the performance of radiosonde systems in the years since the start of the series of the WMO Intercomparison of Radiosondes in 1984/5. It will be condensed to provide an updated chapter 12, Part I, of the CIMO Guide, more suitable for non-specialists in radiosonde measurements to follow. Guidance on procurements of radiosonde systems should be based on the principles outlined in section 10 (Procurement Issues), with reference to sections 1.4 (Uncertainty Requirements) and Annex A and B, along with the performance achieved in operation, as indicated in Tables 2, 3, 5 to 6, 8, 10 and 11 to 16.


1 GENERAL

1.1 Definitions

The following definitions from WMO (1992; 2003a) are relevant to upper-air measurements using a radiosonde:

Radiosonde: Instrument intended to be carried by a balloon through the atmosphere, equipped with devices to measure one or several meteorological variables (pressure, temperature, humidity, etc.), and provided with a radio transmitter for sending this information to the observing station.

Radiosonde observation: An observation of meteorological variables in the upper air, usually atmospheric pressure, temperature, humidity, and often horizontal wind by means of a radiosonde.

Note: The radiosonde may be attached to a balloon (or a slow moving pilotless aircraft), or the design adjusted to be dropped (as a dropsonde) from an aircraft or rocket.

Radiosonde station: A station at which observations of atmospheric pressure, temperature, humidity and usually horizontal wind in the upper air are made by electronic means. (italics underlined, added to basic definition for clarity)

Upper-air observation: A meteorological observation made in the free atmosphere, either directly or indirectly.

Upper-air station, upper air synoptic station, aerological station: A surface location from which upper-air observations are made.

Sounding: Determination of one or several upper-air meteorological variables by means of instruments carried aloft by balloon, aircraft, kite, glider, rocket, and so on.

This chapter will deal with radiosonde systems. Measurements using special platforms, specialized equipment, and aircraft or made indirectly by remote-sensing methods such as microwave radiometers and Raman water vapour lidars in the boundary layer and troposphere will be discussed in various chapters of Part II of the CIMO Guide. Radiosonde systems are normally used to measure pressure, temperature and relative humidity. At most operational sites, the radiosonde system is also used for upper-wind determination (see Part I, Chapter 131). In addition, some radiosondes are flown with sensing systems for atmospheric constituents, such as ozone concentration or radioactivity. These additional measurements are not discussed in any detail in this chapter.

Measurement of upper-air pressure, temperature and humidity

1.2 Units used in upper-air measurements

The units of measurement for the meteorological variables of radiosonde observations are hectopascals for pressure, degrees Celsius for temperature, and per cent for relative humidity. Relative humidity is reported relative to saturated vapour pressure over a water surface, even at temperatures less than 0 °C.

The unit of geopotential height used in upper-air observations is the standard geopotential metre, defined as 0.980 665 dynamic metres. The relationship between geopotential height and geometric height is shown in section 4.5.2. Differences in the lower troposphere are not very large but get larger as the height increases.

The values of the physical functions and constants adopted by WMO (1988) should be used in radiosonde computations.

1.3 Meteorological requirements

1.3.1 Radiosonde data for meteorological operations

Upper-air measurements of temperature and relative humidity and wind are three of the basic measurements used in the initialization of the analyses of numerical weather prediction models for operational weather forecasting. Radiosondes provide most of the in situ temperature and relative humidity measurements over land, while radiosondes launched from remote islands or ships can in practice only provide a very limited coverage but significant over the oceans. Temperatures with resolution in the vertical similar to radiosondes can be observed by aircraft either during ascent, descent, or at cruise levels. Aircraft observations during ascent and descent are used to supplement radiosonde observations over land and in some cases may be used to replace the radiosondes at a given site. Aircraft observations at cruise level give measurements over both land and oceans. Nadir viewing satellite observations of temperature and water vapour distribution have lower vertical resolution than radiosonde or aircraft measurements. Satellite observations have large impact on numerical weather prediction analyses over the oceans and other areas of the globe where radiosonde and aircraft observations are sparse or unavailable.

Accurate measurements of the vertical structure of temperature and water vapour fields in the troposphere are extremely important for all types of forecasting, especially regional, local forecasting and now-casting. Atmospheric temperature profiles have discontinuities in the vertical, and the changes in relative humidity associated with the temperature discontinuities are usually quite pronounced, see Figure 1, where some examples of profiles are shown. The measurements indicate typical structure of cloud or fog layers in the vertical. This vertical structure of temperature and water vapour determines the stability of the atmosphere and, subsequently, the amount and type of cloud that will be forecast. Radiosonde measurements of the vertical structure can usually be provided with sufficient accuracy to meet most user requirements. However, small negative systematic errors in radiosonde relative humidity measurements at high humidity in clouds have caused problems in numerical weather prediction analyses, if the error is not compensated.

High-resolution measurements of the vertical structure of temperature and relative humidity are important for environmental pollution studies (for instance, identifying the depth of the atmospheric boundary layer). This high vertical resolution is also necessary for computing the effects of atmospheric refraction on the propagation of electromagnetic radiation or sound waves.
Measurement of upper-air pressure, temperature and humidity

(a) Examples of daytime temperature and humidity profiles from the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang. The grey sounding was made 8 hours after the black. Relatively small changes in the rate of temperature change in the vertical were associated with rapid drops in relative humidity [near 0.7, 1.6, 3.5, 5.5 and 8 km]

(b) Example of temperature and relative humidity, summer at 06.00 UTC in the UK, showing a shallow layer of 100 per cent relative humidity in fog near the ground and very rapid drops in relative humidity in the temperature inversion layers between 1.5 and 2 km and at 3.8 km

Figure 1. Examples of temperature and relative humidity profiles in the lower and middle troposphere.

Civil aviation, artillery and other ballistic applications, such as space vehicle launches, have operational requirements for detailed measurements of the density of air at given pressures (derived from radiosonde temperature and relative humidity measurements).

Radiosonde observations are also important for studies of upper-air climate change. Hence, it is necessary to keep adequate records of the systems, including software version and corrections, and consumables used for measurements and also the methods of observation (e.g. suspension length from the balloon) used with the systems. Climatologists would prefer that raw data are archived as well as processed data and made available for subsequent climatological studies. It is essential to record any changes in the methods of observation that are introduced as time progresses. In this context, it has proved essential to establish the changes in radiosonde instruments and practices that have taken place since radiosondes
were used on a regular basis (see for instance WMO, 1993a). Climate change studies based on radiosonde measurements require extremely high stability in the systematic errors of the radiosonde measurements. However, the errors in early radiosonde measurements of some meteorological variables, particularly relative humidity and pressure, were too high and too complex to generate meaningful corrections at all the heights required for climate change studies. Thus, improvements and changes in radiosonde design were necessary. Furthermore, expenditure limitations on meteorological operations require that radiosonde consumables remain cheap if widespread radiosonde use is to continue. When new radiosonde designs are introduced it is essential that enough testing of the performance of the new radiosonde relative to the old is performed, so that time series of observations at a station can be harmonised, based on comparison data. This harmonisation process should not degrade good measurements of an improved radiosonde design to be compatible with the poorer measurements of the earlier design, and it should be recognised that in some cases the errors in the earlier measurements were too large for use in climatological studies (particularly true with respect to recent relative humidity measurements, see section 5.7).

Certain compromises in system measurement accuracy have to be accepted by users, taking into account that radiosonde manufacturers are producing systems that need to operate over an extremely wide range of meteorological conditions:

- 1050 to 5 hPa for pressure
- 50 to –95 °C for temperature
- 100 to 1 per cent for relative humidity
- 30 hPa at the surface to 10^-4 hPa at the tropopause for water vapour pressure in the tropics.

Systems also need to be able to sustain continuous reliable operation when operating in heavy rain, in the vicinity of thunderstorms, and in severe icing conditions.

The coldest temperatures are most often encountered near the tropical and subtropical tropopause, although in winter very cold temperatures can also be observed at higher levels in the stratospheric polar vortex. Figure 2 shows examples of profiles from the subtropics, Yangjiang, China in summer and then at 50°N summer and winter, UK. The colder temperatures near the tropopause in the tropics lead to a major challenge for operational relative humidity sensors, because few currently respond very rapidly at temperatures below -70 °C, see section 5.7.6 and 5.7.7. Thus radiosondes which can perform well throughout the troposphere in mid-latitudes may have less reliable relative humidity measurements in the upper troposphere in the tropics.

**Figure 2. Examples of complete individual temperature profiles, made with large balloons suitable for Climate observations.**

A radiosonde measurement is close to an instant sample of a given layer of the atmosphere [the radiosonde usually ascends through 300 m in 1 minute.] In some cases, short term fluctuations in atmospheric temperature from gravity waves and turbulence are small, and the radiosonde measurement represents the situation above a location very effectively for many hours. On the other hand when the atmosphere is very variable (e.g. a convective atmospheric boundary layer) the instant sample may not be valid for longer than a minute and may not represent a good average value above the location, even for an
hour. In Figure 2(a) radiosonde temperatures in the troposphere were more reproducible with time than in the stratosphere, because of the larger influence of gravity waves in the stratosphere. These larger differences at upper levels were not the result of instrument error. Similarly the variation of temperatures in the vertical in the stratosphere in Figure 2(b) was not the result of instrument error, as the same structure was measured by two different radiosonde types on these test flights.

Machine computation of full atmospheric temperature profiles, giving the detailed structures shown in Figure 2, only began in the early 1980s and before this the data were reduced manually by the observer, from chart recorder records or coded signals. The use of full machine processing then spread throughout the world as PC computer systems became available and participation in the series of WMO Radiosonde Comparison tests encouraged national systems/manufacturers to treat stratospheric measurements more carefully. Earlier practices were based on a selection of relatively few significant level points in the stratosphere, that gave a structure in the vertical totally dependent on the ability and motivation of the observer on each shift to keep to the WMO coding guidance.

1.3.2 Relationships between satellite and radiosonde upper-air measurements

Nadir-viewing satellite observing systems do not measure vertical structure with the same accuracy or degree of confidence as radiosonde or aircraft systems. The current satellite temperature and water vapour sounding systems either observe upwelling radiances from carbon dioxide or water vapour emissions in the infrared, or alternatively oxygen or water vapour emissions at microwave frequencies (see Chapter 8, Part II of the CIMO Guide). Both infrared and microwave sounding measurements are essential for current operational numerical weather prediction. The radiance observed by a satellite channel is composed of atmospheric emissions from a range of heights in the atmosphere. This range is determined by the distribution of emitting gases in the vertical and the atmospheric absorption at the channel frequencies. Most radiances from a single satellite temperature channel approximate the mean layer temperature of a layer at least 10 km thick. However, much finer vertical resolution is achieved by recent Fourier transform interferometers operating in the infrared, using information from much larger numbers of channels with slightly different absorption characteristics. The height distribution (weighting function) of the observed temperature channel radiance will vary with geographical location to some extent. This is because the radiative transfer properties of the atmosphere have a small dependence on temperature. The concentrations of the emitting gas may vary to a small extent with location and cloud; aerosol and volcanic dust may also modify the radiative heat exchange. Hence, basic satellite temperature sounding observations provide good horizontal resolution and spatial coverage worldwide for relatively thick layers in the vertical, but the precise distribution in the vertical of the atmospheric emission observed may be more difficult to specify at any given location.

Most radiances observed by nadir-viewing satellite water vapour channels in the troposphere originate from layers of the atmosphere about 4 to 5 km thick. The pressures of the atmospheric layers contributing to the radiances observed by a water vapour channel vary with location to a much larger extent than for the temperature channels. This is because the thickness and central pressure of the layer observed depend heavily on the distribution of water vapour in the vertical. For instance, the layers observed in a given water vapour channel will be lowest when the upper troposphere is very dry. The water vapour channel radiances observed depend on the temperature of the water vapour. Therefore, water vapour distribution in the vertical can be derived only once suitable measurements of vertical temperature structure are available.

Limb-viewing satellite systems can provide measurements of atmospheric structure with higher vertical resolution than nadir-viewing systems; an example of this type of system is temperature and water vapour measurement derived from global positioning system (GPS) radio occultation. In this technique, vertical structure is measured along paths in the horizontal of at least 200 km (Kursinski and others, 1997) and is now in widespread use to provide improved measurements of vertical temperature structure around the tropopause where radiosondes are not available.

Thus, the techniques developed for using satellite sounding information in numerical weather prediction models incorporate information from other observing systems, mainly radiosondes and aircraft or the numerical weather prediction model fields themselves. The radiosonde information may be contained in an initial estimate of vertical structure at a given location, which is derived from

Measurement of upper-air pressure, temperature and humidity

forecast model fields or is found in catalogues of possible vertical structure based on radiosonde measurements typical of the geographical location or air mass type. In addition, radiosonde measurements are used to cross-reference the observations from different satellites or the observations at different view angles from a given satellite channel. The comparisons may be made directly with radiosonde observations or indirectly through the influence from radiosonde measurements on the vertical structure of numerical forecast fields.

Hence, radiosonde and satellite sounding systems, together with aircraft, are complementary observing systems and provide a more reliable global observation system when used together. Radiosonde and aircraft observations improve numerical weather prediction, even given the much larger volumes of satellite measurements available.

1.3.3 Maximum height of radiosonde observations

Radiosonde observations are used regularly for measurements up to heights of about 35 km, see for example Figure 2. However, many observations worldwide will not be made to heights greater than about 25 km, because of the higher cost of the balloons and gas necessary to lift the equipment to the lowest pressures. Temperature errors tend to increase with height, but with modern radiosondes the rate of increase is not that high and useful measurements can be made to 35 km, particularly at night.

Where radiosonde measurements are made for climate monitoring purposes, operational planning, on a Regional basis, needs to ensure sufficient larger balloons are procured to obtain measurements up to 30 km on a regular basis in the Region.

The problems associated with the contamination of sensors during flight and very long time-constants of sensor response at low temperatures and pressures currently limit the usefulness of radiosonde relative humidity measurements to the troposphere.

1.4 Uncertainty requirements [always stated in terms of k=2, see chapter 1, Part 1 of the CIMO Guide]

This section summarizes the requirements for uncertainty of the meteorological variables measured by radiosondes and compares them with typical operational performance. A detailed discussion of performance and sources of errors is given in detail in the later sections dealing with the individual meteorological variable, see sections 3.5, 3.7, 4.7 and 5.7 for pressure, heights, temperature and relative humidity respectively. The definition of uncertainty and systematic bias, and so on can be found in Chapter 1, Part I of the CIMO Guide.

Estimates of achievable optimum uncertainty for radiosonde observations, as of 2012, are included in Annex A. This Annex was generated following the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, WMO (2011). It estimates the optimum performance that can currently be obtained from operational radiosondes.

A summary of requirements for uncertainty and vertical resolution limits for radiosonde observations from WMO documents is presented in Annex B. These tables include information from either the WMO Observing requirements data base, the observation requirement targets published by GCOS (2009) for the GCOS Reference Upper Air Network (GRUAN), and limited information from atmospheric variability studies in WMO (1970).

The WMO Observing requirements data base includes three limits for most meteorological variables.

- The goal is an ideal requirement.
- Threshold is the minimum requirement to ensure data are useful.
- Breakthrough is an intermediate level between threshold and goal which if achieved, would result in a significant improvement for the target application.

Tables 1, 2 and 3 in Annex B, are mainly based on the requirements of the High resolution NWP application area, although information on goals derived from atmospheric variability studies are also shown when the goals differ from the WMO Observation data base goals. Climate requirements use the GCOS GRUAN requirements and those in the WMO Data base for AOPC or SPARC activities. Again when there are significant differences between the goals from the two documents these are

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Measurement of upper-air pressure, temperature and humidity

indicated in the tables. Requirements for geopotential height in Table 4 were derived as described in Annex B.

A radiosonde meeting the less stringent breakthrough requirements, as summarised in Annex A, should provide measurements suitable to provide good value for money in terms of national targeted use. However, the less stringent accuracy requirements will not meet the expectations of some users, e.g. for primary sites for climate change detection. Thus, an operational decision has to be made as to the quality of observation required by the national network, given that the use of the data in forecast operations will improve forecast quality over the country, if the observation quality meets the breakthrough targets.

The requirements for spacing between observations in the horizontal from the WMO Observing requirements data base have not been shown here, but these clearly show that radiosonde observations on their own cannot meet the minimum requirements of WIGOS, and must be supplemented by measurements of temperature, relative humidity and wind by other observing systems.

1.4.1 Geopotential Height: Requirements and performance

Modern radiosonde systems can have systematic pressure bias a little larger than 1 hPa near the surface, but systematic errors as large as this at pressures lower than 100 hPa are now rare, see Table 4. The radiosondes still using the best pressure sensors can measure heights near 10 hPa with a random error (k=2) of between 300 and 400 m, i.e. with a random error in pressure of about 0.6 hPa.

Thus, the goal in uncertainty for height measurements for NWP can be met by most radiosondes using a pressure sensor up to 100 hPa. However, it requires a radiosonde measuring height with GPS technology to measure up to 30 km with a random error in height of only 20 m, i.e. equivalent to a random error less than or equal to 0.05 hPa in pressure. Reliable height measurements at 30 km in the stratosphere were not obtained with the earlier generations of radiosondes.

The uncertainty goal for cloud base heights in the lower troposphere in Table 4 of Annex B requires pressure uncertainties k=2 of only 3 hPa associated with the cloud base height. Most modern radiosondes can come close to this requirement.

Ozone concentrations in the stratosphere, have pronounced gradients in the vertical, and height assignment errors from even relatively small pressure sensor errors, introduce significant errors into the ozonesonde ozone profile reports at all latitudes, and have proved one of the limiting factors in these measurements when using the older type of radiosonde with larger pressure errors in the stratosphere.

1.4.2 Temperature: Requirements and performance

Most modern radiosonde systems (introduced since 2000) measure temperature in the troposphere and in the stratosphere up to a height of about 31 km with an uncertainty (k=2) of between 0.4 and 1 K. This performance is usually close to the optimum performance for numerical weather prediction suggested in Table 2 of Annex B. However, uncertainty well in excess of k=2 is still found in some national radiosonde networks in tropical regions. Measurements with such large errors damage numerical weather prediction forecasts, if used.

In the stratosphere, radiosonde temperature uncertainties can be close to the goal for numerical weather prediction, but require some improvement in daytime conditions to be optimised for climate requirements.

As the goals for climate temperatures are more demanding than for numerical weather prediction, the GRUAN lead centre continues to work with the manufacturers and operators to reduce the uncertainty of the current operational measurements in the troposphere and stratosphere. Here it is extremely important that systematic bias is as near constant with time as possible, requiring tighter limits on the methods of observation than at standard operational sites. To obtain the most useful performance, operators must be careful to prepare and operate the radiosondes according to the instructions, whether from this document, the CIMO Guide, the manufacturer or, at GRUAN stations, according to the procedures agreed with the GRUAN Lead Centre. In the case of GRUAN it is necessary that the details of the radiosonde preparation are noted and archived as part of the METADATA associated with the measurement, Immler et al. (2010).

1.4.3 Relative humidity: Requirements and performance

The uncertainties in modern relative humidity sensor measurements at temperatures higher than -50 °C,
mostly fall within the range 5 to 14 per cent R.H. Thus, the measurements mostly meet the breakthrough limit for numerical weather prediction, but many need improvement to meet the breakthrough limit for climate measurements, see Table 3, Annex B.

At temperatures lower than -50°C, the uncertainties increase, with the best operational radiosonde sensors having an uncertainty of around 16 per cent R.H. at -70°C, i.e. close to the breakthrough for numerical weather prediction and not meeting the breakthrough for climate requirements. However, most modern sensors have uncertainties of around 24 per cent R.H. at the lowest temperatures. Several problems were identified in the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, WMO (2011). It is expected that the uncertainties in upper troposphere relative humidity will now improve with time as these are rectified.

1.5 Measurement methods

This section discusses radiosonde methods in general terms. Details of instrumentation and procedures are given in other sections.

1.5.1 Constraints on radiosonde design

Certain compromises are necessary when designing a radiosonde.

- Temperature measurements are found to be most reliable when sensors are exposed unprotected above the top of the radiosonde, but this also leads to direct exposure to solar radiation. In most modern radiosondes, coatings are applied to the temperature sensor to minimize solar heating and also to minimise heat exchange in the infrared. The radiation corrections work most reliably if the temperature sensor and its supports can be designed so that the solar heating does not vary significantly as the radiosonde rotates in flight relative to the sun. Software corrections for the residual solar heating are then applied during data processing.

- Nearly all relative humidity sensors require some protection from rain. A protective cover or duct reduces the ventilation of the sensor and hence the speed of response of the sensing system as a whole. The cover or duct also provides a source of contamination after passing through cloud. However, in practice, the requirement for protection from rain or ice is usually more important than perfect exposure to the ambient air. Thus, protective covers or ducts are mostly used with a relative humidity sensor. The alternative is to have two sensors which alternate, One is heated to drive off contamination, whilst the other sensor reports the relative humidity, and then the second sensor is heated whilst the first reports the relative humidity, and so on. Humidity sensors are often placed close to the temperature sensor, since until recent years the humidity sensor was assumed to be at the same temperature as the temperature sensor. However, now, many radiosondes measure the temperature of the relative humidity sensor directly, as the humidity sensor is rarely at exactly the same temperature as the air temperature reported by the radiosonde. If the humidity sensor temperature is measured directly then the relative humidity sensor may be given an improved exposure away from contamination from the main temperature sensor and its supports.

- Pressure sensors are usually mounted internally to minimize the temperature changes in the sensor during flight and to avoid conflicts with the exposure of the temperature and relative-humidity sensors.

- In many modern radiosondes a pressure sensor is not used, and geometric height is measured using GPS technology and then converted into geopotential height, given a knowledge of the gravitational fields at the location.

Other important features required in radiosonde design are reliability, robustness, light weight and small dimensions making launch easy. With modern electronic multiplexing readily available, it is also important to sample the radiosonde sensors at a high rate. If possible, this rate should be about once per second, corresponding to a minimum sample separation of about 5 m in the vertical. Since radiosondes are generally used only once, or not more than a few times, they must be designed for mass production at low cost. Ease and stability of calibration is very important, since radiosondes must often be stored for long periods (more than a year) prior to use. (Many of the most important Global Climate Observing System stations, for example, in Antarctica, are on sites where radiosondes cannot be delivered more than once per year.)

A radiosonde should be capable of transmitting an intelligible signal to the ground receiver over a slant
Measurement of upper-air pressure, temperature and humidity

range of at least 200 km. The voltage of the radiosonde battery varies with both time and temperature. Therefore, the radiosonde must be designed to accept battery variations without a loss of measurement accuracy or an unacceptable drift in the transmitted radio frequency.

1.5.2 Radio frequency used by radiosondes

The radio frequency spectrum bands currently used for most radiosonde transmissions are shown in Table 1. These correspond to the meteorological aids allocations specified by the International Telecommunication Union (ITU) Radiocommunication Sector radio regulations.

Table 1. Primary frequencies used by radiosondes in the meteorological aids bands

<table>
<thead>
<tr>
<th>Radio frequency band (MHz)</th>
<th>Status</th>
<th>ITU regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>400.15 – 406</td>
<td>Primary</td>
<td>All</td>
</tr>
<tr>
<td>1 668.4 – 1 700</td>
<td>Primary</td>
<td>All</td>
</tr>
</tbody>
</table>

Note: Some secondary radar systems manufactured and deployed in the Russian Federation may still operate in a radio frequency band centred at 1 780 MHz.

The radio frequency actually chosen for radiosonde operations in a given location will depend on various factors. At sites where strong upper winds are common, slant ranges to the radiosonde are usually large and balloon elevations are often very low. Under these circumstances, the 400-MHz band will normally be chosen for use since a good communication link from the radiosonde to the ground system is more readily achieved at 400 MHz than at 1680 MHz. When upper winds are not so strong, the choice of frequency will, on average, be usually determined by the method of upper-wind measurement used (see Part I, Chapter 13 of the CIMO Guide4). The frequency band of 400 MHz is usually used when navigational aid windfinding is chosen, and 1680 MHz when radiotheodolites or a tracking antenna are to be used with the radiosonde system.

The radio frequencies listed in Table 1 are allocated on a shared basis with other services. In some countries, the national radiocommunication authority has allocated part of the bands to other users, and the whole of the band is not available for radiosonde operations. In other countries, where large numbers of radiosonde systems are deployed in a dense network, there are stringent specifications on radio frequency drift and bandwidth occupied by an individual flight.

Any organization proposing to fly radiosondes should check that suitable radio frequencies are available for their use and should also check that they will not interfere with the radiosonde operations of the National Meteorological Service.

There are now strong requirements from government, to improve the efficiency of radio frequency use. Therefore, radiosonde operations will have to share with a greater range of users in the future. Wideband radiosonde systems occupying most of the available spectrum of the meteorological aids bands will become impracticable in many countries. Therefore, preparations for the future in most countries should be based on the principle that radiosonde transmitters and receivers will have to work with bandwidths of much less than 1 MHz in order to avoid interfering signals. Transmitter stability will have to be better than ±5 kHz in countries with dense radiosonde networks, and not worse than about ±200 kHz in most of the remaining countries.

National Meteorological Services need to maintain contact with national radiocommunication authorities in order to keep adequate radio frequency allocations and to ensure that their operations are protected from

interference. Radiosonde operations will also need to avoid interference with, or from, data collection platforms transmitting to meteorological satellites between 401 and 403 MHz, with the downlinks from meteorological satellites between 1 690 and 1 700 MHz and with the command and data acquisition operations for meteorological satellites at a limited number of sites between 1 670 and 1 690 MHz.

1.6 Radiosonde errors, General considerations

1.6.1 Types of error
This section contains a detailed discussion of the errors encountered with radiosonde sensors. Measurement errors by radiosondes may be classified into three types (WMO, 1975):
(a) Systematic errors characteristic of the type of radiosonde in general;
(b) Sonde error, representing the variation in errors that persist through thick layers in the vertical for a particular type of radiosonde from one flight to the next;
(c) Random errors in individual observations, producing the scatter superimposed on the sonde error through a given ascent.

However, for many users it is also helpful to take note of the magnitude of the representativeness errors that are associated with a measurement, e.g. see Kitchen (1989) and Chapter 1 of Part I of the CIMO guide. For instance radiosonde temperature observations are assigned an error in data assimilation schemes, and this is more a representativeness error than the small instrumentation errors identified in section 3.7. These errors differ with atmospheric situation, and also with the use made of the measurement, e.g. as the scales of motion represented in a numerical weather prediction model increase, then the radiosonde representativeness errors ought to decrease, as the model represents more of what the radiosonde measures. On the other hand a climatologist wants measurements that are close to a longer term average, representing a significant area around the launch site. The structure introduced by localised small scale fluctuations in the radiosonde measurement are undesirable for this purpose.

1.6.2 Potential references
High-precision tracking radar measurements, or GPS height measurements, can allow systematic errors in geopotential height measurements to be quantified. These results can then be used to identify systematic errors in radiosonde pressure sensor measurements, given that errors in temperature measurements are known to be relatively small.

Most newly developed radiosondes measure temperatures at night which fall within a range of ± 0.2 K at a height of 30 km WMO, (2006a), WMO (2011). Thus, at night, it is possible to identify systematic errors that bias radiosonde measurements away from this consensus.

Interpretation of daytime temperature comparisons with similar uncertainty is still not feasible. For instance, the average temperatures in the same tests fall within about ± 0.5 K at a height of 30 km. When used in big international tests, the scientific sounding instrumentation has not yet achieved the required performance in daytime to identify correct measurements with the same uncertainty as at night.

Relative humidity measurements can be checked at high humidity when the radiosondes pass through clouds. Here, laser ceilometer and cloud radars can provide better evidence on the cloud observed by the radiosonde during its ascent. The vertical structure in relative humidity reported by radiosondes, including the presence of very dry layers, can be validated by comparison with Raman lidar measurements.

In most radiosonde comparison tests, the results from one radiosonde design are compared with those of another to provide an estimate of their systematic differences. The values of sonde error and random errors can usually be estimated from the appropriate method of computing the standard deviations of the differences between the two radiosonde types. The most extensive series of comparison tests performed since 1984 have been those of the WMO International Radiosonde Comparison (WMO, 1987: 1991; 1996a; 2006b), and the tests performed in Brazil (2006c), in Mauritius, WMO (2006a) and in Yangjiang, China, WMO (2011). The results from these and other tests to the same standards, in the United Kingdom, e.g. see results from Camborne in WMO (2006a) and also from Camborne in Nash et al. (2010), United States and Switzerland will sometimes be quoted in the subsequent sections.

There are several national facilities allowing the performance of radiosonde sensors to be tested at different pressures and temperatures in the laboratory. In WMO (2006b) the WMO Radiosonde Humidity Sensor Intercomparison contained results from laboratory comparisons with humidity standards in Russia.
Measurement of upper-air pressure, temperature and humidity

These results can be helpful in identifying some but not all of the problems identified when flying in the atmosphere.

1.6.3 Sources of additional error during radiosonde operations

It is extremely important to perform pre-flight radiosonde checks very carefully, since mistakes in measuring values for control data used to adjust calibrations can produce significant errors in measurement during the ascent. Observation errors in the surface data obtained from a standard screen and then included in the radiosonde message must also be avoided. An error in surface pressure will affect all the computed geopotential heights. For the same reason, it is important that the surface pressure observation should correspond to the official station height.

Random errors in modern radiosonde measurements are now generally small. This is the result of improved radiosonde electronics and multiplexing, providing more reliable data telemetry links between the ground station, and reliable automated data processing in the ground station. Thus, the random errors are usually less significant than systematic radiosonde errors and flight-to-flight variation in sensor performance and calibration (sonde error). However, random errors may become large if there is a partial radiosonde failure in flight, if interference is caused by another radiosonde using a similar transmission frequency, or if the radiosondes are at long slant ranges and low elevations that are incompatible with the specifications of the ground system receiver and aerials.

Thus, errors in radiosonde measurements may be caused not only by the radiosonde sensor design, and problems with calibration in the factory during manufacture, but also by problems in the reception of the radiosonde signal at the ground and the effect on subsequent data processing. When signal reception is poor, data-processing software will often interpolate values between the occasional measurements judged to be valid. Under this circumstance, it is vital that the operator is aware of the amount of data interpolation occurring. Data quality may be so poor that the flight should be terminated and a replacement radiosonde launched.

Software errors in automated systems often occur in special circumstances that are difficult to identify without extensive testing. Usually, the errors result from an inadvertent omission of a routine procedure necessary to deal with a special situation or combination of events normally dealt with instinctively by an expert human operator.

2 RADIOSONDE ELECTRONICS

2.1 General features

A basic radiosonde design usually comprises three main parts as follows:
   (a) The sensors plus references;
   (b) An electronic transducer, converting the output of the sensors and references into electrical signals;
   (c) The radio transmitter.

In rawinsonde systems (see Part I, Chapter 13 of the CIMO Guide⁵), there are also electronics associated with the reception and retransmission of radionavigation signals, or transponder system electronics for use with secondary radars.

Radiosondes are usually required to measure more than one meteorological variable. Reference signals are used to compensate for instability in the conversion between sensor output and transmitted telemetry. Thus, a method of switching between various sensors and references in a predetermined cycle is required. Most modern radiosondes use electronic switches operating at high speed with one measurement cycle lasting typically between 1 and 2 s. This rate of sampling allows the meteorological variables to be sampled at height intervals of between 5 and 10 m at normal rates of ascent.

---

2.2 Power supply for radiosondes

Radiosonde batteries should be of sufficient capacity to power the radiosonde for the required flight time in all atmospheric conditions. For radiosonde ascents to 5 hPa, radiosonde batteries should be of sufficient capacity to supply the required currents for up to three hours, given that the radiosonde launch may often be delayed and that flight times may be as long as two hours. Three hours of operation would be required if descent data from the radiosonde were to be used. Batteries should be as light as practicable and should have a long storage life. They should also be environmentally safe following use. Many modern radiosondes can tolerate significant changes in output voltage during flight. Two types of batteries are in common use, the dry-cell type and water-activated batteries.

The use of Dry cell batteries has increased rapidly and these have the advantages of being widely available at very low cost because of the high volume of production worldwide, and of lower occupational health and safety risk (and environmental impact). However, they may have the disadvantage of having limited shelf life. Also, their output voltage may vary more during discharge than that of water-activated batteries.

Water-activated batteries usually use a cuprous chloride and sulphur mixture. The batteries can be stored for long periods. The chemical reactions in water-activated batteries generate internal heat, reducing the need for thermal insulation and helping to stabilize the temperature of the radiosonde electronics during flight. These batteries are not manufactured on a large scale for other users. Therefore, they are generally manufactured directly by the radiosonde manufacturers.

Care must be taken to ensure that batteries do not constitute an environmental hazard once the radiosonde falls to the ground after the balloon has burst.

2.3 Methods of data transmission

2.3.1 Radio transmitter

A wide variety of transmitter designs are in use. Solid-state circuitry is mainly used up to 400 MHz and valve (cavity) oscillators may be used at 1 680 MHz. Modern transmitter designs are usually crystal-controlled to ensure a good frequency stability during the sounding. Good frequency stability during handling on the ground prior to launch and during flight are important. At 400 MHz, widely used radiosonde types are expected to have a transmitter power output lower than 250 mW. At 1 680 MHz the most widely used radiosonde type has a power output of about 330 mW. The modulation of the transmitter varies with radiosonde type. It would be preferable in future if radiosonde manufacturers could agree on a standard method and format for transmission of data from the radiosonde to the ground station, which would allow the user interoperability between radiosonde types without the need to modify the ground reception hardware and software each time. In any case, the radiocommunication authorities in many regions of the world will require that radiosonde transmitters meet certain specifications in future, so that the occupation of the radiofrequency spectrum is minimized and other users can share the nominated meteorological aids radiofrequency bands (see section 1.5.2).

3 PRESSURE SENSORS (INCLUDING HEIGHT MEASUREMENTS)

3.1 General aspects

Radiosonde pressure sensors must sustain accuracy over a very large dynamic range from 3 to 1 000 hPa, with a resolution of 0.1 hPa over most of the range and a resolution of 0.01 hPa for pressures less than 100 hPa. Changes in pressure are usually identified by a small electrical or mechanical change. For instance, the typical maximum deflection of an aneroid capsule is about 5 mm, so that the transducer used with the sensor has to resolve a displacement of about 0.5 µm. Changes in calibration caused by sensor temperature changes during the ascent must also be compensated. These temperature changes may be as large as several tens of degrees, unless the pressure sensor is mounted in a stabilized environment.

Thus, pressure sensors are usually mounted internally within the radiosonde body to minimize the temperature changes that occur. In some cases, the sensor is surrounded by water bags to reduce cooling. When water-activated batteries are used, the heat generated by the chemical reaction in the battery is used to compensate the internal cooling of the radiosonde. However, even in this case, the
radiosonde design needs to avoid generating temperature gradients across the sensor and its associated electrical components. If a pressure sensor has an actively controlled temperature environment, the sensor assembly should be mounted in a position on the radiosonde where heat contamination from the pressure sensor assembly cannot interfere with the temperature or relative humidity measurements.

The pressure sensor and its transducer are usually designed so that sensitivity increases as pressure decreases. The time-constant of response of radiosonde pressure sensors is generally very small, and errors from sensor lag are not significant.

Historically, when manufacturing a reliable pressure sensor for low pressure sensor for low pressure, sensors with poor performance were replaced by pressures deduced from radar heights, as in the UK in the years before 1978. In the former USSR very accurate secondary radars are used to measure geometric heights instead of using a pressure sensor on the radiosonde.

Now many modern radiosonde systems use GPS navigation signals for locating the position of the radiosonde and have dispensed with the use of a pressure sensor on the radiosonde (to save consumable costs) and instead measure geometric height, and hence geopotential height directly, see 3.6, with the pressure changes in flight computed from the radiosonde temperature and humidity measurements.

### 3.2 Aneroid capsules

Aneroid capsules have been used as the pressure sensor in the majority of radiosondes. In the older radiosonde designs, the capsules were usually about 50 to 60 mm in diameter. The sensors are made from a metal with an elastic coefficient that is independent of temperature. The measurement of the deflection of the aneroid capsule can be achieved either by an external device requiring a mechanical linkage between the capsule and the radiosonde transducer or by an internal device (see section 3.3).

Aneroid sensitivity depends mainly on the effective surface area of the capsule and its elasticity. Capsules can be designed to give a deflection that is linearly proportional to the pressure or to follow some other law, for example, close to a logarithmic dependence on pressure. The long-term stability of the capsule calibration is usually improved by seasoning the capsules. This is achieved by exercising the capsules through their full working range over a large number of cycles in pressure and temperature.

When the aneroid is used with a mechanical linkage to a transducer, the sensor usually suffers from a hysteresis effect of about 1 to 2 hPa. This hysteresis must be taken into account during the sensor calibration. The change in pressure during calibration must be of the same sense as that found in actual sounding conditions. The mechanical linkage to the radiosonde transducer often consists of a system amplifying the movement of the capsule to a pointer operating switch contacts or resistive contacts. A successful operation requires that friction be minimized to avoid both discontinuous movements of the pointer and hysteresis in the sensor system.

### 3.3 Aneroid capsule (capacitive)

Many modern radiosonde designs use aneroid capsules of smaller diameter (30 mm or less in diameter) with the deflection of the capsule directly measured by an internal capacitor. A parallel plate capacitor used for this purpose is formed by two plates each fixed directly to one side of the capsule. The capacitance, \( C \), is then:

\[
C = \epsilon \cdot \frac{S}{e} 
\]  

where \( S \) is the surface area of each plate, \( e \) is the distance between the plates and \( \epsilon \) is the dielectric constant. As \( e \) is a direct function of the deflection of the capsule, the capacitance \( C \) is a direct electrical measurement of the deflection. In many radiosonde sensors, each capacitor plate is fixed to the opposite side of the capsule by mounts passing through holes in the other plate. With this configuration, \( e \) decreases when the pressure lowers. The sensitivity of the capacitive sensor is:

\[
-\frac{\epsilon \cdot S}{e^2} \cdot \frac{de}{dp} 
\]  

This will be greatest when \( \epsilon \) is small and the pressure is smallest. The capacitive sensor described is more complicated to manufacture but is best suited for upper-air measurements, as the sensitivity can be 10 times greater at 10 hPa than at 1000 hPa. The value of the capacitance is usually close to 6 pF.
Capacitive aneroid capsules are usually connected to a resistance-capacitance electronic oscillator with associated reference capacitors. This arrangement needs to measure very small variations of capacity (for example, 0.1 per cent change in a maximum of 6 pF) without any significant perturbation of the oscillator from changes in temperature, power supply or ageing. Such high stability in an oscillator is difficult to achieve at a low price. However, one solution is to multiplex the input to the oscillator between the pressure sensor and two reference capacitors. A reference capacitor $C_1$ is connected alone to the oscillator, then in parallel with $C_p$, the pressure sensor capacitor, and then in parallel with a second reference $C_2$ to provide a full-scale reference.

The calibration of an aneroid capacitive sensor will usually have significant temperature dependence. This can be compensated either by referencing to an external capacitor which has a temperature coefficient of similar magnitude or during data processing in the ground system using calibration coefficients from factory calibrations. The correction applied during processing will depend on the internal temperature measured close to the pressure sensor. In practice, both of these compensation techniques may be necessary to achieve the required accuracy.

### 3.4 Silicon sensors

Following rapid developments in the use of silicon, reliable pressure sensors can now be made with this material. A small cavity is formed from a hole in a thick semiconductor layer. This hole is covered with a very thin layer of silicon, with the cavity held at a very low pressure. The cavity will then perform as a pressure sensor, with atmospheric pressure sensed from the deflection of the thin silicon cover.

A method of detecting the deflection of the silicon is to use a capacitive sensor. In this case, the thin silicon layer across the cavity is coated with a thin metallic layer, and a second metallic layer is used as a reference plate. The deflection of the silicon cover is measured by using the variation in the capacitance between these two layers. This type of sensor has a much lower temperature dependence than the strain gauge sensor and is now in widespread use. Because the sensor is very small, it is possible to avoid the calibration errors of the larger capacitive aneroid sensors introduced by changes in temperature gradients across the aneroid sensor and associated electronics during an ascent.

### 3.5 Pressure sensor errors

Systematic errors and the radiosonde error (flight-to-flight variation at $k=2$ have been estimated from the WMO International Radiosonde Comparison for selected radiosonde types and from other earlier tests where precision radars have been used to check pressure sensor performance. The results are shown in Table 2. The range of values of systematic error usually represents the spread of results from several tests. However, in those cases when a test was performed without a radar to cross-check the pressure sensor performance, this may be an indication of uncertainty in the error estimate.

Aneroid capsules were liable to change calibration unless they had been well seasoned through many pressure cycles over their working range before use. Software corrections applied during data processing, but based on ground control readings before launch, went some way toward reducing these errors. Nevertheless, corrections based on ground checks relied on a fixed error correction pattern across the working range. In practice, the change in pressure sensor calibration was more variable over the working range.

Hysteresis errors during ascent should be eliminated largely by calibration, but they become important if observations during descent are used, in which case appropriate corrections should be applied. Systematic errors will arise in the application of temperature corrections if the pressure unit is not at the assumed temperature.
Measurement of upper-air pressure, temperature and humidity

### Table 2. Range of systematic error and radiosonde error (flight to flight, k=2) and overall uncertainty in pressure from the WMO International Radiosonde Comparison and associated tests

<table>
<thead>
<tr>
<th>Radiosonde type</th>
<th>Systematic error</th>
<th>Sonde error</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure level (hPa)</td>
<td>850</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>VIZ 1392</td>
<td>-0.1 to 0.5</td>
<td>-0.5 to 0.1</td>
<td>-0.5 to -0.2</td>
</tr>
<tr>
<td>SMG (China)</td>
<td>-3.3 to -1.8</td>
<td>-2.5 to -0.8</td>
<td>-1.3 to 0.5</td>
</tr>
<tr>
<td>MRZ* (Russian Federation)</td>
<td>-1.5 to -0.5</td>
<td>-2 to -0.8</td>
<td>0 to 0.2</td>
</tr>
<tr>
<td>Vaisala RS80</td>
<td>0.5 to 1</td>
<td>-1 to -0.5</td>
<td>-0.5 to 0</td>
</tr>
<tr>
<td>Meisei RS2-91</td>
<td>0.2 to 1</td>
<td>-0.1 to 0.5</td>
<td>-0.2 to 0.2</td>
</tr>
<tr>
<td>VIZ Mk11</td>
<td>0 to 1</td>
<td>0.7 to 1.1</td>
<td>0.3 to 0.7</td>
</tr>
<tr>
<td>Vaisala RS92</td>
<td>&lt;0.5</td>
<td>&lt;0.3</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Modem* M2K2</td>
<td>-0.4 to -0.8</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Vaisala* RS92</td>
<td>&lt;0.5</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>China (Daqiao)</td>
<td>&lt;0.5</td>
<td>&lt;0.3</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>LMS* LMG-6</td>
<td>&lt;0.5</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

*Does not use a pressure sensor, but computes pressure from geopotential height measurements, see section 3.6

In Table 2 the two pressure systems tested that were in use pre 1980 were the VIZ 1392 and the Chinese SMG. The VIZ 1392 (baroswitch), did not provide continuous output but the mechanical link from the aneroid capsule activated a switch which switched the radiosonde transmission at predetermined pressures between temperature and relative humidity and occasional reference signals. Interpolation between switches at low pressures required good operator skill to obtain the best results. This system could not have coped with the conditions shown in Figure 4. The Chinese SMG also did not have continuous pressure output, but the mechanical linkage from the aneroid capsule changed the contact point on a code sending drum. The coded signal was decoded by the operator in real time on the ground, but in the last years of its use, the process was automated to some extent. Systematic biases for all aneroid sensors were not always small for a variety of reasons, including poor factory calibrations, difficulties in ground checking certain types of radiosonde, and inadequate temperature compensation during the ascent. The uncertainties for pressure were generally in the range of 5 to 8 hPa in the troposphere. However, evidence from comparisons with radar heights in earlier operations suggests that many other early radiosondes of similar sensor type had larger errors than those shown here from the WMO tests.

The MRZ secondary radar system was introduced into the Russian Federation in the mid-1980’s, with the results shown obtained in 1989. There is no pressure sensor and the pressure is computed from measurements of geometric height which are then converted to geopotential height as shown in section 3.5. This system provided more reliable measurements in the upper stratosphere than the mechanically linked aneroid capsules. The quality depended on the performance of each individual
Measurement of upper-air pressure, temperature and humidity

secondary radar, and these were not the easiest systems to maintain, so that in some cases tracking errors and subsequent pressure errors were significantly higher than those obtained in the WMO test.

The Vaisala RS80, VIZ MKII, and Meisei RS2-91 radiosondes all had capacitive aneroid sensors, but of differing design. The uncertainties for the capacitive aneroids were significantly smaller than for the other aneroid types, as quantisation errors were not a problem, and overall uncertainty (k=2) was usually lower than 2 hPa at most pressures. However, these capacitive aneroid capsules could have significant systematic errors, particularly when the internal temperature of the radiosonde changed and temperature gradients developed across the sensor and its associated electronics, but these were usually not larger than ±1hPa. However, errors could be larger if the pressure sensors experienced very large thermal shock during the launch. This might occur in polar conditions if the radiosonde was not allowed to acclimatize to external conditions before launch.

The Vaisala RS92 is a silicon sensor. The performance of these sensors does not show the effects of thermal shock and the uncertainties obtained with the systems were even better than with the previous group.

The consequences of the pressure errors in Table 2 on reported temperatures would be as follows. A 1 hPa pressure error will produce a temperature error, on average, of −0.1 K at 900 hPa, −0.3 K in the upper troposphere (at 200 hPa in the tropics), ±0.5 K at 30 hPa (varying between summer and winter conditions at about 55°N) and up to at least 1 K for most situations at 10 hPa.

3.5.1 Relationship of geopotential height errors with pressure errors

The error, $\epsilon_z(t_1)$, in the geopotential height at a given time into flight is given by:

$$
\epsilon_z(t_1) = R \frac{p_0}{g} \int_{p_1}^{p_0} \left[ \frac{\delta T}{\delta p} \epsilon_T(p) \right] \frac{dp}{p} + \frac{R}{g} \int_{p_1}^{p_0} \left[ T_v(p) + \epsilon_T(p) \right] \frac{dp}{p}
$$

(3)

where $p_0$ is the surface pressure; $p_1$ is the true pressure at time $t_1$; $p_1 + \epsilon_T(p_1)$ is the actual pressure indicated by the radiosonde at time $t_1$; $\epsilon_T(p)$ and $\epsilon_T(p)$ are the errors in the radiosonde temperature and pressure measurements, respectively, as a function of pressure; $T_v(p)$ is the virtual temperature at pressure $p$; and $R$ and $g$ are the gas and gravitational constants as specified in WMO (1988).

For a specified standard pressure level, $p_s$, the second term in equation 3 disappears because there is no error in $p_s$ and so, the error in the standard pressure level geopotential height is smaller:

$$
\epsilon_z(p_s) = R \frac{p_s}{g} \int_{p_s}^{p_0} \left[ \frac{\delta T}{\delta p} \epsilon_T(p) \right] \frac{dp}{p}
$$

(4)

And for radiosondes without a pressure sensor using a radar

$$
\epsilon_z(p_s) = T_v(p_s) \int_{Z_0}^{Z_{ps}} \frac{Z_{ps}}{g/T_v^2} \left[ \epsilon_T(z) + \epsilon_T(Range, \theta) \cdot dT_v/dz \right]
$$

(5)

where $Z_{ps}$ is the geopotential height of the specified pressure level $p_s$, and the error in geopotential height for a radar is a function of slant range and elevation angle ($\theta$), and will vary from flight to flight according to the wind conditions.

Table 3 shows, the errors in geopotential height that are caused by radiosonde sensor errors for typical atmospheres. The geopotentials of given pressure levels have small errors, whether caused by a radiosonde temperature or pressure error. The pressure error has a slightly different effect at different latitudes because of the differences in typical temperature profile structure with latitude. However, the same pressure sensor errors produce much larger errors in the heights of specific structures e.g. temperature inversions, including the tropopause, and cloud tops and bases.
Measurement of upper-air pressure, temperature and humidity

Table 3. Systematic Errors in geopotential height (gpm) from given pressure and temperature errors

<table>
<thead>
<tr>
<th></th>
<th>( \varepsilon_1, \text{error (K)} )</th>
<th>( \varepsilon_p, \text{error (hPa)} )</th>
<th>Latitude</th>
<th>300 hPa</th>
<th>100 hPa</th>
<th>30 hPa</th>
<th>10 hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard pressure</td>
<td>0.25</td>
<td>0</td>
<td>All</td>
<td>9</td>
<td>17</td>
<td>26</td>
<td>34</td>
</tr>
<tr>
<td>height, T error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard pressure</td>
<td>0</td>
<td>-1</td>
<td>25(^\circ)N</td>
<td>3</td>
<td>12</td>
<td>-2</td>
<td>-24</td>
</tr>
<tr>
<td>height, p error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard pressure</td>
<td>0</td>
<td>-1</td>
<td>50(^\circ)N</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>-20</td>
</tr>
<tr>
<td>height, p error</td>
<td></td>
<td></td>
<td>summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard pressure</td>
<td>0</td>
<td>-1</td>
<td>50(^\circ)N</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>-4</td>
</tr>
<tr>
<td>height, p error</td>
<td></td>
<td></td>
<td>winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant level</td>
<td>0</td>
<td>-1</td>
<td>25(^\circ)N</td>
<td>27</td>
<td>72</td>
<td>211</td>
<td>650</td>
</tr>
<tr>
<td>height, p error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant level</td>
<td>0</td>
<td>-1</td>
<td>50(^\circ)N</td>
<td>26</td>
<td>72</td>
<td>223</td>
<td>680</td>
</tr>
<tr>
<td>height, p error</td>
<td></td>
<td></td>
<td>summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant level</td>
<td>0</td>
<td>-1</td>
<td>50(^\circ)N</td>
<td>26</td>
<td>70</td>
<td>213</td>
<td>625</td>
</tr>
<tr>
<td>height, p error</td>
<td></td>
<td></td>
<td>winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The importance of equations (4) and (5) is that the errors in standard pressure level geopotentials are primarily related to the temperature errors, and so if geopotential heights are compared against collocated NWP first guess forecast fields, the height anomalies give an indication of the relative temperature performance at the two sites, e.g. see WMO (2003b).

### 3.6 Use of geometric height observations instead of pressure sensor observations

#### 3.6.1 General

Geometric height observations can now be provided by GPS radiosondes that decode global positioning satellite signals, as opposed to the early GPS radiosondes that did not decode the signals. The geometric height observations are have small enough uncertainty (between 10 and 20 m) to be used to compute pressure at a given time into flight, using surface pressure and temperature and relative humidity observations, see equation 12 and 13. In the stratosphere, the computed pressures are found to have smaller uncertainty than measurements provided by the best radiosonde pressure sensors, see Table 2.

When a radar (now, usually a secondary radar where the radiosonde responds to a pulse emitted by the radar to allow range to be estimated) is in use for windfinding, radar height measurements may also provide an alternative to the use of a radiosonde pressure sensor, but these heights will not be as accurate as those obtainable from the GPS radiosondes. The errors in radar height data depend upon the installation and calibration of individual radars. Thus, it is much more difficult to obtain consistency from station to station in geopotential height and pressure measurements in a national upper-air network that depends on radar height measurements than if the national network uses GPS heights or pressure sensors. The elimination of the pressure sensor from GPS radiosondes provides a considerable saving in terms of the cost of some radiosondes, but it is also necessary to check user requirements for the non-hydrostatic numerical weather prediction models that are being introduced, since direct measurements of pressure and geopotential height in the troposphere may be of some advantage when hydrostatic balance does not represent atmospheric conditions.
3.6.2 Method of calculation

The conversion from geometric height, as measured with a GPS radiosonde to geopotential height is purely a function of the gravitational field at a given location, and does not depend on the temperature and humidity profile at the location. The Gravitational potential energy ($\Phi_1$) of a unit mass of anything is the integral of the normal gravity from mean sea level ($z=0$) to the height of the radiosonde ($z=z_1$), as given by equation (6).

\[
\Phi_1 = \int_0^{z_1} g(z, \varphi) \, dz \quad (6)
\]

Where $g(z, \varphi)$ is the normal gravity above the geoid. This is a function of geometric altitude, $z$ and the geodetic latitude ($\varphi$).

This geopotential is divided by the normal gravity at latitude of 45° to give the geopotential height used by WMO as:-

\[
Z_1 = \Phi_1 / \gamma_{45} \quad (7)
\]

where $\gamma_{45}$ was taken in the definition as $9.80665 \text{ ms}^{-2}$. Note that surface gravity is greatest at the poles ($9.83218 \text{ ms}^{-2}$) and least at the equator ($9.78033 \text{ ms}^{-2}$).

The variation of gravity with height must take into account the ellipsoidal shape of the earth, and the earth’s rotation. However, when the variation of $g$ with height was taken into account, the geopotential height, $Z_1$, at geometric height, $z_1$, was approximated in the Smithsonian tables as:-

\[
Z_1(z_1, \varphi) = (\gamma_{\text{SMT}}(\varphi) / \gamma_{45}) \cdot ((R_{\text{SMT}}(\varphi) \cdot z_1)/(R_{\text{SMT}}(\varphi) + z_1)) \quad (8)
\]

where $R_{\text{SMT}}(\varphi)$ is an effective radius of the earth for latitude ($\varphi$) and is the value in the Smithsonian Tables (List,1968) which was chosen to take account of the actual changes with geometric height in the combined gravitational and centrifugal forces. It is not the actual radius of the earth at the given latitude. This is shown in Figure 3 where the Smithsonian radius increases from the equator to high latitudes, but the actual radius of the earth’s ellipsoid is largest at the equator and smallest at the poles.

As the values for $R_{\text{SMT}}(\varphi)$ in the Smithsonian tables were obtained in about 1949, the International Ellipsoid 1935 was used in the computations rather than the WGS-84 (World Geodetic System 1984) currently used with GPS receivers. Also the Smithsonian tables used, a value for $\gamma_{\text{SMT}}(\varphi)$ of

$\gamma_{\text{SMT}}(\phi) = 9.80616 \cdot (1 - 0.0026373 \cdot \cos(2 \phi) + 0.0000059 \cdot \cos(2 \phi)^2) \text{ ms}^{-2}$ \quad (9)

This formula was not explicitly derived in the published scientific literature, although recommended for meteorological use by the International Association of Geodesy in 1949.

An alternative expression for the relationship in equation 8 has been proposed by Mahoney (personal communication, see [link]) based on the WGS-84
Measurement of upper-air pressure, temperature and humidity

g. Then geopotential height for geometric height, \( z_1 \), becomes

\[
Z_1(z_1, \phi) = \left( \gamma_s(\phi) \right) / \gamma_\phi \cdot \left( (R(\phi) \cdot z_1)/(R(\phi) + z_1) \right)
\]  
(10)

where \( \gamma_s(\phi) \) is the normal gravity on the surface of an ellipsoid of revolution,

and where

\[
\gamma_s(\phi) = 9.780325 \cdot (1 + 0.00193185 \cdot \sin(\phi)^2) / (1 - 0.00669435 \cdot \sin(\phi)^2)^{0.5}
\]  
(11)

with the radius \( R(\phi) = 6378.137/(1.006803 - 0.006706 \cdot \sin(\phi)^2) \), giving results for \( R \) similar to the values in the Smithsonian tables.

If the geopotential height for a geometric height of 30 km is computed it ranges from 29.7785 km at the equator to 29.932 km at 80°N, whether Eq. 8/9 or Eq. 10/11 is used. Differences between the geopotential height values obtained by the two methods are less than 1 m, and as such not critical for meteorologists.

The difference between geometric height and geopotential height increases with height above the earth’s surface and an example of typical differences taken from measurements in the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang at 22°N is shown in Table 4.

**Table 4. Differences between geopotential and geometric height measured at WMO Radiosonde Intercomparison, Yangjiang, 22°N.**

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8 000</td>
<td>25</td>
</tr>
<tr>
<td>16000</td>
<td>70</td>
</tr>
<tr>
<td>24000</td>
<td>135</td>
</tr>
<tr>
<td>32000</td>
<td>220</td>
</tr>
</tbody>
</table>

Once the variation of the geopotential heights with respect to temperature and relative humidity has been established, the pressures can be computed integrating upwards from the measured surface pressure, using the hypsometric relationship,

as in a discrete form,

\[
L_n \left( \frac{p_{i+1}}{p_i} \right) = -9.80665 \cdot \frac{dZ}{R^* \cdot T_v}
\]  
(12)

Where \( p \) = pressure in hPa, \( R^* \) is the gas constant for dry air,

\( T_v \) is the mean virtual pressure for the layer in degrees K

d\( Z \) = layer thickness in geopotential height

\( i \) refers to the lower boundary of this layer.

The virtual temperature \( T_v \) is computed from

\[
T_v = T / \left( 1 - (U \cdot e_s(T)/(100 \cdot p)) \cdot (1 - \varepsilon_a) \right)
\]  
(13)

Where \( U \) is the relative humidity of the air, \( e_s \) is the saturation vapour pressure for water vapour and \( \varepsilon_a \) the ratio of the molecular weight of wet and dry air, with \( \varepsilon_a = 0.622 \)

It has to be emphasised again, that the radiosonde temperature and relative humidity are used only in the computation of the pressures with systems using GPS geometric height measurements, as the geopotential values come purely from the geometric heights and the earth’s gravitational fields.

The algorithms for computing geometric height from windfinding radar observations of slant range and elevation and for the conversion of geometric heights to geopotential heights were included in WMO (1986). The actual algorithm used with secondary radar systems in the Russian Federation can be found in WMO (1991). If radar height observations are used as a replacement for pressure sensor observations, the heights need to be corrected for the effects of the Earth’s curvature and radio-wave refraction before pressure is computed. Corrections for refraction can be made using seasonal averages of atmospheric profiles, but better pressure accuracy might require height corrections for the conditions...
Measurement of upper-air pressure, temperature and humidity

encountered in individual flights.

3.7 Sources of errors in direct height measurements

3.7.1 Sources of error in GPS geometric height measurements

As long as there is no local interference at GPS navigation signal frequencies, most modern radiosonde systems are able to generate heights with good accuracy relative to the height where GPS lock occurs in flight. However, the software has to be able to interpolate reliably back to the surface [taking into account changes in the balloon rate of ascent just after launch] in order to ensure best performance in GPS measurements. In the WMO Intercomparison of High Quality Radiosondes, Yangjiang WMO (2011), some of these interpolation software modules worked better than others, and systematic errors larger than 10 m resulted in the worst cases, persisting throughout the flight of a given radiosonde type.

It is essential to check the height of the local GPS antenna relative to the surface pressure sensor, and ensure this is used correctly in the radiosonde system software computations. Remember that a mismatch (or pressure error) of 1 hPa in the pressure at the antenna relative to the surface pressure sensor on the radiosonde station, will result in a 10m height bias throughout the flight.

In-flight processing must be able to cope with significant variations [positive and negative] in the rates of ascent of the balloons lifting the radiosonde. In the WMO Intercomparison of High Quality radiosondes, Yangjiang, vertical velocity varied considerably with time in the vertical, partly because of gravity wave activity. At least one manufacturer’s software had difficulty in coping with changes in vertical velocity near the tropical tropopause (may partly be because of the performance of the balloons in these conditions). The most extreme variation in the vertical velocity observed at Yangjiang was at much higher levels in the stratosphere, as shown in Figure 4, but the GPS measurements were able to cope with the very large fluctuations with both systems in close agreement.

Errors in temperature and relative humidity will only affect the pressure computation from the geopotential heights, see equations 12 and 13. The effect of temperature errors on pressure computations can be judged from the values of height errors in Table 3 resulting from a 0.25K temperature error. This temperature error would lead to pressure errors of 0.4, 0.3, 0.13, 0.05 hPa at nominal pressures of 300, 100, 30 and 10 hPa respectively.

![Temperature vs. Rate of Ascent](image)

Figure 4. Measurements of temperature and rate of ascent as a function of time by MTR and Multithermistor radiosondes from Flight 66, WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang. Height at minute 87 was 26 km and at minute 111, 31.5 km

Thus, in the stratosphere, GPS geometric heights are able to deliver much more reliable height measurements than any other operational height measuring system. In Figure 4, the differential of the heights with time has allowed the amplitude of the vertical velocity variations in the gravity to be measured reliably, given the peak vertical velocities in the waves were separated by about 5 minutes. This temporal
resolution at high altitude was not achievable with any earlier standard upper air systems.

Near the surface GPS height measurements must be performed with care, for height measurements to be of similar quality to the best pressure sensors. The breakthrough requirements for pressure in Annex A can be achieved with GPS radiosondes at all pressures. However, it is not obvious that all GPS radiosonde systems can achieve the optimum pressure sensor requirements at low levels, whilst at pressures lower than 100 hPa optimum requirements could be achieved as long as temperature errors are low.

3.7.2 Radar height measurements

The effect of radar observational errors upon windfinding is considered in Part I, Chapter 13. However, for radar heights, (random and systematic) errors in elevation are much more significant than for winds. Systematic bias in slant range is also more critical for height than for wind measurements. Therefore, radars providing satisfactory wind measurements often have errors in elevation and slant range that prevent best quality height (and hence pressure) measurements.

Small but significant systematic errors in elevation may arise from a variety of sources as follows:
(a) Misalignment of the axes of rotation of azimuth and elevation of the radar during manufacture. If this is to be avoided, the procurement specification must clearly state the accuracy required;
(b) Errors in levelling the radar during installation and in establishing the zero elevation datum in the horizontal;
(c) Differences between the electrical and mechanical axes of the tracking aerials, possibly introduced when electrical components of the radar are repaired or replaced.

Errors may arise from errors introduced by the transducer system measuring the radar elevation angle from the mechanical position of the tracking aerial.

Systematic errors in slant range may arise from the following:
(a) A delay in triggering the range-timing circuit or incorrect compensation for signal delay in the radar detection electronics;
(b) Error in the frequency of the range calibrator.

Thus, radiosonde systems operating without pressure sensors and relying solely on radar height measurements require frequent checks and adjustments of the radars as part of routine station maintenance. These systems are not suitable for use in countries where technical support facilities are limited.

4 TEMPERATURE SENSORS

4.1 General requirements

The best modern temperature sensors have a speed of response to changes of temperature which is fast enough to ensure that systematic bias from thermal lag during an ascent, typical rate of ascent 5 to 6 ms$^{-1}$, remains less than 0.1 K through any layer of depth of 1 km in the troposphere and less than 0.2 K through any layer of similar depth in the stratosphere. At typical radiosonde rates of ascent of 5 - 6 ms$^{-1}$, this is achieved in most locations using a sensor with a time constant of response faster than 1 s in the early part of the ascent. In addition, the temperature sensors should be designed to be as free as possible from radiation errors introduced by direct or backscattered solar radiation. There must be as small variation as possible in the area of cross-section for solar heating as the sensor rotates relative to the sun during ascent. Heat exchange in the infrared, needs to be avoided by using sensor coatings that have low emissivity in the infrared. In the past, the most widely used white sensor coatings had high emissivity in the infrared. Measurements by these sensors were limited, especially at upper levels, by relatively large errors from infrared heat exchange (see section 4.7.3). The errors depended on the temperatures being measured, the effect of cloud on the infrared background and the surface albedo and are not easy to correct reliably.

Temperature sensors also need to be sufficiently robust to withstand buffeting during launch and sufficiently stable to retain accurate calibration over several years. The main types of temperature sensors in routine use are thermistors (ceramic resistive semiconductors), capacitive sensors, bimetallic sensors and thermocouples.

The rate of response of the sensor is usually measured in terms of the time-constant of response, \( \tau \). This is defined (as in section 1.6.3 in Part I, Chapter 1) by:
Measurement of upper-air pressure, temperature and humidity

\[
dT_e/\text{d}t = -1/\tau \cdot (T_e - T) \quad (14)
\]

where \( T_e \) is the temperature of the sensor and \( T \) is the true air temperature.

Thus, the time-constant is defined as the time required to respond by 63 per cent to a sudden change of temperature. The time-constant of the temperature sensor is proportional to thermal capacity and inversely proportional to the rate of heat transfer by convection/diffusion from the sensor. Thermal capacity depends on the volume and composition of the sensor, whereas the heat transfer from the sensor depends on the sensor surface area, the heat transfer coefficient and the rate of the air mass flow over the sensor. The heat transfer coefficient has a weak dependence on the diameter of the sensor. Thus, the time-constants of response of temperature sensors made from a given material are approximately proportional to the ratio of the sensor volume to its surface area. Consequently, thin sensors of large surface area are the most effective for obtaining a fast response. The variation of the time-constant of response with the mass rate of air flow can be expressed as:

\[
\tau = \tau_0 \cdot (\rho \cdot \nu)^n \quad (15)
\]

where \( \rho \) is the air density, \( \nu \) the air speed over the sensor, and \( n \) a constant.

Note: For a sensor exposed above the radiosonde body on an outrigger, \( \nu \) would correspond to the rate of ascent, but the air speed over the sensor may be lower than the rate of ascent if the sensor were mounted in an internal duct. However, also note that where rapid changes in vertical velocity are due to rapid changes in the vertical velocity of the air, as is shown in the gravity wave in Figure 4, the vertical velocity of the sensor/radiosonde/balloon relative to the atmosphere does not change as much. Thus, it would seem better to average the rates of ascent in the long term to get a mean rate of ascent for the balloon and air speed over the sensor, ignoring the short term fluctuations in vertical velocity caused by the gravity wave.

The value of \( n \) varies between 0.4 and 0.8, depending on the shape of the sensor and on the nature of the air flow (laminar or turbulent). A selection of values of the time-constant of response of both older and modern types of temperature sensors are shown in Table 5. These are for pressures of 1 000, 100 and 10 hPa, with a rate of ascent of 5 m s\(^{-1}\). The values were derived from a combination of laboratory testing and comparisons with very-fast response sensors during ascent in radiosonde comparison tests.

Rod thermistors and the bead thermocapacitor were used by the most common operational radiosondes between 1985 and 2000. The time constants of these sensors were such that in 1 km layers, the systematic errors from thermal lag in the upper troposphere could be as large as 0.25 K, and in the upper stratosphere as large as 0.5 K. The new bead thermistors, wire thermocapacitor and thermocouple are much faster than this, so the systematic errors from thermal lag are then expected to be less than 0.05 K in the upper troposphere for the better sensors, and less than 0.1 K in the upper stratosphere.

The time lag errors with bimetallic sensors were large compared to the faster rod thermistors and other more modern sensors, and some users compensated by adjusting the pressure measurements assigned to the temperatures, e.g. see the Graw DFM-60 radiosonde in Phase II of the WMO Radiosonde Comparison, WMO (1987), but other users did not, and this is one of the many reasons why it is difficult to trace radiosonde systematic errors in those earlier sensor types.

WMO (2011) showed examples where the response speed of most of the bead thermistors used by radiosondes in the test were similar or slightly faster than the chip thermistor included in Table 5.
Table 5. Typical time constants of response of radiosonde temperature sensors

<table>
<thead>
<tr>
<th>Temperature Sensor</th>
<th>Operational use</th>
<th>T (1000hPa)</th>
<th>T (100hPa)</th>
<th>T (10hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip thermistor, 0.4x0.8x0.8mm</td>
<td>2003-</td>
<td>≤1</td>
<td>≤3</td>
<td>≤10*</td>
</tr>
<tr>
<td>Wire thermocapacitor, diameter 0.1mm</td>
<td>2002-</td>
<td>0.4</td>
<td>1.1</td>
<td>3*</td>
</tr>
<tr>
<td>Cu-Constantin thermocouple</td>
<td>1991-</td>
<td>&lt;0.3</td>
<td>&lt;0.8</td>
<td>2*</td>
</tr>
<tr>
<td>Diameter 0.06mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bead thermocapacitor, diameter 1.2mm</td>
<td>1981-2011</td>
<td>2.5</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Rod thermistor</td>
<td>1958-2005</td>
<td>3</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Diameter 1.2mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bimetallic sensor</td>
<td>1960-2005</td>
<td>5-8</td>
<td>12-20</td>
<td>Not reliable at 10 hPa</td>
</tr>
</tbody>
</table>

*The time constants of response at 10 hPa of the chip thermistors in Yangjiang were larger than the Cu-Constantin thermocouple by about 4 s. The other small bead thermistors had time constant of response between 3 and 10 s larger than the Cu-Constantin thermocouple. The wire thermocapacitor showed time constants of response of at least 4s, a little larger than the results from the laboratory test cited above. This may be because the diameter of the wire thermocapacitor in operational radiosondes had been increased in 2007 by incorporating a quartz support fibre, see http://www.vaisala.com/en/meteorology/products/soundingsystemsandradiosondes/soundingdatacontinuity/Pages/reinforcedtemperaturesensor.aspx, and may also be the consequence of the software used with the sensor in Yangjiang.

4.2 Thermistors

Thermistors are usually made of a ceramic material whose resistance changes with temperature. The sensors have a high resistance that decreases with absolute temperature. The relationship between resistance, $R$, and temperature, $T$, can be expressed approximately as:

$$R = A \cdot \exp \left( \frac{B}{T} \right) \quad (16)$$

where $A$ and $B$ are constants. Sensitivity to temperature changes is very high, but the response to temperature changes is far from linear since the sensitivity decreases roughly with the square of the absolute temperature. As thermistor resistance is very high, typically tens of thousands of ohms, self-heating from the voltage applied to the sensor is negligible. It is possible to manufacture very small thermistors and, thus, fast rates of response can be obtained. Solar heating of a modern chip thermistor is around 1 °C at 10 hPa.

4.3 Thermocapacitors

Thermocapacitors are usually made of a ceramic material whose permittivity varies with temperature. The ceramic used is usually barium-strontium titanate. This ferro-electric material has a temperature coefficient of permittivity of the order of $10^{-2}$ per °C. The temperature coefficient is positive at temperatures below the Curie point and negative at temperatures above the Curie point. Sensors can now have a diameter of about 0.1 mm. The wire thermocouple measures the change in capacitance between two fine platinum wires separated by a glass ceramic (see Turtiainen, Tammela and Stuns, 1995). This sensor gives improved speed of response, and solar heating errors are less than 1 °C at 10 hPa.
4.4 Thermocouples

Copper-constantan thermocouple junctions are also used as a temperature sensor in one national radiosonde (WMO, 1989a). Wires of 0.05 mm in diameter are used to form the external thermocouple junction and these provide a sensor with a very fast response. The relationship between the thermal electromotive force and the temperature difference between the sensor and its reference is an established physical relationship. The thermocouple reference is mounted internally within the radiosonde in a relatively stable temperature environment. A copper resistor is used to measure this reference temperature. In order to obtain accurate temperatures, stray electromotive force introduced at additional junctions between the sensor and the internal references must also be compensated.

4.5 Scientific Sounding Instruments

Two specialised scientific temperature sounding sensors were deployed during the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, WMO (2011).

- The MTR temperature sensor uses an ultrathin tungsten wire as a sensor. The wire is 0.01 mm in diameter, 44 cm long wound into a helical coil with a diameter of 0.2 mm and a pitch of 0.1 mm. The wire is coated with aluminium to improve reflectivity and thus reduce solar heating, see Shimizu and Hasebe (2010). This sensor has smaller time constants of response than the Cu-Constantin thermocouple.

- The multithermistor radiosonde in Yangjiang was an independent instrument based on the NASA Accurate Temperature Measuring (ATM) Multithermistor radiosonde, see Schmidlin et al. (1995, 2006). The system made measurements with three aluminized thermistors, one white and one black thermistor. In Yangjiang the time constants of response were similar to those for the modern bead thermistors. With the measurements from the five sensors, and an exact knowledge of the optical properties of the different sensor coatings a true temperature is derived, as well as estimates of the solar and infrared radiation environments. This estimated temperature does not depend on any assumption about the backscattering from the surface and clouds unlike other radiosonde temperature correction schemes.

The reliability of the absolute calibration and daytime corrections of these scientific systems did not prove to be better than those of the good operational radiosondes in the Yangjiang test.

4.6 Exposure

Radiosonde temperature sensors are best exposed in a position above the main body of the radiosonde (but below the body of a dropsonde). Thus, air heated or cooled by contact with the radiosonde body or sensor supports cannot subsequently flow over the sensor. This is usually achieved by mounting the sensor on an arm or outrigger that holds the sensor in the required position during flight. For long-term stability of operation, this position needs to be reproducible and must not vary from flight to flight. For good exposure at low pressures, the supports and electrical connections to the sensor should be thin enough so that heating or cooling errors from thermal conduction along the connections are negligible.

With this method of exposure, the radiosonde temperature sensors are exposed directly to solar radiation and to the infrared environment in the atmosphere. The sensors receive solar radiation during daytime soundings and will exchange long-wave radiation with the ground and the sky at all times. The magnitude of radiation errors is only weakly dependent on the size and shape of the sensors, since convective heat transfer coefficients are only weakly dependent on sensor size. Thus, small radiation errors may be obtained with small sensors, but only when the sensor coating is chosen to provide low absorption for both solar and long-wave radiation. The required coating can be achieved by the deposition of a suitable thin metallic layer. Many white paints have high absorption in the infrared and are not an ideal coating for a radiosonde sensor.

An additional consequence of exposing the temperature sensor above the radiosonde body is that, when ascending during precipitation or through cloud, the sensor may become coated with water or ice. It is extremely important that the sensor design sheds water and ice efficiently. First, evaporation of water or ice from the sensor when emerging from a cloud into drier layers will cool the sensor below true ambient temperature. Secondly, the absorptivity in the infrared of a temperature sensor that remains coated with ice throughout a flight differs from usual. Thus, an abnormal systematic bias from infrared heat exchange will be introduced into the iced sensor measurements, particularly at low
Measurement of upper-air pressure, temperature and humidity

Pressures.

Bimetallic sensors and associated supports absorb too much radiation in daylight to be exposed unprotected above the radiosonde. Thus, this type of sensor has to be protected by a radiation shield. The shield should not allow radiation to reach the sensor directly or after multiple reflections. The internal surfaces of the shield should remain at temperatures close to the true atmospheric temperature and should not influence the temperature of the air incident on the sensor. The shielding should not reduce the ventilation of the temperature sensor to any extent and should not trap water or ice when ascending through cloud and precipitation.

While acceptable radiation shield performance may be achieved at high pressures, it becomes increasingly difficult to fulfill all these requirements at pressures lower than 50 hPa. Good absorption of incoming radiation requires a blackened internal surface on the shield, but this leads to strong coupling of these surfaces to external solar and infrared radiation fields. At low pressures, this results in substantial heating or cooling of the internal surfaces of the shields relative to the ambient atmospheric temperature. Therefore, reliable temperature measurements using radiation shields rapidly become impracticable at the lowest pressures. A compromise shield design might consist of two polished, thin aluminium cylinders arranged coaxially with a spacing of 1 or 2 cm.

4.7 Temperature errors

4.7.1 Calibration

Errors in temperature sensor calibration during an ascent may result from:

- Errors in factory calibration. This can occur from time to time and is one of the reasons the radiosonde measurements should be checked on the ground before launch.

- Small changes in the sensor, e.g. the stray capacitance associated with a capacitative sensor or in the electrical connections to the sensor.

- Instabilities in the radiosonde transducer system and references. This is possible during storage or during the ascent. Sensor or transducer drift during storage can usually be partially corrected during data processing, using adjustments based on pre-flight ground checks.

Table 6 summarizes the relative performance of temperature sensors at night as measured in the WMO International Radiosonde Comparisons and associated tests. The results represent the typical performance averaged over a minimum of at least 15 test flights. NASA-ATM multithermistor measurements, using rod thermistors calibrated by VIZ Inc., were used as an arbitrary reference from Japan until Brazil. Subsequently, another multithermistor version manufactured directly by Sippican using chip thermistors was deployed, Differences between this and the NASA versions particularly in the day are under investigation. The absolute uncertainty of this reference at night is probably better than 0.3 K if the calibration of the sensors has been checked very carefully before launch, with NASA and Sippican ATMs agreeing as well as can be expected from the error analysis.
Table 6. Systematic error, sonde error and uncertainty (k=2) at night from WMO International Radiosonde Comparisons and other associated tests (using NASA-ATM multithermistor reference as an arbitrary reference for systematic offsets).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [hPa]</td>
<td>300</td>
<td>100</td>
<td>30 10</td>
</tr>
<tr>
<td>Bimetalllic spiral + radiation shield, SMG China</td>
<td>± 0.2 ± 0.7</td>
<td>± 0.2 ± 0.7</td>
<td>± 0.3 ±1.0</td>
</tr>
<tr>
<td>Rod thermistor, white paint VIZ, USA</td>
<td>± 0.3 ± 0.4</td>
<td>± 0.2 ± 0.5</td>
<td>± 0.2 ± 0.5</td>
</tr>
<tr>
<td>Rod thermistor, aluminised bead MRZ, Russian Fed.</td>
<td>± 0.2 ± 0.5</td>
<td>± 0.2 ± 0.5</td>
<td>± 0.3 ± 0.7</td>
</tr>
<tr>
<td>Aluminised bead thermocapacitor, Vaisala RS80, Finland</td>
<td>1.0 ± 0.2°</td>
<td>1.1 ± 0.2°</td>
<td>1.1 ± 0.2°</td>
</tr>
<tr>
<td>Cu-Constantin thermocouple, Meteolabor, Switzerland</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>± 0.1 ± 0.2</td>
</tr>
<tr>
<td>Wire thermocapacitor, Vaisala RS92, Finland</td>
<td>0.05 ± 0.1</td>
<td>0.05 ± 0.1</td>
<td>± 0.7 ± 0.2</td>
</tr>
<tr>
<td>Chip thermistor, LMSippican, USA</td>
<td>0 ± 0.1</td>
<td>± 0.05</td>
<td>± 0.07</td>
</tr>
<tr>
<td>Bead thermistor, aluminised, Modern France</td>
<td>-0.1 ± 0.1</td>
<td>0 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Changfeng° China</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Graw° Germany</td>
<td>0.05</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Huayun° China</td>
<td>0.05</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>Internet° S. Africa</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>JinYang° Korea</td>
<td>-0.1</td>
<td>0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>Meisei° Japan</td>
<td>-0.05</td>
<td>0.10</td>
<td>0.0</td>
</tr>
<tr>
<td>Bead thermistor white paint, Daqiao° (China)</td>
<td>0.05</td>
<td>-0.25</td>
<td>-0.2</td>
</tr>
<tr>
<td>NASA-ATM, multi-thermists, used by F. Schmidlin</td>
<td>Bias assumed to be within ±0.1 K</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

** Higher value the results of interaction of white paint with ice in the upper troposphere (both infrared cooling and evaporation of ice adhering to white paint) and would not be as large in situations with a lower tropopause.

Vaisala RS80 temperatures differ because of differences in radiation correction schemes:
° Temperatures corrected using original V80 correction scheme
° Temperatures corrected using V86 correction scheme
° Temperature corrected using V93 correction scheme.
° Result only based on WMO (2011) measurements

Where a range of systematic errors has been attributed to a radiosonde type, the range represents the...
spread in systematic difference found in a number of tests, and also takes into account the range of likely performance up to 30 hPa estimated from radiosonde monitoring (WMO, 2003b). For instance, large ranges in uncertainty are found for the VIZ 1392, where the infrared errors varied a lot between the tests. This was supported by the operational monitoring results in the US radiosonde network and individual measurements of rod thermistor error with the NASA-ATM radiosonde (Schmidlin, 2006).

As modern sensors have aluminised coatings, infrared errors are very small, and any spread in the performance is mainly down to the long term consistency of factory calibration, small instabilities in the sensors, perhaps depending on the atmospheric structure and internal temperature of the radiosonde electronics, etc. It is difficult to differentiate between the best systems in Table 6, so that similar errors have been attributed to these sensors. The reproducibility of the temperature measurements can be measured relatively easily, but it is not currently possible to ascertain the systematic bias better than the limits shown. Large scale tests in the tropics have not given the same results for systematic bias as those in Europe, so the values shown are an average between the two conditions with the range of values necessary to encompass both sets of results as shown.

When the Vaisala RS80 was introduced in 1983 it was not recognised that the aluminised sensor coating, led to extremely small infrared errors, and a software correction for infrared error was made that warmed the measurements up by more than 1 K at 10 hPa. This systematic error was not eliminated from systems emerging from the factory until 1993, and some of the automated systems in operation continued to use the false correction for some time after 1993. Hence, nighttime measurements at upper levels with this radiosonde need to be treated with great care, and the software in use needs to be identified for climatological studies.

Sonde errors are only quoted for pressures of 30 hPa and 10 hPa in Table 6 since, for most modern temperature sensors, sonde errors show little variation between the surface and 30 hPa, although some systems had problems near the tropopause in WMO (2011). For the radiosondes observing at night in the Yangjiang test, Intermet and Jinyang have larger sonde errors because of greater inconsistency in the calibration of the sensors than for the other types, suggesting that some problems in radiosonde manufacture/temperature sensor manufacture remained to be resolved in 2011.

The poorest operational temperature measurements have been found for many years from the Indian MKIII radiosondes manufactured in India by the national meteorological service, but in this case the very poor reproducibility is not just the result of sensor performance, but also instability in the radiosonde electronics during the ascent, giving effective changes in sensor calibration, so data are degraded by the radiosonde system itself. Sonde errors for this radiosonde at 100 hPa have been in the range 2 to 4 K for many years, (WMO, 2003b), although the uncertainties found from the sensors in Phase II of the WMO Radiosonde Comparison were very much smaller than this.

4.7.2 Thermal lag

Most modern radiosonde temperature sensors are fast enough not to require significant correction for thermal lag errors. Errors in the older types of radiosondes were discussed in section 4.1. If the optimum accuracy is required from older types of radiosonde then corrections for thermal lag need to be applied.

4.7.3 Radiative heat exchange in the infrared

Most white paints used on radiosonde sensors have relatively high emissivity in the infrared (> 0.8). Heat exchange with the infrared background is then capable of producing significant errors in temperature measurements. The upward infrared flux incident on the sensor is composed of emissions from the surface and the atmospheric layers below the radiosonde. The downwards infrared flux is often much smaller and is composed of atmospheric emissions from the layers above the radiosonde. The infrared fluxes change as the radiosonde ascends. For a given vertical temperature structure, the infrared fluxes will also vary significantly from flight to flight depending on the cloud present in the vicinity of the ascent. Luers and Eskridge (1998) are a good example of work where users have tried to model the solar and infrared radiation errors on radiosondes in use in the 1990’s. A white painted sensor which has fast time constants of response, i.e. very efficient convective heat transfer between the sensor and the atmosphere will have smaller infrared errors than those found in the radiosondes in the 1990s, however these are still significant in the stratosphere, see for instance the white painted sensor (Daqiao) in the WMO Intercomparison of High Quality Radiosondes, Yangjiang (WMO 2011a).

In a special circumstance, a sensor may be in radiative equilibrium (the infrared radiation emitted by the sensor is balanced by the absorption of infrared fluxes from the atmospheric environment) and so it will provide a correct reading. In the stratosphere, radiative equilibrium temperatures are often around –60 °C in conditions when there are low amounts of upper and middle cloud, although the precise values will...
Measurement of upper-air pressure, temperature and humidity

change with surface temperature, surface state and humidity in the troposphere. Thus, when stratospheric temperatures are close to \(-60^\circ C\), infrared errors will usually be small. Thus a white sensor, giving acceptable test results in mid-latitude conditions can be subject to large errors in conditions when temperatures are much higher or lower than \(-60^\circ C\) in the stratosphere, as in the tropics e.g. see the large cooling errors of in a white painted temperature sensor at night in the WMO Comparison of Radiosondes Vacoas, Mauritius (WMO,2006a) which had had small errors in tests in Europe.

Infrared errors affect both day and night observations, although the examples considered here will be restricted to night-time measurements to facilitate the identification of the errors. The systematic errors of white thermistors in climatological averages will depend on the average air temperature and, hence, will change with latitude and average cloud cover in the larger national networks. The effects of infrared heat exchange errors at night can be seen in the measurements of the VIZ, MODEM and Russian thermistors in Table 6. At high pressures, these sensors give temperatures close to the reference, but at low pressures the temperatures reported are much colder than the reference. At pressures lower than 30 hPa in the tests considered, the radiative equilibrium temperature at night was usually significantly lower than the actual atmospheric temperatures. Therefore, the infrared radiation emitted by the temperature sensor exceeded the infrared radiation absorbed by the sensor from the atmospheric environment and the sensor cooled to a temperature lower than truth.

When atmospheric temperatures are very low, the radiative equilibrium temperature at night can be higher than the atmospheric temperature. The temperature sensor then emits less radiation than it absorbs from the atmospheric environment and the sensor will give readings higher than truth. In the tropics, positive errors of at least 0.5 K can be expected when temperatures fall below \(-80^\circ C\) in layers around the tropopause, if the amounts of upper cloud are low. In a series of tests in the UK it was possible to compare the errors found in white rod thermistors in cloud free conditions as a function of atmospheric temperature, see Figure 5, and the errors in individual flights ranged from +0.8 to -2.5 K at 10 hPa, with positive errors at atmospheric temperature lower than \(-70^\circ C\).

![Figure 5. Error from infrared cooling at night for rod thermistors in cloud free conditions over the UK in tests from 1984 to 1996. The very low temperatures occurred when the polar vortex was present over the UK in winter.](image)

Table 6 shows that white rod thermistors had more variation in systematic errors at night and larger sonde errors than the Vaisala RS92, RS80 and the various bead thermistor sensors. This was usually the result of variation in infrared heat exchange errors from location to location, rather than larger variations in the respective factory calibrations. For instance, changes in upper cloud cover changed white rod thermistor errors by up to 0.5 K during a test in the United Kingdom when the atmospheric temperature structure showed little variation with time (WMO, 1994b). The infrared environment varies so much from flight to flight with cloud cover and surface temperature that the errors in an individual flight are extremely difficult to correct without a full radiative transfer model. Thus, the uncertainty values quoted for the rod thermistor are

32
based on an average situation, but it is quite clear that at any site the systematic error could be larger than this with larger uncertainty results as shown

Infrared heat exchange also influenced the measurements taken by sensors mounted in ducts or radiation shields when the internal surfaces of the ducts were painted black. The black duct surfaces were cooled or heated by infrared radiation in a similar fashion to the white painted sensors described above. The temperature of the air passing through the duct is altered by contact with the black surfaces. Some of this air then flows over the temperature sensor. The resultant temperature error appears to be of similar sign and magnitude to the errors of the white rod thermistors (for example, see the errors for the bimetallic sensor for SMG (China) in Table 6).

The conclusion is that white paint should not be used, whenever possible, so that changes in systematic error from infrared errors will then be negligible across the radiosonde temperature measurement network.

4.7.4 Heating by solar radiation

All radiosonde temperature sensors will have heating errors in daytime caused by incident solar radiation, including backscattered radiation from clouds and the surface. Table 7 shows the day-night differences associated with the temperature measurements of the radiosondes considered in Table 6. Mostly these values were derived from the software corrections used for daytime temperatures by each system for solar elevations between 30 and 80. With sensors in ducts, errors increased very rapidly at pressures lower than 20 hPa, see variation of day-night differences in the vertical for SMG, China radiosonde in Table 7 or the Graw G78C in Phase I of the WMO Radiosonde Comparison. Modern radiosondes mount the sensor on an outrigger directly exposed to the solar radiation using very small sensors with better convective heat transfer between the sensor and the atmosphere than in the earlier radiosondes. So, most of the temperature sensors in the Yangjiang test, WMO (2011) had day-night differences less than half the size of those in the VIZ systems and Vaisala systems from the 1980/90’s.

The performance of the Chinese radiosonde represents one of the better older designs, and for instance the UK MkII radiosonde which was used widely around the world before 1980 had larger day-night differences than those shown in Table 7. The corrections applied to the Chinese SMG were changed in 1996 see Guo Yatian et al.(1996), and resolved problems in the troposphere and lower stratosphere, but problems remained at upper levels. The reasons for the change were complex and give some idea of the many problems affecting the temperature measurements of older types of radiosonde. Russian temperature sensors had relatively poor thermal isolation from supporting structures which could often be heated more than the sensor itself, and so the Russian radiosondes also had large day-might differences at upper levels.

In all modern operational radiosonde systems, software corrections are applied during data processing to compensate for the solar heating, see Table 7. These correction schemes were usually derived from special investigations of day-night differences in temperature (taking into account real diurnal variation in temperature caused by atmospheric tides) coupled with solar heating models, and possibly laboratory testing. The correction is then expressed as a function of solar elevation during the ascent. The correction may also take into account the actual rates of ascent, since ventilation and heating errors will change if the rate of ascent differs from the standard test conditions. At low solar elevations (less than 10°) the heating errors are extremely sensitive to changes in solar elevation. Thus, if the correction software does not update solar elevation during flight, significant errors will be generated when correcting sunrise or sunset flights. A simple correction scheme will work effectively only for certain cloud and surface conditions and cannot provide adequate correction for all flight conditions that might be encountered. For instance, in many ascents from coastal sites the radiosonde proceeds out to sea. In clear sky conditions, the low surface albedo of the sea will reduce backscattered solar radiation by a factor of two or three compared with average atmospheric conditions during flight. In such circumstances, software corrections based on average conditions will be up to 30 per cent too large. On the other hand, in ascents over thick upper cloud with very high albedo or over desert conditions, backscattering may be much larger than usual and the software correction will underestimate the required correction.

In the estimates of the range of systematic error in Table 8 it has been assumed that the standardized software correction schemes produce a range of possible systematic bias of ±30 per cent. During a particular radiosonde test the radiative conditions (cloud, surface albedo) do not usually change too much, so the illusion is given that the systematic bias obtained has low errors. However, a test performed at another location can give systematic errors that differ by very much more than the sonde error found in an individual test. Daytime testing of the Vaisala RS80 in the WMO Radiosonde Comparisons is the best documented example of this.

Table 8 contains a review of the systematic and sonde errors in most modern radiosonde types, where
only the VIZ white rod thermistor was not used with a software correction scheme, but corrected after the radiosonde message was received by the national users. The systematic errors derived from the test in Yangjiang (WMO, 2011) assume that zero systematic bias in Yangjiang was halfway between Vaisala/Modem and LMS/Multithermistor at 30 and 10 hPa. This was because subsequent testing in the USA has not shown significant errors in the multithermistor system used in Yangjiang, i.e. there was some real atmospheric diurnal variation in temperature between 30 and 10 hPa in Yangjiang, with a probable amplitude of at least 0.15 K.

The sonde errors for all radiosondes are larger for daytime than for nighttime conditions, compare Tables 6 and 8. During ascent, radiosondes swing and rotate like a pendulum suspended from the balloon, so the absorption cross sections of the sensor changes as the sensor rotates. Also air heated by contact with either the sensor supports or the radiosonde body may flow over the external sensor from time to time. If these possibilities have not been avoided in the design (e.g. if the temperature sensor is mounted close to the radiosonde body, for instance, halfway between the top and the bottom), much larger sonde errors will result in daytime. Backscattered radiation varies from flight to flight with changing cloud cover and also contributes to the increase in daytime sonde errors.

Comparison of Table 8 with 6 shows that the sonde errors of Huayun in the day were very much larger than at night. The Huayun temperature sensor was not exposed high enough above the radiosonde body to avoid air heated by contact with the radiosonde body, and the single-sided support frame for the sensor also allowed heated air from the support to pass over the sensor causing irregular pulses of warmer temperatures. These pulses can be as large as 1 °C at 10 hPa. The heating pulses can be readily recognized when flying radiosondes on the rigs used in WMO radiosonde comparisons since the radiosondes rotate in a very regular fashion during the flight. In this situation, suitable raw data filtering can remove the positive pulses to some extent. This has been discussed and examples shown in Annex D of WMO (2011).

Thus, the filtering applied to the basic observations of several systems must also be taken into account when investigating daytime radiosonde temperature errors. For example, the sensor support structures on the Vaisala RS92 and Changfeng (China) were very similar, and performance at night was similar, but in the day the Vaisala RS92 temperatures applied software filtered to remove spikes but in the Changfeng spikes were not removed, see Annex D of WMO (2011). In Yangjiang, LMS and Graw temperature sensors were well exposed in the day and sonde errors were small and not much larger than at night, see Tables 6 and 8.
### Table 7. Day-night difference for selected temperature sensors from WMO International Radiosonde Comparisons and other associated tests.

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>Systematic error [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [hPa]</td>
<td>300 100 30 10</td>
</tr>
<tr>
<td>Bimetallic spiral in radiation shield, SMG China</td>
<td>0.8 1.3 3.4 9.9</td>
</tr>
<tr>
<td>Rod thermistor, white paint, MRZ Russian Fed</td>
<td>1 1.8 3.3 5.1</td>
</tr>
<tr>
<td>Aluminised bead thermocapacitor, Vaisala, Finland</td>
<td>0.9 1.3 2.2 2.8</td>
</tr>
<tr>
<td>Rod thermistor, white paint VIZ, USA**</td>
<td>0.4 0.8 ± 0.2 0.9 ± 0.7 1.4 ± 0.8</td>
</tr>
<tr>
<td>Cu-Constantin thermocouple, Meteolabor, Switzerland</td>
<td>0.5† 0.75† 1.1† 1.8†</td>
</tr>
<tr>
<td>Chip thermistor, LMSippican, USA</td>
<td>0.3 0.5 0.8 0.95</td>
</tr>
<tr>
<td>Wire thermocapacitor, Vaisala, Finland</td>
<td>0.15 0.3 0.5 0.8</td>
</tr>
<tr>
<td>Bead thermistor, aluminised, Modem France</td>
<td>0.4 0.7 1 1.5</td>
</tr>
<tr>
<td>Changfeng China</td>
<td>0.2 0.3 0.4 0.6</td>
</tr>
<tr>
<td>Graw Germany</td>
<td>0.3 0.5 0.8 1.0</td>
</tr>
<tr>
<td>Huayun China</td>
<td>0.6 1.1 1.5 2.3</td>
</tr>
<tr>
<td>Intermet S. Africa</td>
<td>0.3 0.5 0.8 1.1</td>
</tr>
<tr>
<td>JinYang Korea</td>
<td>0.6 1.0 1.4 2.1</td>
</tr>
<tr>
<td>Meisei Japan</td>
<td>0.5 0.9 1.3 1.8</td>
</tr>
<tr>
<td>Bead thermistor white paint, Daqiao (China)***</td>
<td>0.2 0.4 0.6 0.9</td>
</tr>
</tbody>
</table>

** derived directly from NASA ATM measurements (Schmidlin, 2006)

† As used in WMO (2011)

‡‡ As revised from subsequent tests (Philipona et al. 2013)
Table 8. Systematic error, sonde error and uncertainty (k=2) for selected temperature sensors in the day from WMO International Radiosonde Comparisons and other associated tests, and from operational monitoring as in WMO (2003b).

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>Systematic error [K]</th>
<th>Sonde error</th>
<th>Uncertainty [K=2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [hPa]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Bimetallic spiral in duct, SMG, China</td>
<td>±0.8 ± 0.8</td>
<td>±a-0.2 ± 1</td>
<td>±a-2.3 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>b-0.1± 0.5</td>
<td>b1 ± 1</td>
<td></td>
</tr>
<tr>
<td>Rod thermistor, white paint, VIZ, USA**</td>
<td>0.8 ± 0.6</td>
<td>0.7 ± 1.3</td>
<td>0.2 ± 1.4</td>
</tr>
<tr>
<td>Rod thermistor, white paint, MRZ, Russian Fed</td>
<td>0.7 ± 0.5</td>
<td>0.5 ± 1</td>
<td>-0.7 ±1.3</td>
</tr>
<tr>
<td>Aluminised bead thermocapacitor, Vaisala, Finland</td>
<td>0.4 ± 0.3</td>
<td>0.4 ± 0.4</td>
<td>0.4 ± 0.7</td>
</tr>
<tr>
<td>*Cu-Constantin thermocouple, Meteolabor, Switzerland</td>
<td>-0.2†</td>
<td>-0.5†</td>
<td>-0.8†</td>
</tr>
<tr>
<td>Wire thermocapacitor, Vaisala, Finland</td>
<td>0 ± 0.2</td>
<td>-0.2 ± 0.2</td>
<td>-0.3 ± 0.3</td>
</tr>
<tr>
<td>Chip thermistor, LMSippican, USA</td>
<td>-0.1 ± 0.2</td>
<td>0.2 ± 0.2</td>
<td>0.3 ± 0.3</td>
</tr>
<tr>
<td>*Bead thermistor, aluminised, Modem France</td>
<td>-0.1</td>
<td>-0.2</td>
<td>-0.3</td>
</tr>
<tr>
<td>Changfeng China</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Graw Germany</td>
<td>0.3</td>
<td>-0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Huayun China</td>
<td>0.1</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Intermet S. Africa</td>
<td>0.0</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>JinYang Korea</td>
<td>-0.2</td>
<td>-0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Meisei Japan</td>
<td>-0.4</td>
<td>-0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>*Bead thermistor, white paint, Daqiao (China)</td>
<td>0.1</td>
<td>0.</td>
<td>-0.3</td>
</tr>
<tr>
<td>Multithermistor</td>
<td>±0.2</td>
<td>±0.2</td>
<td>±0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.3</td>
<td>±0.5</td>
</tr>
</tbody>
</table>

*Only using results from WMO (2011)
** No software correction for heating errors
a Correction procedure for Chinese radiosonde used before 1996
b Correction procedure used for Chinese Radiosonde between 1996 and 2009
† As used in WMO (2011)
†† As revised from subsequent tests (Phlipona et al. 2013)

The range of systematic errors in daytime measurements, given in Table 8, should be smallest for the
radiosonde systems with smallest day-night differences. Given that most of the increase in uncertainty relative to night-time measurements comes from poor sensor position relative to the radiosonde body and also from poor design of the sensor supports, it is hoped that most of the modern radiosondes with the larger errors in Table 7 should be improved within a few years of the Yangjiang intercomparison. Thus, the results of Yangjiang represent a snapshot of performance at the time, and radiosondes with significant systematic errors in Yangjiang, will all have been modified to some extent within a couple of years of completion of the test. For example the radiation errors of the Swiss radiosonde have been revised through additional testing and the solar heating correction is now reduced as shown. This would eliminate the negative bias for Meteolabor seen in the daytime results in WMO (2011) in Table 8.

The WMO Intercomparison tests were performed with the radiosondes suspended at least 30m and most commonly 40m under the balloon. However, many national networks, e.g. China, Japan and Russia have used much shorter suspensions and this will produce additional daytime bias and increased sonde errors compared to those quoted here in Tables 7 and 8, especially at pressures lower than 30 hPa.

Comparing the temperature uncertainty results in Tables 6 and 8, the modern radiosonde uncertainties (2011) are about twice as small compared to the best radiosondes in the 1990’s, and at least four times smaller than the uncertainty of the designs still in use now, but that date back earlier than 1990 in origin.

4.7.5 Deposition of ice or water on the sensor

Another source of temperature error is the deposition of water or ice on the temperature sensor. This will lead to psychrometric cooling (from the wet-bulb effect) of the temperature sensor, once atmospheric relative humidity drops to less than 100 per cent later in the ascent. If the sensor tends to collect water or ice, rather than rapidly shed the precipitation, large parts of the temperature measurements during the ascent may be corrupted. At night, a coating of ice will cause an aluminized sensor to act like a black sensor in the infrared, leading to large cooling at low pressures in commonly encountered conditions.

Furthermore, if water deposited on the sensor freezes as the sensor moves into colder air, the latent heat released will raise the temperature towards 0 °C. If a sensor becomes coated with ice and then moves into a warmer layer, the temperature will not rise above 0 °C until the ice has melted. Thus, isothermal layers reported close to 0 °C in wet conditions should be treated with some caution.

4.7.6 Representativeness issues

Most modern radiosonde temperature measurements observe small-scale variations in temperature in the atmosphere which are not represented, for instance, in current numerical weather prediction models or the volume averaged view of a satellite sounder radiances. The magnitude of representativeness differences (errors) for these two types of users was quantified by Kitchen (1989) using time series of atmospheric observations made in the UK. The representativeness error [k=2] of the radiosonde compared to the numerical weather prediction field in the troposphere was at best 1.6 K, for an ascent which did not drift far in the horizontal. For a microwave sounding radiance observed with a radius of 55 km and collocated in time and space with the radiosonde measurement the representativeness errors were found to be around 1.2 K.

Thus, when radiosonde temperature profiles are compared directly with numerical model output, the standard deviation of observation–numerical model output [k=2] is usually not less than 2 K at most pressures, much larger than the instrumental sonde errors quoted in Tables 4 and 5.
Measurement of upper-air pressure, temperature and humidity

R.M.S. deviation between 11 pairs of temperature observations, vertical resolution 1 km, separated by 2, 6, 18 and 54 hours respectively, WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, China

Figure 6. R.M.S. deviation [k=1] between temperature soundings 2, 6, 18 and 54 hours apart from the WMO Intercomparison of High Quality Radiosonde systems, Yangjiang.

The R.M.S. deviations between radiosonde temperature measurements 2, 6, 18 and 54 hours apart from Yangjiang, China are shown in Figure 6, where the contribution from instrumental error has been removed from the differences at the given time separations. The R.M.S. Deviation can then be expected to relate to time separation using the relationship, after Kitchen (1989):

\[
(\tau_T(\Delta t))^2 = (b \Delta t^\gamma)^2 + (\tau_T(\text{small scale})(\Delta t))^2
\]

where \(\tau_T(\Delta t)\) is the R.M.S deviation between temperature measurements separated by the time separation \(\Delta t\), \(b \Delta t^\gamma\) is the structure function representing the R.M.S. deviation due to synoptic scale and mesoscale changes with time, with \(b\) a constant and \(\gamma\) a constant, with a value near 0.4 for temperature for time separations between 6 and 54 hours., and \(\tau_T(\text{small scale})(\Delta t)\) is the R.M.S. deviation in temperature from small scale structures, e.g. quasi inertial gravity waves, cloud scale changes, turbulent layers.

Thus, if mesoscale and synoptic scale temperature fluctuations are larger than the small scale fluctuations, the R.M.S deviation in temperature will fall by equal increments for the time separations used in Figure 5 on a logarithmic scale plot. For tropical measurements (e.g. in Yangjiang), this only seems to be true from the surface up to about 7 km. In the upper levels there is little difference between the R.M.S. temperature deviations for time separations greater than or equal to 6 hours, and it is only at a time separation of 2 hours that the R.M.S deviations start to decrease, i.e. when the smaller scale fluctuations from the quasi inertial gravity waves start to decrease. This is because at these levels the small scale fluctuations, mostly associated with quasi inertial gravity waves or turbulence are larger than the synoptic or mesoscale fluctuations.

Kitchen (1989) presented a sample of R.M.S. deviations between temperature measurements 4 and 12 hours apart from the UK. In the middle and upper troposphere, the 2, 6 and 18 hour R.M.S. differences in Yangjiang were smaller than the 4 hour R.M.S. in the UK, and representativeness errors in the tropics at these levels would be considerably smaller than those quoted for the UK. However in the stratosphere, the 2 hour R.M.S differences at Yangjiang were significantly higher than those found in summer-time UK by Kitchen (1989). The short term variation in atmospheric conditions in the stratosphere was caused by gravity waves, with the amplitude of the gravity waves increasing with height. This is just a snapshot of conditions in the tropical stratosphere and may not be the same at all tropical locations.

So representativeness errors in the tropical stratosphere can be higher in the rainy season compared to the errors quoted at latitudes higher than 50ºN in Kitchen (1989).

The significance of the representativeness errors is that if you wish to measure the average state of the larger scale atmosphere to a given accuracy, it requires many more flights than might be expected with the
small sonde errors shown in Tables 6 and 7. The low representativeness errors for radiosonde measurements in tropical conditions should allow radiosonde measurements to be very effective in monitoring temperature trends in the tropical troposphere, whereas more radiosonde measurements will be needed in the stratosphere to define a mean value to the same accuracy as in the troposphere.

5 RELATIVE HUMIDITY SENSORS

5.1 General aspects

Operational relative humidity measurements worldwide have a wide range of performance [from good to those of low value] as all the sensor types listed in Table 10 are still in use in some national networks in 2011. The most widely used sensor is the heated thin twin film capacitor. This sensor is mounted externally, without a cover, on a boom which holds it above the top of the radiosonde body. The other modern thin film capacitors are usually deployed externally on a boom with an aluminised cover to protect against contamination from precipitation and to minimise solar heating of the humidity sensor. Carbon hydristor sensors are usually mounted in some type of protective duct in the radiosonde. The use of carbon hydristors is decreasing. Goldbeater’s skin sensors are too inaccurate and limited in coverage in the vertical to meet the requirements of modern users, but are still in use in one national network. Goldbeaters skin is also mounted in some type of protective duct.

A good modern radiosonde relative humidity sensor should be able to measure relative humidity to a useful accuracy at all temperatures from 40°C down to about -70°C. Temperatures are lower than this near the tropical and subtropical tropopause, and radiosonde sensors can make useful measurements at these temperatures given that certain corrections are applied, see below. However, the most reliable practical method of measuring water vapour at these lowest temperatures around the tropopause is with a frostpoint hygrometer, see Vömel et al. (2007b) and the results from the WMO Intercomparison of High Quality radiosondes, WMO (2011). Table 9 shows the range of saturated water vapour with respect to a water surface that must be resolved to provide relative humidity measurements at all levels. At temperatures below 0°C, relative humidity sensors should be calibrated to report relative humidity with respect to a water surface.

Table 9. Variation of saturation vapour pressure over a water surface with temperature as a function of temperature after Sonntag (1994).

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Saturation vapour pressure (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>73.9</td>
</tr>
<tr>
<td>30</td>
<td>42.5</td>
</tr>
<tr>
<td>15</td>
<td>17.1</td>
</tr>
<tr>
<td>0</td>
<td>6.1</td>
</tr>
<tr>
<td>-15</td>
<td>1.92</td>
</tr>
<tr>
<td>-30</td>
<td>0.51</td>
</tr>
<tr>
<td>-45</td>
<td>0.112</td>
</tr>
<tr>
<td>-60</td>
<td>0.0195</td>
</tr>
<tr>
<td>-75</td>
<td>0.0025</td>
</tr>
<tr>
<td>-90</td>
<td>0.00023</td>
</tr>
<tr>
<td>-100</td>
<td>0.000036</td>
</tr>
</tbody>
</table>

The saturation with respect to water cannot be measured much below -50°C, so manufacturers should use one of the following expressions for calculating saturation vapour pressure relative to water at the lowest temperatures, Wexler (1977), Hyland and Wexler (1983) or Sonntag (1994). Saturation vapour pressure in ice cloud at the lowest temperatures in the tropical upper troposphere will be around 50
Measurement of upper-air pressure, temperature and humidity

Satisfactory relative humidity sensor operation becomes extremely difficult at very low temperatures and pressures. The free exchange of water molecules between the sensor and the atmosphere becomes more difficult as the temperature falls. Also, contamination of the sensor from high water vapour concentrations earlier in the ascent may cause substantial systematic bias in sensor measurements at the lowest temperatures. For instance a positive systematic bias of 5 per cent relative humidity is caused by contamination at -60°C, this would become a positive systematic bias of 40 per cent relative humidity at -75°C unless the contamination is ventilated away.

In the lower stratosphere and upper troposphere, water vapour measurements should be evaluated in terms of mixing ratio as well as relative humidity. Figure 7 shows the variation of temperature, relative humidity and mixing ratio with height measured by four different radiosonde sensors in the WMO Intercomparison of High Quality Radiosonde Systems, WMO (2011). Just under the tropopause, relative humidity was slightly higher than saturation, but the water vapour mixing ratio is close to the minimum, having dropped rapidly with temperature, as would be expected from Table 9. Where the temperature rises above the tropopause, the two relative humidity sensors with slower response (grey) show much higher water vapour mixing ratio than is realistic. The corrected sensor and the chilled mirror hygrometer (black) show a short-lived maximum in water vapour mixing ratio immediately above the tropopause. This is unlikely to be real, and suggests that the relative humidity reported by the black sensors in this layer between minute 48.4 and 50 are too high, by up to a factor of 2.5, probably the result of contamination of the payload or the radiosonde sensing area, and not a calibration issue. Contamination could have occurred earlier in the flight between minutes 33 and 38 when the payload passed through a thick layer of cirrus cloud detected by the cloud radar.

Figure 7. Temperature, relative humidity and water vapour mixing ratio presented as a function of time into flight, from Flight 56, WMO Intercomparison of High Quality Radiosonde Systems. The cloud radar at Yangjiang showed a thick cirrus between 11 and 13 km (minutes 33 to 38) and nothing above at the levels shown here. The grey measurements are from radiosondes with capacitative sensors, uncorrected for slow response time, and the black measurements from a heated twin capacitor sensor (corrected for time constant of response) and a frostpoint hygrometer (the frost point hygrometer shows more variation with time in relative humidity and mixing ratio than the heated twin capacitor).

The time constant of response for the relative humidity sensors can be defined as:

\[
dU_r/dt = -1/\tau \cdot (U_r - U)
\]  

where \(U_r\) is the relative humidity reported by the sensor and \(U\) is the actual relative humidity and \(\tau\) is the time constant of response. A further complication is that the relative humidity sensor reports relative humidity for the temperature of the humidity sensor. If this differs from the true atmospheric temperature then an additional error is introduced because of the thermal lag of the humidity sensor relative to the air temperature. Modern humidity sensors have become much smaller than in the older radiosonde types to minimise this problem, and the temperature of the sensor is in any case measured directly in many, but not all, widely used modern radiosondes.

The time-constant of response of a relative humidity sensor increases much more rapidly during a radiosonde ascent than the time-constant of response of the temperature sensor. This can be seen in Table 10 where approximate values of the time-constant of response of three older and then three modern sensor types are shown. In the case of goldbeaters skin the time-constant of response quoted
is for changes between about 70 and 30 per cent relative humidity. The time-constants of response of the goldbeater’s skin sensors are much larger at a given temperature if measuring high or low relative humidity.

Table 10. Time constants of response of relative humidity sensor, \( \tau \) (in seconds)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>In use</th>
<th>( T ) at 20(^\circ)C</th>
<th>( T ) at 0 (^\circ)C</th>
<th>( T ) at -20 (^\circ)C</th>
<th>( T ) at -40 (^\circ)C</th>
<th>( T ) at -70 (^\circ)C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heated twin thin film capacitor</td>
<td>2004</td>
<td>&lt;0.15</td>
<td>0.4</td>
<td>2</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>Other single thin film capacitors</td>
<td>2000-</td>
<td>0.1-0.6</td>
<td>0.6-0.9</td>
<td>4-6</td>
<td>15-20</td>
<td>*150-300</td>
</tr>
<tr>
<td>Thin film capacitor used with bead thermocapacitor (A)</td>
<td>1981-2011</td>
<td>0.2</td>
<td>0.9</td>
<td>6</td>
<td>15</td>
<td>180</td>
</tr>
<tr>
<td>Thin film capacitor used with bead thermocapacitor (H)</td>
<td>1981-2011</td>
<td>0.3</td>
<td>1.5</td>
<td>9</td>
<td>22</td>
<td>300</td>
</tr>
<tr>
<td>Carbon hygristor</td>
<td>1960-</td>
<td>0.3</td>
<td>1.5</td>
<td>9</td>
<td>20</td>
<td>Not reliable</td>
</tr>
<tr>
<td>Goldbeater’s skin</td>
<td>1950-</td>
<td>6</td>
<td>20</td>
<td>100</td>
<td>&gt;300</td>
<td>Not usable</td>
</tr>
<tr>
<td>Frostpoint hygrometer, CFH</td>
<td>2003- for science</td>
<td>&lt;2**</td>
<td>&lt;4**</td>
<td>&lt;25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chilled mirror hygrometer, Snow-White at night</td>
<td>1996- for science</td>
<td>&lt;2**</td>
<td>&lt;4**</td>
<td>&lt;25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*values derived from comparison with hygrometers, in WMO Intercomparison of High Quality Radiosondes, WMO (2011), may include problems with the ventilation of the caps covering the sensor.

** value estimated from in-flight comparison with best quality radiosonde relative humidity sensors, in WMO.

Two different thin-film capacitors were used with the bead thermocapacitor designated the Vaisala RS80-A and -H Humicap. These used different polymers, with the H-Humicap requiring a higher order polynomial calibration than the original A-Humicap. Time constants for both sensors can be seen in Miloshevich et al. (2004). These times are probably the response times of the sensor in laboratory tests, and may not take account of the effect of the protective cap on the sensing system. The values for the twin thin film capacitor (Vaisala RS92), in this table differ from those in Miloshevich et al. (2004) and were taken from updated information supplied by the manufacturer. This twin sensor uses the same polymer as the H-Humicap, but the thickness of the film and the mounting of the sensor are different from the original H-Humicap sensor.

Two profiles of radiosonde temperature and relative humidity are shown in Figures 8 and 9. Fig. 8 is an example of a radiosonde ascent in the UK, where the measurements from two different sensors have been combined. The sudden changes in relative humidity with height occur on many flights, and in this case the very dry layers are associated with temperature inversions. The existence of these very dry layers is accepted as correct, but in the past they were considered erroneous, because the earlier sensors could not measure these well. In this case the rate of change of relative humidity with height above the lowest inversion was 6 per cent R.H. per second, and so the modern sensors offer advantages to those who needed a detailed knowledge of the variation of atmospheric refractive index with height, significant for radio propagation. At mid-levels rates of change of 3 per cent R.H. per second are often found.
Measurement of upper-air pressure, temperature and humidity

Figure 8. Average of simultaneous measurements at 1s intervals by two radiosondes suspended together under one balloon, from UK test in Camborne, measurements at night.

Miloshevich et al. (2004) proposed a method of correction for slow time constant of response in humidity measurements based on the equation:

\[ U = U_e(t_2) - U_e(t_1)X/(1-X) \]  \hspace{1cm} (19)

where \( U \) = the true ambient relative humidity, \( U_e \) is the reported relative humidity for two times, \( t_1 \) and \( t_2 \). \( U \) is assumed not to change significantly between \( t_1 \) and \( t_2 \) (limiting the size of the time step used,) and \( X = e^{-\frac{t_2-t_1}{\tau}} \) where \( \tau \) is the time constant of response of the relative humidity sensor.

For the algorithm to give satisfactory results, the data used must be as free as possible of anomalous data, noise, etc. so some form of quality control has to be applied to the basic observations and also other corrections (e.g. for solar heating of the humidity sensor) before the time constant of response correction is attempted.

This correction cannot retrieve exact detail of the vertical profile of relative humidity at a much higher temporal resolution than the time constant of response of the sensor. It generates a smoothed vertical profile, with higher rates of change of relative humidity than in the original measurements, but any detail in the profile at time steps much smaller than the time constant of response should be treated with caution. As seen in Miloshevich et al. (2004), for a given original measurement there are quite a few possible answers, consistent with the known time constants of response. The type of smoothing applied to the original data influences the retrieved profile, so the smoothing used needs to be well documented and the assumptions made in the use of the algorithm need to be explained to the users.

When the time constant of response is very long with respect to the time step used in the algorithm, \( 1-X \) becomes small. For instance, for a time step of 10s and a time constant of response of 200s, \( 1-X \) becomes 0.049. Then if the measured relative humidity is 40 per cent and it increases by 0.5 per cent R.H. in the 10s time step, it would indicate that the true relative humidity at that time was 50 per cent R.H.. On the other hand a sensor with a time constant of response of 80s in the same conditions would require the increase in relative humidity over the time step to be measured only to better than 0.6 per cent R.H. to give the same accuracy. If these corrections are to work there must be nothing that causes the sensitivity of the sensor to change over the time step. Contamination and electronic noise can undermine this short term stability, and so in Yangjiang, some of the corrected measurements from the sensors at low temperatures were not always correct, especially from those sensors with the largest time constants of response.

From the examples seen in Yangjiang (WMO, 2011, Annex D) it was concluded that to report relative humidity structure near the tropical tropopause, the humidity sensing system should have had a time constant of response of 3 minutes or better, so that the adjustments for slow time constant of response are
Measurement of upper-air pressure, temperature and humidity

not too large and are not merely amplifying errors from noise in the measurements or from water/ice contamination.

Figure 9 illustrates the magnitude of the adjustments in relative humidity profile for a sensor with time constant of response about 80 s at -70 °C observing in the tropical upper troposphere during the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, WMO (2011). The corrected profile in Fig.9 is clearly very much smoother than the relative humidity profiles measured in the upper troposphere by the chilled mirror hygrometers in Figure 7. In Yangjiang, where corrections for slow response were applied, the result looked reasonable in about 65 per cent of the cases and quite wrong the rest of the time. Further testing of this type of adjustment and the type of smoothing applied, seems to be justified at this time.

![Image of Figure 9](image-url)

Figure 9. Twin thin film capacitor measurement in the upper troposphere at night in Yangjiang, China, showing the humidity profile, as a function of time into flight, measured directly by the sensor and then the profile corrected for time constant of response errors. Black is the original “raw” measurements and grey the corrected values.

During the Yangjiang test, the highest rates of change observed in the troposphere/stratosphere transition were about 30 per cent relative humidity over about 30 seconds. Thus, even the fastest operational radiosonde relative humidity sensor cannot define the true height of the rapid drop in humidity at the tropical tropopause without correction at the moment. Corrections to the height of the top of the humid layer in Yangjiang were found to be in the range 200 to 500m. However, the two scientific sounding instruments in Yangjiang had faster response and could resolve this height better when the instruments were functioning correctly, see Table 10.

5.2 Thin-film capacitors

Capacitive thin-film sensors are now used by nearly all modern radiosonde designs. These sensors rely on the variation of the dielectric constant of a polymer film with ambient water vapour pressure. The dielectric constant is proportional to the number of water molecules captured at binding sites in the polymer structure. The lower electrode of the capacitor is usually formed by etching a metal-coated glass plate. Dimensions either 5 by 3 mm or 4 by 1.5 mm, and thickness 0.55 or 0.2 mm. There is often a trade-off in thickness with a thinner film having faster time constant of response at low temperatures, but, perhaps less stable in performance with time. The upper electrode is vacuum-evaporated onto the polymer surface and is permeable to water vapour. Sensor capacitance is usually a nearly linear function of relative humidity; and the temperature dependence of calibration is not large. These sensors are always mounted on a supporting boom which should expose the sensor above the top of the radiosonde, or a long way away from the radiosonde body to the side.

The calibration of these relative humidity sensors is temperature dependent. The correction for this dependence must be applied during data processing by the ground system if the accuracy claimed for the sensor at room temperatures in the laboratory is to be obtained throughout most of the troposphere.

Contamination from rain, water drops in clouds or ice accretion, has to be driven off if no protective cap is used with the sensor. This can be achieved by heating the sensor well above ambient temperature,
Measurement of upper-air pressure, temperature and humidity

and twin sensors are used with one sensor measuring whilst the other is being heated and then cooled back to normal operation (Paukkunen, 1995). The twin sensors are mounted about 1.5 mm apart. These particular sensors also have a thin hydrophobic coating to minimise contamination from liquid water. As the sun shines directly on the sensors and their supports, the humidity sensors warm up relative to the correct temperature, particularly in the upper troposphere. In early versions of this sensor system the surrounding printed circuit board was not coated with a highly reflective surface, and the humidity sensor was warming too much in the upper troposphere in daytime. So, all the support surfaces were then aluminised, and was the first tested in Mauritius, WMO (2006a) and then as operational products in Yangjiang, China, WMO (2011). The manufacturer now advises users to use this sensor with correction software for slow time constants of response at low temperatures and a correction for solar heating of the humidity sensor in the daytime.

Four radiosondes in the WMO Intercomparison of High Quality Radiosondes, WMO (2011), used another sensor, manufactured by E+E. This sensor was always deployed with a protective cap, to minimise contamination. This cap usually has a highly reflective coating, so the sensor does not warm up too much in the daytime in the upper troposphere. Also the sensor supports and the cap must not be hygroscopic, otherwise outgassing from these surfaces will cause significant errors. Some of the manufacturers apply corrections for slow time constant. With this sensor the errors from slow time constant are larger than with the twin sensor. Most of the radiosondes using this sensor used an additional thermistor to measure the temperature of the humidity sensor directly, rather than assuming the humidity sensor was at the same temperature as the corrected temperature sensor.

A further four radiosondes in the WMO Intercomparison of High Quality Radiosondes, WMO, 2011, used sensors manufactured independently of Vaisala and E+E, with time constant of response characteristics mostly close to those of E+E.

5.3 Carbon hygristors

Carbon hygristor sensors are made by suspending finely divided carbon particles in a hygroscopic film. A modern version of the sensor consists of a polystyrene strip (of approximately 1 mm thick, 60 mm long and 18 mm wide) coated with a thin hygroscopic film containing carbon particles. Electrodes are coated along each side of the sensor. Changes in the ambient relative humidity lead to dimensional changes in the hygroscopic film such that the resistance increases progressively with humidity. The resistance at 90 per cent relative humidity is about 100 times as large as the resistance at 30 per cent relative humidity. Corrections can be applied for temperature dependence during data processing. The sensors are usually mounted on a duct within the radiosonde body to minimize the influence of precipitation wash and to prevent direct solar heating of the sensor.

The implementation of this sensor type requires a manufacturing process that is well controlled so that the temperature dependence of the sensors does not have to be determined individually. The hygristors will normally be subjected to many seasoning cycles over a range of relative humidity at room temperatures in the factory to reduce subsequent hysteresis in the sensor during the radiosonde ascent. The resistance of the sensor can be adjusted to a standard value during manufacture by scratching part of the carbon film. In this case, the variables can be issued with the appropriate standard resistance value for the specified conditions, and the sensors can be made interchangeable between radiosondes without further calibration. The sensor must be kept sealed until just before it is used, and the hygroscopic surface must not be handled during insertion into the sensor mount on the radiosonde.

However, the sensors do not seem to that have stable calibration at high humidity, and the reproducibility of the sensor measurements at lower humidity is often poor. In the WMO Radiosonde Humidity Sensor Intercomparison (WMO 2006b) it was shown that if the sensors (supplied by the main hygristor manufacturer) were kept at a high humidity for several hours, the calibration of the sensor changed irreversibly. Also the sensors did not measure low humidity, less than 20 per cent R.H., in a reproducible fashion, see Wade (1994, 1995), and measurements from this sensor misled many meteorologists into thinking that relative humidity lower than about 20 per cent did not occur in the lower troposphere.

5.4 Goldbeater’s skin sensors

Goldbeater’s skin (beef peritoneum) is still used in one major national network. The length of a piece of goldbeater’s skin changes by between 5 to 7 per cent for a change in humidity from 0 to 100 per cent. While useful measurements can be obtained at temperatures higher than −20 °C, sensor response
becomes extremely slow at temperatures lower than this (see Table 10). Goldbeater’s skin sensors also suffer from significant hysteresis following exposure to low humidity.

The goldbeater’s skin used for humidity variables should be single-ply and unvarnished, with a thickness of about 0.03 mm. The skin should be mounted with a tension of about 20 g cm\(^{-1}\) width and should be seasoned for several hours, in a saturated atmosphere, while subjected to this tension. To minimize hysteresis, it is advisable to condition the variable by keeping it in a saturated atmosphere for 20 min both before calibration and before use. Calibration should be carried out during a relative humidity cycle from damp to dry conditions. The variable must be protected from rain during flight.

The time-constant of response of the sensor is much higher than the values quoted in Table 10 at very high and very low humidity (McIlveen and Ludlam, 1969). Thus, it is difficult to avoid large bias in goldbeater’s skin measurements during an ascent (low bias at high humidity, high bias at low humidity) even in the lower troposphere.

5.5 Scientific Sounding Instruments

Three specialised scientific water vapour sounding instruments were deployed during the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, WMO (2011).

- The Cryogenic Frostpoint Hygrometer (CFH) Vömel et al. (2007b) is a chilled mirror hygrometer. The CFH uses a feedback loop that actively regulates the temperature of a small mirror, which is coated with ice (or dew in the lower troposphere). In the feedback loop an optical detector senses the amount of ice covering the mirror, and the feedback controller regulates the temperature of the mirror such that the amount of ice remains constant.

When the feedback controller is operating correctly the mirror temperature is equal to the frostpoint temperature, and if there is no internal ice/water contamination then the frostpoint temperature of the atmosphere. The inlet tubes to the CFH are stainless steel and 17 cm long with a diameter of 2.5 cm, directly above and below the hygrometer. This is intended to ensure that contamination from the air passing through the hygrometer is minimal, and the test results in Yangjiang confirmed that the CFH contamination was lower than experienced by the Snow White chilled mirror hygrometer in the upper troposphere and lower stratosphere.

Time constants of response vary from a few seconds in the lower troposphere and increase with height up to about 20 to 30s in the stratosphere. Thus, in the lower troposphere, the CFH time constant of response is not distinguishable from the best operational radiosondes. However, in the upper troposphere and lower stratosphere, it is faster in response than the best operational radiosondes. The main measurement uncertainty in CFH measurements is the stability and drift of the feedback controller. Thus, the total measurement uncertainty is estimated to be about 0.5ºC in dewpoint or frost point temperature, corresponding approximately to about 9 per cent R.H. at the tropical tropopause and 4 per cent R.H. in the lower troposphere.

The CFH uses a cold liquid at a temperature below -100 ºC, to cool the mirror during flight. Preparation and handling of this coolant before flight requires training and special handling procedures to avoid personal injury.

Correction schemes (solar heating, time constant) applied to the operational radiosonde relative humidity in the upper troposphere had benefitted from comparisons with CFH measurements, e.g. unpublished comparisons at the LAUTLOS test at Sodankyla, 2004, and in the LUAMI test at Lindenberg, 2008.

- The Snow White hygrometer also uses the chilled mirror principle for sensing water vapour, see Fujiwara, et al. (2003). However this uses a Peltier cooler to cool its mirror. There are two versions of the sensing system. The daytime mirror hygrometer was mounted in an internal duct in the sensing system. This configuration did not prevent contamination affecting the accuracy of the measurements below temperatures of about -50ºC and was only used on a few flights in Yangjiang. In the night time version, the mirror hygrometer was mounted above the radiosonde body. Thus, the night mirror hygrometer had little direct protection against contamination, but a very good exposure to ambient conditions. In Yangjiang the Snow White night time system was able to measure dewpoint
temperatures down to below -75°C on 70 per cent of the night-time flights. Two daytime flights suffered bad contamination near thunderstorms in the afternoon, but night time Snow White sensing systems were not significantly contaminated in upper cloud, because on this occasion ascent conditions were favourable to the Snow White operation. However, contamination around the hygrometer structure limited the use of Snow white to heights less than 18 km, just above the tropical tropopause in Yangjiang. Snow white has the same advantage as CFH with the Snow white time constants of response much smaller than the operational humidity sensors in the upper troposphere.

A skilled operator is required with the system to recognise when the mirror film changes phase from water to ice (requires the Snow white to be flown with a good operational humidity sensor). The operator must also be able to detect possible failure modes (such as the mirror losing its ice film) in the middle and upper troposphere. Identifying when contamination has corrupted the hygrometer measurements is a skill required for both Snow-white and CFH.

The two chilled mirror hygrometers have the advantage over the operational relative humidity sensors, of being sensitive in the upper troposphere and lower stratosphere down to the lowest temperatures, given contaminated measurements are recognised and excluded. Their measurements also do not have significant day-night differences in performance, so as working references their measurements have proved the best method of identifying these differences. Comparison with the chilled mirror measurements has allowed the development of correction procedures or changes in operational procedures to produce better quality operational measurements in the middle and upper troposphere.

- Sensors in ducts do not provide the best method of observing relative humidity structure through rain and low cloud, so that it is unwise to treat the chilled mirrors as more reliable than the best operational radiosonde sensors in the lower troposphere. The Vaisala RD100 Drycap sensor used a capacitive thin film sensor specifically developed for low water vapour conditions in the upper troposphere and lower stratosphere. In Yangjiang this required a protective shield to prevent contamination in the lower and middle troposphere, but the design of this proved faulty. This shows the difficulty encountered by a major manufacturer in trying to build a prototype version of an operational reference radiosonde, to provide reliable water vapour measurements in the stratosphere.

5.6 Exposure

Rapid changes in relative humidity with time of greater than 25 per cent are common during radiosonde ascents. Accurate measurements of these changes are significant for some users. Accurate measurements require that the humidity sensor is well ventilated, but the sensor also needs to be protected as far as possible from the deposition of water or ice onto the surface of the sensor or its supports, and also from solar heating.

Thus, the smaller relative humidity sensors, such as thin-film capacitors, are mounted on an external outrigger. The sensor may be covered by a small protective cap, or the sensors may be heated periodically to drive off contamination from water or ice in cloud or fog. The design of the protective cap may be critical, and it is essential to ensure that the cap design is such that the humidity sensor is well ventilated during the radiosonde ascent.

Larger sensors were usually mounted in an internal duct or a large protective duct on the top or side of the radiosonde body. The duct design should be checked to ensure that air flow into the duct guarantees adequate sensor ventilation during the ascent. The duct should also be designed to shed ice or water, encountered in cloud or heavy precipitation, as quickly as possible. The duct should protect the sensor from incident solar radiation and should not allow significant backscattering of solar radiation onto the sensor. Particular care is required in duct design if contamination in upper cloud is to be avoided.

Protective covers or duct coatings should not be hygroscopic, e.g. see the stainless steel inlet pipes used by CFH, or the aluminised sensor mounts of some operational radiosondes.
5.7 Relative humidity errors

5.7.1 General considerations

Operational relative humidity sensors have improved greatly compared to the sensors in use before the 1980’s, especially at low temperatures in the middle and upper troposphere. Relative humidity observations at temperatures lower than -40 °C were not reported in most of the early radiosonde systems. Significant use of relative humidity reports at temperatures lower than -40 °C did not develop until about 2000.

Real-time operational assessment of radiosonde relative humidity measurements by users is not very extensive, and methods need to be developed for providing information to the manufacturers on the calibration performance of the humidity sensors, e.g. records of the relative humidity reported when the radiosonde was known to pass through low cloud, or the statistics of the pre-flight ground checks. In testing radiosondes it should not be assumed that the uncertainty in the measurements is the same for all relative humidity bands. Non-uniform performance across the relative humidity range was still found for many systems in the WMO Intercomparison of High Quality Radiosondes, WMO (2011). However, the better systems are now much closer to uniformity at all relative humidity than was found at the start of the WMO Radiosonde Comparison series in 1984. During manufacture, calibrations on individual sensors are often performed only at a few (less than three) pre-set relative humidity points, and possibly only at one temperature (see, for example, Wade, 1995). In many cases, the temperature dependence of the sensor calibration is not checked individually, or in batches, but is again assumed to follow curves determined in a limited number of tests. Sensor calibrations have often varied by several per cent in relative humidity from batch to batch, as can be seen from measurements in low-level cloud (Nash, Elms and Oakley, 1995). This may be a consequence of faulty calibration procedures during manufacture. For instance, actual sensor performance in a given batch may differ from the standardized calibration curves fitted to the pre-set humidity checks. On the other hand, it could be the result of batch variation in the stability of the sensors during storage. In addition in some thin-film capacitors the thickness of the film is not always the same, so the thicker sensors are sometimes quite unresponsive to humidity changes at low temperatures where the majority of the sensors of the same type respond quite well in the same conditions.

In the following sections, the errors are first considered for temperatures greater than -20 °C, where both old and newer sensors were expected to work reliably. Before 1990, most of the radiosondes in use had significant problems with measurements at temperatures lower than -30 °C. For instance, the relative humidity reports from widely used carbon hygristors were not consistent from flight to flight, because the systematic bias in the bands non-uniformly depended on the vertical structure of relative humidity and whether the asens passed through any cloud. Thus, only the errors of the more modern sensors are considered for the temperature bands -20 °C to -50 °C where they work more reliably and then for temperatures of -50 °C to -70 °C where only the newest relative humidity sensors could respond quickly enough to make useful measurements. The analysis is then further divided into night and daytime performance. Night time measurements may not necessarily be more reliable than daytime because in many cases there seems to be a greater chance of contamination around the sensor at night, if its ventilation is poor, whilst solar heating of the sensor surrounds drives off more of the contamination in the day or produces a compensating low bias in the daytime humidity.

Water vapour pressure is obtained by multiplying the saturation vapour pressure computed from the radiosonde temperature by the radiosonde relative humidity measurement. If the temperature of the relative humidity sensor does not correspond to the temperature reported by the radiosonde, the reported water vapour (and hence any derived dewpoint) will be in error. In a region of the troposphere where temperature is decreasing with height the humidity sensor temperature will be higher than the air temperature reported. If the humidity sensor temperature is higher than true temperature by 0.5 K at a temperature close to 20 °C, the relative humidity reported by the sensor will be about 97 per cent of the true relative humidity. This will result in an error of −1.5 per cent at a relative humidity of 50 per cent. As temperature decreases to −10 °C and then to −30 °C, the same temperature lag in the sensor causes the reported relative humidity to decrease to 96 per cent and then to 95 per cent of the true value.

Systematic errors in relative humidity measurements may occur because of changes in calibration during storage. This may be simple effects of sensor aging or the build-up of chemical contamination, where contamination occupies sites that normally would be open for water vapour molecules. Chemical contamination of thin film capacitor sensors causes the sensor to have a dry bias, see the examples for Vaisala RS80 - A and -- H in Table 11. The rate of contamination may depend on the chemicals used in manufacturing the radiosonde body or the packaging, and cannot be assumed to be the same when the manufacturing of the radiosonde body or printed circuit boards changes with time. The manufacturer’s instructions regarding the storage of the sensors and preparations for use must be applied carefully. For instance it is essential that the ground check process is performed with the Vaisala RS92 sensor before
launch, since this drives off any build-up of chemical contamination and hence low bias early in the ascent.

### 5.7.2 Relative humidity, night, temperatures higher than -20°C

Table 11 summarizes night-time systematic differences in relative humidity at temperatures higher than -20°C for the most widely used sensors tested during the WMO International Radiosonde Comparison. The results shown in Table 11 have been limited to night flights to eliminate complications caused by solar heating. More detailed results on the earlier tests may be found in Nash, Elms and Oakley (1995). From 1984 until 2000 the performance of the Vaisala RS80 A-Humicap was used as an arbitrary reference linking the earlier tests in the WMO Radiosonde Comparison. More recent tests in Brazil and Mauritius have also utilized the Meteolabor “Snow White” chilled-mirror hygrometer as a working standard. The errors for the RS80-A were deduced from laboratory tests of a limited number of sensors and operational measurement quality in low-level clouds. It would be unwise to assume that the assumed average performance for the RS80-A arbitrary reference fell closer than ±3 per cent relative humidity to the actual absolute errors of the radiosonde measurements. Both Snow White and CFH measurements were used in the WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, and the systematic error in the reference used in these tests was probably somewhere in the range ± 2 per cent for the temperature range in Table 11.

In the comparisons in Table 11, the time-constants of response of most thin-film capacitors and the carbon hygristor were similar and fast enough to avoid significant systematic bias from slow sensor response. Goldbeater’s skin is able to respond reasonably well to rapid changes in mid-range relative humidity at these temperatures. Nonetheless, the very slow response of this sensor at high and low humidity contributes to the large systematic differences for goldbeater skin at high and low humidity in Table 11, with measurements too low at high relative humidity and too high at low relative humidity.

Note that in the tests performed before 2000, the data used for analysis in WMO Radiosonde Comparisons were limited to flights where the radiosondes had not passed through low-level cloud. When the VIZ 1392 and Vaisala RS80 sensors became wet for a short time in low cloud the VIZ radiosonde calibration changed to lower values by at least 10 per cent R.H., and the Vaisala observations could often be biased high by at least 10 per cent for the remainder of the ascent. If dry conditions were not separated out, the combination of the effects of the water and the basic calibration of the sensors gave very much higher sonde errors than those quoted in Table 11. The sonde errors for VIZ1392 and Vaisala RS80 (uncontaminated) are thus the best that could be expected, but often the results obtained were very much worse than shown.

The Vaisala RS80 radiosondes used in the early WMO Radiosonde Tests were fresh from the factory so dry bias from contamination was not an issue for these tests. In Wang et al. (2002), evidence from Vaisala showed that RS80-A radiosondes stored for a year had very small dry bias, about -2 per cent R.H., whereas the RS80-H had a dry bias of -11 per cent at 100 per cent R.H. when stored for a year. A similar test performed in the UK in 1990 had also shown RS80-A with small changes in performance over a year. However, tests performed on RS80-A radiosondes used by Argentina and Brazil during the RAIII Radiosonde Training Workshop in 2006 showed these had dry bias of at least 10 per cent at 90 per cent R.H., Nash et al. (2006), so something changed between the early RS80-A tests and what happened in later years. This bias was removed if the radiosonde sensor was heated with a hand drier before use. Further detailed evidence of the operational performance of the Vaisala RS80-H sensor can be found in Turner, et al., (2003), for instance, showing how the H-Humicap dry bias increased with storage time. Typical dry bias that could result after storing for about a year is shown in Table 9, with the consequent large degradation in the uncertainty of the RS80 measurements at high and medium relative humidity. Vaisala redesigned the packaging of the sensors to try and rectify the storage problem, but this redesign does not seem to have been very effective and chemical contamination dry bias seemed to persist to the end of the RS80 operational use in 2011. Note: as long as the Vaisala RS92 is prepared following the manufacturer’s instructions, the degradation of performance from dry bias from chemical contamination does not occur.

The VIZ MKII carbon hygristor sensor was smaller than the carbon hygristor used in the VIZ 1392 radiosonde. The results quoted for the VIZ MKII carbon hygristor, show very wide ranges in uncertainty, especially at very low humidity. The results were different according to whether the conditions were dry or generally very moist (especially with liquid water present in cloud or rain). This seemed to be because the calibration of this newer hygristor sensor also changed when conditions were very moist (in cloud), giving a significant dry bias at lower humidities. Proposed changes in algorithms, especially at low humidity, did not result in any consistent improvement in the measurement quality. The VIZ 1392 sensors would have had a similar large range in performance. The LMS-6 radiosonde, successor to the VIZ MkII, now uses a capacitor sensor. Carbon hygristors have been in use in India and China in the last decade.
Measurement of upper-air pressure, temperature and humidity

Thus, between 1984 and 2000 contamination effects and instability in calibration led to the uncertainty in relative humidity measurements at temperatures above -20 °C at night mostly in the range 10 to 20 per cent, (but larger than this for goldbeaters skin and the carbon hygristor at low humidity). The Vaisala RS80 thin film capacitor could do better than this if used within a few months of delivery from the factory so chemical contamination remained small. These results were obtained with cloudy flights excluded from the data sets.
Table 11. Systematic differences, sonde error and uncertainty \([k=2]\) of radiosonde relative humidity measurements at night for temperatures higher than \(-20 ^\circ C\).

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>System Bias (per cent R.H.)</th>
<th>Sondeerror</th>
<th>Uncertainty ([K=2])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 - 90 40-60 10-20</td>
<td>80-90 40-60 10-20</td>
<td>80-90 40-60 10-20</td>
</tr>
<tr>
<td>Goldbeaters skin MRZ, Russian Fed, RS3, UK**.</td>
<td>-8 -1 9</td>
<td>12 18 16</td>
<td>20 19 25</td>
</tr>
<tr>
<td>Carbon hygristor, VIZ 1392, USA**</td>
<td>4 -3 12</td>
<td>8 8 12</td>
<td>12 11 24</td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-A** Possible Contamination after 1 year†:</td>
<td>-2 ± 3, 1 ± 3, 2 ± 3, 6, 6, 4, 6 – 11, 6 – 10, 4 – 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al. (2002)</td>
<td>-4 ± 3, -2 ± 3, 2 ± 3, 6, 6, 4, 7 – 13, 6 – 11, 4 – 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nash et al. (2006)</td>
<td>-13 ± 3, -7 ± 3, -1 ± 3, 6, 6, 4, 16 – 22, 10 – 16, 4 – 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-H** Possible Contamination after 1 year</td>
<td>-1 ± 3, 0 ± 3, 0 ± 3, 6, 6, 4, 6 – 10, 6 – 9, 4 – 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon hygristor, VIZ MkII, USA</td>
<td>4 -10, -4 to 4, -20 -10, 10, 4 - 16, 6 - 20, 14 - 20, 4 - 20, 6 - 40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin thin film capacitor, Vaisala RS92 Finland</td>
<td>1** 0 ± 2, 0 ± 2, 3, 5, 3, 3 - 6, 5 - 8, 3 - 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor, used in LMS-6** E+E, USA</td>
<td>-1 ± 2, 1 ± 3, 2 ± 2, 3, 5, 3, 4 - 6, 6 - 9, 5 - 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor</td>
<td>4±4, 6 ± 8, 3±3, 4, 4, 2, 4 – 12, 4 – 18, 3 – 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Changfeng</td>
<td>4</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Daqiao</td>
<td>3</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Graw E+E</td>
<td>-7±1</td>
<td>-1±1</td>
<td>2±1</td>
</tr>
<tr>
<td>Huayun E+E</td>
<td>4</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Intermet E+E</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Jinyang E+E</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Meisei</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Meteolabor Switz.</td>
<td>4**</td>
<td>3**</td>
<td>0</td>
</tr>
</tbody>
</table>

** Data from dry conditions only used in the analysis.

E+E uses E+E sensor from Germany

M Uses information from Miloshevich et al. (2009) as well as other WMO and UK tests

** CFH seemingly had positive bias at low levels in WMO (2011), similar to the situation in Miloshevich et al. (2009)

† A-Humicap contamination effects seemed to change with time and needed better operational monitoring.
Since 2005, the majority of the modern humidity sensors have shown improved stability and improved protection against contamination in cloud [ contamination effects normally being short lived and not resulting in permanent offsets during the ascent], and improved reproducibility batch to batch. Thus, now the results from dry and wet conditions can be combined, apart from in very heavy rain, when no system performs reliably. Table 11 shows there are at least eight radiosonde systems capable of providing relative humidity measurements with uncertainty better than or in the range 5 to 10 per cent, at night and at temperatures higher than -20 °C. The wide performance ranges quoted for Modern, at night, reflect a situation where the systems have been tested a lot since 2005, but sometimes the factory calibration has been in error.

For all the systems, the test results in Yangjiang (2011) are useful as a guide to performance. However, new designs need further evaluations to check whether the systems will show good reproducibility from test to test. On the other hand where there were uncertainties larger than 10 per cent in Yangjiang, further tests would need to show that the origin of the higher uncertainty has been identified and rectified.

The Cryogenic Frostpoint Hygrometer was used for the first time in a WMO Radiosonde Comparison in Yangjiang. The number of direct comparisons with Vaisala RS92 at temperatures higher than -20°C was limited and the CFH measurements had a positive bias of about 2 per cent relative to Vaisala at high humidity. The positive bias observed in Miloshevich (2009) in the lower troposphere was also seen in the night flights in Yangjiang.

5.7.3 Relative humidity, day, temperatures above -20°C

Table 12 contains the summary of daytime systematic differences, sonde error and uncertainty of the radiosonde relative humidity measurements for temperature higher than -20°C. This Table only includes information on the Vaisala RS80 thin film capacitor and then the modern humidity sensor designs. With the other earlier sensors the uncertainty was so large that test samples were not sufficiently large to look for meaningful differences between day and night.

During daytime flights, direct heating by solar radiation can also produce significant heating of the relative humidity sensor. In addition, the sensor may be heated indirectly by air that has previously flown over contact protective covers or duct walls heated directly by solar radiation. Brousaides and Morrissey (1974) quantified the errors that could occur with early VIZ radiosondes. Cole and Miller (1985) investigated the errors that could occur when Vaisala RS80 radiosondes were launched from poorly ventilated shelters in the tropics. The daytime differences between carbon hygristor and thin-film capacitor measurements obtained in the early phases of the WMO Radiosonde Comparisons were very close to the values obtained at night. Thus, while both sensor types must have some negative error caused by the direct or indirect solar heating of the relative humidity sensor, the errors were of similar magnitude for both types of sensors and could not be quantified by the early testing.

However, comparison with collocated remote-sensing observations (microwave radiometers or GPS water vapour) has confirmed that there is a day-night difference in modern radiosonde relative humidity measurements, for example, see Turner and others (2003) and WMO (2006a). The day-night difference in relative humidity at high and middle range relative humidity for the Vaisala RS80 was typically around 3 per cent, see Turner et al., (2003). However, in overcast conditions, the difference could be as low as 1 per cent. The day-night difference can also be estimated independently from comparisons with the Snow White hygrometer, as Snow White measurements are relatively consistent between day and night at temperatures higher than -40 °C. In the tropics, the day-night differences in Vaisala RS80-A and RS90 relative humidity measurements in high humidity shortly after launch were about 5 per cent relative humidity (WMO Radiosonde Comparison, Brazil, 2006c).

The situation with the Vaisala RS92 is complicated, because significant changes in sensor support designs led to large changes in performance in daytime up to 2011. Early versions had a bare printed circuit board as part of the sensor supports. In the day, these supports heated up much more than the aluminised surfaces, and thus led to greater heating of the air passing over the humidity sensors. This was recognised as causing a problem and by the time of the WMO Radiosonde Comparison in Mauritius, WMO (2006a) the sensor supports had been fully aluminised, with the results corresponding to V1 in Table 12. Thus, the measurements reported by Vömel et al. (2007a), performed with the original RS 92 version, V0, show larger dry biases than those observed in Mauritius. This aluminisation did not eliminate the solar heating problem, but did reduce the magnitude of the effect, and as can be seen represents the main step forward in reducing the uncertainty of these Vaisala daytime relative humidity measurements at higher temperatures. In the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, WMO (2011) software was used to correct the daytime negative bias from solar heating. Thus, the daytime twin film capacitor measurements were only optimised after the software used in the Yangjiang comparison was introduced operationally worldwide, and the uncertainty in the daytime measurements was much worse than in the nighttime measurements, until the hardware and software modifications were introduced after
The implementation of E+E sensors by the various radiosonde manufacturers has not resulted in uniform humidity quality between the radiosondes using this sensor. In Yangjiang, the E+E sensors had quite different uncertainty characteristics, e.g. Intermet had a significant negative bias at high humidity, but very little day-night difference, whilst Jinyang seemed to have contamination/ventilation problems like Modem with biases smaller in the day than at night.
Table 12. Systematic differences, sonde error and uncertainty\([k=2]\) of radiosonde relative humidity measurements in the day for temperatures higher than -20 °C.

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>System Bias (per cent R.H.)</th>
<th>Sonde error</th>
<th>Uncertainty ([K=2])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 - 90</td>
<td>40-60</td>
<td>10-20</td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-A**, Possible Contamination after 1 year*1: -Wang et al. (2002)</td>
<td>-7 ± 3</td>
<td>-4 ± 3</td>
<td>0 ± 3</td>
</tr>
<tr>
<td>Nash et al. (2006)</td>
<td>-16 ± 3</td>
<td>-9 ± 3</td>
<td>-3 ± 3</td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-H**, Possible Contamination after 1 year</td>
<td>-4 ± 3</td>
<td>-3 ± 3</td>
<td>-2</td>
</tr>
<tr>
<td>Carbon hygristor, VIZ MkII, USA</td>
<td>-2 ± 4</td>
<td>-3 ± 6</td>
<td>0± 10</td>
</tr>
<tr>
<td>Twin thin film capacitor, Vaisala RS92, Finland</td>
<td>v0-9 ±2</td>
<td>v1-3±2</td>
<td>v1-1±2</td>
</tr>
<tr>
<td>Thin film capacitor, LMS-6E+E, USA</td>
<td>-3 ± 2</td>
<td>0 ± 3</td>
<td>0± 2</td>
</tr>
<tr>
<td>Thin film capacitor</td>
<td>Modem France</td>
<td>0 ± 1</td>
<td>1 ± 6</td>
</tr>
<tr>
<td>Changfeng China</td>
<td>-1</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>Daqiao China</td>
<td>1 ± 4</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>GravE+E Germany*</td>
<td>2</td>
<td>2 ± 2</td>
<td>2</td>
</tr>
<tr>
<td>HuayunE+E China*</td>
<td>-1</td>
<td>-1</td>
<td>5</td>
</tr>
<tr>
<td>InternetE+E S. Africa</td>
<td>-6</td>
<td>-2</td>
<td>-1</td>
</tr>
<tr>
<td>JinyangE+E Korea</td>
<td>0</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Meisei Japan</td>
<td>0</td>
<td>-1</td>
<td>-2</td>
</tr>
<tr>
<td>Meteolabor Switz.</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Snow White, Meteolabor, Switzerland</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>CFH, USA/Germany</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

\*E+E uses E+E sensor from Germany

*1A-Humicap contamination effects seemed to change with time and needed better operational monitoring

\(v0\) Vaisala RS92 original with bare printed board in supports for relative humidity sensors, values for tropics from Vömel; et al. (2007)

\(v1\) Vaisala RS92 with fully aluminiised supports, but no correction for solar heating, WMO (2006)

\(v2\) Vaisala RS92 with fully aluminiised sensor support, with correction for solar heating, tropics WMO (2011)
Table 12 shows there were at least seven radiosonde systems capable of providing relative humidity measurements with uncertainty better than or in the range 5 to 10 per cent, in daytime and at temperatures higher than -20 °C.

5.7.4 Relative humidity, night, temperatures between -20°C and -50°C

Table 13 contains a summary of night-time systematic differences, sonde error and uncertainty of the radiosonde relative humidity measurements for temperature between -20 °C and -50 °C.

**Table 13. Systematic differences, sonde error and uncertainty [k=2] of radiosonde relative humidity measurements at night for temperatures between -20 °C and -50 °C**

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>System Bias [per cent R.H.]</th>
<th>Sonde error</th>
<th>Uncertainty [K=2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Humidity [per cent R.H.]</td>
<td>60-80 40-60 10-20 60-80 40-60 10-20 60-80 40-60 10-20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-A** to -20 to -50 °C</td>
<td>-2 ± 3 to -1 ± 3 to 2 ± 3 to 6 to to to 6 to 6 to 6 ± 11 to 6 ± 10 to 6 ± 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-H**</td>
<td>-1 ± 3 to 0 ± 3 to 0 ± 3 to 6 to 6 to 4 6 ± 10 6 ± 9 6 ± 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon hygristor, VIZ MkII, USA**</td>
<td>0 - -5 to -4 to -10 -20 to 10 8 7 10 -15 12 -18 17 -27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin thin film capacitor, Vaisala RS92 Finland</td>
<td>1M ± 3 to 0 ± 3 to 0 ± 2 to 6 to 6 to 4 6 ± 10 6 ± 9 4 ± 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor, used in LMS-E+E, USA</td>
<td>-1 ± 2 to 1 ± 3 to 2 ± 2 to 6 to 6 to 4 6 ± 9 6 ± 10 4 ± 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor</td>
<td>14 ± 4 to 11 ± 3 to 4 ± 4 to 9 to 9 to 7 19 -27 17 -23 7 -15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modem France</td>
<td>2 -2 to 5 24 32 32 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changfeng China</td>
<td>6 15 32 32 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daqiao China</td>
<td>7 3 7 6 12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GrawE+E Germany</td>
<td>-3 7 2 7 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HuayunE+E China</td>
<td>-3 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IntermetE+E S. Afr. JinyangE+E Korea</td>
<td>-5 9 8 6 4 11 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meisei Japan</td>
<td>-5 5 3 6 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteolabor Switzerland</td>
<td>0 - -10 4 - 0 16 28 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow White, Meteolabor, Switzerland</td>
<td>-2 -1 3 6 8 4 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFH, USA/Germany</td>
<td>2 1 0 5 5 5 7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Data from dry conditions only used in the analysis.

E+E uses E+E sensor from Germany

M Uses information from Miloshevic et al. (2009) as well as other WMO and UK tests
For most radiosonde systems designed before 2000, the relative humidity sensor performance was usually influenced by the conditions experienced earlier in the flight, so the values obtained in early tests in this temperature range were not very reproducible, even when thick cloud and rainy conditions were excluded. Of the two early thin film capacitors, the Vaisala RS80A had a calibration error at lower temperatures than gave rise to the range of values in Table 13, whereas the Vaisala RS80-H did not have these calibration errors but the time constant of response was significantly slower than the modern thinfilm capacitors in the upper troposphere. The chemical contamination errors from storage noted in Table 11, also affected both Vaisala RS80 measurements in this temperature range. These results were for flights with no significant upper cloud.

Table 13 shows there were at least four radiosonde systems capable of providing relative humidity measurements with uncertainty in the range 5 to 10 per cent, at night and at temperatures between -20 °C and -50 °C whether cloud was present or not.

Three radiosonde systems in Yangjiang had significant systematic error problems at night in this temperature range, Modem and Jinyang seemed to have contamination issues giving large systematic errors and the Daqiao sensor was not reproducible in its performance, with some ascents giving reasonable measurements and others very bad measurements with contamination also a problem. The Rotronic humidity sensor used by Meteolabor was too slow to cope with the rapid changes in relative humidity observed at Yangjiang at these temperatures, and so its sonde errors were large in Table 13.

5.7.5 Relative humidity, day, temperatures between -20 °C and -50 °C

Table 14 contains a summary of daytime systematic differences, sonde error and uncertainty of the radiosonde relative humidity measurements for temperature between -20 °C and -50 °C.

The problems with the Vaisala RS80-A calibration was similar to that at night, with slightly more negative bias because of solar heating. The systematic errors in the VIZ MkII carbon hygristor at low relative humidity were offset by about 10 per cent R.H. between day and night, but this could easily have been the result of the very poor reproducibility of the hygristor measurements between different conditions.

The systematic errors in the twin film capacitor measurements in daytime had larger negative biases than at higher temperatures in Table 12, until the sensor supports were aluminised, so it took until about 2011, before the erroneous dry biases were removed from the daytime twin thin film capacitor measurements.

The large positive systematic errors in Modem and Jinyang nighttime measurements were not found in daytime measurements. However, Intemet had strong negative bias at higher humidities in the daytime. This was the result of a software error that made incorrect use of the temperature of the humidity sensor and should not be present once this error is rectified.

Daqiao and Meteolabor relative humidity measurements again had large sonde errors as at night, but were joined by Huayun because of the poor exposure of the sensor relative to the radiosonde body, a similar problem to that causing poor temperature sensor performance in daytime.

Table 14 shows there were at least four radiosonde systems capable of providing relative humidity measurements with uncertainty in the range 5 to 10 per cent, in daytime and at temperatures between -20 °C and -50 °C whether cloud was present or not.
### Table 14. Systematic differences, sonde error and uncertainty [k=2] of radiosonde relative humidity measurements in daytime for temperatures between -20 °C and -50 °C

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>System Bias [per cent R.H.]</th>
<th>Sonde error</th>
<th>Uncertainty [K=2]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60-80 40-60 10-20</td>
<td>60-80 40-60 10-20</td>
<td>60-80 40-60 10-20</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>[per cent R.H.]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-A**</td>
<td>-5 ± 3 to -11 ± 3</td>
<td>6 6 6</td>
<td>8 - 14 to 14 - 20</td>
</tr>
<tr>
<td>-20 to -50 °C</td>
<td></td>
<td>6 6 6</td>
<td>6 - 12 to 9 - 15</td>
</tr>
<tr>
<td>Thin film capacitor, Vaisala RS80-H**</td>
<td>-4 ± 3 to -2 ± 3</td>
<td>6 6 4</td>
<td>7 - 13 to 6 - 11</td>
</tr>
<tr>
<td>Not sensitive to T</td>
<td></td>
<td>6 6 4</td>
<td>4 - 8</td>
</tr>
<tr>
<td>Carbon hygristor, VIZ MkII, USA**</td>
<td>-8 to -10</td>
<td>10 8 7</td>
<td>18 17 7 - 17</td>
</tr>
<tr>
<td>Twin thin film capacitor, Vaisala RS92 Finland</td>
<td>V0 -16 ±4 V1 -7 ± 2 V2 2 ± 2</td>
<td>V1.5 ±2 V2.3 ±2 V1.3±2 V2.1±2</td>
<td>16 - 24 11 - 15 6 - 10 7 - 11 3 - 7 2 - 5</td>
</tr>
<tr>
<td>Thin film capacitor, used in LMS-6 E-E, USA</td>
<td>-2 ± 2 to -3 ± 3</td>
<td>0 ± 2</td>
<td>6 8 2</td>
</tr>
<tr>
<td>Thin film capacitor</td>
<td>Modem France 0 5 - 2 4</td>
<td>8 9 6</td>
<td>8 9 - 14 7 - 15</td>
</tr>
<tr>
<td>Changfeng China -10 -4</td>
<td>-4</td>
<td>6 10 2</td>
<td>20 14 6</td>
</tr>
<tr>
<td>Daqiao China -6 24</td>
<td>-4 - 9</td>
<td>-6</td>
<td>32 32 9</td>
</tr>
<tr>
<td>Grav E-E Germany* -3</td>
<td>3</td>
<td>6 4 2</td>
<td>7 7 6</td>
</tr>
<tr>
<td>Huayun E-E China* 0 0</td>
<td>0 0 - 2</td>
<td>5 18 9</td>
<td>20 - 32 18 - 23 14</td>
</tr>
<tr>
<td>Jinyang E-E S. Africa -12 0 2</td>
<td>-4 0</td>
<td>-5</td>
<td>7 5 4</td>
</tr>
<tr>
<td>Intermet E-E Korea 2 - 4</td>
<td>2</td>
<td>6 5</td>
<td>4 10 - 19 8 - 10 6</td>
</tr>
<tr>
<td>Meisei E-E Japan -4 0</td>
<td>-4</td>
<td>6 6 5</td>
<td>3 10 19 17 19</td>
</tr>
<tr>
<td>Meteolabor Switz. 6 - 6</td>
<td>1 - 2</td>
<td>0 12 17 6</td>
<td>12 - 18 17 - 19</td>
</tr>
<tr>
<td>Snow White, Meteolabor, Switzerland</td>
<td>0 2</td>
<td>1 6 8 4</td>
<td>8 9 7</td>
</tr>
<tr>
<td>CFH, USA/Germany 2 1</td>
<td>0</td>
<td>5 5 5</td>
<td>7 6 5</td>
</tr>
</tbody>
</table>

** Data from dry conditions only used in the analysis.

E-E uses E+E sensor from Germany

V0 Vaisala RS92 original with bare printed board in supports for relative humidity sensors, values for tropics from Vömel; et al. (2007)

V1 Vaisala RS92 with fully aluminised supports, but no correction for solar heating, WMO (2006)

V2 Vaisala RS92 with fully aluminised sensor support, with correction for solar heating, tropics WMO (2011)

### 5.7.6 Night, temperatures between -50°C and -70°C

Table 15 shows the systematic differences, sonde error and uncertainty [k=2] for night time measurements at temperatures between -50 and -70 °C. For only the modern sensors. These sensors/ sensing systems
Measurement of upper-air pressure, temperature and humidity

differ in terms of time constant of response, and all the operational radiosondes have longer than optimum time constants in the upper troposphere /lower stratosphere in the tropics, with some becoming slow at -60°C and some at -80°C. The chilled mirror hygrometers are capable of working reasonably quickly at these low temperatures and have thus provided evidence on the speed of response of the operational sensors. None of the earlier radiosonde humidity sensors worked in a reliable fashion in this temperature band, apart from the Vaisala RS80, which could be used at temperatures lower than -40°C in the troposphere.

The Vaisala RS80-A had errors in the calibration polynomial used at very low temperatures, for instance, for a relative humidity between 30 and 70 per cent, the Vaisala RS92 thin-film capacitor sensors reported relative humidity values at -60 °C at night that were 14 per cent higher than the Vaisala A-type in Brazil (WMO, 2006c). The same sensors agreed within a few per cent at higher temperatures (see Table 11). Corrections for the calibration error in the A-Humicap were proposed by Miloshevich et al. (2001) and Leiterer et al. (2005). The equivalent calibration polynomial error for the RS80-H was about 3 per cent R.H. at -60°C. Time constant errors for RS80-H measurements at -60°C were much bigger than those shown earlier in Fig.9 for the Vaisala RS92, which uses the same polymer as the RS80-H, but in a much thinner film. Thus, time lag errors in thin upper cloud, 1 km thick, near the tropopause in the UK were found to be as large as -10 per cent for the RS80-H relative to the RS92 measurements without any time lag error corrections applied to the RS92.

The sonde errors in Table 15 at -60 °C are generally around twice as large as those at temperatures higher than -20 °C in Table 9, the exception being the CFH with more reproducible measurements at upper levels than in the lower troposphere. Daqiao and Meteolabor sensors were too slow at the lowest temperature, so data are not included in Table 11. Modern, Changfeng and Huayun sonde errors increased more rapidly at lower temperatures compared to the best performing radiosondes at these temperatures.

The reference used in Table 15 for systematic errors cannot be defined better than ±4 per cent, as all the sensors including CFH (possible contamination) have limitations. CFH, Changfeng, Intermet, LMS-6, Meisei, Snow-white and Vaisala had small biases at these temperatures. The time constant of response corrections applied to Vaisala RS92 in 2011 only changed the systematic bias by + 0.5 per cent R.H. in the band 40-60 per cent and -1.2 per cent R.H in the band 20 to 40 per cent R.H.. In analysing the results from the WMO Intercomparison of High Quality Radiosonde Systems, some CFH and Snow White flights had to be flagged out because of technical problems. Remember that the systematic errors in Table 15 are straightforward difference in R.H., and are not presented as a percentage ratio of the relative humidity being measured.
Measurement of upper-air pressure, temperature and humidity

Table 15. Systematic differences, sonde error and uncertainty [k=2] of radiosonde relative humidity measurements at night for temperatures between -50 °C and -70 °C within the troposphere.

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>System Bias [per cent R.H.]</th>
<th>Sonde error</th>
<th>Uncertainty [K=2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Humidity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[per cent R.H.]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40-60</td>
<td>20-40</td>
<td>40-60</td>
<td>20-40</td>
</tr>
<tr>
<td>Twin thin film capacitor, Vaisala RS92 Finland</td>
<td>M0 ± 4</td>
<td>1 ± 3</td>
<td>7</td>
</tr>
<tr>
<td>Thin film capacitor, used in LMS-6E+E, USA</td>
<td>1 ± 4</td>
<td>-1 ± 3</td>
<td>12</td>
</tr>
<tr>
<td>Thin film capacitor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modem, France</td>
<td>10 ± 3</td>
<td>8 ± 3</td>
<td>17 ± 1</td>
</tr>
<tr>
<td>Changfeng, China</td>
<td>2</td>
<td>6</td>
<td>23</td>
</tr>
<tr>
<td>Graw E+E, Germany*</td>
<td>7</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Huayun E+E, China*</td>
<td>-2</td>
<td>7</td>
<td>18</td>
</tr>
<tr>
<td>Internet E+E, S. Africa</td>
<td>1</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>JinYang E+E, Korea</td>
<td>10</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>Meisei, Japan.</td>
<td>-2</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>Snow White, Meteolabor, Switzerland</td>
<td>-3 ± 3</td>
<td>-2</td>
<td>9</td>
</tr>
<tr>
<td>CFH, USA/Germany</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

M Uses information from Miloshevich et al. (2009) with WMO and UK tests
E+E uses E+E sensor from Germany

In interpreting the standard deviations associated with the differences between the radiosondes, it was not possible to discriminate between the performance of the Graw and Vaisala RS92 in terms of sonde error, and these sonde errors have been assumed to be identical for this temperature band. The CFH data were only a limited sample and were analysed separately, with the CFH sonde errors for the limited samples within the expected performance of the CFH at these temperatures.

Table 15 shows that probably only two radiosonde systems were capable of providing relative humidity measurements with uncertainty in the range 6 to 14 per cent, at night and at temperatures between -50 °C and -70 °C whether cloud was present or not, with another four capable of providing measurements in the range 10 to 20 per cent.

At very low humidity in the stratosphere, the expected sonde error of CFH becomes about 2 per cent when measuring 10 per cent R.H. and 0.4 per cent when measuring 2 per cent R.H., whereas operational radiosonde errors will stay near the values quoted in Table 15, and are thus not usually suitable for stratospheric measurements where fractions of a per cent R.H. make a significant difference to the water vapour mixing ratio reported.

5.7.7 Day, temperatures between -50°C and -70°C

Table 16 shows the systematic biases, sonde errors and uncertainty for daytime humidity measurements centred at a temperature of -60 °C. The sonde errors were larger in the day for the Huayun radiosonde, but otherwise the daytime sonde errors were similar or slightly smaller than the night-time sonde errors. Thus any increase in sonde error from solar heating effects was balanced by a decrease in some of the other sources of error at night, e.g. contamination. It appeared that the structures in the vertical were similar between day and night, but it is possible that time constant of response errors were bigger in night-time conditions than others, so this may have influenced the difference in the sonde errors between day and
Measurement of upper-air pressure, temperature and humidity

**Table 16. Systematic differences, sonde error and uncertainty [k=2] of radiosonde relative humidity measurements in the day for temperatures between -50 °C and -70 °C within the troposphere.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative humidity [per cent R.H.]</td>
<td>40-60</td>
<td>20-40</td>
<td>40-60</td>
<td>20-40</td>
<td>40-60</td>
</tr>
<tr>
<td>Twin thin film capacitor, Vaisala RS92 Finland</td>
<td><strong>V0-22 ± 4</strong></td>
<td><strong>-14 ± 4</strong></td>
<td>5</td>
<td>3</td>
<td><strong>23 - 31</strong></td>
</tr>
<tr>
<td></td>
<td><strong>V1-12 ± 3</strong></td>
<td><strong>-7 ± 3</strong></td>
<td>5</td>
<td>3</td>
<td><strong>14 - 20</strong></td>
</tr>
<tr>
<td></td>
<td><strong>V2-3 ± 3</strong></td>
<td><strong>0 ± 3</strong></td>
<td>5</td>
<td>3</td>
<td><strong>5 - 11</strong></td>
</tr>
<tr>
<td>Thin film capacitor, used in LMS-6E+E, USA</td>
<td>-4 ± 3</td>
<td>-3 ±3</td>
<td>8</td>
<td>10</td>
<td>9 - 15</td>
</tr>
<tr>
<td>Thin film capacitor</td>
<td>Modern France</td>
<td>-8 ± 3</td>
<td>-5</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Changfeng China</td>
<td>-7</td>
<td>1</td>
<td>16</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>Graw<em>E+E Germany</em></td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Huayun<em>E+E China</em></td>
<td>-8</td>
<td>1</td>
<td>24</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>Internet*E+S. Africa</td>
<td>-12</td>
<td>-6</td>
<td>12</td>
<td>10</td>
<td>24</td>
</tr>
<tr>
<td>JinYang*E+E Korea</td>
<td>-2</td>
<td>1</td>
<td>9</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Meisei Japan.</td>
<td>-8</td>
<td>-2</td>
<td>12</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>CFH, USA/Germany</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

E+E uses E+E sensor from Germany

V0 Vaisala RS92 original with bare printed board in supports for relative humidity sensors, values for tropics from Vömel; et al. (2007)

V1 Vaisala RS92 with fully aluminised supports, but no correction for solar heating, WMO (2006)

V2 Vaisala RS92 with fully aluminised sensor support, with correction for solar heating, WMO (2011)

The system with the most pronounced negative bias in daytime was the Vaisala RS92 in its original form. The temperature sensors were heated both directly by solar heating of the humidity sensor, but also by air heated by the bare copper surfaces on the supports near the sensor, which then passed over the sensor. The other systems mostly have aluminised covers so direct solar heating is not primarily the problem, but air heated by passing over the supports and plastic does affect the humidity sensor temperature. Some manufacturers, such as LMS and Internet measure the temperature of the humidity sensor with a dedicated sensor. With the LMS this has worked reasonably well, but Internet had faulty software in the Yangjiang test and the independent temperature sensor has not been used correctly, with the resultant large negative bias in daytime measurements. It is expected that this problem should be rectified quickly.

In the most recent tests, the Vaisala RS92 had a software correction for heating, as did the Graw system, see Annex D of WMO (2011). Values reported in cloud at very low temperatures for both systems seemed higher in the daytime than at night and much higher than was shown by Snow white or CFH. Thus, at this stage it is probable that the corrections applied to the operational radiosondes may have errors, especially in the cloudy conditions, although the corrections probably bring the systematic bias closer to the correct values compared to measurements without the correction, see the Vaisala results.

Table 16 shows that probably only two radiosonde systems were capable of providing relative humidity measurements with uncertainty in the range 6 to 14 per cent, in daytime and at temperatures between -50 °C and -70 °C whether cloud was present or not (given the twin film capacitor had the complete set of corrections used in Yangjiang), with another four capable of providing measurements in the range 10 to 20 per cent.
Most of the test data used for Tables 15 and 16 has been obtained in the tropics where the temperature band centred on -60 °C may be 4 km higher than at higher latitudes, see Figure 2. The systematic biases for heating error for a given temperature can be expected to have a range of values, with the lower biases associated with the mid-latitude operation in cloudy conditions at higher pressures and the large negative biases associated with tropical operations in clear situations.

5.7.8 Wetting or icing in cloud

When the performance of the older relative humidity sensors was compared after passing through low cloud or fog (where the external temperature sensors have clearly become wet), the systematic differences between the sensors measurements were not close to those shown in Table 8. In particular, the systematic differences between the Vaisala thin-film capacitor and VIZ carbon hygristor measurements at a relative humidity from 0 to 70 per cent increase the relative humidity by at least 10 per cent on average (Nash, Elms and Oakley, 1995). Both of these sensor types had possible additional errors in wet conditions, although the mechanisms causing the additional errors were quite different for the two types.

Vaisala thin-film capacitors, together with the protective covers for the sensor, usually became contaminated to some extent in low cloud. On emerging from cloud in severe icing conditions, the sensors may report a relative humidity that is up to 30 per cent high. Positive errors resulting from sensor contamination are more usually in the range of 1 to 20 per cent relative humidity. In some cases, the contamination may last for only a few minutes, but in others, the contamination can continue to affect measurements into the upper stratosphere. Heating the sensors during the ascent does eliminate the contamination more quickly with the Vaisala RS92, although the RS92 versions that only heat down to –40 °C become contaminated in upper cloud, and the versions heating to –60 °C do not experience so much contamination. At temperatures below –70 °C, the saturation vapour pressure of water is very low, and more work needs to be carried out to check whether decontamination of the sensors at these very low temperatures is necessary to obtain reliable measurements.

The VIZ carbon hygristor calibrations are not very stable when the sensors are exposed to high relative humidity for long periods of time in the laboratory. If the sensors become wet during an ascent, or if they are exposed to very moist conditions, it appears that the calibration often changes on emerging from the cloud. The effect of the change in calibration causes the relative humidity reported in the remainder of the flight to fall by between 1 and 15 per cent, on average, compared to relative humidity reports in dry conditions.

Hence, relative humidity measurements in the upper troposphere after ascents have passed through cloud layers in the lower troposphere need to be treated with more caution than measurements made in dry conditions.

5.7.9 Representativeness errors

In operational radiosoundings the balloon is normally launched when it is not raining if possible, so radiosonde samples often will not show the wettest conditions that have occurred in a given observational period.

As was seen above, many modern radiosonde relative humidity measurements have relatively small errors in the troposphere, so it is possible to derive statistics of the root mean square differences for closely spaced radiosonde measurements. Kitchen (1989) used time series of atmospheric observations made in the UK. He showed that the root mean square deviation between samples at 4 hour intervals was about 14 per cent R.H. in the lower troposphere, increasing to greater than 20 per cent for heights between 3 and 5 km in the winter and 3 and 9 km in the summer in the UK.

An example of structure which is unlikely to be represented in most current numerical models is the example of relative humidity modified by waves, downstream of the hill in Yangjiang, shown in Figure 10. The measurements shown were taken 6 hours apart in daylight. The humidity structures are supported by at least four other radiosondes on the two flights. The low level winds were similar in both cases and the effects of waves can be seen in both measurements with a vertical wavelength of about 700m. Note: the heights of the perturbations in relative humidity changed between the two flights.
Figure 10. Profiles of temperature and relative humidity, Flights 16 and 17 WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, black flight 16 launched at 08.31 local time and grey flight 17 launched at 14.53 local time.

When the time separation is reduced to nearly two hours there were still large differences in relative humidity between the two samples, see Figure 11 where measurements were from Snow White and CFH respectively. Large differences in relative humidity were observed at most height above 1.5 km, with very large differences in layers at 10 and 13.5 km.

Figure 11. Profiles of temperature and relative humidity, Flights 9 (Snow white) and 10 (CFH), WMO Intercomparison of High Quality Radiosonde Systems, and Yangjiang. Black flight 10 launched at 03.00 local time and grey flight 9 launched at 00.58 local time.
The R.M.S. deviations between radiosonde relative humidity measurements 2, 6, 18 and 54 hours apart from Yangjiang, China are shown in Figure 12. In Figure 12 the contribution from instrumental error has been removed from the differences at the given time separations. The R.M.S. deviation in relative humidity is then expected to relate to time separation using the relationship, after Kitchen (1989):-

\[
\sigma_r(\Delta t)^2 = (\sigma_{U(\text{large scale})})^2 + (\sigma_{U(\text{small scale})}(\Delta t))^2
\]

where \(\sigma_r(\Delta t)\) is the R.M.S deviation between relative humidity measurements separated by the time separation \(\Delta t\),

\(\sigma_{U(\text{large scale})} = (b_0 \Delta t^\gamma)^2\) is the R.M.S. deviation due to synoptic scale and mesoscale changes with time, and with a structure function fitted to the observations in Figure 12, once a suitable estimate of the small scale variations is made.

and \(\sigma_{U(\text{small scale})}(\Delta t)\) is the R.M.S. deviation in relative humidity from small scale structures, e.g. gravity waves, cloud scale changes, turbulent layers.

An interpretation of the results in Figure 12 is that \(\sigma_{U(\text{small scale})}(\Delta t)\) was probably near 8 per cent between 0 and 6 km, and up to about 12 per cent ± 4 per cent R.H. between 6 and 14 km. In order to get the small scale deviations significantly lower than this, it would be necessary to go to much smaller time separations than was possible in Yangjiang. Assuming these small scale deviations are as stated, the large scale structure function has a value of \(\gamma\) near 0.4, similar to the value found for temperature, with synoptic and mesoscale variations reducing from about 11 per cent to 3 per cent R.H. for the layer 0 to 4 km, and from about 27 per cent to 8 per cent on average for the layer 9 to 13 km, from the largest to shortest time separations observed in Yangjiang. Thus, the small scale deviations at 2 hour time separation were probably a little higher than the synoptic and mesoscale fluctuations.

The significance of these representativeness errors is that if you wish to measure the average state of the larger scale atmosphere to a given accuracy, it requires many more flights than might be expected with the small sonde errors shown in Tables 11 to 16. The representativeness errors are likely to be largest between 6 and 14 km in the rainy season tropics.

6 GROUND STATION EQUIPMENT

6.1 General features

The detailed design of the ground equipment of a radiosonde station will depend on the type of radiosonde that is used. However, the ground station will always include the following:
Measurement of upper-air pressure, temperature and humidity

(a) An aerial and radio receiver for receiving the signals from the radiosonde;
(b) Equipment to decode the radiosonde signals and to convert the signals to meteorological units;
(c) Equipment to present the meteorological measurements to the operator so that the necessary messages can be transmitted to users, as required.

Other equipment may be added to provide wind measurements when required (for example, radar interface, and Loran-C or GPS trackers).

The output of the decoder should usually be input to a computer for archiving and subsequent data processing and correction.

Modern ground station systems can be either purchased as an integrated system from a given manufacturer, or may be built up from individual modules supplied from a variety of sources. If maintenance support will mainly be provided by the manufacturer or its agents, and not by the operators, an integrated system may be the preferred choice. A system composed of individual modules may be more readily adapted to different types of radiosonde. This could be achieved by adding relevant decoders, without the extra cost of purchasing the remainder of the integrated ground system offered by each manufacturer. A modular type of system may be the preferred option for operators with their own technical and software support capability, independent of a given radiosonde manufacturer. Systems built from modules have encountered problems in the last 10 years because of the complexity of testing such systems and the problems introduced when adapting manufacturers’ standard correction software to non-standard use by another processing system.

Note: The rate of development in modern electronics is such that it will prove difficult for manufacturers to provide in-depth support to particular integrated systems for longer than 10 to 15 years. Thus replacement cycles for integrated ground systems should be taken as about 10 years when planning long-term expenditure.

6.2 Software for data processing

Satisfactory software for a radiosonde ground system is much more complicated than that needed merely to evaluate, for example, standard level geopotential heights from accurate data. Poor quality measurements need to be rejected and interpolation procedures developed to cope with small amounts of missing data. There is a serious risk that programmers not thoroughly versed in radiosonde work will make apparently valid simplifications that introduce very significant errors under some circumstances. For instance, if reception from the radiosonde is poor, it is counterproductive to allow too much interpolation of data using mathematical techniques that will be quite stable when data quality is generally good, but will become unstable when data quality is generally poor. A good example of an algorithm that can become unstable when signal quality is poor is the time constant of response correction used by some manufacturers for temperature.

In the past, certain problems with signal reception and pressure errors near the launch were sometimes compensated by adjusting the time associated with incoming data. This may not cause significant errors to reported measurements, but can make it almost impossible to check radiosonde sensor performance in radiosonde comparison tests.

Thus, it is essential to use the services of a radiosonde specialist or consultant to provide overall control of the software design. The specialist skills of a professional programmer will usually be necessary to provide efficient software. This software will include the display and interactive facilities for the operator which are required for operational use. The software must be robust and not easily crashed by inexpert operators. In the last decade, most software for commercial radiosonde ground systems has required at least two or three years of development in collaboration with testing by National Meteorological Services. This testing was performed by highly skilled operators and test staff, until the software had become thoroughly reliable in operation. The ground system software was then suitable for use by operators without any significant specialized computing skills.

The software in the ground system should be well documented and should include clear descriptions of the algorithms in use. The overall system should be designed to allow sounding simulations for testing and comparison purposes. It is proposed that sets of a suitable range of raw pressure, temperature and

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6 As recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998), through Recommendation 2 (CIMO-XII).
7 See Recommendation 2 (CIMO-XII).
humidity data records should be used to check the reliability of newly developed software. Software errors are often the limiting factors in the accuracy of data reports from the better radiosonde types.

7 RADIOSONDE OPERATIONS

7.1 Control corrections immediately before use

It is recommended that radiosonde measurement accuracy should always be checked in a controlled environment before the radiosonde is launched. These control checks should be made when the radiosonde is ready for flight, and should take place a few minutes before release. The aim is to prevent the launch of faulty radiosondes. A further aim is to improve calibration accuracy by adjusting for small changes in calibration that may have occurred when the radiosonde was transported to the launch site and during storage.

These control checks are usually performed indoors. They can be conducted in a ventilated chamber with a reference temperature and relative humidity sensors of suitable accuracy to meet user specifications. Relative humidity can then be checked at ambient humidity and lower and higher humidity, if necessary. If no reference psychrometer is available, known humidity levels can be generated by saturated saline solutions or silica gel.

The differences between the radiosonde measurements and the control readings can be used to adjust the calibration curves of the sensors prior to flight. The sensors used for controlling the radiosonde must be checked regularly in order to avoid long-term drifts in calibration errors. A suitable software adjustment of radiosonde calibration normally improves the reproducibility of the radiosonde measurements in flight to some extent. The type of adjustment required will depend on the reasons for calibration shift following the initial calibration during manufacture and will vary with radiosonde type.

If there are large discrepancies relative to the control measurements, the radiosonde may have to be rejected as falling outside the manufacturer's specification and returned for replacement. Maximum tolerable differences in ground checks need to be agreed upon with the manufacturer when purchasing the radiosondes.

It is also wise to monitor the performance of the radiosonde when it is taken to the launch area. The reports from the radiosonde should be checked for compatibility with the surface observations at the station immediately before launch.

In view of the importance of this stage of the radiosonde operation, the Commission for Instruments and Methods of Observation recommends that:

(a) The performance of the radiosonde pressure, temperature and relative humidity sensors should be checked in a controlled environment, such as a calibration cabinet or baseline check facility prior to launch;
(b) The baseline check should be automated as far as possible to eliminate the possibility of operator error;
(c) The temperature and relative humidity observations should also be checked against the standard surface temperature and relative humidity observations at the station immediately before the launch;
(d) The sensors used as the reference should be at least as accurate as the radiosonde sensors and be calibrated regularly according to the manufacturer's instructions.

7.2 Deployment methods

Radiosondes are usually carried by balloons rising with a rate of ascent of between 5 and 8 m s⁻¹, depending on the specifications and characteristics of the balloon in use (see Part II, Chapter 10). These

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8 As recommended by the Commission for Instruments and Methods of Observation at its eleventh session, held in 1994, through Recommendation 9 (CIMO-XI).

rates of ascent allow the measurements to be completed in a timely fashion – i.e. about 40 min to reach 16 km and about 90 min to reach heights above 30 km – so that the information can be relayed quickly to the forecast centres. The designs and positioning of the temperature and relative humidity sensors on the radiosonde are usually intended to provide adequate ventilation at an ascent rate of about 6 m s\(^{-1}\). Corrections applied to temperature for solar heating errors will usually only be valid for the specified rates of ascent.

A radiosonde transmits information to a ground station that is usually at a fixed location. However, advances in modern technology mean that fully automated radiosonde ground systems are now very small. Therefore, the ground systems are easily deployed as mobile systems on ships or in small vans or trailers on land.

Dropsondes deployed from research aircraft use parachutes to slow the rate of descent. Temperature sensors are mounted at the bottom of the dropsonde. Rates of descent are often about 12 m s\(^{-1}\) to allow the dropsonde measurement to be completed in about 15 min. The high descent rate allows one aircraft to deploy sufficient dropsondes at a suitable spacing in the horizontal for mesoscale research (less than 50 km). The dropsonde transmissions will be received and processed on the aircraft. Systems under development will be able to take and transmit direct readings and operate automatically under programme control. Systems are also under development to use remotely piloted vehicles to deploy dropsondes.

7.3 Radiosonde launch procedures

Once a radiosonde is prepared for launch, the meteorological measurements should be checked against surface measurements either in an internal calibration chamber or externally against surface observations in a ventilated screen. This is necessary since the radiosonde may have been damaged during shipment from the factory, manufacture may have been faulty, or sensor calibrations may have drifted during storage. Radiosondes producing measurements with errors larger than the limits specified in the procurement contract should be returned to the manufacturer for replacement.

Radiosondes are usually launched by hand or using a launch aid from a shed or shelter. The complexity of the shed and the launch procedures will depend on the gas used to fill the balloon (see Part II, Chapter 10) and on the strength and direction of the surface winds at the site. Even during the last decade, people have been killed in the global radiosonde network through careless use of hydrogen gas. Managers of radiosonde stations using hydrogen gas must be aware of the dangers of an explosion and must ensure all staff are also properly informed and trained in the use of hydrogen. It is essential that equipment for generating and storing hydrogen is well maintained. Faulty equipment shall not be used, but repaired first. The balloon filling equipment must be grounded to earth to prevent static discharge.

In strong winds the launching procedure is aided by the use of unwanders that allow the suspension cord for the radiosonde to deploy slowly following the launch. Very strong surface winds require unwinders that deploy the suspension cord at rates as low as 0.5 to 1 m s\(^{-1}\).

Automatic launch systems for radiosondes are commercially available. These may offer cost advantages at radiosonde stations where staff are used solely for radiosonde operations. These systems may not be suitable for operations in very exposed conditions where very strong surface winds are common.

If users require accurate vertical structure in the atmospheric boundary layer, the surface observations incorporated in the upper-air report should be obtained from a location close to the radiosonde launch site. The launch site should also be representative of the boundary layer conditions relevant to the surface synoptic network in the area. It is preferable that the operator (or automated system) should make the surface observation immediately after the balloon release rather than prior to the release. The operator should be aware of inserting surface observations into the ground system prior to launch, as meteorological conditions may change before the launch actually takes place when a significant delay in the launch procedure occurs (for instance, a balloon burst prior to launch, or air traffic control delay).

The speed of response of the radiosonde sensors is such, that conditioning the radiosonde before launch is less critical than in the past. However, when it is raining, it will be necessary to provide some protection for the radiosonde sensors prior to launch.
7.4 Radiosonde suspension during flight

The radiosonde must not be suspended too close to the balloon when in flight. This is because the balloon is a source of contamination for the temperature and relative humidity measurements. A wake of air, heated from contact with the balloon surface during the day and cooled to some extent during the night, is left behind the balloon as it ascends. The balloon wake may also be contaminated with water vapour from the balloon surface after ascent through clouds. The length of suspension needed to prevent the radiosonde measurements from suffering significant contamination from the balloon wake varies with the maximum height of observation. This is because the balloon wake is heated or cooled more strongly at the lowest pressures. A suspension length of 20 m may be sufficient to prevent significant error for balloons ascending only to 20 km. However, for balloons ascending to 30 km or higher, a suspension length of about 40 m is more appropriate (see, for instance, WMO, 1994a).

Note: When investigating the influence of the balloon wake on radiosonde measurements, it is vital to ensure that the sensors on the radiosonde used for the investigation are correctly exposed. The sensors must be mounted so that it is impossible for air that has had contact with other surfaces on the radiosonde to flow over the radiosonde sensor during ascent. Possible sources of heat or water vapour contamination from the radiosondes are the internal surfaces of protective ducts, the mounts used for the sensor, or the external surfaces of the radiosonde body.

7.5 Public safety

The radiosonde design must fall well within existing air traffic safety regulations as to size, weight and density. These should ensure that the radiosonde should not cause significant damage if it collides with an aircraft or if ingested by the aircraft engine. In many countries, the national air traffic authority issues regulations governing the use of free flight balloons. Balloon launch sites must often be registered officially with the air traffic control authorities. Balloon launches may be forbidden or possible only with specific authorization from the air traffic controllers in certain locations. The situation with respect to flight authorization must be checked before new balloon launch locations are established.

In some countries, safety regulations require that a parachute or other means of reducing the rate of descent after a balloon burst must also be attached to the radiosonde suspension. This is to protect the general public from injury. The parachute must reduce the rate of descent near the surface to less than about 6 m s\(^{-1}\). The remains of the balloon following a burst usually limit the rate of descent at lower levels. However, on occasion, most of the balloon will be detached from the flight rig following a burst and the rates of descent will be too high unless a parachute is used.

It is important that radiosondes should be environmentally safe after returning to Earth or after falling in the sea, whether picked up by the public or by an animal, or left to decay.
8 COMPARISON, CALIBRATION AND MAINTENANCE

8.1 Comparisons

The overall quality of operational measurements of geopotential height by radiosonde (and hence temperature measurements averaged through thick layers) is monitored at particular forecast centres by comparison to geopotential heights at standard pressures with short-term (6 h) forecasts from global numerical weather prediction models for the same location. The statistics are summarized into monthly averages that are used to identify both substandard measurement quality and significant systematic changes in radiosonde performance. The European Centre for Medium-Range Weather Forecasts, in Reading (United Kingdom), is the lead centre currently designated by the Commission for Basic Systems for this work, but other national forecast centres also produce similar statistics.

Random errors in geopotential height (and hence temperature) measurements can also be identified at individual stations from analyses of the changes in the time series of measurements of geopotential height, at 100 hPa or lower pressures, where atmospheric variability is usually small from day to day. Examples of the compatibility between the results from this method and those from comparison with short-term forecast fields is provided in Nash (1984), WMO (1989b, 1993b, 1998 and 2003b).

Statistics of the performance of the relative humidity sensors are also generated by the numerical weather prediction centres, and also in comparison with satellite observations.

The performance of radiosondes or radiosonde sensors can be investigated in the laboratory with suitably equipped test chambers, where temperature and pressure can be controlled to simulate radiosonde flight conditions.

Detailed investigations of temperature, pressure and relative humidity sensor performance in flight are best performed using radiosonde comparison tests, where several radiosonde types are flown together on the same balloon ascent. Annex C gives guidelines for organizing radiosonde intercomparison and for the establishment of test sites. When testing a new radiosonde development, it is advisable to have at least two other types of radiosonde with which to compare the newly developed design. The error characteristics of the other radiosondes should have been established in earlier tests. An ideal comparison test site would have an independent method of measuring the heights of the radiosondes during flight. This can now be achieved by using measurements taken from two different well-tested GPS radiosondes.

8.1.1 Quality evaluation using short-term forecasts

For the better global numerical weather prediction models, the random error in short-term (6 h) forecasts of 100 hPa geopotential heights is between 10 and 20 m in most areas of the world. These errors correspond to a mean layer temperature error from the surface to 100 hPa of between 0.15 and 0.3 K. Thus, the comparison with the forecast fields provides good sensitivity in detecting sonde errors in temperature, if sonde errors are greater than about 0.3 K. Forecast fields, rather than analysis fields, are used as the reference in this comparison. Forecast fields provide a reference that is less influenced by the systematic errors in geopotential heights of the radiosonde measurements in the area than the meteorological analysis fields. However, 6 h forecast fields will have small systematic errors and should not be considered as an absolute reference. Uncertainty in the systematic error of the forecast field is at least 10 m at 100 hPa. The systematic differences of forecasts from the measurements of a given radiosonde station vary between forecast centres by at least this amount. In addition, systematic errors in forecast fields may also change with time by similar amounts, when forecast models and data assimilation techniques are improved. Nonetheless, comparisons with the forecast fields at the lead centres for operational monitoring give clear indications of those radiosonde stations and radiosonde types where there are large systematic errors in the radiosonde reports. Reference WMO (2003b) provides the most recent reported review of radiosonde errors in the global network for heights up to 30 hPa but subsequent monitoring statistics can be found on the WMO web site at http://www.wmo.int/pages/prog/www/IMOP/monitoring.html.

8.1.2 Quality evaluation using atmospheric time series

Random errors in radiosonde measurements can be estimated from the time series of closely spaced measurements of geopotential heights, at pressure levels where the geopotential heights change only slowly with time. Suitable pressure levels are 100, 50, or 30 hPa. For radiosonde observations made at 12 h intervals, this is achieved by computing the difference between the observation at +12 h, and a linear
interpolation in time between the observations at 0 and +24 h. Further differences are subsequently computed by incrementing in steps of 24 h through the time series. An estimate of the random errors in the radiosonde measurements can then be derived from the standard deviation of the differences. For much of the year, the sensitivity of this procedure is similar to the comparison made with forecast fields. One exception may be during winter conditions at middle and high latitudes, when the geopotential heights at 100 up to 30 hPa will sometimes change very rapidly over a short time.

The average values of the differences from the time series may provide information on the day-night differences in radiosonde temperature measurements. The interpretation of day-night differences must allow for real daily variation in geopotential height caused by diurnal and semidiurnal tides. Real day-night differences at mid-latitudes for 100 hPa geopotential heights can be as large as 30 m between observations at 1800 and 0600 local time (Nash, 1984), whereas real day-night differences between observations at 1200 and 0000 local time will usually be in the range 0 ± 10 m.

It is beneficial if individual radiosonde stations keep records of the variation in the time-series of geopotential height measurements at 100 hPa and in the geopotential height increment (100–30) hPa. This allows the operators to check for large anomalies in measurements as the ascent is in progress.

8.1.3 Comparison of water vapour measurements with remote sensing

Given that many radiosonde stations now have collocated GPS water vapour sensors, and some scientific sites have collocated microwave radiometers, it is practical to use the integrated water vapour measurements from these two systems to check the quality of the radiosonde water vapour measurements, primarily at low levels. Comparison with GPS measurements was performed during the last two WMO Radiosonde Comparisons, WMO (2006a) and WMO (2011) where the GPS measurements were used to quantify day-night differences in the radiosonde relative humidity measurements. A more extensive global study was performed by Wang and Zhang (2008). The use of microwave radiometers to check day-night differences is illustrated in Turner, et al. (2003).

Whereas identification of day-night differences with integrated water vapour measurements seems relatively reliable, this does not mean that all the differences seen between radiosonde and remotely sensed water vapour are due to errors in the radiosonde water vapour, since both GPS water vapour and microwave radiometer measurements have errors that are not necessarily constant with time.

8.1.4 Radiosonde comparison tests

Radiosonde comparison tests allow the performance of the pressure, temperature and relative humidity sensors on the radiosonde to be compared independently as a function of time. However, it is important to design the support rig for the radiosondes so that the motion of the radiosondes under the supports is not too dissimilar from the motion when flown on an individual balloon, and that in daylight the support rig (including the balloon), does not shed warmer air onto some of the sensors from time to time.

Laboratory tests should be performed in facilities similar to those required for the detailed calibration of the radiosondes by the manufacturer. These tests can be used to check the adequacy of radiosonde calibration, for example, the dependence of calibration on sensor temperature. However, in the laboratory, it is difficult to simulate real atmospheric conditions for radiative errors and wetting or icing of sensors. Errors from these sources are best examined in comparisons made during actual ascents.

In order to compare measurements taken during actual ascents, the timing of the samples for the different systems must be synchronized as accurately as possible, ideally to better than ±1 s. In recent years, software packages have been developed to support WMO radiosonde comparison tests (WMO, 1996b). These allow all the radiosonde samples to be stored in a comparison database and to be compared by the project scientists immediately following a test flight. It is important that comparison samples are reviewed very quickly during a test. Any problem with the samples caused by test procedures (for example, interference between radiosondes) or faults in the radiosondes can then be identified very quickly and suitable additional investigations initiated. The software also allows the final radiosonde comparison statistics to be generated in a form that is suitable for publication.

Initial tests for new radiosonde designs may not merit large numbers of comparison flights, since the main faults can be discovered in a small number of flights. However, larger scale investigations can be justified once systems are more fully developed. As the reproducibility of the measurements of most modern radiosondes has improved, it has become possible to obtain useful measurements of systematic bias in temperature and pressure from about 10 to 15 flights for one given flight condition (i.e., one time of day). Since it is unwise to assume that daytime flights at all solar elevations will have the same bias, it is preferable to organize tests that produce at least 10 to 15 comparison flights at a
similar solar elevation. The measurements of temperature sensor performance are best linked to other test results by comparisons performed at night. The link should be based on measurements from radiosondes with wire or aluminized sensors and not from sensors with significant infrared heat exchange errors. If a continuous series of comparison flights (alternating between day and night) can be sustained, it is possible to use the atmospheric time-series technique to estimate the magnitude of day-night differences in temperature measurements.

As noted earlier, the most extensive series of comparison tests performed in recent years were those of the WMO International Radiosonde Comparison. Initial results have been published in WMO (1987; 1991; 1996a; 2006a; 2006b; 2006c; 2011). The results from these tests were the basis of the information provided in Tables 6 to 12.

The first international comparison of radiosondes was held at Payerne (Switzerland) in 1950. Average systematic differences between radiosonde pressures and temperatures [pressure higher than 100 hPa] were 4 hPa and 0.7 K, with random errors (two standard deviations) of 14 hPa and 2 K. These values should be compared with the results for modern systems shown in Tables 6 to 8. The results from a second comparison carried out at the same site in 1956 showed that accuracy needed to be improved by the application of radiation corrections to the temperature readings. The errors in pressure and temperature at the 50-hPa level were quite large for most radiosondes and increased rapidly at higher levels, especially during daylight. In 1973, a regional comparison was held in Trappes (France). This identified significant calibration errors in some radiosondes, with one bimetallic temperature sensor having a radiation error as large as 10 K.

8.2 Calibration

The calibration methods used by manufacturers should be identified before purchasing radiosondes in large numbers. The quality control procedures used to ensure that measurement accuracy will be sustained in mass production must also be checked for adequacy. Purchasers should bear in mind that certain specified levels of error and product failure may have to be tolerated if the cost of the radiosonde is to remain acceptable. However, the in-flight failure rate of radiosondes from reliable manufacturers should not be higher than 1 or 2 per cent.

Unless radiosonde sensors can be produced in large batches to give the reproducibility and accuracy required by users, it is necessary to calibrate the instruments and sensors individually. Even if the sensors can be produced in large batches to meet an agreed set of standardized performance checks, it is necessary for representative samples, selected at random, to be checked in more detail. The calibration process should, as far as possible, simulate flight conditions of pressure and temperature. Calibrations should normally be performed with falling pressure and temperature. Relative humidity will probably be checked in a separate facility. The reference sensors used during calibration should be traceable to national standards and checked at suitable intervals in standards laboratories. The references should be capable of performing over the full temperature range required for radiosonde measurements.

The design of the calibration apparatus depends largely on whether the complete radiosonde must be calibrated as a unit or on whether the meteorological units can be tested while separated from the radiosonde transmitter. In the latter case, a much smaller apparatus can be used. The calibration facility should be able to cover the range of pressures and temperatures likely to be encountered in actual soundings. It should be possible to maintain the conditions in the calibration chamber stable at any desired value better than ±0.2 hPa min⁻¹ for pressure, ±0.25 K min⁻¹ for temperature and 1 per cent relative humidity per minute. The conditions in the calibration chamber should be measured with systematic errors less than ±0.2 hPa for pressure, ±0.1 K for temperature and ±1 per cent relative humidity. Reference thermometers should be positioned in the calibration chamber in order to identify the range of temperatures in the space occupied by the sensors under calibration. The range of temperatures should not exceed 0.5 K. Sufficient measurements should be taken to ensure that the calibration curves represent the performance of the sensors to the accuracy required by the users. Pressure sensors which are not fully compensated for temperature variations must be calibrated at more than one temperature. Thus, it may be an advantage if the temperature calibration chamber is also suitable for the evaluation of the pressure units.

Humidity calibration is usually carried out in a separate apparatus. This can take place in a chamber in which a blower rapidly circulates air past a ventilated psychrometer or dewpoint hygrometer and then through one of four vessels containing, respectively, warm water, saturated solutions of sodium nitrate and calcium chloride, and silica gel. Any one of these vessels can be introduced into the circulation system by means of a multiple valve, so that relative humidities of 100, 70, 40 and 10 per cent are
Measurement of upper-air pressure, temperature and humidity

readily obtained. The standard deviation of the variation in relative humidity should not exceed 1 per cent in the space occupied by the units under calibration.

An alternative arrangement for humidity calibration is a duct or chamber ventilated with a mixture of air from two vessels, one of which is kept saturated with water while the other is dried by silica gel, with the relative humidity of the mixture being manually controlled by a valve which regulates the relative amounts passing into the duct.

Because of the importance of the type or batch calibration of radiosondes, the Commission for Instruments and Methods of Observation urges Members to test, nationally or regionally, selected samples of radiosondes under laboratory conditions in order to ensure that the calibrations supplied by the manufacturer are valid. 10

8.3 Maintenance

Failure rates in the ground system should be low for radiosonde systems based on modern electronics, as long as adequate protection is provided against lightning strikes close to the aerials. The manufacturer should be able to advise on a suitable set of spares for the system. A faulty module in the ground system would normally be replaced by a spare module while it is returned to the manufacturer for repair.

The maintenance requirements for radiosonde systems relying on radar height measurements to replace radiosonde pressure measurements are quite different. In this case, local maintenance should be readily available throughout the network from staff with good technical capabilities (both mechanical and electrical). This will be essential if accurate tracking capability is to be retained and if long-term drifts in systematic height errors in are to be avoided.

9 COMPUTATIONS AND REPORTING

There are no prescribed standardized procedures for the computation of radiosonde observations. The main issue is the selection of levels or the provision of measurements in sufficient detail to reproduce accurately and efficiently the temperature and humidity profile (e.g. heights of temperature inversions) against geopotential from the radiosonde data. Guidance is given in WMO (1986) and in the coding procedures agreed by WMO (1995) (Code FM 35-X Ext. TEMP). The accuracy of this reporting method was suitable for the performance of radiosondes in 1970, but not now. In order to justify the cost of the radiosonde, it is essential that the radiosonde information is reported more accurately and in more detail than in the TEMP code using relevant BUFR codes. In some cases, the use of BUFR code has just retained the description of the ascent as contained in the TEMP code. This is not the intention of this document, a BUFR template should be used allowing a more detailed representation of the vertical structure reported with the values of the meteorological variables, reported with a resolution that does not generate additional uncertainty in the measurements of the meteorological variables.

9.1 Radiosonde computations and reporting procedures

Upper-air measurements are usually input into numerical weather forecasts as a series of layer averages, with the thickness of the layers depending on the scales of atmospheric motion relevant to the forecast. The layers will not necessarily be centred at standard pressures or heights, but will often be centred at levels that vary as the surface pressure changes. Thus, the variation in temperature and relative humidity between the standard levels in the upper-air report must be reported to sufficient accuracy to ensure that the layer averages used in numerical forecasts are not degraded in accuracy by the reporting procedure.

Prior to 1980, most radiosonde measurements were processed manually by the operators by using various computational aids. These methods were based on the selection of a limited number of significant levels to represent the radiosonde measurement, possibly about 30 significant levels for a flight up to 30 km. The WMO codes reflected the difficulties of condensing a large amount of

10 As recommended by the Commission for Instruments and Methods of Observation at its eleventh session held in 1994, through Recommendation 9 (CIMO-XI).
Information on vertical structure into a short message by manual methods. The coding rules allowed linear interpolations in height between significant levels to differ from the original measurements by up to ±1 K for temperature and up to ±15 per cent for relative humidity in the troposphere and up to ±2 K for temperature in the stratosphere. It was expected that operators would not allow large interpolation errors to persist over deep layers in the vertical.

In modern radiosonde ground systems, the use of cheap but powerful computing systems means that much higher sampling rates can be used for archiving and processing the radiosonde measurements than is possible with manual computations. The manual processing of radiosonde measurements nearly always introduces unnecessary errors in upper-air computations and should be eliminated.

The available algorithms for automated upper-air TEMP message generation often have significant flaws. For instance, when there are few pronounced variations in relative humidity in the vertical, automated systems often allow large temperature interpolation errors to extend over several kilometres in the vertical. Furthermore, the algorithms often allow large systematic bias between the reported relative humidity structure and the original measurements over layers as thick as 500 m. This is unacceptable to users, particularly in the atmospheric boundary layer and when the radiosonde passes through clouds. Interpolation between significant cloud levels must fit close to the maximum relative humidity observed in the cloud.

Therefore, reports from automated systems need to be checked by operators to establish whether reporting procedures are introducing significant systematic bias between the upper-air report and the original radiosonde measurements. Additional significant levels may have to be inserted by the operator to eliminate unnecessary bias. TEMP messages with acceptable systematic errors are often produced more easily by adopting a national practice of reducing the WMO temperature fitting limits to half the magnitude cited above. Now, the advent of improved meteorological communications should allow the approximation in reporting upper-air observations to be reduced by reporting measurements in detail using the appropriate BUFR code message.

Given the large amount of money spent each year on radiosonde consumables, radiosonde operators should migrate urgently to BUFR (or equivalent) codes, to enable them to report accurately all the information that is measured and is needed by the user community.

### 9.2 Corrections

It should be clear from earlier sections that the variation in radiosonde sensor performance caused by the large range of conditions encountered during a radiosonde ascent is too large to be represented by a simple calibration obtained at a given temperature. Modern data processing allows more complex calibration algorithms to be used. These have provided measurements of better accuracy than that achieved with manual systems. It is vital that these algorithms are adequately documented. Users should be informed of any significant improvements or modifications to the algorithms. Records archived in radiosonde stations should include the model numbers of radiosondes in use and an adequate reference to the critical algorithms used for data processing.

All radiosonde temperature measurements have radiation errors. Therefore, it is recommended that a radiation correction (based on expected sensor performance in usual conditions) should always be applied during data processing. The details of this radiation correction should be recorded and kept with the station archive, along with an adequate archive of the original raw radiosonde observations, if required by national practice.

Errors from infrared heat exchange pose a particular problem for correction, since these errors are not independent of atmospheric temperature. Thus, it is preferable to eliminate as soon as possible the use of white paint with high emissivity in the infrared as a sensor coating, rather than to develop very complex correction schemes for infrared heat exchange errors.

Similarly, it is unwise to attempt to correct abnormally high solar radiation heating errors using software, rather than to eliminate the additional sources of heating by positioning the sensor correctly with respect to its supports, connecting leads and radiosonde body.

Relative humidity measurements may have corrections applied for slow time constant of response and for daytime heating of the humidity sensor system. As with temperature, the records of corrections and changes to the correction procedures need to be known by the user and retained with the station archive of observations, preferably with a raw data archive. The details of these algorithms need to be clear to those purchasing new systems.

Considering the importance of the ways in which corrections are applied, the Commission for Instruments and
Measurement of upper-air pressure, temperature and humidity

Methods of Observation\(^{11}\) urges Members to:
(a) To correct and make available the corrected upper air data from the various Global Observing System upper-air stations;
(b) To make users of the data aware of changes in the methodology used to correct reports, so that they may be adjusted, if desired;
(c) To archive both the corrected and uncorrected upper-air observations and produce records for climatological applications of the correction applied. The method used should be determined nationally;
(d) To inform WMO of the method of correction applied.

10 PROCUREMENT ISSUES

10.1 Use of results from WMO Intercomparison of High Quality radiosondes, and update of these results.

The results of the WMO Intercomparison of High Quality Radiosonde Systems, WMO (2011) were published to provide a snapshot in 2010 of the relative performance of the different systems in tropical conditions. The Report includes an assessment of the operational performance of the radiosonde systems, Table 1. Whilst many of the systems performed well, some radiosondes had limitations in their measurements, mostly in daytime temperature, and night-time relative humidity at temperatures higher than -40ºC, and daytime relative humidity in the upper troposphere at temperatures lower than -40ºC.

Table 1 was intended to help manufacturers identify where the most critical problems lay. Once these deficiencies have been identified, it is probable that many can and will be improved within a year or two, as was done with the Modem temperature after non-optimum performance at night in the Mauritius Radiosonde Comparison WMO (2006a). So, WMO recommends that manufacturers, especially those with markings below 3 in Table 1, WMO (2011), arrange for a limited number of independent tests to be performed to provide evidence to WMO that the performance has been improved once the problem has been rectified. Otherwise manufacturers with promising products may be rejected inappropriately in the procurement process.

Tables 5 to 16 also contain extracts from the test in Yangjiang, and these can also be used as a guide to the systems with low systematic bias, and fast enough time constants of response leading to small sonde error. Low and stable bias is very desirable for radiosonde measurements for climate records.

10.2 Some issues to be considered in procurement

Thus, the first stage in the procurement process should be to determine what quality of radiosonde is necessary for use in a given network. Here, it is recommended that any radiosonde used should be capable of meeting the breakthrough requirements indicated in Annex A in the climate of that country. If the radiosonde station is considered important for climate records then a radiosonde performing closer to the optimum requirement should be considered. Ideally the procurement should be competitive, and this may mean cooperating with other countries in a similar region to procure larger numbers together and to try and set up a system where the radiosondes are procured on a regular basis, for instance each year or every two years. It should be remembered that where there are small differences between the performance of systems, it is probable that if the test were repeated, those close together in performance would come out in a different order, so only marked differences in performance should be treated as significant, and not small differences in the relative marking.

Experience from consultations in regional training workshops suggests that there are some issues which need to be considered when procuring equipment.

- Equipment must be sustainable in long term use, i.e. not only should the hardware and software be purchased, but arrangements must be made for the long term support of the system, either by the manufacturer or the local staff, or a mixture of both.

\[^{11}\] As recommended by the Commission for Instruments and Methods of Observation at its eleventh session, held in 1994, through Recommendation 8 (CIMO: XI).
Measurement of upper-air pressure, temperature and humidity

- Make sure that the ground antenna is sufficiently sensitive to receive signals under all conditions at the site, whether upper winds are very weak or whether they are very strong. Do not try to save money by buying a cheap antenna which is inadequate in some conditions.
- Decide whether local staff can maintain a secondary radar and so use cheaper non-GPS radiosondes, or whether a fully automated GPS radiosonde system is more likely to be successful and run successfully in the long run.
- Check whether there is any source of local radiofrequency interference likely to cause problems with a GPS radiosonde system, if a GPS radiosonde system is to be procured.
- Decide what size balloons will be used, because if the radiosondes are not to be used at pressures lower than 30 hPa, then there is a wider range of suitable radiosonde available, see Tables 5 to 8.
- Decide what relative humidity sensor performance is required, e.g. a GRUAN or GUAN station has a higher standard required than a routine GOS station, basing the requirement on Table1, WMO (2011), and Tables 11 to 16.
- If conditions are often wet and cloudy, specify that radiosonde sensors need to have some protection against wetting and contamination, and ask for evidence how this works.
- Ask for a compensation agreement, if too many radiosondes fail in flight.
- Ask for evidence that the manufacturer has reliably supplied radiosondes to other users on the scale that will be used at the station.
- Make sure that the ground equipment can produce messages which allow higher resolution data to be reported compared to the old TEMP message. This message must be suitable for the communications available from the site and meet user requirements for data with good vertical resolution.
- Ensure the ground equipment computers are compatible with communicating using the local telecommunications (including INTERNET links, if required).
### Measurement of upper-air pressure, temperature and humidity

**Annex A**

**BREAKTHROUGH† AND OPTIMUM UNCERTAINTY REQUIREMENTS (STANDARD ERROR, K=2) FOR RADIOSONDE MEASUREMENTS FOR SYNOPTIC AND CLIMATE METEOROLOGY, GIVEN CURRENT TECHNOLOGICAL CAPABILITY AS ASSESSED IN THE WMO RADIOSONDE COMPARISON, YANGJIANG, CHINA, WMO (2011)

† VALUES DERIVED FOR THE MAIN TARGETED APPLICATIONS FOR RADIOSONDES

<table>
<thead>
<tr>
<th>Variable</th>
<th>Height [km]</th>
<th>Breakthrough† uncertainty requirement</th>
<th>Optimum uncertainty requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>1</td>
<td>3 hPa</td>
<td>2.0 hPa</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3 hPa</td>
<td>1 hPa</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>2 hPa</td>
<td>0.6 hPa</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>1 hPa</td>
<td>0.2 hPa</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>0.4 hPa</td>
<td>0.1 hPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>0 to 16</td>
<td>1 K</td>
<td>0.4 K</td>
</tr>
<tr>
<td></td>
<td>Above 16</td>
<td>2 K</td>
<td>0.8 K</td>
</tr>
<tr>
<td>Relative Humidity,</td>
<td>0 to 12**</td>
<td>15 per cent R.H.</td>
<td>6 per cent R.H.</td>
</tr>
<tr>
<td>[Troposphere only]</td>
<td>12 to 17**</td>
<td>30 per cent R.H.</td>
<td>10 per cent R.H.</td>
</tr>
<tr>
<td>Mixing ratio,</td>
<td>12 to 25</td>
<td>20 per cent ppmv</td>
<td>4 per cent ppmv</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[specialised systems]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind direction</td>
<td>0 to 16</td>
<td>10º, speed&lt;10 m s⁻¹ 4º at higher speeds</td>
<td>5º, speed&lt;10 m s⁻¹ 2º at higher speeds</td>
</tr>
<tr>
<td></td>
<td>Above 16</td>
<td>20º, speed&lt;10 m s⁻¹ 8º at higher speeds</td>
<td>5º, speed&lt;10 m s⁻¹ 2º at higher speeds</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0 to 16</td>
<td>2 m s⁻¹</td>
<td>1 m s⁻¹</td>
</tr>
<tr>
<td></td>
<td>Above 16</td>
<td>4 m s⁻¹</td>
<td>1 m s⁻¹</td>
</tr>
<tr>
<td>Wind components</td>
<td>0 to 16</td>
<td>2 m s⁻¹</td>
<td>1 m s⁻¹</td>
</tr>
<tr>
<td></td>
<td>Above 16</td>
<td>3 m s⁻¹</td>
<td>1 m s⁻¹</td>
</tr>
<tr>
<td>Geopotential height of</td>
<td>1</td>
<td>30 gpm</td>
<td>20 gpm</td>
</tr>
<tr>
<td>significant level</td>
<td>5</td>
<td>40 gpm</td>
<td>20 gpm</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>60 gpm</td>
<td>20 gpm</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>120 gpm</td>
<td>40 gpm</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>200 gpm</td>
<td>40 gpm</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>240 gpm</td>
<td>60 gpm</td>
</tr>
</tbody>
</table>

**Change in expected relative humidity sensor performance should correspond to heights with temperatures around -50 ºC in the troposphere.**
Measurement of upper-air pressure, temperature and humidity

Annex B

ESTIMATES OF GOAL, BREAKTHROUGH AND THRESHOLD LIMITS FOR UPPER WIND, UPPER AIR TEMPERATURE, RELATIVE HUMIDITY AND GEOPOTENTIAL HEIGHT [DERIVED FROM WMO ROLLING REQUIREMENTS REVIEW FOR UPPER AIR OBSERVATIONS]

Table 1. Summary of WMO/GCOS limits for uncertainty [R.M.S. vector error,k=2] and vertical resolution for Upper Wind measurements

<table>
<thead>
<tr>
<th>Layer</th>
<th>Goal for NWP</th>
<th>Goal for climate</th>
<th>Breakthrough for NWP</th>
<th>Breakthrough for climate</th>
<th>Threshold for NWP</th>
<th>Threshold for climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower troposphere</td>
<td>Uncertainty</td>
<td>1''+-2 m s⁻¹</td>
<td>1.4''+-4 m s⁻¹</td>
<td>4 m s⁻¹</td>
<td>6 m s⁻¹</td>
<td>10 m s⁻¹</td>
</tr>
<tr>
<td>Lower troposphere</td>
<td>Vertical resolution</td>
<td>200m</td>
<td>50''+-500'm</td>
<td>300m</td>
<td>800 m</td>
<td>500m</td>
</tr>
<tr>
<td>Upper troposphere</td>
<td>Uncertainty</td>
<td>1''+-2 m s⁻¹</td>
<td>1.4''+-4 m s⁻¹</td>
<td>4 m s⁻¹</td>
<td>6 m s⁻¹</td>
<td>10 m s⁻¹</td>
</tr>
<tr>
<td>Upper troposphere</td>
<td>Vertical resolution</td>
<td>500m</td>
<td>50''+-500'm</td>
<td>700m</td>
<td>800 m</td>
<td>1km</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td>Uncertainty</td>
<td>2 m s⁻¹</td>
<td>1.4''+-4 m s⁻¹</td>
<td>4 m s⁻¹</td>
<td>6 m s⁻¹</td>
<td>10 m s⁻¹</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td>Vertical resolution</td>
<td>1km</td>
<td>250''+-500'm</td>
<td>2 km</td>
<td>800 m</td>
<td>3km</td>
</tr>
<tr>
<td>Upper stratosphere</td>
<td>Uncertainty</td>
<td>2 m s⁻¹</td>
<td>1.4''+-4 m s⁻¹</td>
<td>6 m s⁻¹</td>
<td>8 m s⁻¹</td>
<td>16 m s⁻¹</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td>Vertical resolution</td>
<td>1km</td>
<td>250''+-500'm</td>
<td>2 km</td>
<td>800 m</td>
<td>3km</td>
</tr>
<tr>
<td>Long term stability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 ms⁻¹ in 10 years</td>
<td></td>
</tr>
</tbody>
</table>

*Limit derived from CBS Rolling Review of Requirements, WMO Observing Requirements Data base, sampled August 2011
**Limit derived from GCOS Reference Upper Air Network observation requirements, GCOS-134, (2009), WMO/TD No 1506.
***Limit from atmospheric variability studies, WMO (1970).

- The “goal” is an ideal requirement above which further improvements are not necessary
- The “breakthrough” is an intermediate level between “threshold” and “goal” which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems
- The “threshold” is the minimum requirement to be met to ensure that data are useful

It is recommended expenditure on radiosondes should be justified when the accuracy and vertical resolution obtained is equal to or better than the threshold, and as close to the goal as is affordable
Table 2: Summary of WMO/GCOS Uncertainty [k=2] and vertical resolution limits for Upper Air temperature measurements. [Note: these limits are for temperatures at a given height, and may be different to those when temperatures are integrated over relatively deep layers, e.g. See Table 4 for breakthrough limits derived from requirements for 100 hPa geopotential height.]

<table>
<thead>
<tr>
<th>Layer</th>
<th>Goal for NWP</th>
<th>Goal for climate</th>
<th>Breakthrough for NWP</th>
<th>Breakthrough for climate</th>
<th>Threshold for NWP</th>
<th>Threshold for climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower troposphere</td>
<td>Uncertainty 0.6***-1 K</td>
<td>0.2**-1 K</td>
<td>1.8 K</td>
<td>1.2 K</td>
<td>6 K [extra tropics]</td>
<td>2 K</td>
</tr>
<tr>
<td></td>
<td>Vertical resolution 100 m</td>
<td>100 m</td>
<td>200 m</td>
<td>800 m</td>
<td>1 km</td>
<td>2 km</td>
</tr>
<tr>
<td>Upper troposphere</td>
<td>Uncertainty 0.6***-1 K</td>
<td>0.2**-1 K</td>
<td>1.8 K</td>
<td>1.2 K</td>
<td>6 K [extra tropics]</td>
<td>2 K</td>
</tr>
<tr>
<td></td>
<td>Vertical resolution 300 m</td>
<td>100 m</td>
<td>400 m</td>
<td>800 m</td>
<td>1 km</td>
<td>2 km</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td>Uncertainty 1 K</td>
<td>0.4**-1 K</td>
<td>1.8 K</td>
<td>1.2 K</td>
<td>6 K [extra tropics]</td>
<td>2 K</td>
</tr>
<tr>
<td></td>
<td>Vertical resolution 1 km</td>
<td>1 km</td>
<td>100***-500* m</td>
<td>1.5 km</td>
<td>800 m</td>
<td>3 km</td>
</tr>
<tr>
<td>Upper stratosphere</td>
<td>Uncertainty 1 K</td>
<td>0.4**-1 K</td>
<td>2.8 K</td>
<td>1.2 K</td>
<td>6 K</td>
<td>2 K</td>
</tr>
<tr>
<td></td>
<td>Vertical resolution 1 km</td>
<td>1 km</td>
<td>100***-500* m</td>
<td>1.5 km</td>
<td>800 m</td>
<td>3 km</td>
</tr>
<tr>
<td>Long term Stability</td>
<td>0.05 K in 10 years**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Limit derived from CBS Rolling Review of Requirements, WMO Observing Requirements Database, sampled August 2011
**Limit derived from GCOS Reference Upper Air Network observation requirements, GCOS-134, (2009), WMO/TD No 1506.
*** Limit from atmospheric variability studies, WMO (1970).

- The “goal” is an ideal requirement above which further improvements are not necessary
- The “breakthrough” is an intermediate level between “threshold” and “goal” which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems
- The “threshold” is the minimum requirement to be met to ensure that data are useful

It is recommended expenditure on radiosondes should be justified when the accuracy and vertical resolution obtained is equal to or better than the threshold, and as close to the goal as is affordable.
Measurement of upper-air pressure, temperature and humidity

Table 3. Summary of WMO/GCOS performance limits for aerological instruments measuring humidity

<table>
<thead>
<tr>
<th>Layer</th>
<th>Goal for NWP</th>
<th>Goal for climate</th>
<th>Breakthrough for NWP</th>
<th>Breakthrough for climate</th>
<th>Threshold for NWP</th>
<th>Threshold for climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower troposphere</td>
<td>Uncertainty</td>
<td>2***--4* per cent R.H.</td>
<td>4 per cent R.H.</td>
<td>16 per cent R.H.</td>
<td>6 per cent R.H.</td>
<td>40 per cent R.H.</td>
</tr>
<tr>
<td>Lower troposphere</td>
<td>Vertical resolution</td>
<td>100m</td>
<td>500--5000m</td>
<td>200m</td>
<td>800 m</td>
<td>1 km</td>
</tr>
<tr>
<td>Upper troposphere</td>
<td>Uncertainty</td>
<td>4 per cent R.H.</td>
<td>4 per cent R.H.</td>
<td>16 per cent R.H.</td>
<td>6 per cent R.H.</td>
<td>40 per cent R.H.</td>
</tr>
<tr>
<td>Upper troposphere</td>
<td>Vertical resolution</td>
<td>300m</td>
<td>1000--5000m</td>
<td>500m</td>
<td>800 m</td>
<td>1km</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td>Uncertainty</td>
<td>10 per cent mixing ratio ppmv</td>
<td>4 per cent mixing ratio ppmv</td>
<td>16 per cent mixing ratio ppmv</td>
<td>6 per cent mixing ratio ppmv</td>
<td>40 per cent mixing ratio ppmv</td>
</tr>
<tr>
<td>Lower stratosphere</td>
<td>Vertical resolution</td>
<td>1km</td>
<td>1000--5000m</td>
<td>1.5 km</td>
<td>800 m</td>
<td>3km</td>
</tr>
<tr>
<td>Upper stratosphere</td>
<td>Uncertainty</td>
<td>Not stated</td>
<td>4 per cent mixing ratio ppmv</td>
<td>Not stated</td>
<td>6 per cent mixing ratio ppmv</td>
<td>Not stated</td>
</tr>
<tr>
<td>Upper stratosphere</td>
<td>Vertical resolution</td>
<td>Not stated</td>
<td>1000--5000m</td>
<td>Not stated</td>
<td>800 m</td>
<td>Not stated</td>
</tr>
<tr>
<td>Long term stability</td>
<td>0.3 per cent in 10 years**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Limit derived from CBS Rolling Review of Requirements, WMO Observing Requirements Data base, sampled August 2011
**Limit derived from GCOS Reference Upper Air Network observation requirements, GCOS-134, (2009), WMO/TD No 1506.
*** Limit from atmospheric variability studies, WMO (1970).

Units: Rolling requirement and GCOS requirement refers to specific humidity, but this leads to far too stringent limits on accuracy in layers where relative humidity is very low in the lower and middle troposphere. So values are shown as approximately equivalent relative humidity, and mixing ratio should be used at very low temperatures or in the stratosphere.

- The “goal” is an ideal requirement above which further improvements are not necessary.
- The “breakthrough” is an intermediate level between “threshold” and “goal” which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems.
- The “threshold” is the minimum requirement to be met to ensure that data are useful.

It is recommended expenditure on radiosondes should be justified when the accuracy and vertical resolution obtained is equal to or better than the threshold, and as close to the goal as is affordable.
<table>
<thead>
<tr>
<th>Layer</th>
<th>Goal for NWP</th>
<th>Goal for climate</th>
<th>Breakthrough for NWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface to 100 hPa</td>
<td>24 gpm [equivalent to 0.4 K layer T]</td>
<td>12 gpm [equivalent to 0.2 K layer T]</td>
<td>50 gpm [equivalent to 0.8 K layer T]</td>
</tr>
<tr>
<td>Lower troposphere</td>
<td>40 gpm</td>
<td>16 gpm on average</td>
<td>120 gpm</td>
</tr>
<tr>
<td>Lower troposphere</td>
<td>30 gpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper troposphere</td>
<td>40 gpm</td>
<td>14 gpm on average</td>
<td>120 gpm</td>
</tr>
<tr>
<td>Lower stratosphere equatorial</td>
<td>70 gpm</td>
<td>48 gpm° K</td>
<td>200 gpm</td>
</tr>
<tr>
<td>Lower stratosphere extra tropical</td>
<td>100 gpm</td>
<td>68 gpm</td>
<td>300 gpm</td>
</tr>
<tr>
<td>Upper stratosphere</td>
<td>80 gpm</td>
<td>60 gpm</td>
<td>240 gpm</td>
</tr>
<tr>
<td>Long term Stability</td>
<td>4-8 gpm in 10 years**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Limit for height error produces a typical temperature error of half the magnitude specified for the limits for temperature in Table 2

2Limit derived to be compatible with measurements from operational laser ceilometers in the lower troposphere.

- The “goal” is an ideal requirement above which further improvements are not necessary
- The “breakthrough” is an intermediate level between “threshold” and “goal” which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems
- The “threshold” is the minimum requirement to be met to ensure that data are useful

It is recommended expenditure on radiosondes should be justified when the accuracy and vertical resolution obtained is equal to or better than the threshold, and as close to the goal as is affordable.
Measurement of upper-air pressure, temperature and humidity

Annex C

GUIDELINES FOR ORGANIZING RADIOSONDE INTERCOMPARISONS AND FOR THE
ESTABLISHMENT OF TEST SITES

PART I — GUIDELINES FOR ORGANIZING RADIOSONDE INTERCOMPARISONS

1. Introduction

1.1 These guidelines assume that procedures that may be established by various test facilities are consistent with procedures established by other national and international organizations. They also assume that an Organizing Committee will be formed of participants (Members) interested in comparing radiosondes and that at least one non-participant will be included with ability to provide guidance for conducting the Intercomparison. The involvement of an independent non-participant is important in order to avoid bias during the planning of the Intercomparison. Consideration must also be given to whether radiosonde manufacturers' personnel should actively participate or whether independent operational personnel of the host should prepare and launch such radiosondes.

1.2 All intercomparison differs from each other to some extent; therefore, these guidelines are to be construed only as a generalized checklist of tasks needing to be accomplished. Modifications should be made by the Organizing Committee, as required, but the validity of the results and scientific evaluation should not be compromised.

1.3 Final reports of previous intercomparison and organizational meeting reports of other Organizing Committees may serve as an example of the methods that can be adopted for the Intercomparison. These previous reports should be maintained and made available by the WMO Secretariat.

2. Objectives of intercomparisons

2.1 The intercomparison objectives must be clear, must list what is expected from the intercomparison and identify how results will be disseminated. The Organizing Committee is tasked to examine the achievements to be expected from the radiosonde intercomparison and to identify and anticipate any potential problem. The Organizing Committee's role is to provide guidance, but it must also prepare clear and detailed statements of the main objectives and agree on the criteria to be used in evaluating the results. The Organizing Committee should also determine how best to guarantee the success of the intercomparison by drawing on background knowledge and accumulated experience from previous intercomparison.

3. Place, date and duration of intercomparison

3.1 The host facility should provide to the Organizing Committee and to the participants a description of the proposed intercomparison site and facilities (locations, etc.), environmental and climatological conditions, and site topography. The host facility should also name a Project Leader or Project Manager who will be responsible for the day-to-day operation and act as the facility point of contact.

3.2 The Organizing Committee should visit the proposed site to determine the suitability of its facilities and to propose changes, as necessary. After the Organizing Committee agrees that the site and facilities are adequate, a site and environmental description should be prepared by the Project Leader for distribution to the participants. The Project Leader, who is familiar with his facility’s schedule, must decide the date for the start of the intercomparison, as well as its duration. A copy of this schedule shall be delivered to the Organizing Committee.

3.3 In addition to the starting date of the intercomparison, the Project Leader should propose a date when his facility will be available for the installation of the participant’s equipment and arrange for connections to the data acquisition system. Time should be allowed for all of the participants to check and test equipment prior to starting the intercomparison and to allow additional time to familiarize the operators with the procedures of the host facility.

4. Participation

4.1 As required, the Project Leader and/or Organizing Committee should invite, through the Secretary-General of WMO, participation of Members. However, once participants are identified, the Project Leader should
handle all further contacts.

4.2 The Project Leader should draft a detailed questionnaire to be sent by the Secretary-General to each participant in order to obtain information on each instrument type proposed to be intercompared. Participants are expected to provide information on their space, communication, unique hardware connection requirements, and software characteristics. They also should provide adequate documentation describing their ground and balloon-borne instrumentation.

4.3 It is important that participants provide information about their radiosonde calibration procedures against recognized standards. Although it is expected that operational radiosondes will be intercompared, this may not always be the case; new or research-type radiosondes may be considered for participation with the agreement of all of the participants, the Project Leader, and the Organizing Committee.

5. Responsibilities

5.1 Participants

5.1.1 The participants shall be responsible for the transportation of their own equipment and costs associated with this transportation.

5.1.2 The participants should install and remove their own equipment with the cognizance of the Project Leader. The host facility shall assist with unpacking and packing, as appropriate.

5.1.3 The participants shall provide all necessary accessories, mounting hardware for ground equipment, signal and power cables, spare parts and expendables unique to their system. The participants shall have available (in the event that assistance from the host facility should become necessary) detailed instructions and manuals needed for equipment installation, operation, maintenance and, if applicable, calibration.

5.2 Host facility

5.2.1 The host facility should assist participants in the unpacking and installation of equipment as necessary, and provide storage capability to house items such as expendables, spare parts and manuals.

5.2.2 The host facility should provide auxiliary equipment as necessary, if available.

5.2.3 The host facility should assist the participants with connections to the host facility’s data acquisition equipment, as necessary.

5.2.4 The host shall insure that all legal obligations relating to upper-air measurements (for example, the host country’s aviation regulations and frequency utilization) are properly met.

5.2.5 The host facility may provide information on items such as accommodation, local transportation and daily logistics support, but is not obligated to subsidize costs associated with personnel accommodation.

6. Rules during the intercomparison

6.1 The Project Leader shall exercise control of all tests and will keep a record of each balloon launch, together with all the relevant information on the radiosondes used in the flight and the weather conditions.

6.2 Changes in equipment or software will be permitted with the cognizance and concurrence of the Project Leader. Notification to the other participants is necessary. The Project Leader shall maintain a log containing a record of all the equipment participating in the comparison and any changes that occur.

6.3 Minor repairs (for example, fuse replacement, etc.) not affecting instrumentation performance are allowed. The Project Leader should be made aware of these minor repairs and also submit the information to the record log.

6.4 Calibration checks and equipment servicing by participants requiring a specialist or specific equipment will be permitted after notification to the Project Leader.

6.5 Any problem that compromises the intercomparison results or the performance of any equipment shall be addressed by the Project Leader.

7. Data acquisition

7.1 The Organizing Committee should agree on appropriate data acquisition procedures such as
measurement frequency, sampling intervals, data averaging, data reduction (this may be limited to an individual participant’s capability), data formats, real-time quality control, post-analysis quality control and data reports.

7.2 The initial International Organising Committee shall decide on the data acquisition hardware and software for the test. This should be well tested before commencement of the intercomparison, and the use of an established processing package such as described in WMO (1996b) is to be preferred. 7.3 The time delay between observation and delivery of data to the Project Leader shall be established by the Project Leader and agreed by the participants. One hour after the end of the observation (balloon burst) should be considered adequate.

7.4 The responsibility for checking data prior to analysis, the quality control steps to follow, and delivery of the final data rests with the Project Leader.

7.5 Data storage media shall be the Project Leader’s decision after taking into consideration the capability of the host facility, but the media used to return final test data to participants may vary in accordance with each of the participant’s computer ability. The Project Leader should be cognizant of these requirements.

7.6 The Project Leader has responsibility for providing final data to all participants and, therefore, the host facility must be able to receive all individual data files from each participant.

8. Data processing and analysis

8.1 Data analysis

8.1.1 A framework for data analysis should be encouraged and decided upon even prior to beginning the actual intercomparison. This framework should be included as part of the experimental plan.

8.1.2 There must be agreement among the participants as to methods of data conversion, calibration and correction algorithms, terms and abbreviations, constants, and a comprehensive description of proposed statistical analysis methods. It is essential that the data processing is performed by experienced experts, nominated by WMO.

8.1.3 The Organizing Committee should verify the appropriateness of the analysis procedures selected.

8.1.4 The results of the intercomparisons should be reviewed by the Organizing Committee, who should consider the contents and recommendations given in the final report.

8.2 Data processing and database availability

8.2.1 All essential meteorological and environmental data shall be stored in a database for further use and analysis by the participants. The Project Leader shall exercise control of these data.

8.2.2 After completion of the intercomparison, the Project Leader shall provide a complete set of all of the participants’ data to each participant.

9. Final report of the intercomparison

9.1 The Project Leader shall prepare the draft final report which shall be submitted to the Organizing Committee and to the participating members for their comments and amendments. A time limit for reply should be specified.

9.2 Comments and amendments should be returned to the Project Leader with copies also going to the Organizing Committee.

9.3 When the amended draft final report is ready, it should be submitted to the Organizing Committee, who may wish to meet for discussions, if necessary, or who may agree to the final document.

9.4 After the Organizing Committee approves the final document for publication, it should be sent to the Secretariat for publication and distribution by WMO.

9.5 Reproduction for commercial purposes of any plots or tables from the final report should not be allowed without specific permission from WMO.

10. Final comments
10.1 The Organizing Committee may agree that intermediate results may be presented only by the Project Leader, and that participants may present limited data at technical conferences, except that their own test data may be used without limitation. Once the WMO Secretariat has scheduled the final report for publication, WMO shall make the data available to all Members who request them. The Members are then free to analyse the data and present the results at meetings and in publications.
Part II — GUIDELINES FOR THE ESTABLISHMENT OF TEST SITES

1. Introduction

1.1 In order to support the long-term stability of the global upper-air observing system, it is essential to retain the capability of performing quantitative radiosonde comparisons. Current and new operational radiosonde systems must be checked against references during flight on a regular basis. Members must ensure that a minimum number of test sites with the necessary infrastructure for performing radiosonde comparison tests are retained.

1.2 Experience with the series of WMO Radiosonde Intercomparisons since 1984 has shown that it is necessary to have a range of sites in order to compare the radiosondes over a variety of flight conditions.

1.3 Relative humidity sensor performance is particularly dependent on the conditions during a test, for example, the amount of cloud and rain encountered during ascents, or whether surface humidity is high or low.

1.4 Daytime temperature errors depend on the solar albedo, and hence the surface albedo and cloud cover. Thus, temperature errors found at coastal sites may differ significantly from continental sites. Infrared errors on temperature sensors will not only depend on surface conditions and cloud distribution, but also on atmospheric temperature. Thus, infrared temperature errors in the tropics (for instance near the tropopause) will be quite different from those at mid-latitudes.

1.5 The errors of many upper-wind observing systems depend on the distance the balloon travels from the launch site (and also the elevation of the balloon from the launch site). Thus, comparison tests must cover situations with weak upper winds and also strong upper winds.

2. Facilities required at locations

2.1 Locations suitable for testing should have enough buildings/office space to provide work areas to support the operations of at least four different systems.

2.2 The site should have good quality surface measurements of temperature, relative humidity, pressure and wind, measured near the radiosonde launch sites. Additional reference quality measurements of temperature pressure and relative humidity would be beneficial.

2.3 The test site should have a method of providing absolute measurements of geopotential height during test flights (probably using a Global Positioning System (GPS) radiosonde capable of producing accurate heights).

2.4 The test site should have a well-established surface based GPS sensor for measuring integrated water vapour or ground based radiometers and interferometers.

2.5 Cloud observing system at the test site, such as laser ceilometers and cloud radars are desirable.

2.6 Aerosol lidars, and relative humidity lidars, may also prove useful at the test site.

2.7 The site must be cleared by the national air traffic control authorities for launching larger balloons (3,000 g) with payloads of up to 5 kg. Balloon sheds must be able to cope with launching these large balloons.

3. Suggested geographical locations

3.1 In order to facilitate testing by the main manufacturers, it is suggested that test sites should be retained or established in mid-latitudes in North America, Europe and Asia. Ideally, each of these regions would have a minimum of two sites, one representing coastal (marine) conditions, and another representing conditions in a mid-continent location.

3.2 In addition, it is suggested that a minimum of two test locations should be identified in tropical locations, particularly for tests of relative humidity sensors.

3.3 If the main test sites noted above do not provide adequate samples of extreme conditions for relative humidity sensors (for example, very dry low-level conditions), it may be necessary to identify further test sites in an arid area, or where surface temperatures are very cold (below –30 °C in winter). It is possible that some of these could be selected from GRUAN sites which have been established.
Measurement of upper-air pressure, temperature and humidity

PART III GUIDELINES FOR PROTOTYPE TESTING

1. Introduction

1.1 The major WMO radiosonde comparisons are organised at about 5 to 6 year intervals, when a large group of manufacturers benefit from a large scale test, with systems that have already been through prototype testing. For new designs or those manufacturers rectifying problems identified in the WMO Radiosonde Comparisons there is a need to perform smaller, less expensive tests.

1.2 This could be at one of the designated CIMO Test sites, which is probably best for manufacturers trying to demonstrate a problem has been resolved.

1.3 On the other hand, the development and selection of new national radiosonde designs merits prototype testing at suitable national locations.

2. Recommended procedures

2.1 Testing to prove problems have been rectified needs to be done to similar standards and methods used in the WMO Radiosonde Comparisons. This requires that any CIMO Test Site must have staff fully conversant with the procedures and techniques of the WMO Radiosonde Comparisons, and to use two radiosonde types of known good quality as working references/link radiosondes to the WMO radiosonde Comparison results.

2.2 With national prototype testing it is essential to compare measurements with radiosondes flown together under one balloon. Ideally the radiosondes should be suspended in a manner that they are free to rotate in flight, as this is what happens on individual ascents. The radiofrequency performance of the new radiosonde needs to be good enough that the radiosonde frequency does not drift and cause interference to the radiosonde with which it is being compared. Comparison of results should be performed as a function of time into flight, since it is unwise to assume that height/pressure assignments to temperature and relative humidity measurements have negligible errors. The numbers of test flights initially flown may be quite small since some initial errors are often large and can be quickly identified even by comparison with a lower quality national radiosonde.

2.3 However, once the aim is to improve the new national radiosonde design so that its measurement quality comes close to that of the high quality radiosondes tested in the WMO Intercomparison of High Quality Radiosondes, then it will be necessary to use one of the better quality radiosondes as a test reference. Always follow the manufacturer’s instructions when preparing the better quality radiosonde for the test flights. Testing must be performed both day and night, since the sonde errors for daytime temperatures need to be identified, whereas at night the errors in relative humidity are often worse than in daytime measurements.

2.4 Final prototype tests need to be performed at a time of year when the variation of relative humidity in the vertical and with time is high at all levels in the troposphere.

3. Archiving of results

3.1 Results of tests at CIMO test centres need to be forwarded to the relevant CIMO Expert team for checking and then display on the CIMO web sites.

3.2 Once, a new national development becomes mature, it would also be helpful for the future to forward Comparison test results to the relevant CIMO Expert Team.
References and further reading


Hyland, R. W. and A. Wexler, 1983:Formulations for the Thermodynamic Properties of the saturated Phases of H2O from 173.15 K to 473.15 K, ASHRAE Trans, 89(2A), 500-519,


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Measurement of upper-air pressure, temperature and humidity

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Measurement of upper-air pressure, temperature and humidity


