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WMO INTERCOMPARISON OF RADIOSONDE SYSTEMS

Vacoas, Mauritius, 2-25 February 2005

J. Nash *(United Kingdom)*
R. Smout *(United Kingdom)*
T. Oakley *(United Kingdom)*
B. Pathack *(Mauritius)*
S. Kurnosenko *(United States)*

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FOREWORD

The Thirteenth Session of the Commission for Instruments and Methods of Observation (CIMO) recognized the need to conduct an Intercomparison of high quality radiosondes being introduced into portions of the global upper-air network. Dr John Nash, Chairman of the Expert Team on Upper-Air System Intercomparisons facilitated his team's organization, execution and evaluation of the WMO Upper-Air Intercomparison conducted in Vacoas, Mauritius, 7-27 February 2005.

This Intercomparison was performed in Mauritius under the management of a small WMO Project Team. The team was responsible for conducting the intercomparisons and for training local staff from Mauritius Meteorological Services. The Intercomparison demonstrated that the local staff was experienced enough and could be trained quickly in advanced test procedures. This resulted in enhanced skills and knowledge within the Mauritius Meteorological Services. The deployment of a WMO Project Team to supervise the test was successful, however, for future tests it should be recognized that the supervisory work involves a significant amount of time, in consultation with participants, and involves much more than purely managing the test procedures. In this case, the consultation period extended for several months beyond the completion of the intercomparison.

The WMO Intercomparison of High Quality Radiosonde Systems held in Vacoas was organized in order to evaluate a new generation of radiosondes being introduced into the global upper air network. Six operational radiosonde systems (Vaisala, Sippican, Modem, MEISEI Electric Co., Graw Radiosondes and Meteolabor) participated in the intercomparison, which consisted of 62 successful comparison flights. In addition, 3-thermistor radiosondes (Sippican MKII) were flown to provide a daytime *working reference* for temperature, as well as a Snow-white chilled mirror hygrometer, as *working reference* for dewpoint/relative humidity. The *working references* were flown to provide additional evidence on the accuracy of the operational radiosondes. The intercomparison was intended to identify significant flaws in the new radiosonde designs, so that these could be rectified before use became widespread.

Measurements of wind by GPS radiosonde systems were consistent in quantity and of high quality. Flight preparations for GPS radiosondes have become much easier since the 2001 intercomparison conducted in Brazil. GPS heights measured by the GPS radiosondes were so accurate that in most situations there is no longer a need to use a pressure sensor. The Intercomparison in Mauritius also demonstrated that most errors identified in the WMO Intercomparison of GPS Radiosondes in Brazil had been rectified. Temperature, pressure and relative humidity measurements by the participating radiosondes agreed more closely than in any previous WMO Radiosonde Intercomparisons. Thus, all radiosondes in this Intercomparison were of better quality than in the previous Intercomparison, and were therefore judged to merit the designation of high quality radiosonde. It can be stated that all Manufacturers have contributed with significant innovations, generating a more competitive environment.

Recommendations on suitable radiosondes for future climate observing networks are presented within the report. For temperature measurements there is a large range of suitable sensors. For water vapour/ relative humidity the range of sensor type is much more limited and further development of new sensors would be beneficial.

I wish to express my sincere appreciation for the efforts of Dr Nash and his team; to Dr Patheck of the Mauritius Meteorological Services for their logistic support; and Mr Kurnosenko for his technical support in the area of data collection and processing. Their joint collaborative efforts, the support of their parent agencies, as well as the contribution from the manufacturers made this Intercomparison of the most successful on Upper-Air instruments to date.

(Dr. R.P. Canterford)

Acting President
Commission for Instruments and
Methods of Observation

WMO INTERCOMPARISON OF RADIOSONDE SYSTEMS

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1. INTRODUCTION

1.1 *Objectives*

The objectives for the intercomparison were agreed by the first session of the Joint meeting of the CIMO Expert Team and International Organizing Committee on Upper-Air Systems Intercomparisons (ET/IOC), Geneva, Switzerland, 17 – 20 March 2004.

These can be summarized as:

- To improve the accuracy of daytime radiosonde measurements and correction procedures (see discussion in section 10 and recommendations in 13);
- To test GPS wind measuring systems for accuracy and availability (see results in section 6);
- To investigate the usefulness of geopotential height derived from geometric height measured by GPS radiosondes (see results in section 7);
- To evaluate the differences of operational radiosondes against high performance sensors (see results in sections 8,9 and 10);
- To recommend the best combinations of radiosondes for referencing for GCOS and for satellite data calibration (see section 11);
- To assess the practices used in the preparation of radiosondes for launch (see section 4);
- To assess the usefulness of remote sensing measurements in support of radiosonde system intercomparisons (see section 12).

1.2 Relevance of the test for weather forecast and climate monitoring operations

This intercomparison was organized because a new generation of radiosondes is being introduced into most of the global upper air network. Five new operational radiosonde systems from Europe, Japan and the US were intercompared. None of them had been intercompared previously in the earlier WMO Radiosonde Intercomparisons. Two additional working references were flown within the intercomparison to provide additional evidence on the accuracy of the operational radiosondes.

The intercomparison was intended to identify any significant flaws in the new radiosonde designs, so that these could be rectified before use became widespread in the operational radiosonde networks.

The intercomparison results also inform users, both operational and research, of the improved measurement accuracy that can be achieved with these new operational systems. This information can be used to assess the trade-off of certain radiosonde systems regarding accuracy and performance on the one hand and costs on the other hand for specific application.

Radiosonde/dropsonde measurements underpin much atmospheric research. Also, the improvement of upper air remote sensing systems to operational standards relies on comparisons and calibration from radiosondes. The intercomparison provides an extensive evaluation of the error characteristics of the various radiosondes in a challenging measurement environment, i.e. rainy season in the subtropics.

Planning for future climate networks is in progress. The results from the intercomparison are intended to inform this process. In particular, results from the working

references illustrate the problems that may be found with more expensive high quality equipment that is not tested to the same extent as the operational radiosondes.

1.3 Relationships with previous intercomparisons

This intercomparison was not designed with a strong link to earlier WMO Radiosonde intercomparisons. Some results from these Intercomparisons are summarized in the WMO Guide to Meteorological Instruments and Methods of Observation (WMO No. 8, sixth edition, 1996). Some of the radiosonde designs intercompared in Mauritius were mature versions of the GPS systems that were first intercompared in the WMO GPS Radiosonde Intercomparison in Alcantara, Brazil in 2001. However, nearly all the temperature sensing systems of the new generation radiosondes have been modified (either signal channel electronics, exposure of the sensor) since then, even if the basic temperature sensors are similar in some cases.

The requirement for improved relative humidity sensors for nearly all radiosondes became apparent in the WMO Relative Humidity Sensor Intercomparison in 1995. At that time, capacitance sensors were found to be suffering from chemical contamination leading to dry bias errors and carbon hygristor sensors were found to be very unstable both when placed in high humidity in the laboratory or after passing through clouds during radiosonde intercomparison flights. As with the temperature sensors, very few of the relative humidity sensors in Mauritius were exactly the same as those intercompared in Alcantara, although some were similar in general principle of operation.

The measurement of geometric height by GPS radiosondes was at an early stage in Alcantara and the height results from Brazil contained many errors, which made it difficult to interpret the discrepancies between the different systems. Thus, the height measurements contained in this report represent the first extensive intercomparison of height measurements from a large group of GPS radiosonde types.

Linking to the earlier radiosonde intercomparisons will be discussed to some extent in sections 8 to 10 where individual sensor performance is discussed.

1.4 Relationships with recent scientific studies

The WMO Guide to Meteorological Instruments and Methods of Observation (WMO No 8, Seventh edition of English version to be published in early 2006) contains peer-reviewed tables of typical radiosonde sensor errors based mainly on the results of earlier WMO Radiosonde Intercomparisons. These mostly show the error characteristics from the radiosondes in use between 1980 and 2001, but to some extent also information from the results of the Mauritius intercomparison.

Development of the 3-thermistor temperature measurements technique has been pursued by F. Schmidlin (1991) and F. Schmidlin (2005) and errors for this NASA system have been discussed in J. K. Luers (1992).

Most of the recent papers published about radiosonde sensor performance in the scientific literature have been concerned with relative humidity sensor performance. The studies relevant to tropical measurements have been concerned with the deficiencies in calibration of the earlier Vaisala RS80-A radiosonde, e.g. Miloshevich, et al (2001), Leiterer, et al (2005). In addition studies including the Vaisala RS90 relative humidity sensor have been published, e.g., by Miloshevich, et. al. (2004), results from the WMO Intercomparison of GPS Radiosonde in Brazil by Sapucci et. al. (2005), and from the EU STAR Project by Verver et. al. (2005).

The use of Snow White chilled mirror hygrometers as high quality dewpoint measurements has been demonstrated in (Fujiwara, et al, 2003).

In the US, Wang et. al. (2003) published comparisons of US radiosondes with Snow White measurements. It should be noted that the Sippican carbon hygristor was not deployed in Mauritius as earlier WMO intercomparisons have shown that the sensor has limitations that make it unsuitable for good quality measurements in the middle and upper troposphere in the tropics. Many, but not all, carbon hygristor sensors fail to respond adequately to relative humidity changes at temperatures lower than -40 °C, as occurred in the examples shown in Wang, et al. (2003).

Two working references were used in Mauritius:

- Sippican three thermistor (for temperature);
- Meteolabor SRS radiosonde (Snow White) processed on the Meteolabor Argus ground system (for relative humidity).

These were tested by the Met Office during the summer of 2004 when the Met Office Vaisala RS92 acceptance test was in progress at the UK Camborne test site. Camborne also possesses Graw and Sippican GPS radiosondes to provide height references for testing. The Camborne test ensured that many of the larger problems with the two working references were resolved before the Mauritius intercomparison. The test at Camborne was performed to similar standards as a WMO intercomparison, but was spread out over a very much longer time period whilst problems with the working reference were resolved. Results from this test were summarized by Smout et. al. (2005).

2. SUMMARY OF INTERCOMPARISON ORGANIZATION

The WMO Intercomparison of High Quality Radiosonde Systems was organized by the CIMO Expert Team on Upper-Air Systems Intercomparisons, chaired by Dr. J. Nash. The intercomparison consisted of 62 successful multiple radiosonde intercomparison flights, performed between 7 and 25 February 2005 at the headquarters of the Mauritius Meteorological Services, Vacoas, Mauritius.

The Mauritius Meteorological Services had the privilege to host this intercomparison and February 2005 was chosen to allow the radiosonde relative humidity sensors to be tested in both wet and dry conditions. Dr B. Pathack, supported by staff from the Meteorological Services, see Annex A, performed a wide range of tasks as Project Manager. The typical number of people from Meteorological Services Mauritius involved in the intercomparison during one week was more than 20. Four teams of 3 persons were trained to prepare balloons, provide surface observations and manage the launch of the balloons. The teams working on the intercomparison were enthusiastic and performed well, so it was decided to widen the number of local people participating by bringing in further staff at later stages in the intercomparison. The number of international participants present in Mauritius at any time during the intercomparison was about 15, see Annex B for list of international participants.

Import and export of equipment proved a major effort, but all equipment was delivered on time.

Provision of facilities for the intercomparison included the installation of a hydrogen generator to facilitate filling of 2000 g balloons, improved balloon filling adaptors within the balloon shed, stabilized power supply for the ground system computers and Internet connections for the participants.

Mauritius Meteorological Services provided technical support to participants throughout the intercomparison. Repair work was performed on the power supplies of the cloud radar brought from the UK, without which measurements would not have been obtained.

Vaisala provided a CT75K ceilometer and the UK Met Office a GPS receiver and antenna. The deployment of 78 GHz cloud radar for part of the experiment and the logging of remote sensing data were supported by the COST 720 activity, with one representative from Switzerland and three from the UK. Without these four people the intercomparison would probably have failed to complete the specified intercomparison schedule, because the workload expected of Dr. Nash and Richard Smout (travel supported by WMO) was much too high.

Mr. Kurnosenko attended the intercomparison to sort out data logging and processing problems. He ensured the databases were built correctly in real time, whilst also developing procedures to speed up the real time checking of intercomparison data. He also facilitated the resubmission of data where errors in the set up of the ground systems were identified.

Training in balloon handling and intercomparison launch procedures were provided by J. Nash and R. Smout for two days before the commencement of the intercomparison. Radiosonde support rigs were assembled in advance from green bamboo canes obtained locally. Most launches were supervised by UK personnel, with the support of senior managers from Mauritius Meteorological Services.

3. RADIOSONDES TESTED

The ET/IOC chose eight radiosonde types to participate in the intercomparison, with the option for a radiosonde from China to participate if China considered that a suitable radiosonde was ready for intercomparison. In practice, International Met Systems decided not to participate, and NASA also decided not to participate with the Accurate Temperature Measuring radiosonde (5-thermistor system). This system was substituted by the Lockheed Martin Sippican multi-thermistor system on very short notice before the intercomparison started. China did not request to participate, but sent observers to the intercomparison. Arrangements were made to reduce the staff support costs for MODEM and Graw. For part of the intercomparison these two systems were operated by Mauritius and UK staff respectively, without supervision by the manufacturer. Local staff only received a short period of training before starting the intercomparison, but coped well with unpredictable launch conditions with low level winds varying significantly between launches.

Seven radiosonde types were tested, see table below:

Table 3.1 Types of sensor for the radiosondes tested in the WMO Intercomparison of High Quality Radiosonde Systems.

Type	**Temperature sensor**	**Humidity Sensor**	**Pressure Sensor**	**GPS height**	**Wind measurement**
Graw DFM-97 (Germany)	Aluminized bead thermistor	External Thin film capacitance	Yes	Yes	GPS code correlating
Meisei RS-01G (Japan)	Aluminized bead thermistor	External Thin film capacitance	No	Yes	GPS code correlating
Meteolabor** SRSD-C34 (Switzerland)	Thermocouple	Chilled mirror Hygrometer (Snow White)	Hypsometer (Boiling point of water)	No	Not Submitted
MODEM M2K2 (France)	White bead thermistor	External Thin film capacitance	No	Yes	GPS code correlating
Sippican LMS-5 (USA)	Aluminized chip thermistor	Internal Thin film capacitance	No	Yes	GPS code correlating
Sippican multi-thermistor (USA)	3 aluminized chips, one black and one White	Not submitted	Not submitted	Not submitted	Not submitted
Vaisala RS92-SGP (Finland)	Aluminized capacitance	Dual External Thin film capacitance	Yes	Yes	GPS code correlating

***The SRSD-C34 is a new radiosonde design with different processing software to the operational SRS radiosonde used for many years at Payerne Radiosonde Station, Switzerland.*

Pictures of the individual radiosondes plus associated ground system antenna can be found in Annex C.

Vaisala, Modem and Meisei radiosondes and Vaisala, Graw and Sippican radiosondes were flown together as two groups with either Meteolabor or five-thermistor radiosondes included as the high performance reference. The use of two groups had been agreed at the ET/IOC and the HMEI representatives. Vaisala were allowed to participate in all flights as a result of a decision of the Chairman of the ET/IOC. This was to provide a comprehensive link between the two groups for temperature measurements. There was a very high risk that multi-thermistor radiosondes would not be available for the intercomparison at all. The intercomparison was commenced with only six viable multi-thermistor radiosondes available. However, enough multi-thermistor radiosondes arrived as the intercomparison progressed to provide a partial but not comprehensive day-night link reference for temperature measurements.

Fig. 3.1 shows preparation for launching the Vaisala-Sippican-Graw group with a multi-thermistor radiosonde. Note the radiosondes were hung at the end of the bamboo, about 1 m below the bamboo cross level so that they were free to oscillate under the bamboo.

Fig. 3.1 Graw and Sippican 3-thermistor radiosondes ready for a nighttime intercomparison of the Vaisala-Sippican-Graw radiosonde group on the bamboo cross support rig.

All radiosondes tested were operating in the band 400.5 to 405.5 MHz. It would have been possible to fly all the radiosondes supported by one balloon if the frequency stability and bandwidth of the Sippican transmitters had been similar to the other radiosondes.

Fig. 3.2(a), (b), (c) show the ground systems for all of the radiosonde systems plus the laser ceilometer, GPS water vapour, and cloud radar. In Phase 1 of the WMO Radiosonde Intercomparison held in 1984 each radiosonde system required as much space as five of the systems shown here. Each radiosonde system took less than a day to install. Many systems were delivered to the site on the Saturday before the official start and were in full operational use by the afternoon of the following Monday.

Fig. 3.2(a) Preparing Vaisala RS92 and Snow white for a nigh time flight. The PCs on the left hand bench are STAR (Mauritius) operational monitor, Laser ceilometer, and GPS water vapour data loggers. On the central bench Modem ground system + pre-flight check box, + Vaisala ground system + pre-flight check near the window, Meteolabor radiosonde preparation + ground system behind this, and near the window the data logger and radar electronics for the cloud radar.

Fig. 3.2 (b) View of the operations room in the opposite direction with Sippican and Sippican multi-thermistor ground systems on the bench at the back, Graw display to the left hand side of the central bench and Modem to the right hand side of the central bench and more of the STAR ground system on the right hand side.

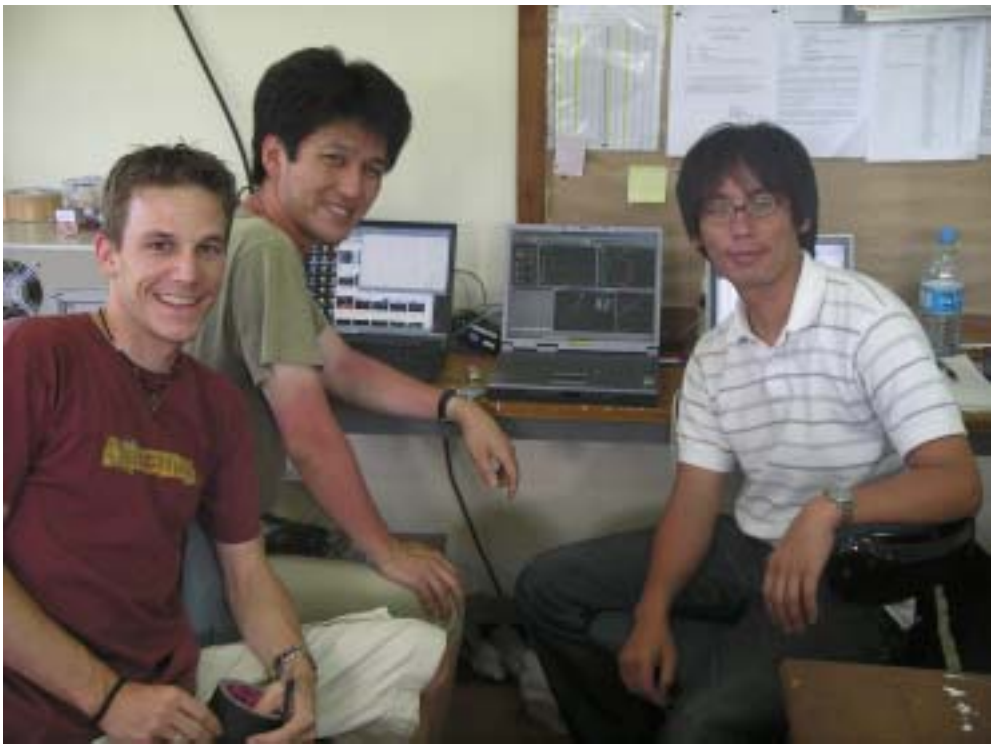


Fig. 3.2(c) Meisei ground system, showing in-flight data displays

As noted above, it was necessary to use Vaisala RS92 measurements as the link radiosonde between the two groups. Launch times were separated by about 5 hours to allow enough time to generate hydrogen to fill the 2000 g balloons, but this separation was shortened at night in the second and third weeks. The two daytime flights were launched at 09.00 and 14.00 local time, so that solar elevation was similar in the stratosphere for both groups. Nighttime launches were at 19.00 and between 22.00 to 23.30 local time.

Twenty-four Sippican MKII, multi-thermistor radiosondes were flown, (5 at night, 19 in the day) to provide a “non-operational link measurement” for temperature. The Snow White chilled mirror hygrometer was successfully deployed as a “non-operational link measurement” for dew point/ relative humidity measurements on 34 flights. The consequences of this will be discussed later in section 9 for temperature and 10 for relative humidity.

Fig. 3.3 shows Mauritius staff operating the MODEM system in the latter part of the intercomparison.

Fig. 3.3 Staff from the teams of Mauritius Meteorological Services working with the MODEM system during the second half of the intercomparison.

Fifty flights reached higher than 30 km and sufficient flights ascended to heights above 34 km to provide useful comparisons up to this level, where the errors in temperature tend to increase more rapidly than at the lower heights. The balloon performance was judged as good given the rainy conditions. The presence of thick upper cloud at night led to very low infrared radiation temperatures above the cloud for a part of the intercomparison

4. PREPARATIONS FOR LAUNCH

4.1 GPS initiation issues

Before GPS radiosondes are launched it is preferable to ensure that the signals received by the radiosonde are being decoded correctly and providing valid position estimates. Of the GPS systems in the intercomparison, the Graw system was found to be a little simpler to initiate than the rest. This simplicity of preparation probably indicates the likely future for all the systems. All the GPS radiosonde systems were easier to operate in terms of lockup and functional reliability than was found in the WMO GPS Radiosonde Intercomparison, Brazil in 2001, but some improvements can still be made to make the use easier.

In preparing to launch, the Sippican radiosondes had to be positioned on the rig so that the communication link between the radiosonde and the ground system antenna was not lost during launch. The operators of the other GPS systems were not concerned about the position of the GPS radiosonde antenna during launch.

4.2 Radiofrequency issues

Before each flight every radiosonde was assigned a specific frequency. For a given group of radiosondes the assigned frequencies would be changed according to the working

reference being flown with the group. The tuning of the radiosondes was agreed with the operators, especially when changes in flight configuration required some alterations. Tuning all the radiosondes to a specified frequency was performed easily and effectively before launch. All the radiosondes, apart from the two Sippican radiosondes, would remain close to their nominal frequency throughout flight. There was no evidence of any interference between the radiosondes or from any external source, apart from in the first SRS flight when the radiosonde was given 400 MHz, a frequency outside the normal range of use for the SRS in a region where the PC's in the ground systems were generating interference.

4.3 Pressure sensor check

Vaisala, Graw and SRS performed a pressure sensor check before launch, which was then used to modify the pressure sensor calibrations used in flight. The hypsometer pressure sensor of the SRS radiosonde requires much longer to initiate than the other pressure sensors. The SRS pressures were not always reliable near the surface, see section 8. Preparation of the hypsometer to obtain best accuracy on launch requires an extremely stable environment for the SRS radiosonde. In Mauritius the lack of a pre-flight calibration box, usually used in Switzerland, gave rise to larger pressure errors than normal on launch. Also even though ground checks were performed some systems did not have the correct pressures immediately after launch, see section 8.

4.4 Temperature and relative humidity check

MODEM, Meisei and Vaisala performed ground checks (termed baseline check by some users) on the temperature and humidity measurements before launch, but it was only Vaisala that uses the comparison values to modify the conversion of sensor output to meteorological variable during the radiosonde ascent. It is recommended that some check on the reliability of temperature and relative humidity output is made before a radiosonde launch in order to prevent the launch of radiosondes which are faulty. The temperature and relative humidity comparisons in sections 9 and 10 do not give any strong indication as to which pre-flight practice is best. The older the radiosondes that are used, the more likely that the baseline check will be valuable.

The pre-flight check should be made according to the manufacturer's specification and does not necessarily require the use of a dedicated ground check device.

In the case of Vaisala, the ground check procedure was also used to heat the relative humidity sensors to drive off chemical contamination. Other manufacturers of thin film capacitance sensors need to consider whether chemical contamination during radiosonde storage is likely to be a problem. Procedures for driving off the relative humidity sensor contamination before launch should be implemented where necessary.

4.5 Battery preparation

Most of the radiosondes batteries were such that the longer than normal wait before launch and the relatively long ascent times did not cause very pronounced problems. The one exception was the Meisei radiosonde where the batteries were not sufficient to sustain operation reliably to the end of every intercomparison flight. This is due to unexpected long ascent times. Meisei will extend battery life from the present time to longer time based on this experience. GPS radiosondes consume more power than the older generation radiosondes, and it is possible that occasional degradation in the battery output at the end of some flights may have led to some drift in effective temperature calibration. MODEM and GRAW used dry-cell batteries instead of water-activated batteries. The Mauritius tests proved that this user-friendly technology can replace water activated batteries and hence reduce the preparation time and the total weight of the radiosondes.

4.6 Launch procedure

It was quite unusual to prepare for an intercomparison flight without a shower passing over the intercomparison site. Thus the radiosondes were only tied onto the bamboo cross at

the last minute. Sensors that might be liable to serious contamination in rain before launch (Snow White, 3-thermistor) were provided with some protection, which was removed at the last minute.

As the SRS plus Snow White combination was much larger and heavier than the other radiosondes, this caused problems in balancing the bamboo crosses during launch. It would be preferable that some attempt be made to reduce the size and weight of this combination for future intercomparisons work.

The bamboo cross would be carried across the launch area to the balloon shed by a mixture of local staff and international participants, where the 30 m suspension was attached to the balloon. In the conditions in Mauritius, it was decided that the use of unwinders was an unnecessary complication for the local staff. Similarly, Dr Pathack recommended that because of the wind speed and direction, the flight rigs would not fall on populated areas of the island so parachutes could be omitted from the flight rig. This was expected to reduce drag during ascent and increase the average burst height. Unlike the intercomparison in Brazil where there was nearly always a significant low-level trade wind, the wind conditions at Vacoas were much more variable in direction, with occasional strong updraughts or downdraughts when showers were near the site. Thus, the balloon and bamboo cross were normally positioned about 10 to 15 m apart with the person holding the centre of the cross responsible for positioning the cross underneath the balloon in whichever direction the balloon took. This person was always from the nominated support team of the Mauritius Meteorological services.

It took some time before the launch technique was perfected, so that some of the early launches were not as smooth as was achieved after more practice. During the launches Vaisala RS92 temperature sensor was damaged in two soundings. This very thin temperature sensor broke more easily than the other temperature sensors.

When it was raining fairly heavily from the middle troposphere, it proved impossible to launch successfully. The balloons seemed to become damaged by the rain with a relatively high raindrop size.

5. DATA PROCESSING, INCLUDING DATA EDITING

5.1 Software used

The processing software used for this intercomparison was provided by Mr Kurnosenko. This was an updated version of the RSKOMP software used to analyze results from Phases III and IV of earlier WMO Radiosonde Intercomparisons (see Kurnosenko and Oakley, 1996) and Annex D.

5.2 Intercomparison Procedures

Mr Kurnosenko was present at the intercomparison in Mauritius to manage the data input from the files provided by the manufacturers. The workload associated with data entry was increased by the large number of last moment modifications made to proposed file formats by participants in the intercomparison. The intercomparison database consisted of samples extracted at 1 s intervals from the files provided by the manufacturers, using extraction software modified on site in Mauritius. Recommendations for improving the consistency of data output files can be found in Annex E.

The attempt to use GPS timing as a method of synchronizing samples did not work because of a lack of consistency in the use of GPS time between the systems. This problem could be overcome if the manufacturers cooperated together to agree standard methods of use. Thus, data samples were synchronized in practice by matching temperature and relative humidity profiles near the ground using the WVIEW software. The adjustment procedure works well with temperature and humidity data sampled at 1 s intervals. The timing adjustment procedure may not work so well for pressure near the ground where the reported

values may have been adjusted by software to match the surface measurement, when an incorrect launch time has been used by the radiosonde ground system.

Input data for the intercomparison database were checked by the WMO supervisory team as soon as possible following the flight. This was always within 2 to 4 hours of the launch. Problems with systems were discussed with the specific teams, e.g. the filtering of the Japanese GPS measurements and a solution agreed. The aim was to ensure that data represented correct functioning of the systems deployed in Mauritius. For some of the systems, this entailed ensuring that algorithms for converting GPS geometric height to geopotential height used the correct value of “g” for Mauritius.

Intercomparison procedures and early results were reviewed towards the end of the first week by all the participants. The team leaders agreed that intercomparison procedures were satisfactory.

5.3 Reprocessing of submitted data

Some other data problems were not recognized until near the end of the trial and this required some rework of the observations after the final flight. Namely:

- Sippican multi-thermistor daytime flights were re-calculated, because of errors in the original processing software supplied, see section 9.
- Vaisala reprocessed daytime temperature measurements using a different filter to process reported data from raw data. This was requested by Vaisala because the temperature perturbations from the sensor protective support in daytime were larger in the test flights than is usually experienced in single radiosonde ascents, see section 9.
- Meisei recomputed temperatures because incorrect corrections [the result of incorrect local time in the computer] had been applied to nighttime measurements during the intercomparison, see section 9.
- Meteolabor reprocessed geopotential heights because of errors in the height computation software, see section 7.
- MODEM reprocessed geopotential height computations since an incorrect value of local g had been used for the geometric height to geopotential conversion, see section 7.

In all cases, original data had been submitted and were retained in the intercomparison database. Those responsible for reprocessing had no access to the observations from other systems. The chairman of the IOC supervised the rework.

5.4 Principles of data editing

Data from the database were edited by the Chairman of the IOC before the statistics were processed. Editing is the process of hiding measurements in the database, where the origin of the error is understood and not relevant to the aims of the intercomparison. Thus, if for one radiosonde type there is one 1 s temperature sample with a difference of 10 K compared to a high quality reference and all the other 6000 differences are within 0.3 K, the 10 K difference will be hidden as it clearly does not represent the typical performance from the radiosonde that the intercomparison is trying to identify. In another case, the smoothing applied by the Meisei GPS height computation fitted to the data obtained after balloon burst so that substantial height errors occurred near balloon burst in many flights. The smoothing was applied after balloon burst since Meisei had been using a moving average on height in every +/- 30 second. These were hidden, because balloon burst occurred at a variety of heights throughout the intercomparison and so corrupted the impression of the Meisei height measurement accuracy away from balloon burst. This problem with the height estimation will be recorded in section 7. The systematic bias and random errors in height measurement for Meisei in section 7 are relevant to normal performance at a height and not the occasions when the balloon was about to burst

For most radiosonde types, data reception was very good and there was no need to eliminate outliers. For all data types, the RSKOMP software has a histogram display function, so that the user can look at the distribution of the individual errors and identify where the anomalies are occurring. Thus, the reader can assume that in the following result plots standard deviations are computed for difference distributions with minimal or no significant outliers. Standard deviations are computed by two different methods in Kurnosenko software. In the first, all the difference samples within the chosen band (whether delineated by height or pressure) for all the relevant flights (e.g. all night or all day flights) are used to calculate the standard deviation. In the second method, an average difference for the height band chosen is computed for each individual flight in the category, and then the standard deviation of these differences is computed, this is termed flight by flight standard deviation in RSKOMP output. The two values will be the same if the standard deviation is primarily caused by difference in sensor performance flight to flight. If the random errors in the individual comparison samples within a given test flight are larger than those found in flight-to-flight, then the flight-by-flight standard deviations will be smaller than the basic standard deviation. In most of the results processed here, the two methods of computing the standard deviation of the differences give very similar results, i.e. the differences in sensor performance are primarily flight by flight. However, with GPS winds, flight by flight standard deviations are generally much smaller. Thus, random differences in the detailed structure within a test flight were larger than the averaged differences flight to flight, see section 6.

5.5 Data editing of working reference measurements

Editing was mostly required by the two “working reference” sensing systems. Snow White had various identifiable failure modes:

- High instability in dewpoint measurement at middle and upper levels in some flights. This is readily identified by the very large fluctuations relative to the other relative humidity sensors. This can occur in some flights because of water contamination of from disturbance of the sensor control electronics.
- Contamination in the daytime Snow White design, with the sensor mounted in a duct. The contamination probably builds up on some of the cold surfaces near the sensor where ventilation may be poor. This contamination resulted in dewpoints that were much too high compared to the values established by scientific experiments in the tropics. These dewpoint values would be derived from other measurement techniques e.g. using cryogenically cooled hygrometers flown on balloons or limb sounding observations from satellites. In the nighttime Snow White design the chilled mirror is exposed directly in the atmosphere, and this contamination problem is not so common. Snow White dewpoints in the tropical lower stratosphere may then be close to those expected from scientific studies. In a “daytime” Snow White sensor type, where the chilled mirror sensor is in an internal duct the positive bias from contamination seems to start at temperatures between -50 and -60 °C. If daytime and nighttime Snow Whites are flown together at night the daytime sensor measurements will start to show significant positive bias (+10 per cent relative humidity) relative to the nighttime sensor measurements at the temperatures indicated. Thus, it is unwise to conclude that when a Snow White with the internal chilled mirror mounting is indicating values higher than other radiosonde sensors in cirrus that the Snow White is entirely correct. In this report, because of the wet conditions at low levels in Mauritius, contamination problems were worse than normal with Snow White and there are very few reported daytime Snow White measurements at temperatures lower than -50 °C visible in the final database.
- Loss of the water film on the chilled mirror in very dry layers. This occurs quite often in very dry layers in the lower troposphere. When the film on the mirror disappears the Peltier cooler drives the mirror temperature down to an unreasonably low value.

There was also at least one case near the tropopause in Mauritius, when the Snow White mirror temperature dropped much too quickly to be a realistic response to a change in the atmosphere.

Most of the current Snow White failure modes can be most easily identified when the system is flown together with other good quality radiosondes. Thus, until these failure modes can be eradicated it is unwise to use Snow White as a stand-alone reference system

Similarly the Sippican multi-thermistor radiosondes had several identifiable failure modes:

- Sensors connected into wrong positions on the radiosonde. This occurred on several radiosondes, with the black sensor clearly not in the correct position.
- All the sensors coated with ice during an ascent. In this case all the sensors behaved as if they were black giving large infrared cooling relative to the standard radiosondes.
- Calibration of all channels drifts with time to values higher than are reasonable, i.e. much higher than the Vaisala RS92 raw data.
- Calibration of individual sensor is incorrect, e.g. one aluminized sensor reading 1 K higher than the others, or similarly the White and aluminized sensors differing by 1K in the lower stratosphere in daytime. This can be checked to some extent by comparing the output of the thermistors on the ground before launch.

This latter error may be corrected to some extent because of the redundancy in the multi-thermistor sensing system. About 30 per cent of the Sippican multi-thermistor radiosondes originally flown in Mauritius were rejected for one of the reasons noted above.

5.6 Data editing of temperature and humidity errors caused by wet conditions

When a temperature sensor becomes wet in passing through a cloud, the sensor is cooled on emerging into a drier layer above the cloud by the water evaporating. The Vaisala sensor was least sensitive to this problem, see Fig. 5.1

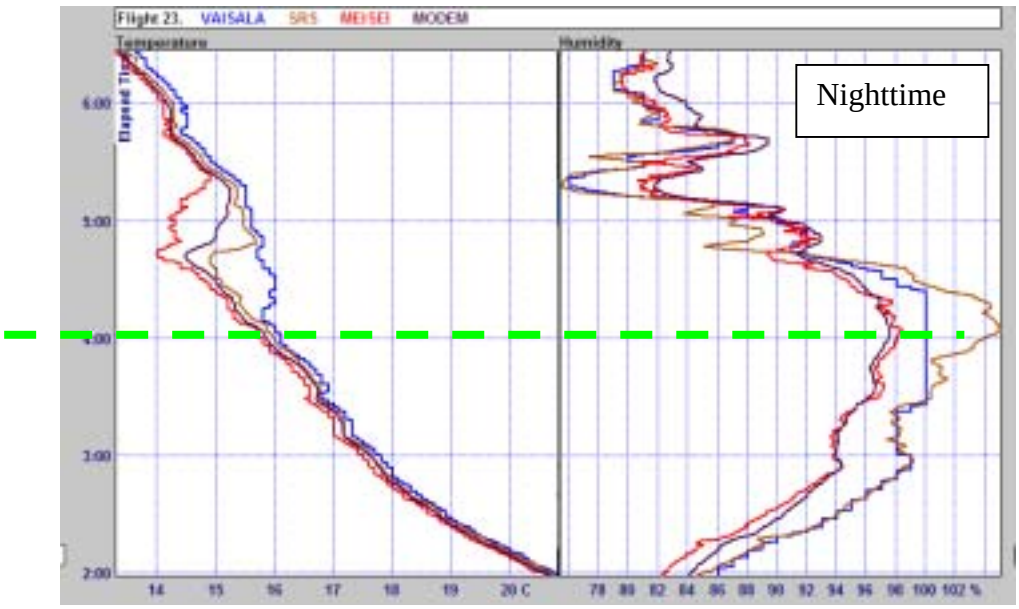


Fig. 5.1 Detailed second-by-second intercomparison of radiosonde temperature and relative humidity from Flight 23 in the Mauritius intercomparison. The temperatures differ above the cloud top (green dashed line) due to evaporative cooling of temperature sensors wetted in cloud.

The temperature measurements in the layers where the wetting error happened were hidden and not used in the statistics in section 9. This follows the practice established in earlier WMO Radiosonde Intercomparisons. The systematic bias values presented in section 9 are then the values expected in dry conditions. In wet conditions, each of the sensors affected will read lower to some extent than the values shown in section 9. In the current intercomparison, the main effect would be to increase the random errors in temperature associated with a radiosonde type from less than 0.2 K to about 1 K. This would only occur below heights of about 7 km.

Similarly the relative humidity measurements in the region above the cloud where water vapour contamination has influenced the humidity measurements were also hidden, here for about 40 s after emerging from the cloud top.

Even though the Vaisala humidity sensors are heated to drive off contamination, the delay before the contamination is removed after emerging from the cloud depends on the delay before the radiosonde switches to the sensor that has been decontaminated.

5.7 References for results of statistical processing

Statistical processing was based on the WSTAT program supplied by S. Kurnosenko. This software has a wide range of options for data processing, so that vertical resolution of the statistics can be selected as required by the operator.

The statistical results for all meteorological variables were always processed initially using Vaisala as the link radiosonde. Subsequently, the absolute value of the systematic bias for each system was adjusted to a value referenced to the averaged performance of all those radiosonde types that did not have large systematic errors from an identifiable error source. Vaisala measurements were of good quality, but it should not be assumed without other evidence that in every situation the Vaisala measurements were the most reliable.

The details of the resulting arbitrary references are given in the sections where the meteorological measurements are compared, sections 7 to 10.

5.8 Estimating random errors using the standard deviations of the differences between two radiosonde types

The standard deviations of the differences between the other radiosonde types and Vaisala were computed using WSTAT. The standard deviations have been used in sections 6 to 10 to estimate the probable random error in the radiosonde measurements as a function of height.

For instance, the estimates of random error in u and v wind component measurements in Fig. 6.3 were derived from the standard deviations of the differences between measurements by the different systems on the assumption that the errors were not correlated between the different systems.

Then, $\{\text{Standard deviation (differences of type1 – Vaisala)}\}^2 = \varepsilon_1^2 + \varepsilon_{Vais}^2$

where ε_1 and ε_{Vais} are the random errors for the measurements of type 1 and Vaisala respectively.

The choice of the value of ε_{Vais} for the computation is largely arbitrary, with the values normally chosen so the values of ε_1 and ε_{Vais} were similar for the radiosonde type that agreed most closely with Vaisala. Thus, in the plots of estimated random error , such as Fig. 6.3, the radiosonde types with largest errors are usually clearly identified, but it is not possible to discriminate between the measurement accuracy of the best radiosonde measurements .

The random error values of the better radiosonde measurements indicate a typical error value for these radiosondes, but the plots do not identify which was the best radiosonde measurement during the test.

6. SIMULTANEOUS WIND COMPONENT INTERCOMPARISONS

6.1 Data availability

Wind data availability from Vaisala radiosondes that functioned correctly on launch was 98 per cent. Graw, Modem, Sippican showed similar availability to Vaisala. Meisei measurements had similar availability to Vaisala in the troposphere and lower stratosphere, but some amounts of Meisei data were lost above 27 km, when problems with the batteries on the slower flights led to data drop out. Most of the radiosonde types had two or three intercomparison flights where a radiosonde was faulty. Either they did not function on launch or failed to pass the preflight checks, with the radiosonde missed from the scheduled test flight.

There were no flights where there were long gaps in the wind measurements, so that the data loss noted is not expected to cause significant problems for radiosonde operations.

6.2 Examples of intercomparisons from individual flights

In this section the relative performance of the GPS wind measurements is compared in terms of orthogonal wind components, since the error estimates obtained are not directly dependent on the strength of the winds, whereas the errors in wind direction are strongly dependent on wind speed at low wind speed.

Fig. 6.1(a) and (b) show plots of north-south and east-west wind components from Meisei, Modem and Vaisala GPS radiosondes taken from the intercomparison data base. The data are plotted as a function of time into flight. Fig. 6.1(a) is from an intercomparison flight with relatively strong low-level winds when a tropical storm was passing around Mauritius. Fig. 6.1(b) was sampled towards the end of a flight where the winds were strong in the stratosphere near 8 hPa.

Fig. 6.2(a) and (b) show the equivalent plots to Fig. 6.1 for the Graw, Sippican and Vaisala comparison group.

The main differences between the wind measurements of the different systems were related to the filtering used. In particular, on an individual radiosonde ascent a filter is often deigned to eliminate the pendulum motion of the radiosondes underneath the balloon. The motion of the radiosondes on the bamboo cross used in Mauritius is different from that on the individual ascent, so some manufacturers switched the pendulum filtering off, whilst others did not modify their filtering.

- Meisei and Vaisala did not change the filtering of GPS winds.
- Graw, Modem and Sippican were not using pendulum filtering.

Fig. 6.1(a) Example of comparison between N-S and E-W wind components from Flight 28, showing the difference in filtering between MODEM, Vaisala and Meisei winds. Meisei winds were smoothed to the greatest extent and MODEM winds smoothed the least.

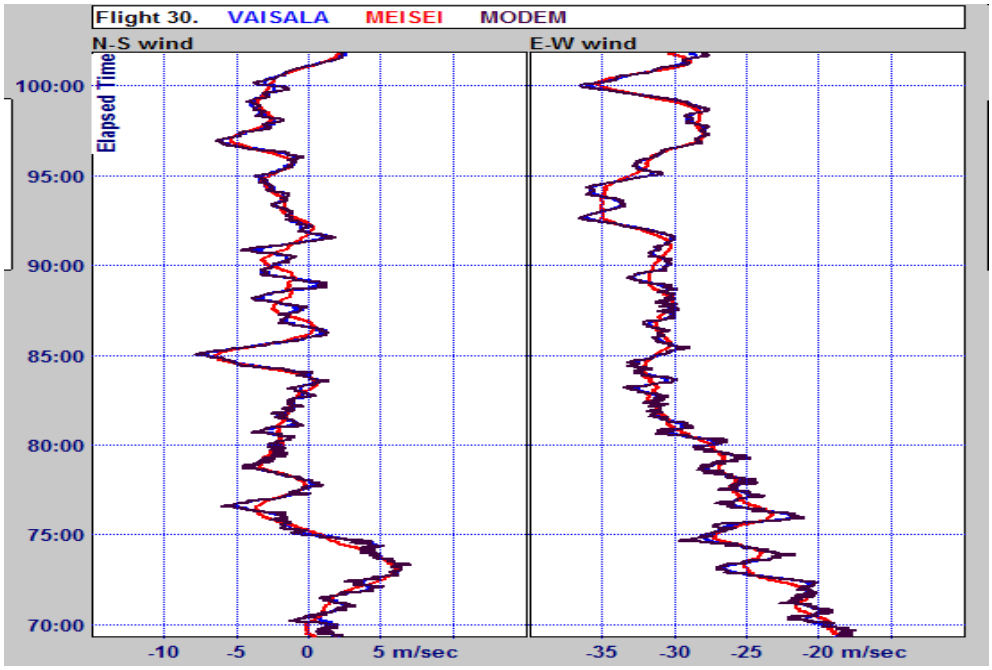


Fig. 6.1(b) GPS Wind component comparison towards the end of a flight with easterly winds strongest at minute 93, pressures near 8 hPa.

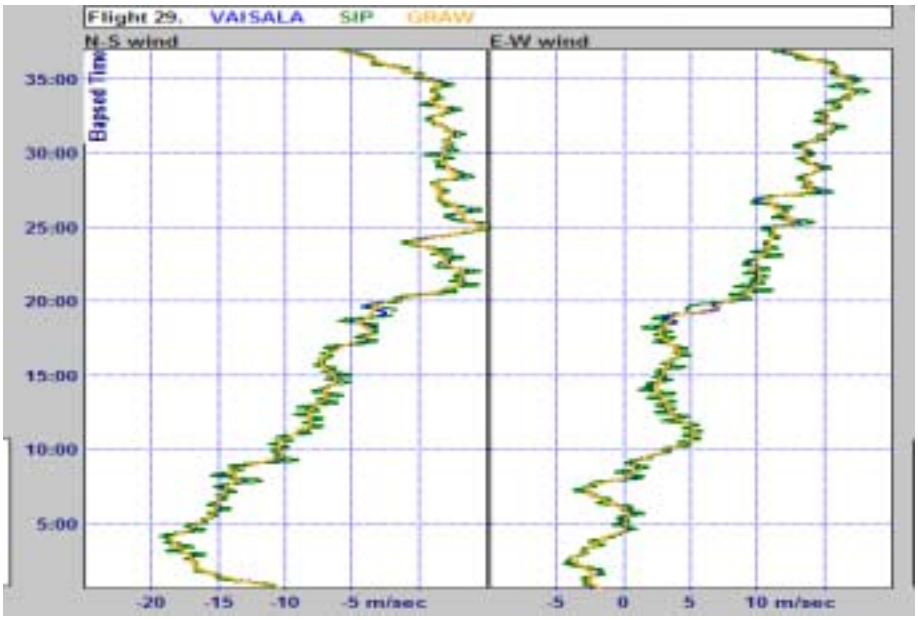


Fig. 6.2(a) Example of comparison between N-S and E-W wind components from Flight 29, showing the difference in filtering between Sippican, Graw and Vaisala winds. Graw winds were smoothed to the greatest extent and the smoothing of Vaisala and Sippican GPS winds was similar.

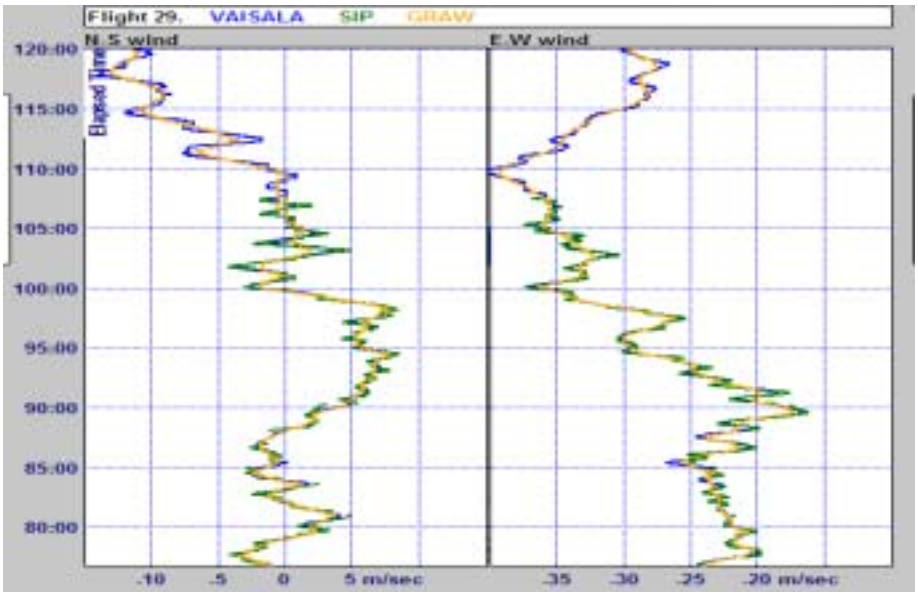


Fig. 6.2(b) GPS Wind component comparison towards the end of a flight with easterly winds strongest at minute 110, pressures near 8 hPa.

6.3 Results of statistical processing

The WSTAT statistical package was used to compute the standard deviations of the wind components differences of Vaisala with Graw, Meisei, Modem and Sippican respectively. Here, Vaisala was chosen as the working link radiosonde since it was present on most test flights. It should not be assumed that it has the most accurate measurements,

although the Vaisala measurements were clearly of high quality. For convenience of presentation, a height resolution of 2 km was used for each height category when processing the statistics. The number of difference samples in each category was usually between 6000 and 10000.

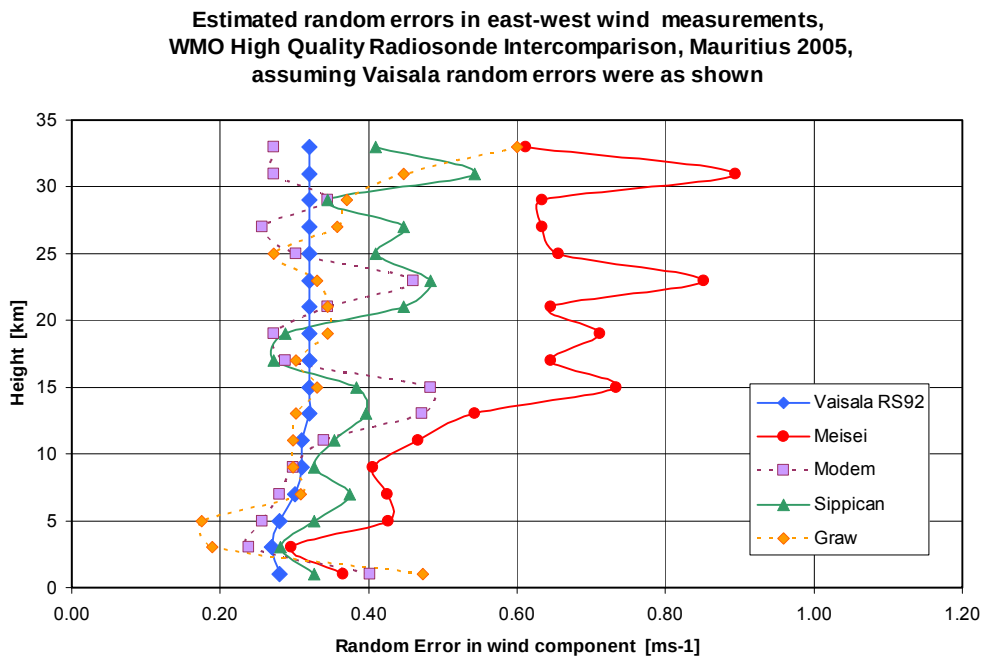


Fig. 6.3. (a) Estimates of random error in east-west wind components derived from the standard deviations of the differences between pairs of radiosonde types. Errors are apportioned equally between the better quality measurements.

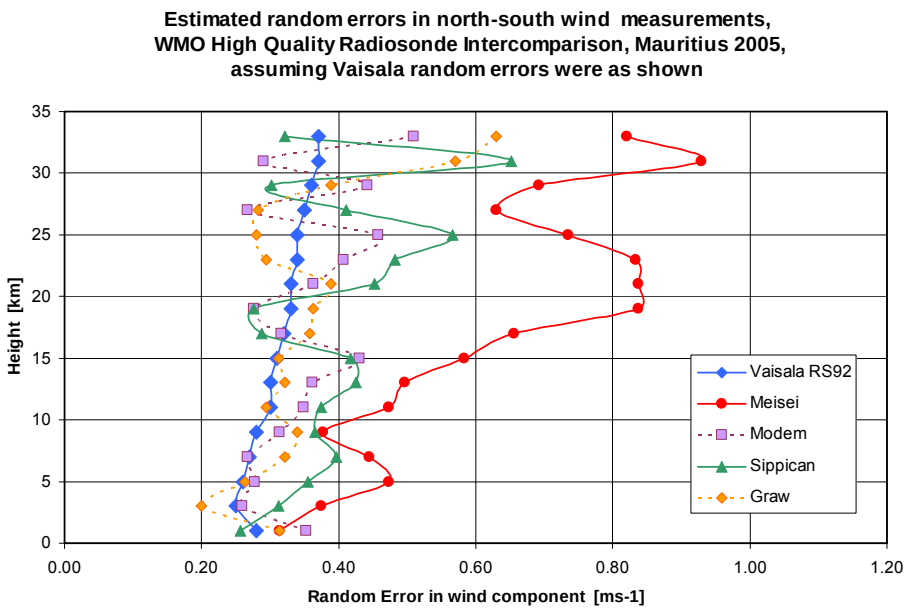


Fig. 6.3 (b) Estimates of random error in north-south wind components derived from the standard deviations of the differences between pairs of radiosonde types. Errors are apportioned equally between the better quality measurements.

Systematic bias between the wind component measurements from the different radiosonde types was only larger than 0.1 ms^{-1} for Meisei winds at a few heights in the stratosphere. Thus systematic bias was very much smaller than the estimated random errors of the u and v wind components in Figs. 6.3 (a) and (b). These estimates of the random errors in the wind components were computed assuming that the random errors in the two wind finding systems compared were unrelated. Typical random errors in wind component [u, v] measurements for GPS radiosondes were most probably between 0.2 and 0.4 ms^{-1} (1 s.d.) in the troposphere and 0.3 to 0.5 ms^{-1} (1 s.d.) in the stratosphere.

The exceptions were Meisei wind measurements in the stratosphere where random errors were probably in the range 0.7 to 0.8 ms^{-1} (1 s.d.). Investigations during the test showed that the raw GPS tracking data of each Meisei radiosonde was similar to the Modem and Vaisala tracking. The differences found with Meisei measurements came from the filtering method used by Meisei, as specified by the Japan Meteorological Agency. Meisei suggested that recommendations should be made on the filters most suitable for GPS wind processing.

The wind measurement accuracy achieved in Mauritius was clearly suitable for operational network users, who usually request wind component measurement accuracy in the range 0.5 to 2 ms^{-1} (1.s.d.). This accuracy was achieved with systems that were installed and in operation within 24 hours.

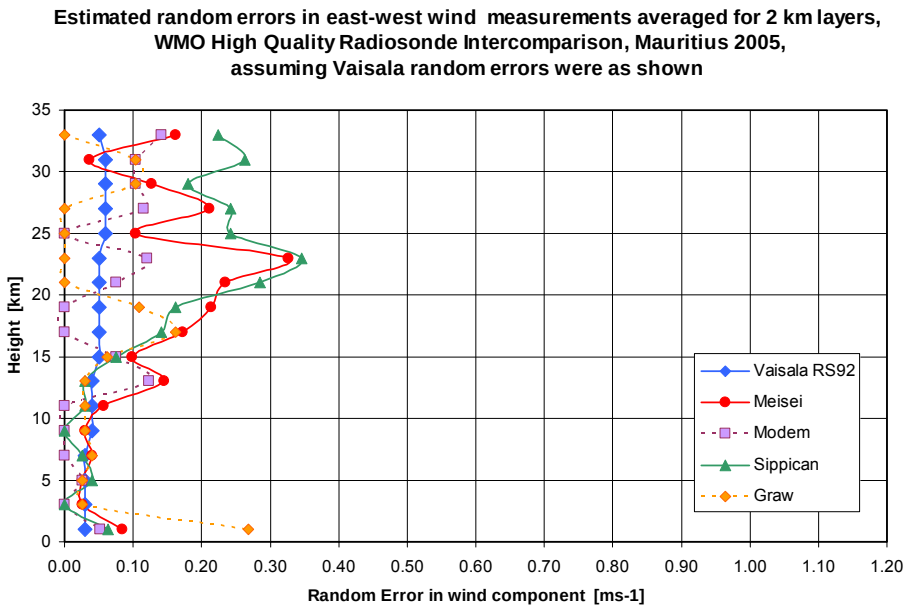


Fig. 6.4. (a) Estimates of random error in 2 Km layer averages east-west wind components derived from the standard deviations of the differences between pairs of radiosonde types. Errors are apportioned equally between the better quality measurements.

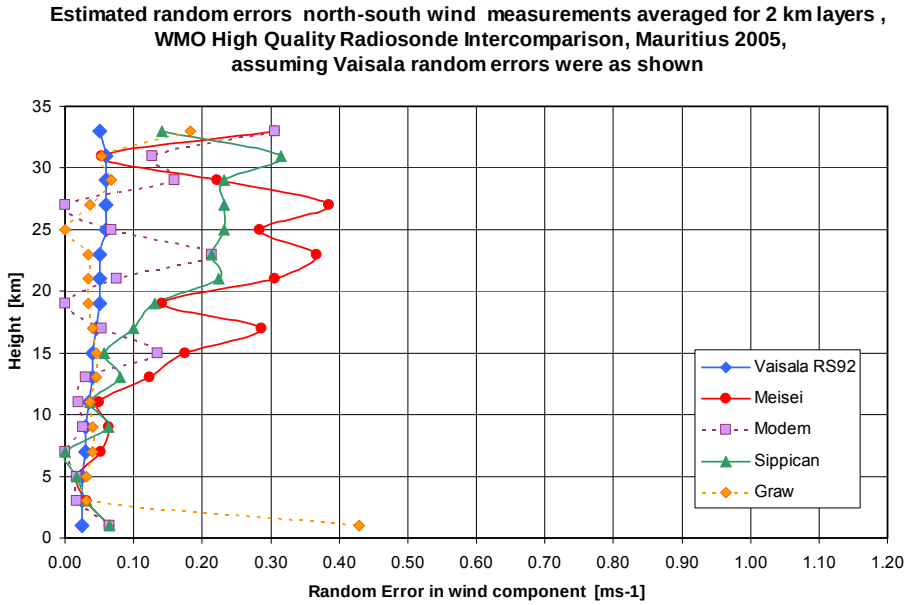


Fig. 6.4.(b) Estimates of random error in 2 Km layer averages north-south wind components derived from the standard deviations of the differences between pairs of radiosonde types. Errors are apportioned equally between the better quality measurements.

When the wind measurements were considered in terms of layer averages over 2 km in the vertical, the estimates of random errors were very much smaller than in Fig. 6.3, see Fig. 6.4 (a) and (b). Typical random errors in 2 km layer averages for wind component [u,v] measurements for GPS radiosondes were most probably close to 0.05 ms^{-1}(1 s.d.) in the troposphere and for the better GPS radiosondes better than 0.1 ms^{-1}(1 s.d.) in the stratosphere. The very good reproducibility of layer averages of wind demonstrates that GPS wind finding systems are well suited for climatological network operations.

Thus, it is concluded that the new generation of GPS radiosondes should be capable of very accurate wind measurements in tropical locations, with missing data normally 5 per cent or less. This will be true even when there are strong upper winds as were seen in Mauritius with wind speed often higher than 40 ms^{-1} at heights above 30 km.

7. SIMULTANEOUS GEOPOTENTIAL HEIGHT MEASUREMENTS

The simultaneous height intercomparisons demonstrated that GPS height measurements gave geopotential heights that were more accurate than the best pressure sensors at all heights above 16 km and were of similar accuracy to pressure sensor measurements at heights below 16 km.

Figs. 7.1(a) and 7.1(b) show typical examples of simultaneous height differences plotted as a function of time into flight from both groups of radiosondes.

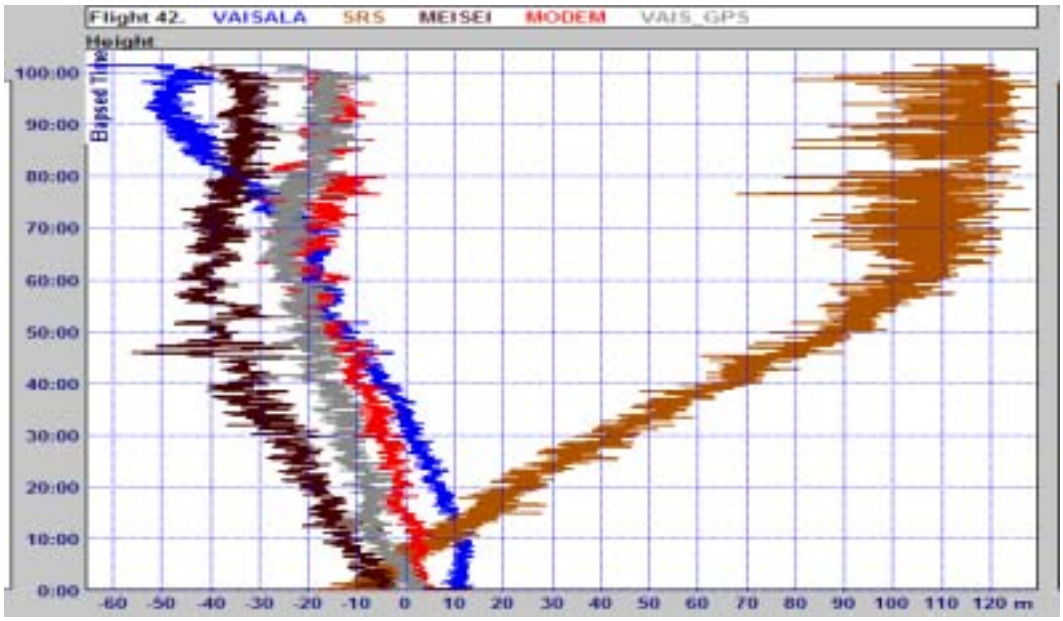


Fig. 7.1(a) Example of differences between simultaneous height measurements from the Meisei-Modem-Vaisala group, as a function of time into flight. The zero difference at each heights the average of all the measurements. Vaisala and SRS were derived from pressure sensor measurements, the Meisei, Modem and Vaisala GPS from GPS height measurements.

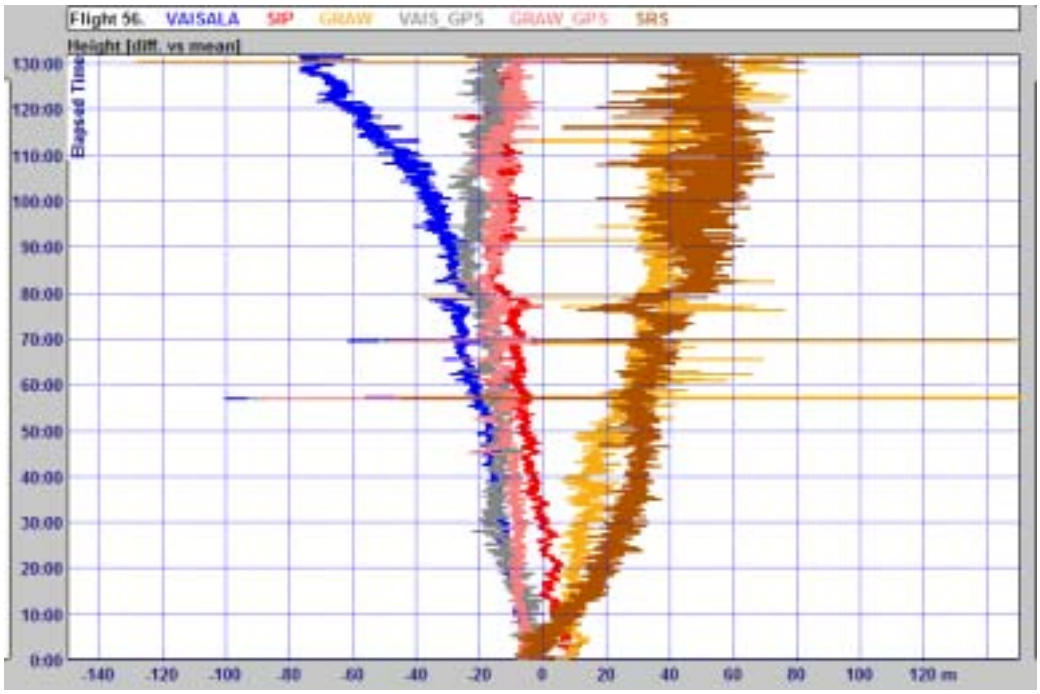


Fig. 7.1(b) Example of differences between simultaneous height measurements from the Graw-Sippican-Vaisala group, as a function of time into flight. The zero difference on this plot is the average of all the measurements. Graw, Vaisala and SRS were derived from pressure sensor measurements, Sippican, Graw GPS, Vaisala GPS were from GPS height measurements.

In section 5 it was noted that because the Meisei GPS height software is smoothed for 2 minutes, the heights in the last minute before balloon burst fit to tracking data from descent, so the maximum height reached by the balloon is underestimated. For instance, in Flight 9,, see Fig. 7.2, the maximum height was at least 1 km too low. All the Meisei height measurements in the last minute of the flight had to be hidden. The smoothing was applied after balloon burst because Meisei had been using a moving average on height of +/- 30 second.

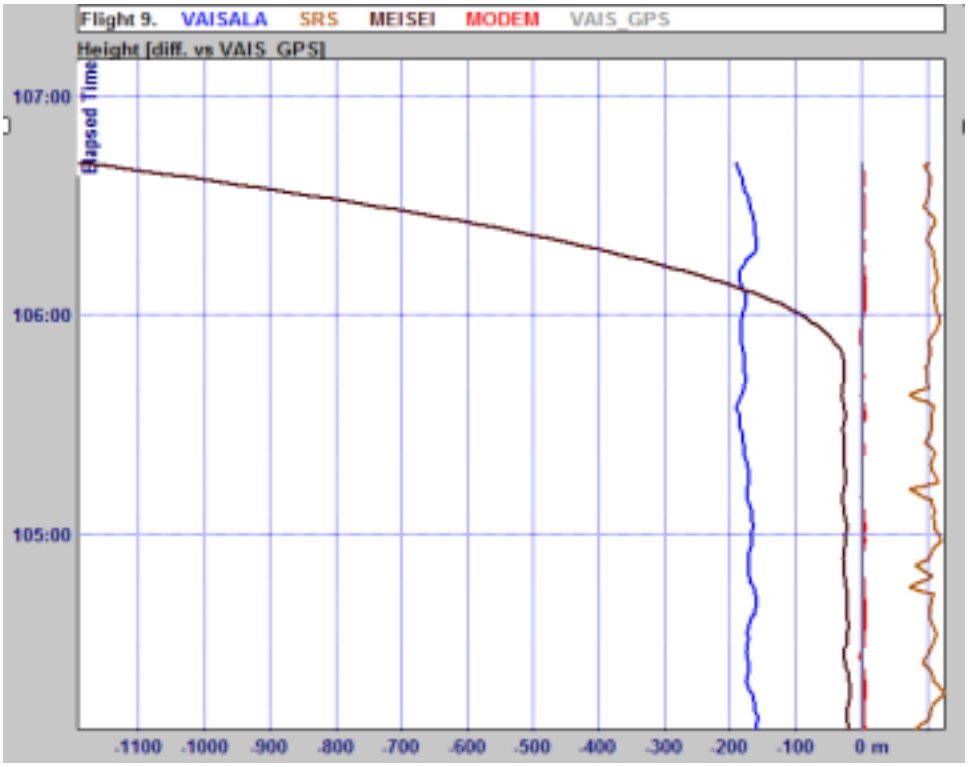


Fig. 7.2 Typical Meisei geopotential height error in the minute preceding balloon burst. These errors were hidden when using the WSTAT processing package

The RSKOMP statistical package was used to compute the direct differences between all the measurements and Vaisala GPS (since Vaisala GPS was available on most flights) for height categories at 2 km resolution. The systematic bias of all the geopotential heights was then presented relative to the average of the GPS height measurements as shown in Fig. 7.3.

All the GPS height measurements agreed on average to within ± 20 m from the surface to 34 km. At 30 km pressure sensors were in error by values between -70m (Vaisala) up to +120m (SRS). The pressure sensors considered here were of extremely good quality compared to earlier generations of sensors, but were unable to provide very reliable heights at pressures lower than 10 hPa.

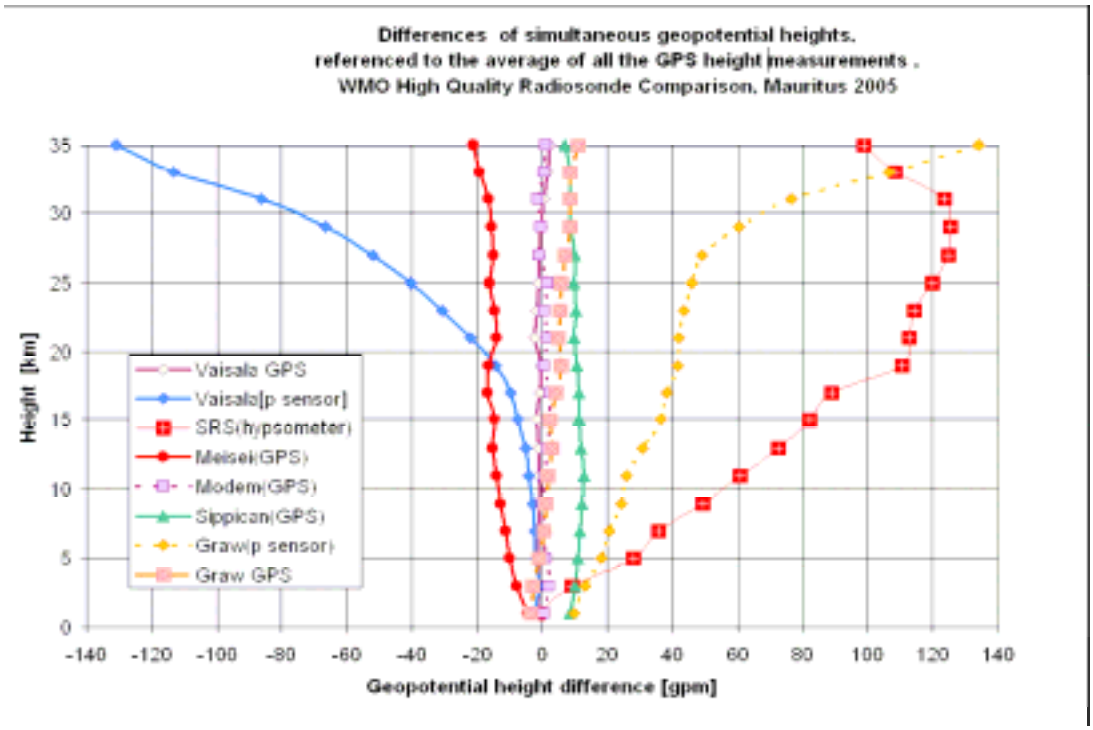


Fig. 7.3 Systematic difference between geopotential height measurements (gpm), Vaisala, SRS and Graw heights derived from high quality pressure sensors.

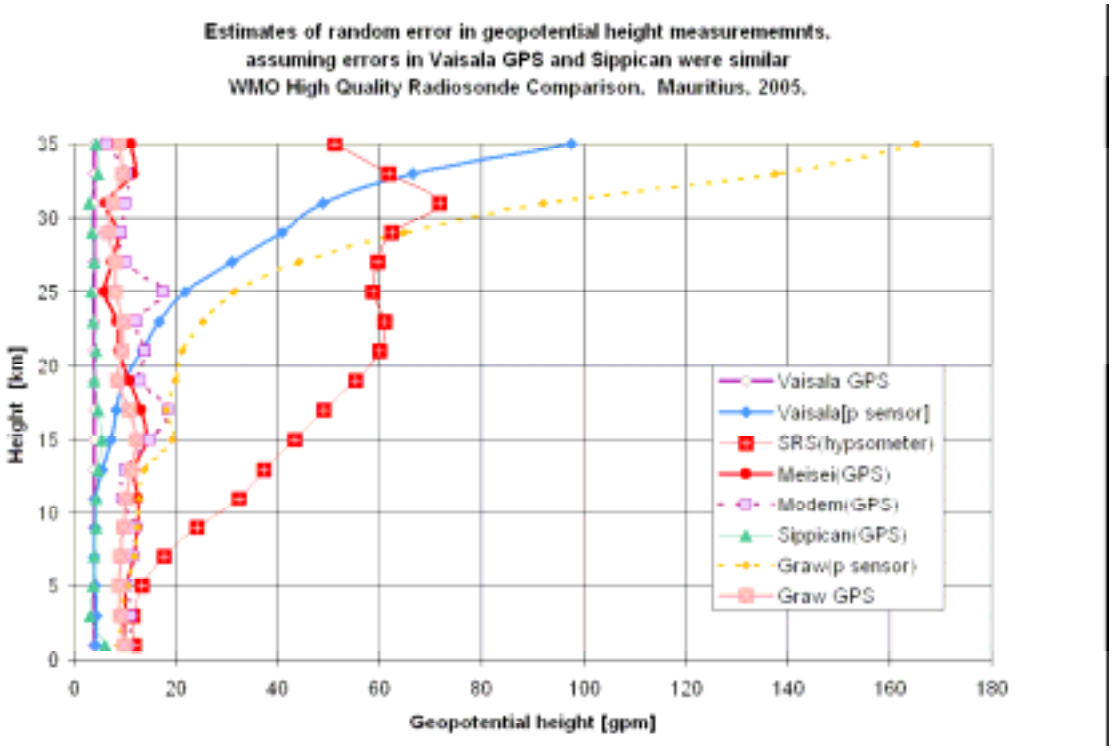


Fig. 7.4 Estimates of random error in geopotential height measurements (gpm). Vaisala, SRS and Graw heights were derived from high quality pressure sensors, Meisei, Modem, Sippican, Graw GPS and Vaisala GPS from GPS height measurements

Fig. 7.4 contains estimates of the random error (1 s.d.) in geopotential height measurements, assuming that the errors in the individual radiosonde height measurements were uncorrelated. The best GPS systems had random errors in height measurements of around 4m or better, with the random errors in the worst GPS height systems still better than 15 m at most heights. Thus, GPS heights are suitable to replace geopotential from pressure sensors at all heights, i.e. a pressure sensor is no longer a necessity for a best quality radiosonde. The reproducibility of the GPS geopotential heights at 32 km was an order of magnitude better than the reproducibility of the heights from the best pressure sensors. Thus, temperature errors caused by height errors in radiosonde output will become very small with the new GPS height measurements, even at pressures lower than 5 hPa.

The good agreement in GPS geopotential heights shown in Fig. 7.1 and Fig. 7.3 was only obtained once errors were eliminated from the conversion of GPS geometric height to geopotential height in several radiosonde types. It is essential to perform this conversion with the appropriate gravitational constant for the geographic location of the radiosonde launch site. The necessary software for this conversion needs to be an inherent part of GPS radiosonde systems in future.

8. SIMULTANEOUS PRESSURE MEASUREMENT INTERCOMPARISON

In comparing simultaneous pressure values from the various radiosonde systems, some will be the results of direct sensor measurements (Graw, SRS and Vaisala) and some will be the results of computation from the geopotential height derived from the GPS geometric height (Meisei, Modem and Sippican). The computation from the geometric height uses the temperature and relative humidity measurements from the radiosonde and is similar in principle to that used for Russian radiosonde measurements (see the CIMO Guide) where height measurements come from secondary radar.

The average pressure differences (systematic bias) were computed relative to Vaisala (since these measurements were available on most flights). The RSKOMP statistical package was used with a resolution of 2 km for the height categories. The reference for the differences was then changed. In the layer immediately above the surface, the reference value chosen was the average of the pressure values that fitted correctly down to the surface value at Vacoas, i.e. Modem GPS and Vaisala p sensor. At heights above 8 km the average of the pressure estimates from Meisei, Modem and Sippican was used. The reference between 1 and 8 km was an arbitrary adjustment between the surface and this upper reference. Fig. 8.1 shows the results of this process. In this plot the systematic bias between radiosonde types at any height will always be correct.

Two Modem flights, where water/ice apparently shunted the temperature sensor for part of the flight giving very large negative temperature anomalies, were excluded. Similarly, three Meisei flights with poor temperatures were also excluded. Four out of 34 SRS pressure sensor measurements were also judged atypical (with very large pressure errors in the stratosphere) and excluded, whilst another five did not appear to match to the surface pressure correctly (errors greater than 5 hPa) and were excluded in the lower troposphere but appeared to give reasonable values in the stratosphere.

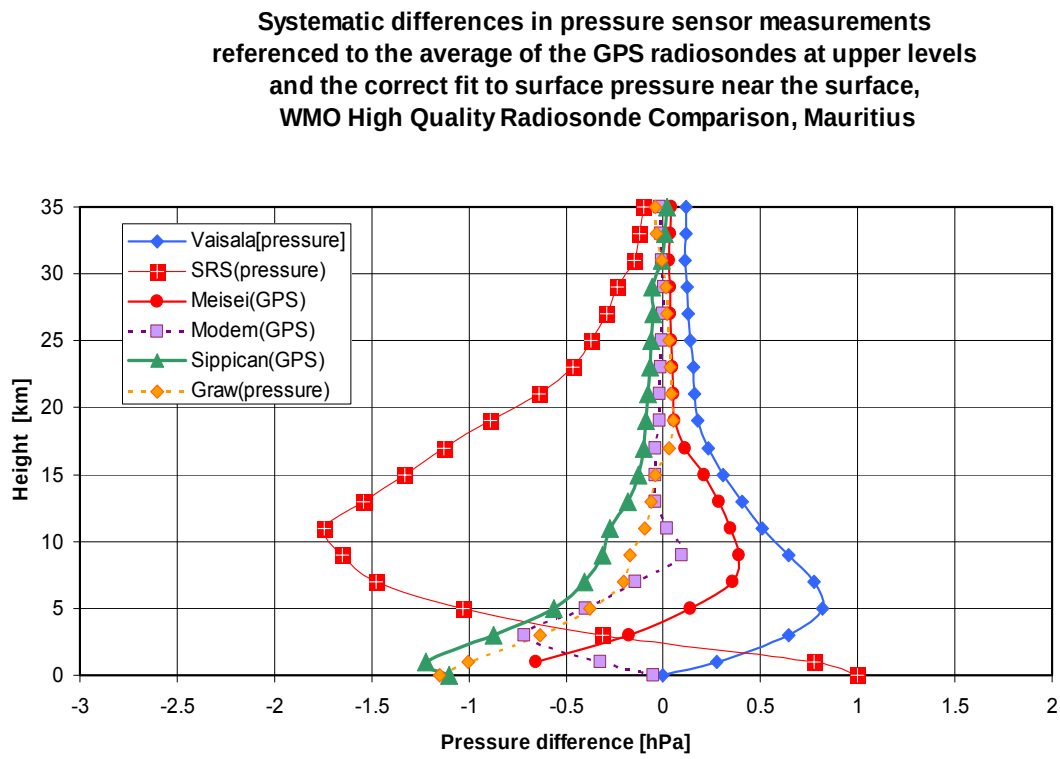


Fig. 8.1 Systematic differences of simultaneous comparisons between radiosonde pressure observations (hPa). Systematic differences of simultaneous comparisons between pressure measurements (hPa) include pressure data just above the surface, but not the actual surface observation. In the layer just above the surface Meisei pressure data are missing. This should have been the value supplied by the Mauritius surface observers and is not a radiosonde measurement.

Near the surface the pressures of Vaisala and Modem were closest to the truth. If a system was not identifying launch time very accurately then the timing adjustment used to synchronies the sampling may have introduced error into the observed pressure. Meisei measurements often had large timing adjustments, and so the Meisei pressure values near the surface have been hidden. On the other hand the systematic bias in Sippican geopotential height near the surface was consistent with a negative pressure error of about 1 hPa, as shown.

The reasons why the pressures near the surface did not match correctly to the surface observations should be investigated by the respective manufacturers and actions taken to rectify the problem if the errors were real and not an artefact of the sample synchronization. One of the problems with testing heights and pressures near the surface is that the Intercomparison test rigs usually accelerate much more slowly after launch than would be the case with an individual radiosonde ascent. Thus, where a manufacturer's software has been developed to interpolate back to the surface for an individual ascent, it may not work so well with the slower acceleration of the test rig. Testing these processes more accurately in future comparisons will require a method of ensuring launch detection is synchronized between all the systems.

Fig. 8.2 contains the estimates of random error in the individual sensors. Here the assumption about the performance of the Vaisala pressure sensor takes into account that the standard deviation of the differences between Modem and Meisei was lower than that of Modem and Vaisala between 8 and 12 km.

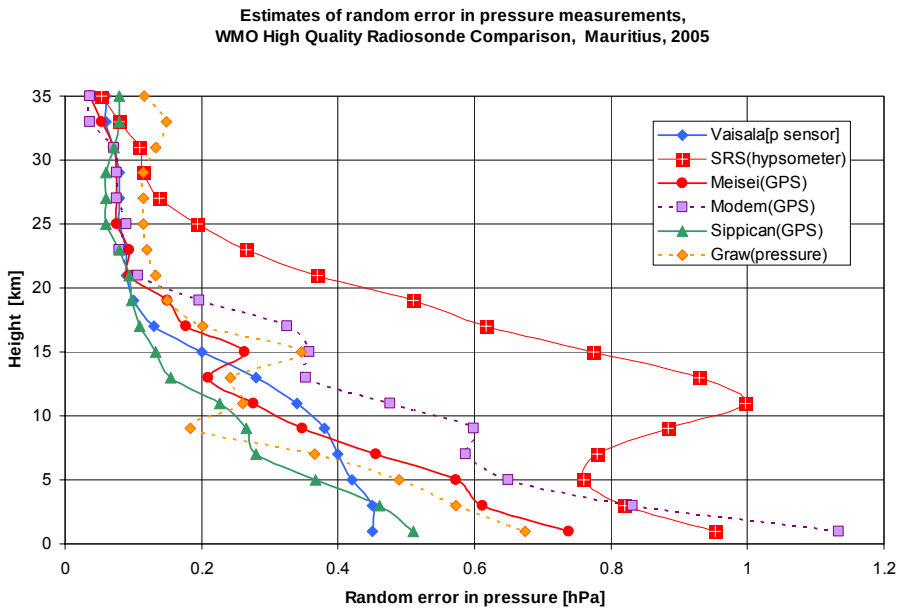


Fig. 8.2 Estimates of random error (1 s.d.) of pressure measurements (hPa). Modem, Meisei and Sippican pressure were derived from GPS height measurements.

From Fig. 8.2 it can be seen that the random error of pressures derived from GPS heights was similar to the random errors in the pressures measured directly.

9. SIMULTANEOUS TEMPERATURE MEASUREMENT INTERCOMPARISON

9.1 Introduction

Temperature sensors used in modern radiosondes are often much smaller than those in use in earlier years. Fig. 9.1 summarizes the seven temperature sensors used in Mauritius. The dates on the sensors in Fig. 9.1 are estimates of when the particular sensors were exposed in the same way as in the Mauritius test (the actual sensor may be a little older than indicated).

The Sippican multi-thermistor radiosonde had five thermistors as shown in Fig. 9.1 and the UK Met Office regulation required the thermistors to be adjusted so that each thermistor was located above the level of the supporting wires and frame as shown.

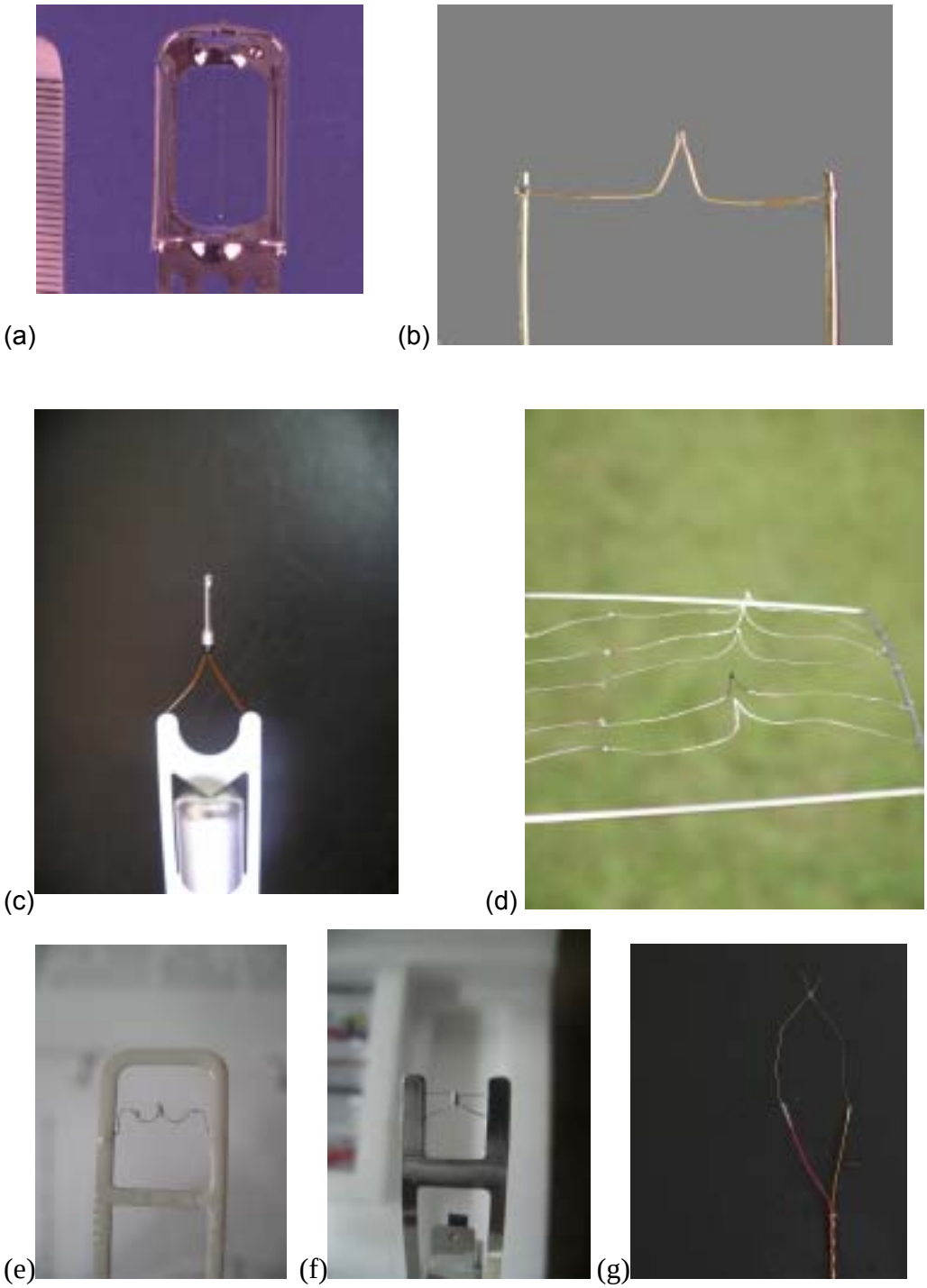


Fig. 9.1 Temperature sensors used in the WMO Intercomparison of High Quality Radiosonde Systems, Mauritius, 2005. (a) Vaisala [2004], (b) LMS chip thermistor [2004], (c) Meisei bead thermistor [1993] (d) Sippican Multi-thermistor [2004], (e) Modem bead thermistor [2001], (f) Graw bead thermistor [2002] (g) SRS thermocouple [1990], 50 µm wires. Pictures not to the same scale

9.2 Temperature intercomparisons at night

9.2.1 Multi-thermistor radiosondes as a reference in individual flights

Fig. 9.2 shows an example of the differences between aluminized, white and black l multi-thermistor sensor measurements as a function of time into flight at night. The aluminized sensor on the multi-thermistor radiosonde stays close to the multi-thermistor solution throughout the flight. The White painted and black painted sensors differ from the aluminized sensor and are cooled down by the infrared radiation fields by varying amounts during the ascent. The change from positive difference to negative difference cantered around minute 28 in Fig. 9.2 is the result of the radiosonde moving from inside an ice cloud into the clearer air above the cloud. Probably the top of the cloud was at about minute 30. Thus, the infrared radiation fields experienced at night can give clues to the presence of cloud during an ascent, so attaching a black sensor to all nighttime test flights would be beneficial in future tropical tests.

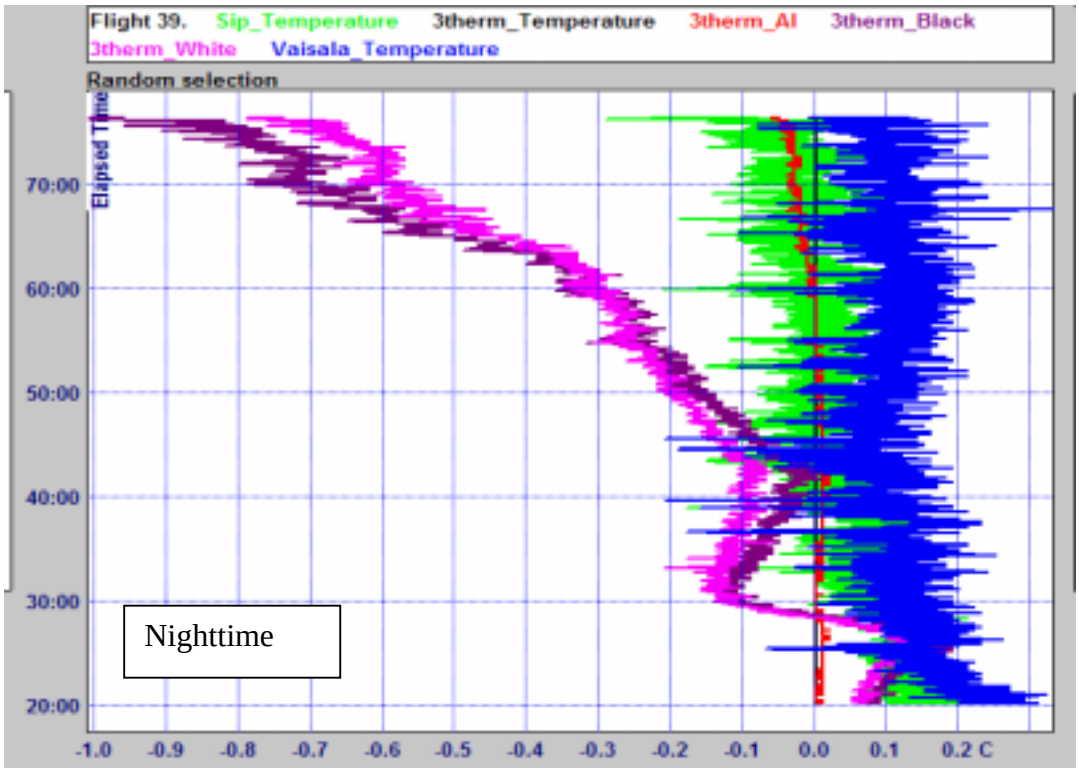


Fig. 9.2 Simultaneous differences between the multi-thermistor estimate, the individual sensors of the multi-thermistor radiosonde, and the Vaisala radiosonde on the same flight. Minute 20 corresponds to a pressure of 300 hPa and minute 75 to a pressure of about 16 hPa. See Fig. 9.10 for an equivalent daytime plot.

Only six multi-thermistor radiosondes were flown at night in Mauritius, partly because there were not enough radiosondes available, but also because there was not enough UK staff to cope with the workload. Six flights with multi-thermistor radiosondes were enough to demonstrate that the chip sensors used in the Sippican multi-thermistor radiosondes were close to expected performance (see Fig. 9.6) but more nighttime multi-thermistor observations would probably have been beneficial in linking the nighttime and daytime data sets together.

Further detailed samples of temperature comparisons against multi-thermistor measurements at night from an individual flight are shown in Fig. 9.3 and Fig. 9.4. Note the good consistency of the temperature differences of Sippican and Vaisala with respect to the

multi-thermistor measurements in Fig. 9.3. The Graw measurements were not so consistent as Sippican and Vaisala. In Fig. 9.4, only Meisei and Vaisala difference were consistent across the data sample. The systematic bias for Modem relative to the multi-thermistor drifted by about 0.2 K and the systematic bias for SRS was 0.4 K in the same data sample.

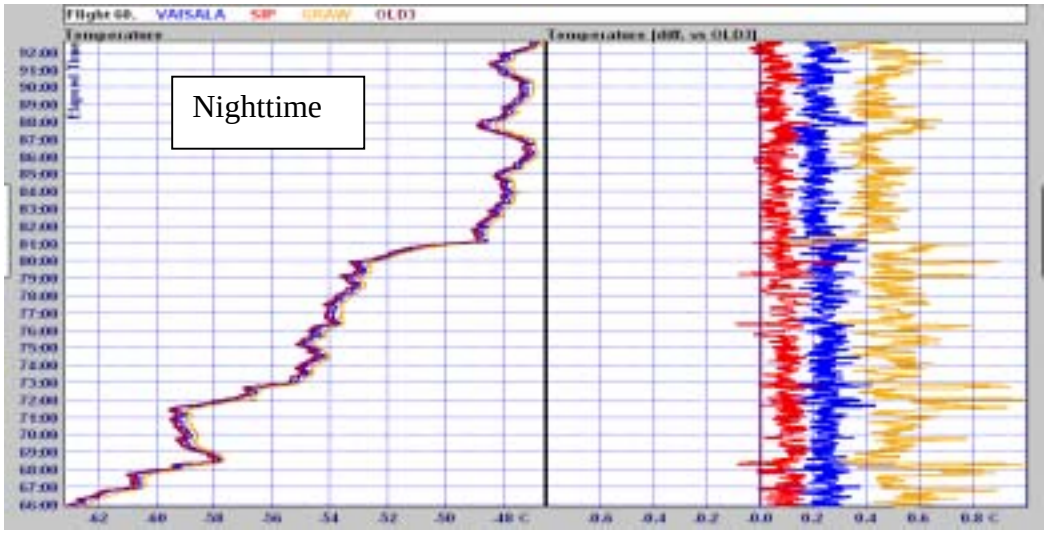


Fig. 9.3 Sample of basic data samples and temperature differences between nighttime temperature measurements from the Graw Sippican Vaisala group compared to a multi-thermistor measurement (here designated OLD3). Minute 66 corresponded to a pressure of about 43 hPa and minute 92 to a pressure of about 13 hPa.

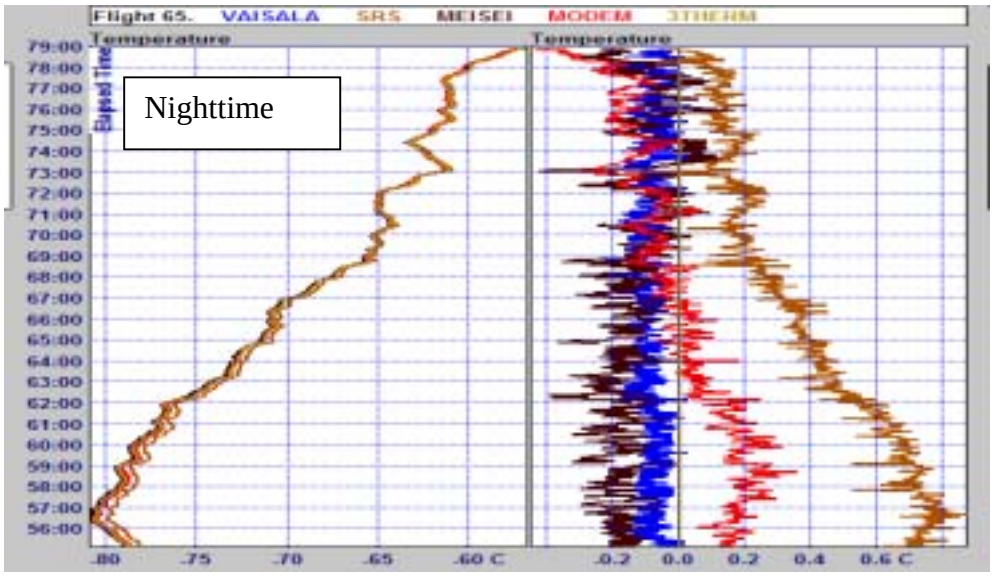


Fig. 9.4 Sample of basic data samples and temperature differences between nighttime temperature measurements from the Meisei Modem Vaisala group compared to a multi-thermistor measurement. Minute 52 corresponded to a pressure of about 105 hPa and minute 79 to a pressure of about 33 hPa. Drifts in SRS temperatures associated with calibration errors in thermocouple sensor, drifts in Modem measurements associated with changes in infrared errors, see section 9.2.2

9.2.2 Results of statistical processing

The WSTAT statistical package was applied to a comparison database where the effects of evaporative cooling of temperature sensors wetted in cloud were hidden, Fig. 5.1 and Fig. 9.5 contain two examples of cooling episodes. Evaporative cooling occurred for limited periods of time in the majority of flights in Mauritius.

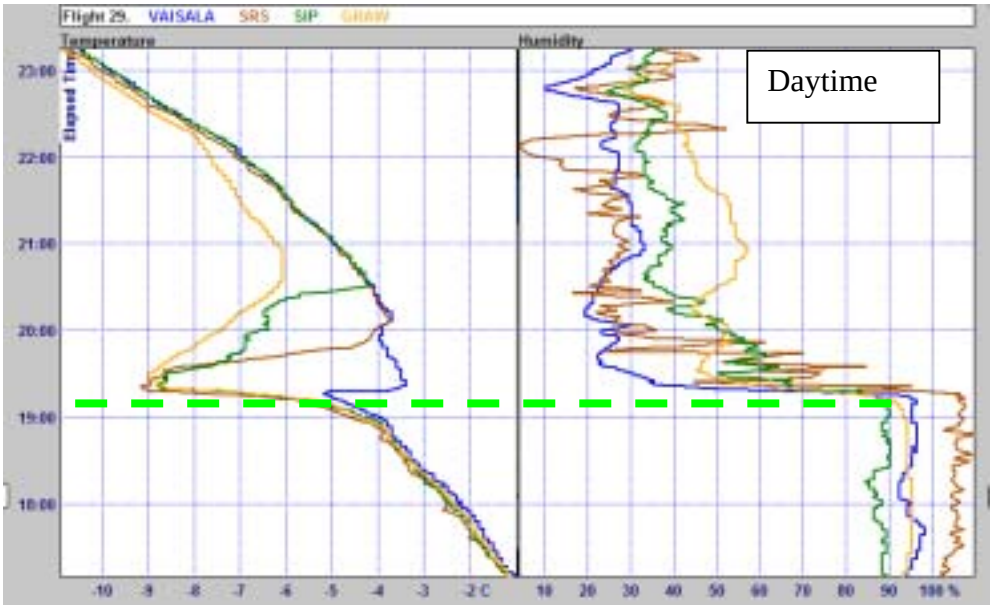


Fig. 9.5 Detailed, second by second, comparison of radiosonde temperature and relative humidity from Flight 29 for Graw-Sippican-Vaisala group, similar to Fig. 5.1 for the Meisei-Modem-Vaisala Group. The temperatures differ above the cloud top, indicated by the green dashed line, because of evaporation of water from the sensors.

The Vaisala sensor had a hydrophobic coating and Vaisala measurements were clearly not affected as badly as the other radiosonde types on emerging from cloud. The heavy rain that occurred from time to time in Mauritius induced faults in certain types of radiosonde, suggesting that some of the radiosonde types had not been thoroughly tested in wet conditions. Radiosonde systems need to be tested for tropical rain conditions and manufacturers should consider whether the application of a hydrophobic coating to the temperature sensor would improve measurement accuracy in these conditions.

The WSTAT statistical package was again used to compute comparisons of all radiosonde types against Vaisala (Vaisala measurements were available on most flights to link temperatures together). Height categories for temperature were again set at a vertical resolution of 2 km. In Fig. 9.6, the systematic bias between the radiosonde temperature measurements is shown, but in this plot the reference has been changed from Vaisala to the average of Meisei, Sippican, Vaisala and SRS-adjusted. SRS-adjusted are values that take into account recent investigations of the SRS thermocouple sensor performance. These were performed after the Mauritius test was completed, when the SRS thermocouple was evaluated against national temperature standards in Switzerland. The drift in temperature of the SRS temperature measurements relative to 3-thermistor in Fig. 9.4 was mainly the result of thermocouple calibration errors at low temperatures.

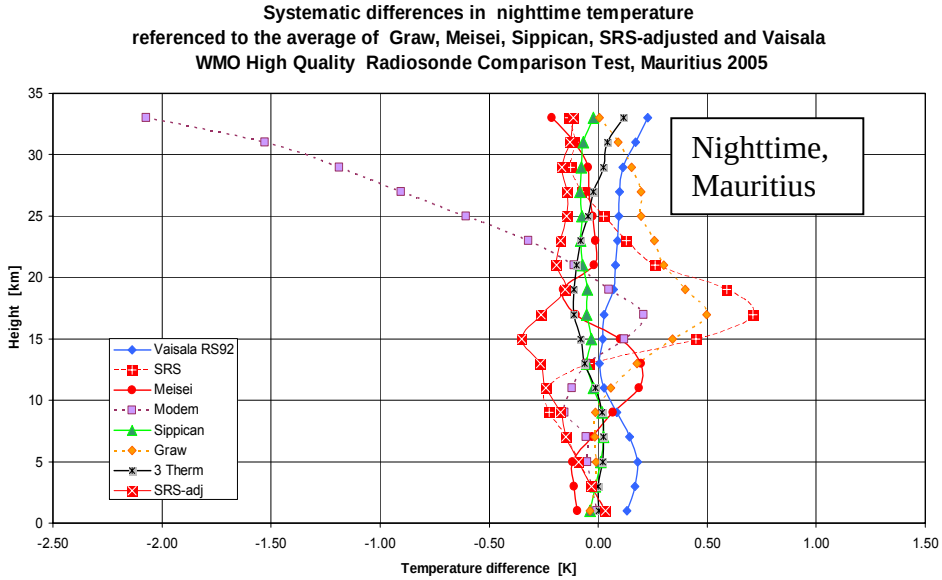


Fig. 9.6 Systematic bias between simultaneous temperatures (K) at night.

In Fig. 9.6, Meisei, Sippican, Sippican 3-thermistor, and Vaisala measurements agreed to within 0.3 K from the surface to 31 km. At the lowest temperatures (-80 deg C) in the upper troposphere, Graw and SRS had errors in effective calibration of the temperature measurements of about +0.5 K. SRS- adjusted values are consistent with height and mainly between -0.2 and -0.3K relative to the reference.

Similarly, data processing and presentation can be applied to the data base of the WMO Intercomparison of GPS Radiosondes in Brazil from 2001 which is now available for general use. The results are shown in Fig. 9.7, where the linking references to Mauritius were SIPP chip and Vaisala RS90.

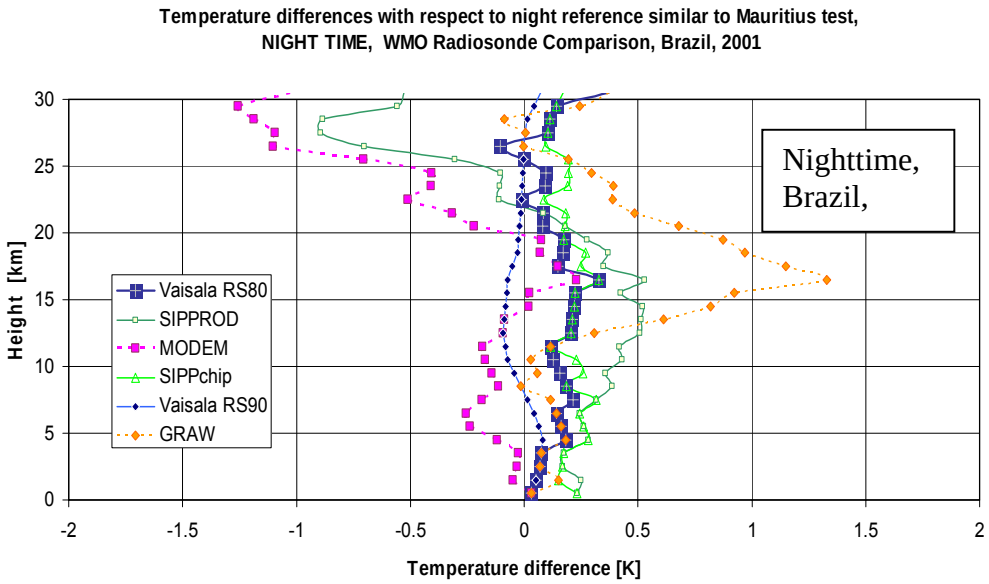


Fig. 9.7 Systematic bias between simultaneous temperatures (K) at night, WMO Intercomparison of GPS Radiosondes, Brazil, 2001.

When comparing the results in Fig. 9.6 and 9.7, the following can be concluded:

- The systematic bias between Sippican/chip and Vaisala RS90/92 reversed sign between the two tests. This may not be surprising, because the Sippican thermistors in Brazil were early versions of the sensor.
- The Graw temperature measurements in Mauritius had very much smaller positive bias in Mauritius than in Brazil. Following the test in Brazil, Graw identified and rectified a temperature dependent problem in the DFM signal channel electronics.
- Modem temperatures showed similar trends with height, with the negative bias at upper levels similar to that observed with the Sippican White rod thermistor. Unfortunately, the origin of this tendency in Modem temperatures was not adequately communicated to Modem following the Brazilian test. This deficiency has now been rectified both during the intercomparison in Mauritius and in subsequent follow up meetings.
- The results from Mauritius vary much more smoothly with height compared to Brazil, because the data set obtained was more reliable.
- The good balloon performance in Mauritius allowed useful results to be obtained to greater heights than in Brazil.

All temperature sensors in Mauritius apart from Modem had aluminized or metallic coatings, with very weak absorption in the infrared. The Modem radiosonde had a temperature sensor coated with White paint, which absorbs infrared radiation. So Modem temperatures at night were in error by more than 1 K at 30 km. The expected magnitude of cooling in Mauritius can also be seen from the black and White sensors of the 3-thermistor radiosonde in Fig. 9.2. It is concluded that the drift in Modem temperature relative to 3-thermistor in Fig. 9.4 was induced by changes in infrared heat exchange. At the coldest temperature near the tropical tropopause, infrared heat exchange warmed the sensor, but as the atmospheric temperature increase with height the sensor moves towards or past radiative equilibrium and the infrared heating reduces or changes sign to strong cooling near 30 km. The problems with the infrared cooling of the Modem temperature sensor have been discussed in details with the manufacturer, both during the Mauritius test and in subsequent meetings. It is expected that temperature sensors with a more suitable coating will be available on Modem radiosondes by 2006.

The Vaisala RS92 temperatures in Mauritius in the lower troposphere were higher than the other radiosondes by about 0.3 K from the surface to 7 km. Similar radiosondes in Brazil, see Fig. 9.7 and in the UK test in Camborne see Fig. 9.8, did not have this bias. This illustrates that it takes time and more than one test before a complete view of the performance of an individual radiosonde type can be obtained. It is possible that the Vaisala measurements were higher than the others in Mauritius between 0 and 7 km, because there were large numbers of occasions when low amplitude cooling at high humidity cooled the wet sensors of the other radiosonde types by small amounts, and these were not flagged out of the data set.

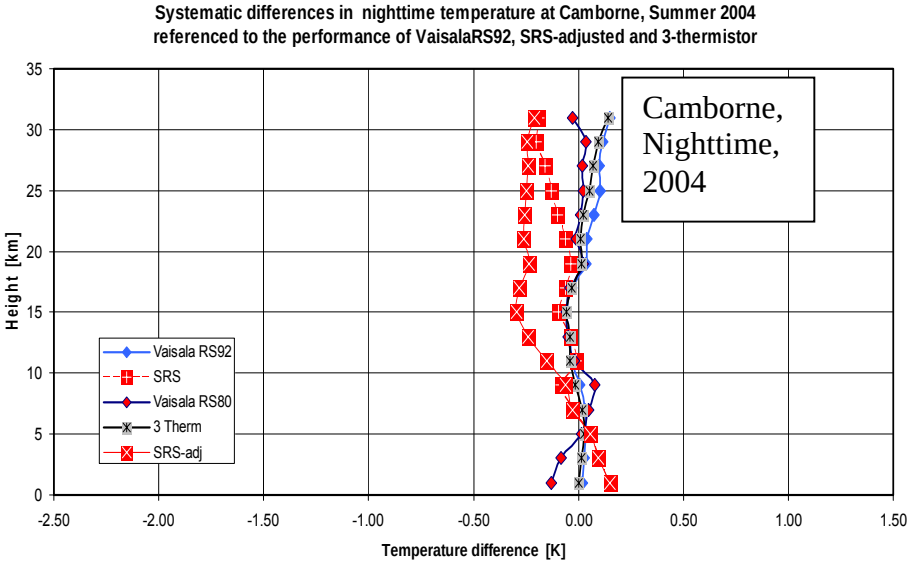


Fig. 9.8 Systematic bias between simultaneous temperatures (K) at night, Camborne, 2004.

The estimated values of random error for Vaisala and multi-thermistor were assumed to be similar since there was no method of discriminating between the two sensors at heights between 7 and 30 km. In nearly all cases the sensor calibrations seem reproducible to about 0.1 K. Larger random errors at upper levels in the Sippican measurements may be the result of changes in Sippican signal channel performance rather than changes in sensor performance. Sippican temperature measurements on individual ascents seemed to drift off calibration towards the end of flights, rather than become extremely noisy. In the case of the Modem sensor variability in the infrared environment induced more variation towards the end of the flight than in the other temperature sensors.

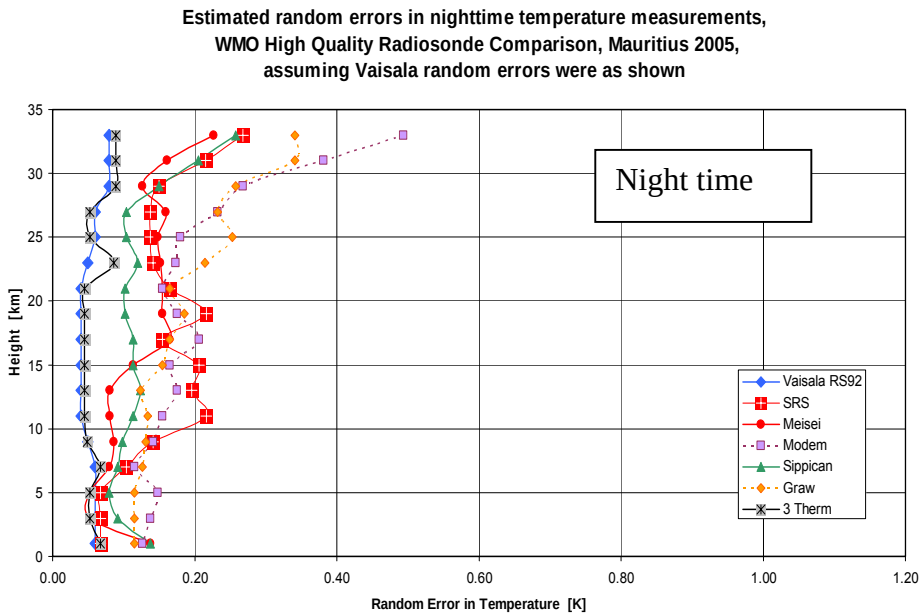


Fig. 9.9 Estimated random errors in temperature sensor measurements at night.

9.3 Temperature intercomparisons in daytime conditions

9.3.1 Multi-thermistor radiosondes as a reference in individual flights

Fig. 9.10 shows an example of the differences between the individual multi-thermistor sensor measurements as a function of time into flight in the day. The black sensor on the multi-thermistor radiosonde heats up much more than the other sensors with the heating highest at the end of the flight. The white painted and aluminized sensors show similar heating in the lower stratosphere, but the white painted sensor cooled down a little relative to the aluminized sensor towards the end of the flight, as the infrared cooling of the white sensor increased.

The multi-thermistor temperatures on this flight were about 1 K lower than the temperatures observed by the white and aluminized sensors. The multi-thermistor estimate depends on the radiative properties assumed for the White and aluminized sensors. If the values used by Sippican for the computations were in error then the multi-thermistor estimates will be in error. In this context, it would be helpful if some comparison were performed between the current NASA ATM radiosonde and the current Sippican multi-thermistor radiosondes, using the revised software supplied to the Met Office, following the completion of the test in Mauritius.

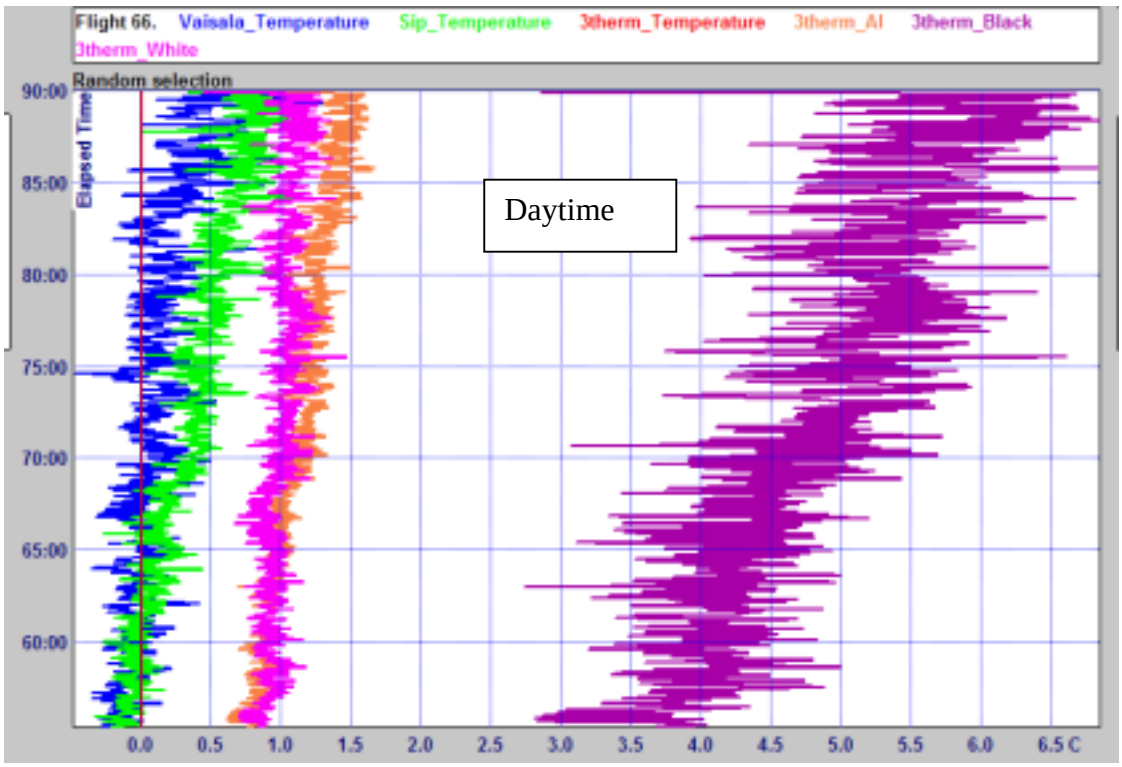


Fig. 9.10 Simultaneous differences between the multi-thermistor estimate, the individual sensors of the multi-thermistor radiosonde, and the Vaisala radiosonde on the same flight. Minute 60 corresponds to a pressure of 35 hPa and minute 90 a pressure of about 6 hPa.

Only nineteen multi-thermistor radiosondes were flown successfully in daytime, partly because there were not enough radiosondes available, and partly because there was not enough UK staff to cope with the workload for any higher number of radiosondes. This workload was much higher than expected given that:

- During flight the radiofrequencies drifted and with the ground receiver requiring frequent retuning.
- There were serious flaws in the software supplied for processing. These flaws were identified and rectified by Sippican following the completion of the test in Mauritius, and both Sippican and Met Office staff had to re-compute the values for all daytime flights and identify which of the radiosondes had failed during flight.

There were enough daytime multi-thermistor flights to relate Vaisala daytime temperature to Vaisala nighttime temperatures, but there were insufficient to link the other radiosonde types. Thus, the method of referencing daytime temperatures to night was to relate all daytime radiosonde temperature measurements to Vaisala daytime, and all nighttime temperatures to Vaisala nighttime. Multi-thermistor in the day was then assumed to be equivalent to multi-thermistor at night, and hence all measurements could be related to the nighttime reference.

The nature of the problems with the Sippican multi-thermistor radiosondes (see section 5) means that it would be most unwise to assume that the link between nighttime and daytime temperature measurements was achieved to a better accuracy than ±0.2 K (1 s.d.) in the stratosphere.

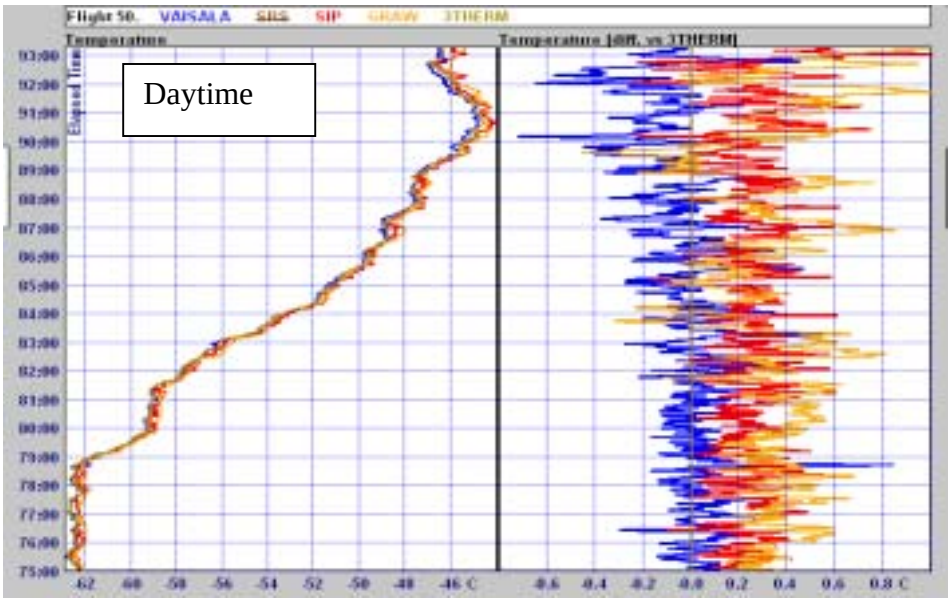


Fig. 9.11 Sample of basic data samples and temperature differences between daytime temperature measurements from the Graw Sippican Vaisala group compared to a multi-thermistor measurement. Minute 75 corresponded to a pressure of about 36 hPa, and minute 92 to a pressure of about 17 hPa.

Examples of detailed daytime temperature sensor comparisons against multi-thermistor measurements during the day for individual flights are shown in Fig. 9.11 and Fig. 9.12. In daytime, simultaneous temperature comparisons show much greater variation than at night, compare with Figs. 9.3 and 9.4.

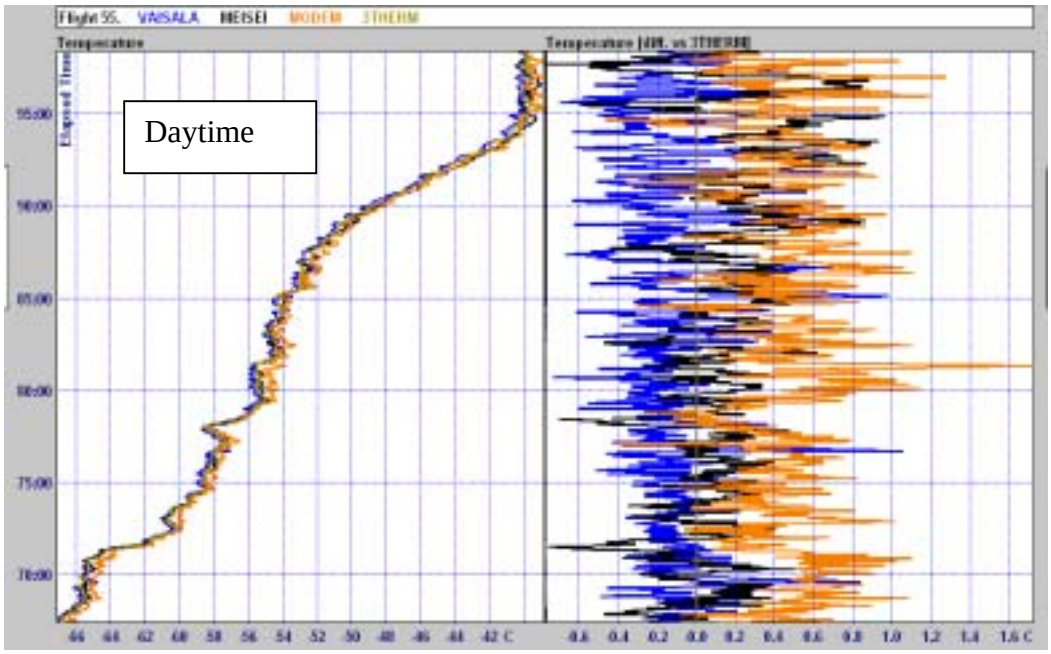


Fig. 9.12 Sample of basic data samples and temperature differences between daytime temperature measurements from the Meisei Modem Vaisala group compared to a multi-thermistor measurement. Minute 69 corresponded to a pressure of about 45 hPa and minute 97 to a pressure of about 13 hPa.

This is because unless the sensor is extremely uniform in shape and optical properties, the solar heating of the sensor will vary rapidly with time as the radiosondes rotate during the ascent. For instance see the large short-term oscillations in heating of the chip thermistor in the multi-thermistor radiosonde, Fig. 9.10. Ideally, the thermistors for the multi-thermistor technique need to present an absorption cross-section to the sun that is as independent of sensor orientation as possible.

At least four of the temperature systems in Fig. 9.1, have protective surrounds or non-sensing parts of the sensor that extend above the level of the temperature sensor during ascent. These surrounds heat up in daylight at very high altitudes by at least 1K and air that passes over the surround passes over the sensor from time superimposing positive temperature pulses onto the true temperature observations. The rotation of radiosondes suspended under the test flight rig is not the same as that experienced by an individual radiosonde in flight. In test flight the rotation is very orderly and the spurious temperature pulses are quite regular and easy to edit out even if they are of larger amplitude. In an individual ascent the anomalies are less regular and more difficult to edit out, but of lower amplitude. To increase random oscillation Vaisala experimented with a piece of clear plastic some distance below the radiosonde in a dozen flights. This may have caused one radiosonde to drop from the rig during sounding. Vaisala editing software filters the raw observations into the reported values takes out most of the positive temperature pulses. However some are not filtered out and the resultant occasional temperature spikes can be seen in Figs. 9.11 and 9.12. The software used for filtering was modified following the test in Mauritius and revised values were submitted to the intercomparison database. This changed the systematic bias of the daytime temperatures by about 0.2 K at pressure around 10 hPa. The noise level in Fig 9.12 does not significantly differ between Meisei, Modem and Vaisala.

In Figs. 9.11 and 9.12 the daytime Sippican samples have relatively low variability relative to the 3-thermistor measurements. Mounting the sensor pointing up, without any support surfaces above the sensor, see Fig. 9.1, offers the best practical method of reducing spurious temperature anomalies from the sensor supports.

The other important issue when seeking to improve the stability of daytime temperature measurements is to minimize variations from one flight to the next by ensuring the sensor is deployed in the same position in every flight. If the operator can choose large numbers of different positions, it will prove impossible to get reproducible values in daytime. Very few of the radiosondes tested have yet implemented a fixed position for the temperature sensor. Thus, there is room for improvement in the deployment of temperature sensors in nearly all the radiosondes tested in Mauritius.

9.3.2 Results of statistical processing

The WSTAT statistical package was again used to compute comparisons of all radiosonde types against Vaisala in the daytime flights (Vaisala measurements were available on most flights to link temperatures together). As indicated, in the previous section, the daytime measurements were than linked to the reference used for nighttime measurements in Fig. 9.6 through the multi-thermistor radiosonde results.

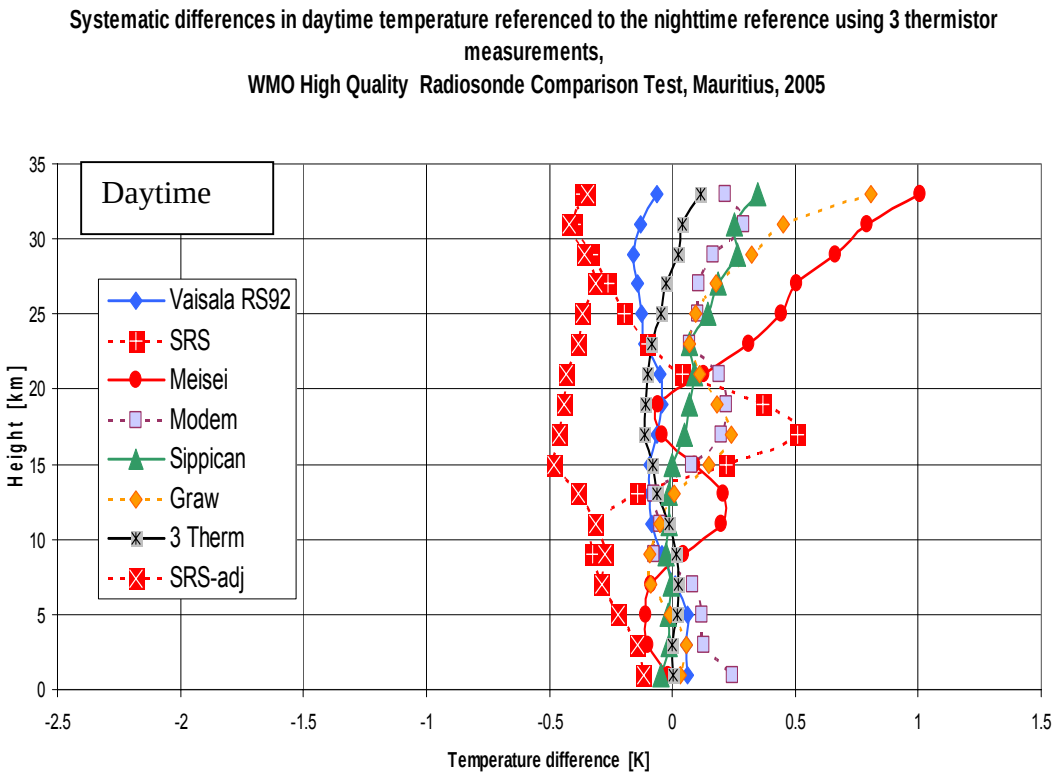


Fig. 9.13 Systematic difference between simultaneous daytime temperatures (K) referenced to the nighttime reference, using multi-thermistor measurements as a link.

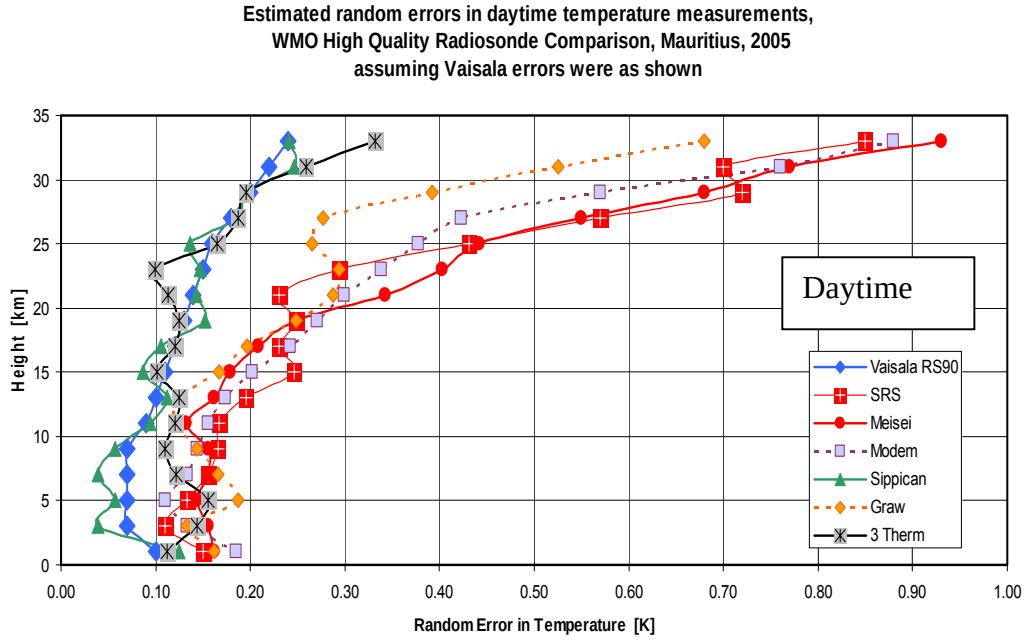


Fig. 9.14 Estimates of random error in daytime temperatures (K).

Figure 9.13 shows the systematic differences for daytime temperature comparisons. The absolute accuracy of the multi-thermistor measurements may be biased by up to ± 0.2 K from truth, and this limits the accuracy of referencing to the nighttime measurements as explained earlier.

Vaisala made the smallest daytime radiation correction to temperature (about 0.5 K at 10 hPa). SRS and Sippican made corrections of just over 1 K at about 30 km. From Fig 9.13, Vaisala and SRS daytime temperatures were closest to the 3-thermistors at upper levels.

Modem temperature corrections were about 2 K at upper levels. Meisei daytime temperature corrections were about 2.5 K at 30 km and were larger than most of the other radiosondes.

With the upper cloud conditions experienced in Mauritius, the results show that Meisei temperature corrections needed to be larger by at least 0.8 K at 10 hPa. Meisei checked that no errors had been introduced to the radiosonde used in Mauritius, following the intercomparison. A difference in cloud albedo between Japan and Mauritius is likely to be the cause of the positive bias seen in Meisei measurements in Fig. 9.13.

The random error estimates in Fig. 9.14 were deduced from the standard deviations of the differences between radiosondes using the method used in the nighttime comparisons. However, for daytime measurements it was assumed Vaisala random errors after filtering were of similar magnitude to the Sippican random errors.

Fig. 9.14 shows that random errors in Sippican and Vaisala daytime temperature measurements were less than 0.2 K at heights up to 30 km., whereas random errors in the other temperature sensors were larger than 0.2 K at heights above 16 km. As noted earlier the temperature sensors with largest random errors at 10 hPa will benefit from a redesign of the temperature sensor mount to minimize the fluctuations from air that has passed over surrounding sensor support structures.

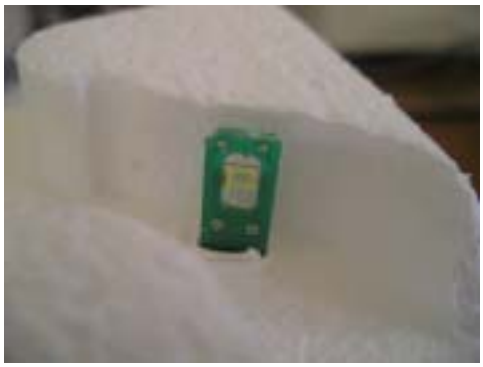
10. SIMULTANEOUS RELATIVE HUMIDITY MEASUREMENT INTERCOMPARISON

10.1 Introduction

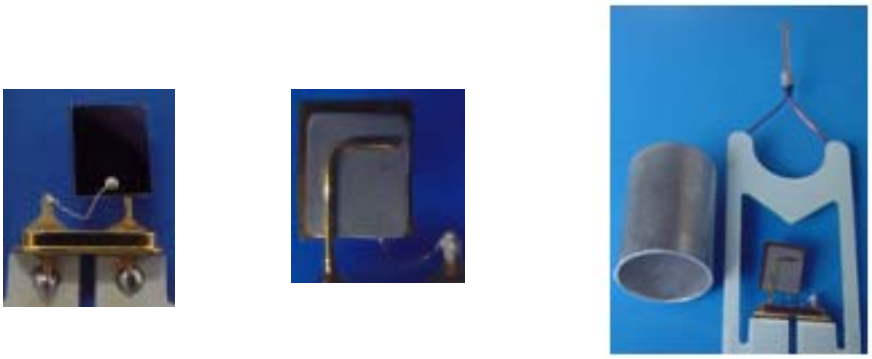
10.1.1 Operational Sensors used

Most of the relative humidity sensors tested in Mauritius were of a similar type, thin film capacitance sensors. Fig. 10.1(a) shows pictures of the various capacitance sensors, only the LMS sensor was mounted internally in a duct within the body of the radiosondes.

(1) One of two sensors, Vaisala RS92



(2) LMS-5 sensor



(3) Meisei [viewed from both sides] + protective cap

(4) Modem

(5) Graw

Fig. 10.1(a) Relative humidity sensors used in Mauritius, not to scale.
(1) Vaisala RS92 (2) LMS-5, (3) Meisei, (4) Modem , (5) Graw.

However, differences between the sensors can be expected because of:

- Differences in the properties of the polymer film used.
- Chemical contamination changing sensor performance.
- Method of exposure of the sensor.
- Method of estimating the temperature of the relative humidity sensor.
- Method of eliminating water vapour/ice contamination during the ascent.
- Effects of hygroscopic surfaces near the sensor.

Thin film capacitance sensors tested in Mauritius were:

Graw***	mounted externally, protected by cap
Meisei	mounted externally, protected by cap
Modem	mounted externally, protected by cap
LM-Sippican	mounted internally, temperature of the sensor measured directly
Vaisala	mounted externally, dual sensors pulse heated to drive off contamination**

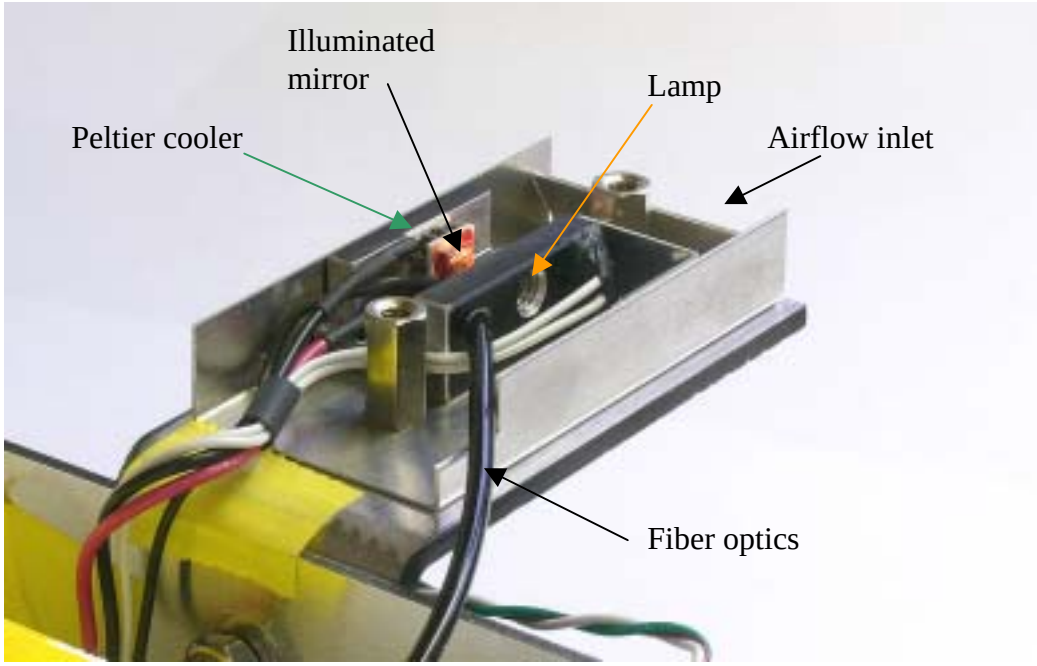
** The Vaisala radiosondes used in Mauritius were supplied with pulse heating that ceased at -40 °C. However, from Flight 38 onwards the termination of the pulse heating was changed to -60 °C, at the request of the chairman of the IOC. It had been established in previous WMO tests in the USA and Brazil and subsequent collaborative tests with Vaisala in the UK that sensors were often contaminated in high cloud at temperatures lower than –40 °C, especially in the tropics.

Production models of the Vaisala RS92 have had termination of pulse heating at -60 °C since the middle of 2005.

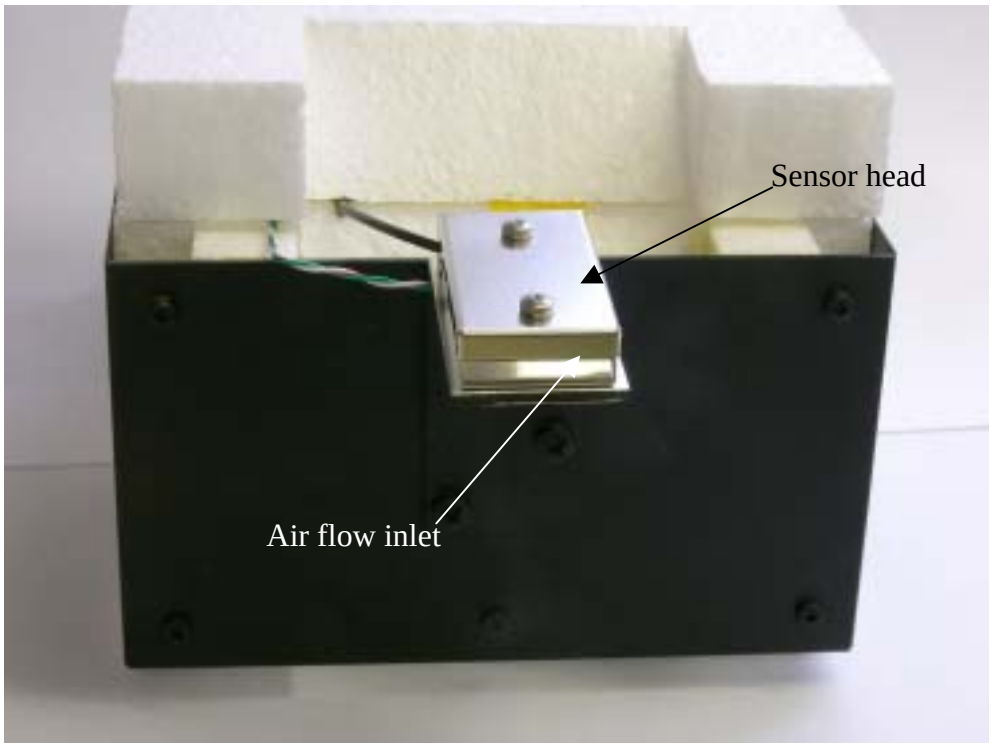
*** Production of Graw humidity sensor ceased in October 2005 and was replaced by an improved sensor.

10.1.2 Characteristics of Snow White sensors in Mauritius

Whereas all the operational radiosondes measure relative humidity and are calibrated with respect to relative humidity, the Snow White chilled mirror measures dewpoint or frost point directly (depending on whether the film on the mirror is water or ice), see Fig. 10.1(b).



(1) Inside a nighttime Snow White sensor



(2) Nighttime – Snow White ®, viewed from above

Fig. 10.1 (b) Views of Nighttime Snow White sensing system.

The conversion from dewpoint to relative humidity requires an accurate air temperature measurement. In Mauritius, the temperature of the SRS radiosondes was used for the conversion, except on the one flight where the SRS temperature failed, and temperature data from the RS92 radiosonde were used instead. The calibration error found in the SRS temperature measurements, see the differences between SRS and SRS-adjusted in Fig. 9.6, may also affect the Snow White frost point measurements at temperatures lower than –50 °C. No attempt has been made to make adjustments for this error in the Snow White data.

It is necessary to estimate when the film on the mirror turns from water to ice. The change in phase does not normally occur at a mirror temperature near 0°C, but usually in the range -20 to –30 °C. The choice of freezing point for the film was made by the Snow White operator.

Several variants of Snow White were deployed In Mauritius.

The “daytime” Snow White system has the chilled mirror mounted in an internal duct to protect the sensor from daylight. The circulation through the duct system is good once established (the duct entrance can be almost sealed up and the speed of response of the Snow White will be similar to the operational radiosondes), but this good ventilation cannot be guaranteed until the test rig has accelerated up to normal ascent rate for several minutes. At low temperatures, with relatively wet conditions in the lower atmosphere, contamination can build up in the duct, see section 5.

The “nighttime” Snow White eliminates the internal duct and the chilled mirror sensor is exposed directly in the atmosphere. However, in Mauritius, many of the nighttime ascents were preceded by continuous rain. In these circumstances, “daytime” Snow Whites with the sensor in an internal duct were flown on the night flight to prevent ingress of rain to the chilled mirror sensor.

On most flights with “daytime” Snow White in Mauritius, the normal entrance to the internal duct, located at the top of the SRS radiosonde was blocked off, and a chrome plated pipe inserted into the side of the radiosonde so the air was sucked into the internal duct near the chilled mirror sensor. This reduced contamination of Snow White measurements in drizzle, and light rain, but successful Snow White measurements could not be obtained at higher rainfall intensity.

10.2 Examples of relative humidity intercomparisons from individual flights

10.2.1 Lower and middle troposphere

In the lower and middle troposphere the different relative humidity sensors usually provided very similar vertical structure, see Fig. 10.2(a) and (b) for examples from the Graw-Sippican-Vaisala group and Fig. 10.3(a) and (b) for examples from the Meisei-Modem-Vaisala group.

It can be seen that in general the time constants of response of all the relative humidity sensing systems was quite similar at these heights. For instance, there were a large number of very rapid changes from high relative humidity to low humidity in Fig 10.2, and the level of agreement between the different sensors under these conditions can only be achieved if the time constants of response were similar.

The same explanation is also relevant to the very large changes seen in Fig. 10.3. Occasionally one of the radiosonde types seems slower than the others, e.g. Sippican in Fig. 10.2(b), but the Sippican sensor seems of similar response to the other sensors in Fig. 10.2(a).

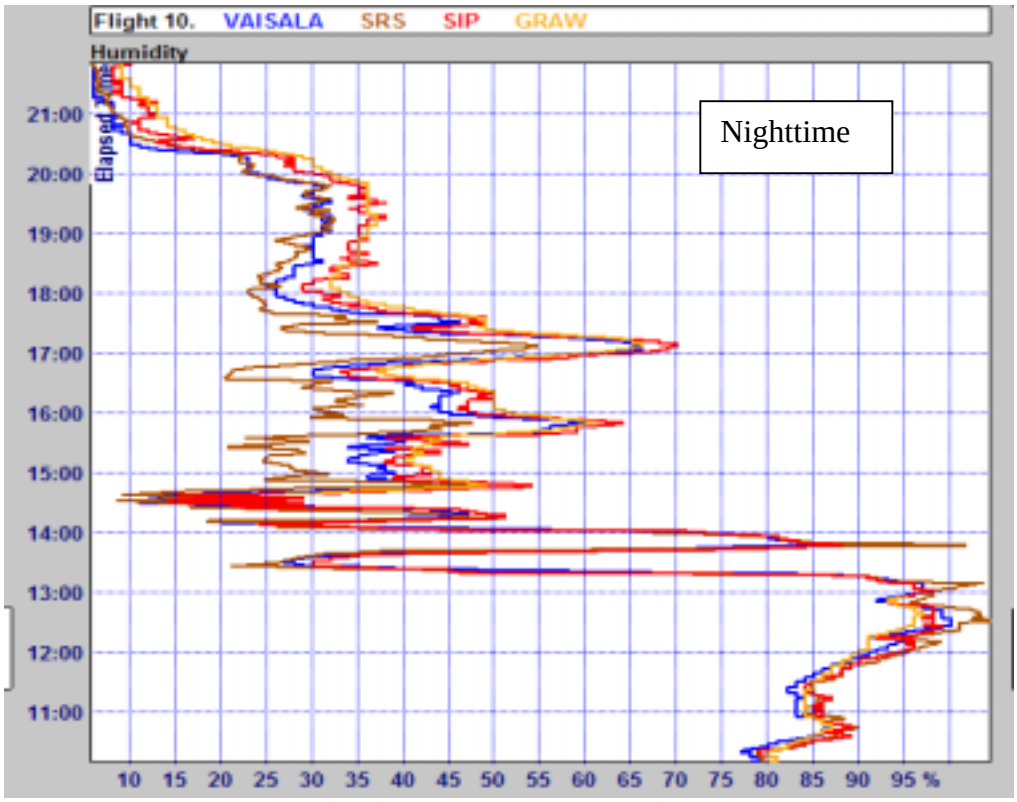


Fig. 10.2(a) Sample of detailed vertical structure from an individual flight, Graw-Sippican-Vaisala group plus Snow White. Sample centered at about 5 km above the ground.

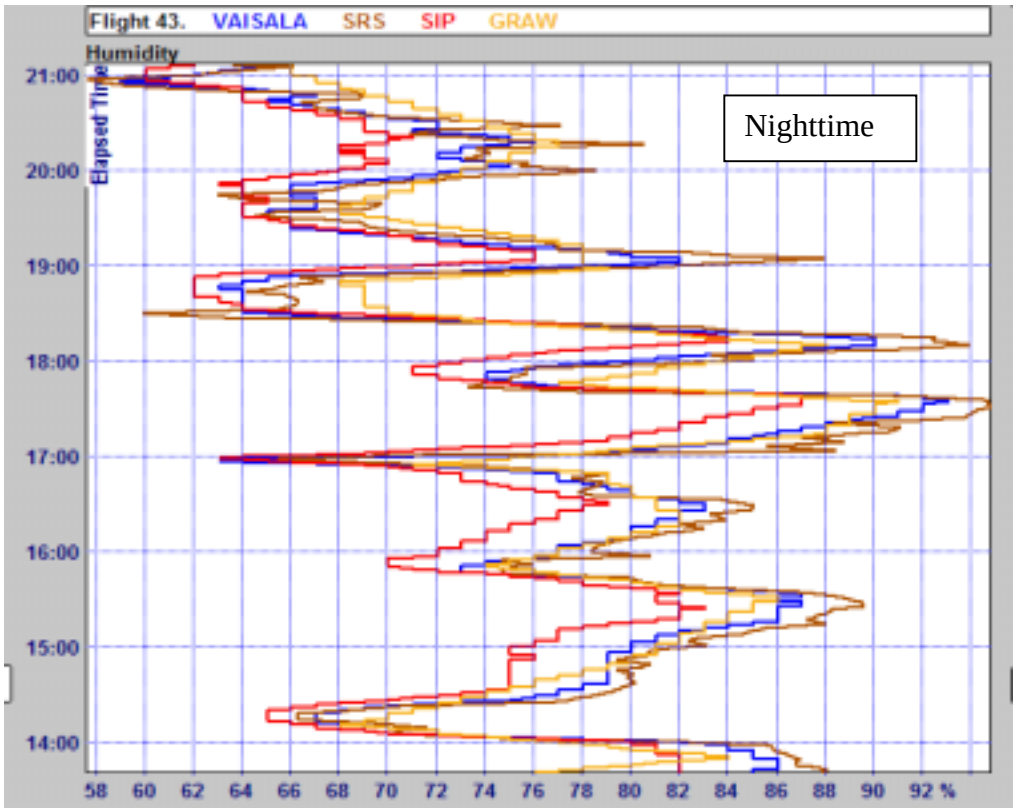


Fig. 10.2(b) Sample of detailed vertical structure from an individual flight, Graw-Sippican-Vaisala group plus Snow White. Sample centered at about 5 km above the ground.

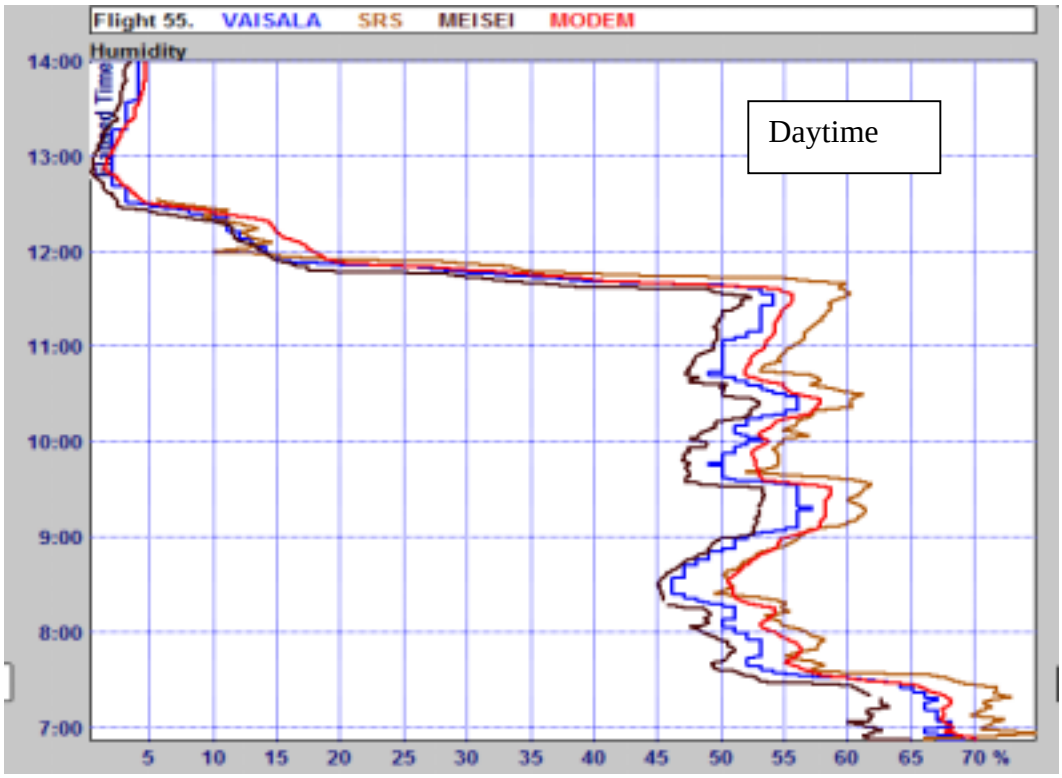


Fig. 10.3(a) Sample of detailed vertical structure from an individual flight, Meisei-Modem-Vaisala group plus Snow White, centered at about 3.5 km above the ground.

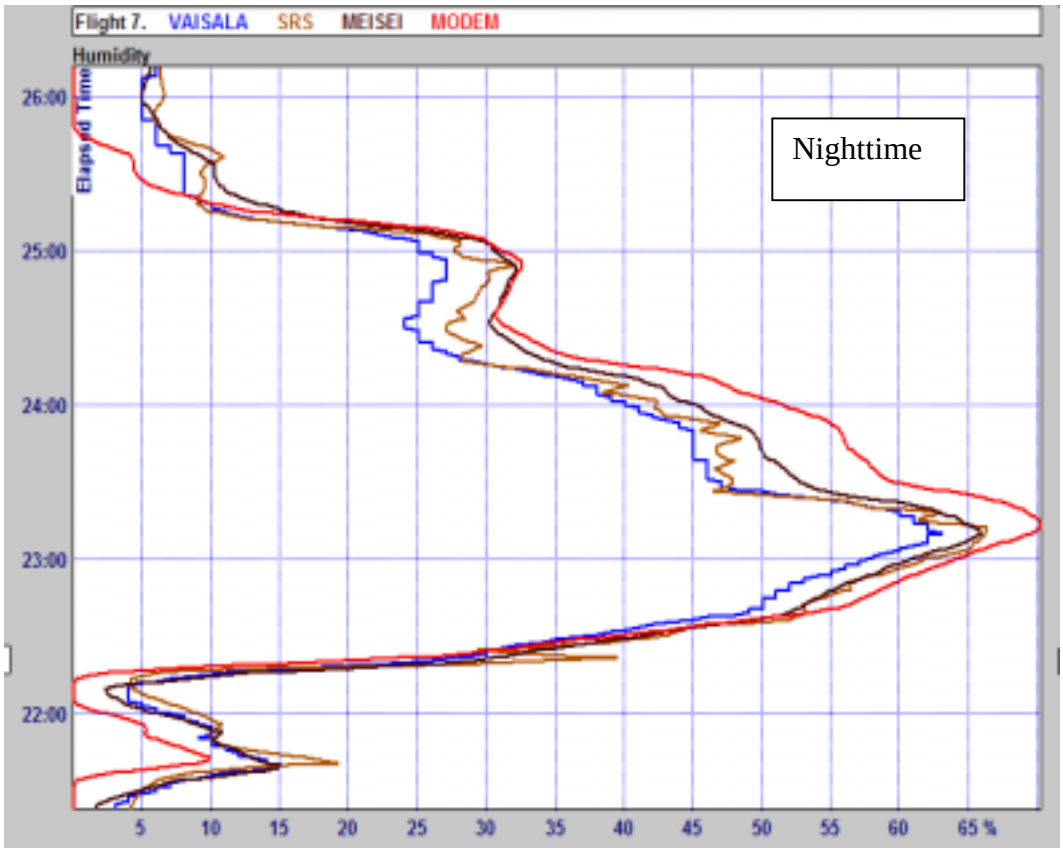


Fig. 10.3(b) Sample of detailed vertical structure from an individual flight, Meisei-Modem-Vaisala group plus Snow White, centered at about 9 km above the ground.

The Snow White sensor is not a perfect reference, since it has a variety of error and failure modes see section 5, and it is only possible to identify these when Snow White is flown together with good quality operational radiosondes. However, the Snow White sensor was extremely important in the Mauritius test, because it used a completely different principle of measurement to the other sensors. When operational sondes and Snow White agree in general as shown here, it proves that there is a group of higher quality sensors agreeing together, and not a group of poor quality sensors with similar faults.

10.2.2 Upper Troposphere

The upper troposphere and lower stratosphere present the greatest challenge to radiosonde relative humidity measurements, because of the low temperature involved, down to -80 °C in Mauritius, and because of the problems of contamination of water vapour picked up on passing through upper cloud, or in the lower layers of the atmosphere at warmer temperatures.

Fig. 10.4 shows three individual flights from the time when the pulse heating of the Vaisala RS92 sensors were programmed to stop at –40 °C.

- In Flight 7 the test flight has probably passed through an upper ice cloud, cloud top at minute 42 near -80 °C. All the humidity measurements agreed closely down to –60 °C, but diverged widely after this. The structure shown by Snow White measurements is judged the most likely to be correct, with contamination causing Vaisala to overestimate relative humidity immediately above the cloud.
- In Flight 10, Snow White relative humidity structure at temperatures lower than -55 °C is quite different from Vaisala and Sippican. It is suggested that there were probably some ice particles, possibly falling through drier air, so that the relative humidity peak at minute 37 was probably correct. The traces of the Vaisala and Sippican sensors above this look like the curves obtained when sensors are known to have been contaminated. Thus, the Snow White measurements may be correct.
- In Flight 14, the different relative humidity sensor curves diverge after passing through the cloud at minute 30. As with flight 10, the relative humidity reports from the other sensors look like possible contamination curves, so again the Snow White measurement looks plausible.

In two of these flights very large differences have occurred between Snow White measurements and the other sensors. It is impossible to be exactly sure whether Snow White was correct, but on these flights there was evidence that sensor contamination could have occurred or not been driven of at temperatures lower than –40 °C.

It would seem essential that the pulse heating of the sensors in the system used by Vaisala be continued up to the tropopause, to assure the quality of the measurements in the upper troposphere.

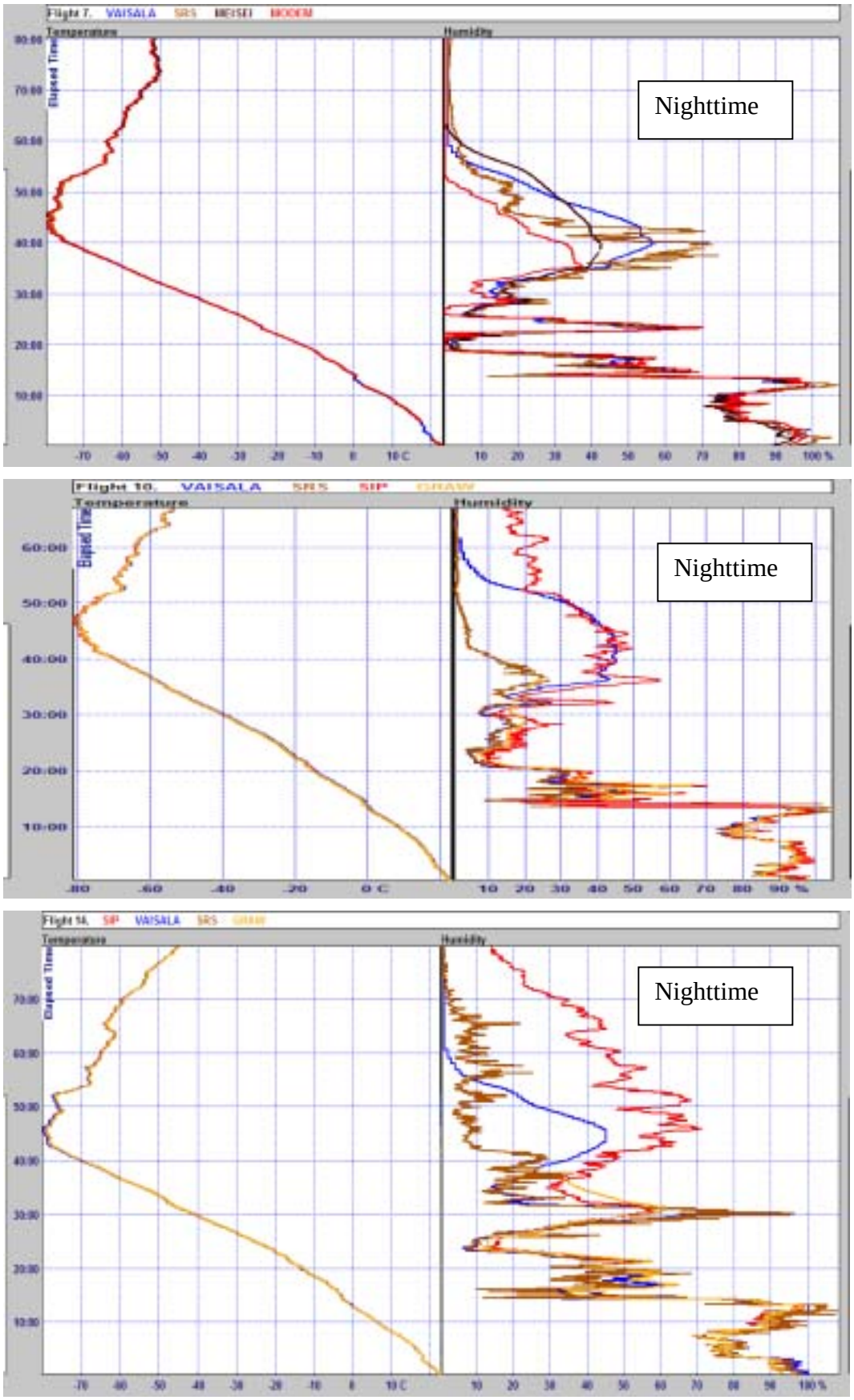
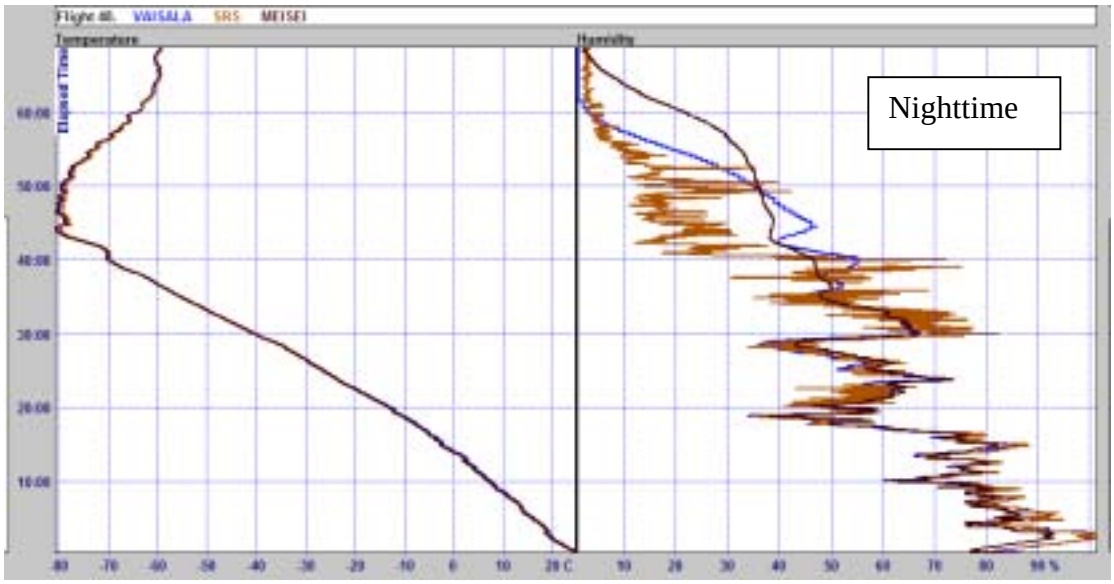
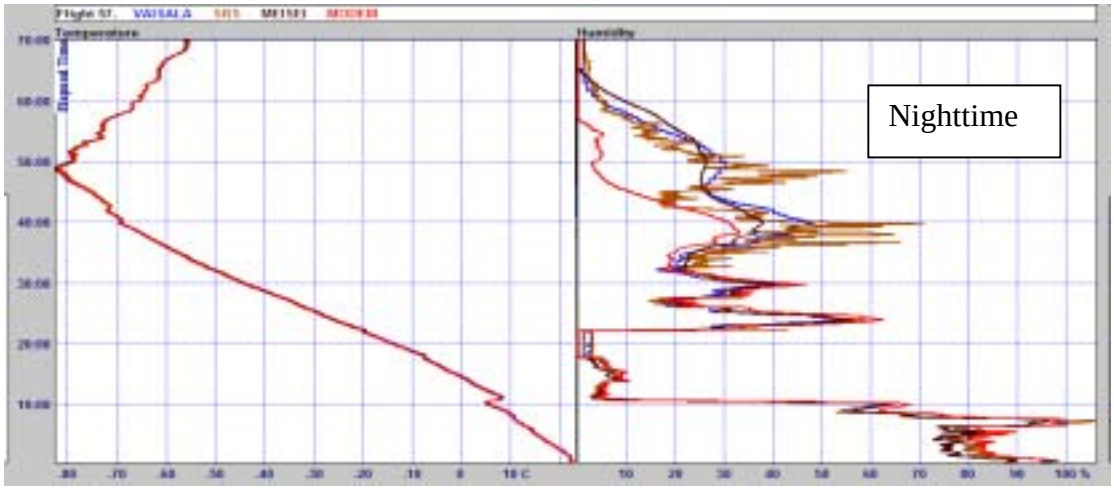


Fig. 10.4 Three examples of relative humidity profiles for the period of the intercomparison when Vaisala pulse heating was programmed to stop at –40 °C.





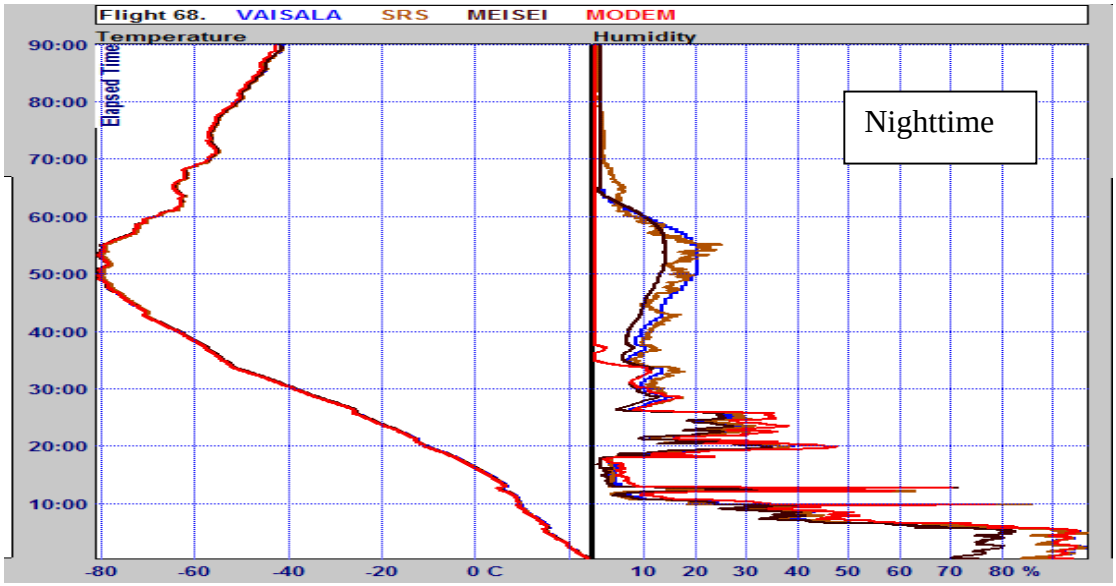


Fig. 10.5 Three examples of relative humidity profiles for the period when Vaisala pulse heating was programmed to stop at -60℃.

Once, the pulse heating of the Vaisala radiosondes continued down to -60°C, large discrepancies between Snow White and the Vaisala RS92 were much less common, see Fig. 10.5. In Flight 48, The Vaisala RS92 measurements may have become contaminated at temperatures below -60 °C. Agreement between Vaisala RS92 and Snow White was good in moist conditions in Flight 57 and in drier conditions in Flight 68.

At temperatures lower than -60°C, Sippican measurements were tending to be higher than average in the upper troposphere, and Modem measurements were tending to be lower than average. This will be examined in more detail in the following sections. Relative humidity measurements of GRAW below -60° have been eliminated, as the response time of the sensor tested was too slow at these low temperatures. This problem has now been addressed by GRAW, with a new relative humidity sensor design.

10.3 Relative humidity intercomparisons at night - Results of statistical processing

The WSTAT statistical package was used to compute the systematic bias between the different relative humidity sensors and Vaisala for 2 km height bands and bands of relative humidity, 0 to 15, 15 to 35, 35 to 55, 55 to 75, 75 to 95 and 95 to 100 per cent relative humidity. The reference was then adjusted to a nighttime reference for presenting results which was the average of Sippican, SRS (Snow White) and Vaisala measurements. Sippican measurements were omitted from the reference computation in regions where the measurements were considered to have large systematic bias away from the working reference (Snow White), i.e. above 14 km and above 8 km for the band 55 to 75 per cent relative humidity.

The resultant systematic bias between the relative humidity sensors is presented using contour plots of systematic bias plotted as a function of height and relative humidity for each of the individual sensor types in Figs. 10.6 (a) to (f) for nighttime measurements. Data are only plotted in a box if there were comparison samples from at least 5 separate test flights.

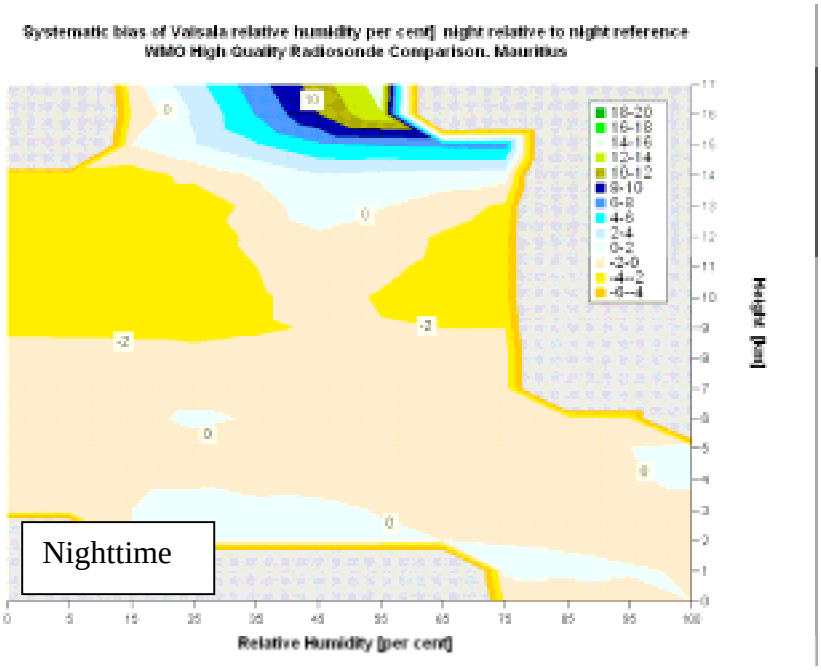


Fig. 10.6(a) Systematic bias for Vaisala nighttime relative humidity, referenced to the average of Vaisala, Snow White and Sippican.

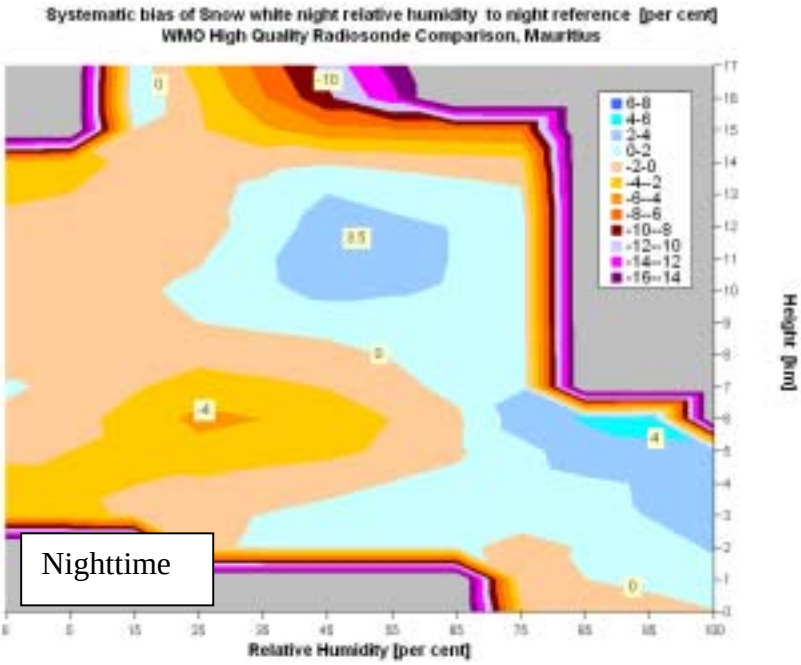


Fig. 10.6(b) Systematic bias for Snow White nighttime relative humidity, referenced to the average of Vaisala, Snow White and Sippican.

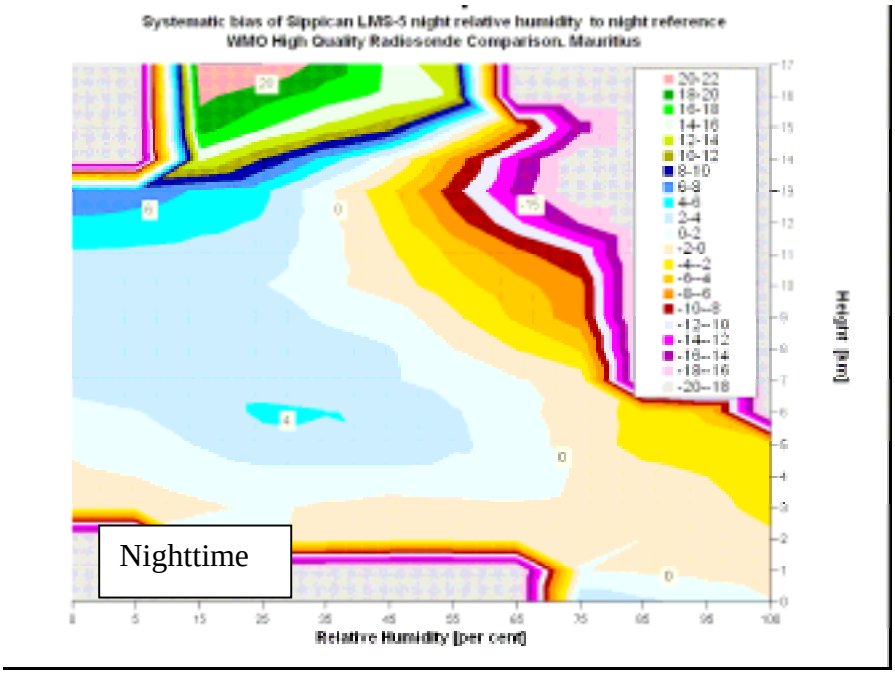


Fig. 10.6(c) Systematic bias for LMS-5 night time relative humidity, referenced to the average of Vaisala, Snow White and Sippican.

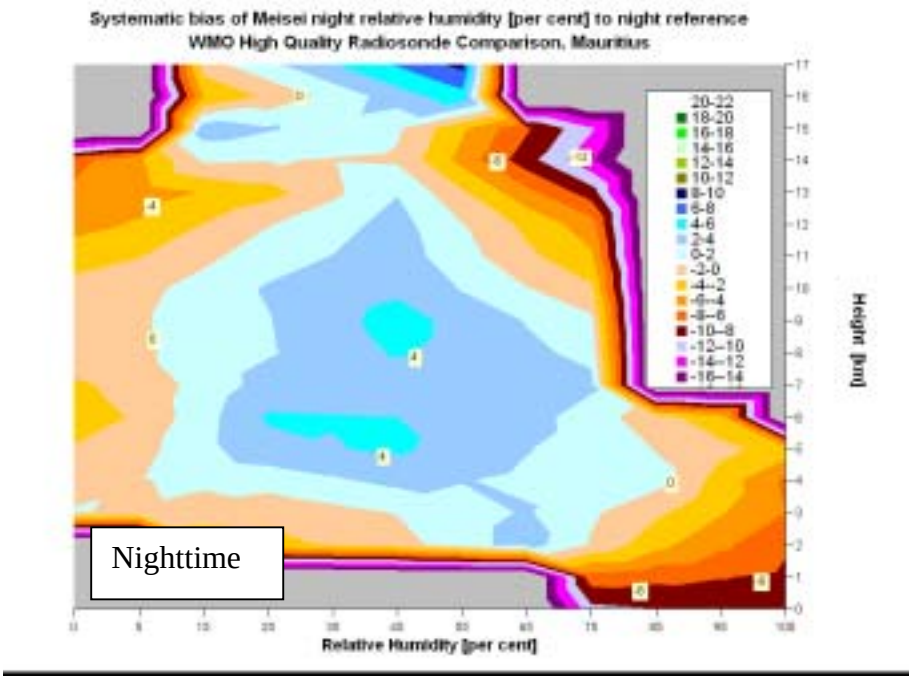


Fig. 10.6(d) Systematic bias for Meisei nighttime relative humidity, referenced to the average of Vaisala, Snow White and Sippican.

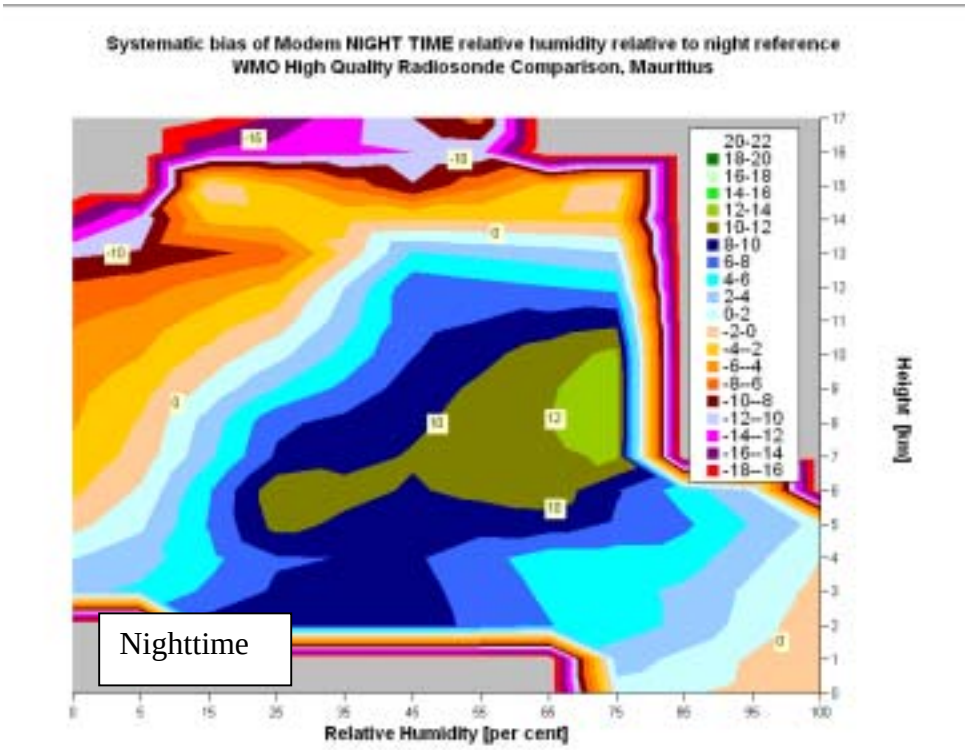


Fig. 10.6(e) Systematic bias for MODEM nighttime relative humidity, referenced to the average of Vaisala, Snow White and Sippican.

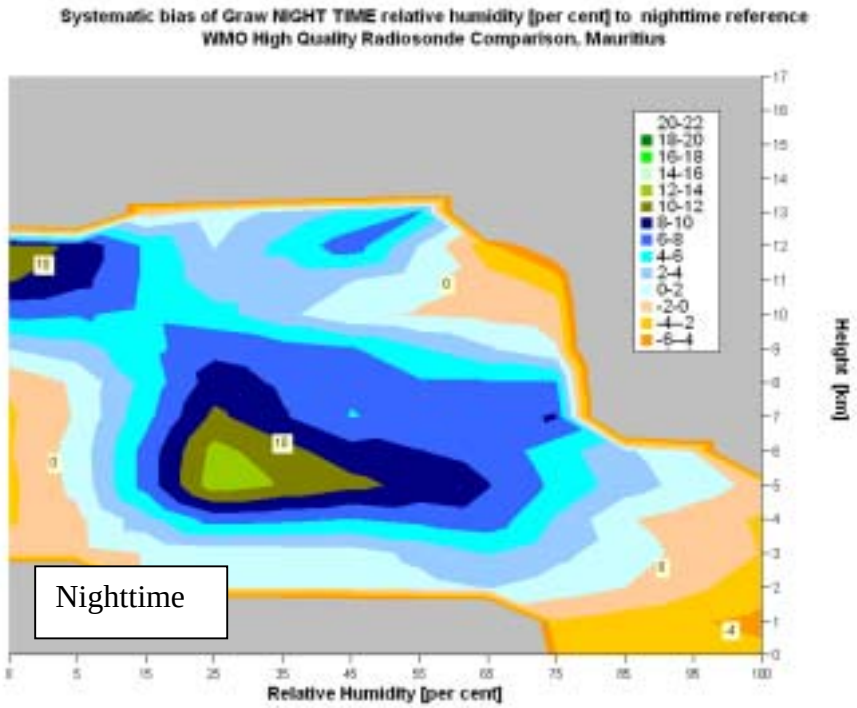


Fig. 10.6(f) Systematic bias for Graw nighttime relative humidity, referenced to the average of Vaisala, Snow White and Sippican.

Fig. 10.6(a) and (b) show that Vaisala and Snow White measurements were generally within 4 per cent of the reference at night at all heights up to 14 km, but were not in close agreement at heights above 15 km. The temperature at 15 km was about -70 °C. Thus, Snow White showed much lower relative humidity than Vaisala at temperatures near -80 °C, as in Fig. 10.4 and 10.5.

Sippican measurements at night, Fig. 10.6(c), were generally within 5 per cent of the reference at heights up to 11 km, i.e. down to a temperature of -40 °C, but the values reported in cloud at heights around 13 km were low by at least 15 per cent relative to Snow White and Vaisala. Fig. 10.8 shows that Vaisala relative humidity measurements were around 10 per cent higher than saturation with respect to ice in the highest clouds. Thus, it is possible that both Snow white [possible evaporation of ice crystals from the cloud by heating in the sample chamber] and Vaisala [contamination in cloud] were reporting relative humidity that was too high. However, in the drier regions at 16 km, Sippican relative humidity measurements were at least 20 per cent too high. Improved calibration of this new sensor at temperatures below -40 °C is now being addressed by the manufacturer.

Meisei measurements at night, Fig. 10.6(d), were generally within 5 per cent of the reference from 2 to 13 km. The negative bias of 8 per cent near the surface was caused by chemical contamination of the sensors in shipment from Japan. Tests by Meisei after the intercomparison showed that chemicals from a sticky label on the radiosonde, which was specially placed on the radiosonde for the Mauritius intercomparison, could cause relative humidity at high humidity to fall by 5 per cent in one month's storage.

MODEM and Graw relative humidity measurements, Fig. 10.6(e) and (f) showed positive bias greater than 5 % at night when the sensors were observing drier layers after emerging from moist low-level conditions. This was probably caused by water contamination on the sensor or its supports and protective cap, and was probably not just the result of poor calibration; compare the daytime measurements in Figs 10.9 (e) and (f). The positive bias

persisted further in the vertical in the MODEM measurements than in the Graw measurements. MODEM measurements showed significant negative bias (15 %) at heights above 16 km where temperatures were as low as -80 °C.

10.4 Relative humidity intercomparisons in the day - Results of statistical processing

During the intercomparison a GPS water vapour sensor was installed on the roof at Vacoas Headquarters**.** Some problems were encountered with data logging and ideally the location of the sensor should have been readjusted to minimize multipath problems. However, sufficient IWV values were reported at hourly intervals to provide a reference between daytime and nighttime Vaisala radiosonde measurements of IWV, see also Fig. 12.2. Fig. 10.7 shows the results of the differences (Radiosonde – GPS) integrated water vapour for Vaisala RS92 and Snow White, separated into daytime and nighttime flights. The nighttime radiosonde measurements are generally within 2 kg.m^{-2} of the GPS measurements. The daytime Vaisala measurements have a negative bias relative to radiosondes of at least 5 kg.m^{-2}. If it is assumed that there is no day-night difference in the systematic bias of GPS water vapour measurements, then the day-night difference in IWV measurements would be about -4 ± 0.6 in 48 kg.m^{-2} corresponding to an average day–night difference in relative humidity of about -6.5 ± 1 %. However, alternatively, the Snow White radiosonde may have no day-night difference in IWV, so then the GPS water vapour has a day-night difference of -1 kg.m^{2} in systematic bias, and the day-night difference in Vaisala relative humidity reduces to -5 ±1 per cent relative humidity.

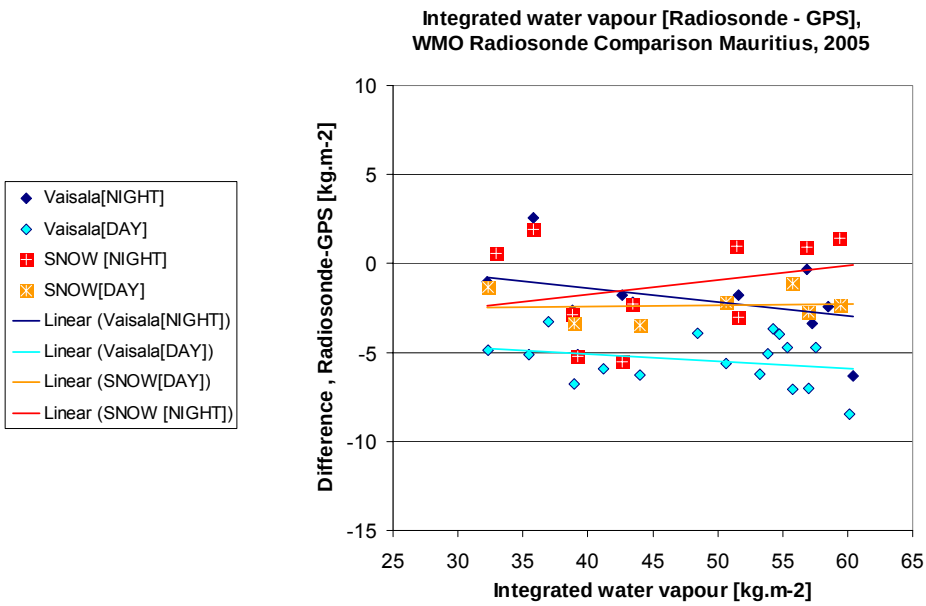


Fig. 10.7 Results of daytime and nighttime comparisons of integrated water vapour from radiosondes and GPS water vapour (Radiosonde-GPS) for Snow White and Vaisala.

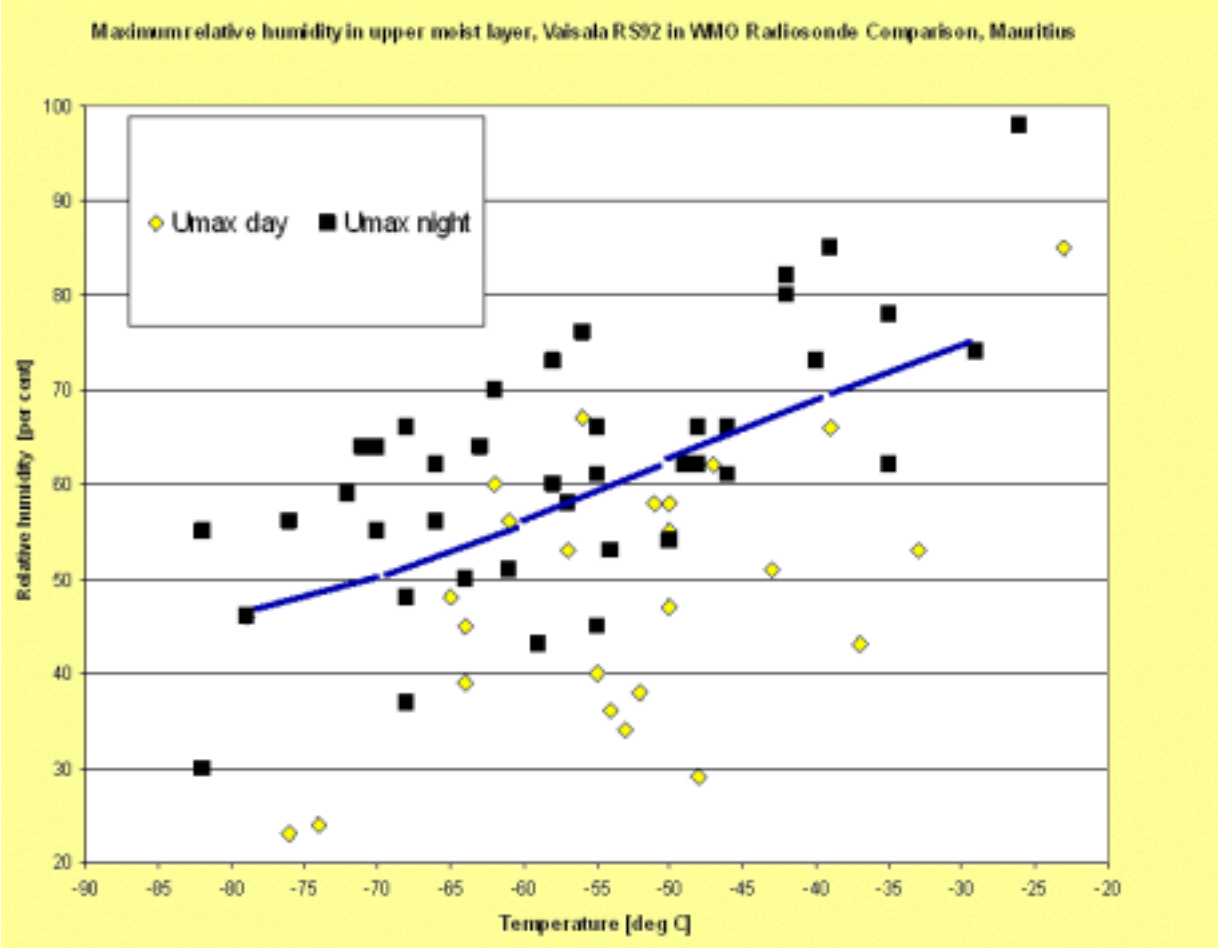


Fig. 10.8 Maximum relative humidity in upper moist layer reported by Vaisala RS92 in Mauritius. Blue line indicates saturation with respect to ice.

Above 13 km, daytime Snow White measurements were unreliable and could not be used to link to nighttime Snow White measurements. An alternate method of estimating differences between daytime and nighttime Vaisala measurements in this part of the upper troposphere is to examine the distribution of the maximum relative humidity reported by the radiosonde day and night. The results for Vaisala are shown in Fig. 10.8 and indicate that the day-night difference in relative humidity measurements in the upper troposphere was at least 10 per cent.

The method of computing the daytime systematic bias relative to the nighttime reference was to use the WSTAT package to find the systematic bias relative to Vaisala for daytime relative humidity. The Snow White day measurements were assumed to be equivalent to the night measurements, apart from at temperatures below about –40 °C where the duct of the daytime system led to some positive bias relative to the nighttime measurements. Where reliable daytime Snow White measurements in the upper troposphere were unavailable, day-night differences in Vaisala relative humidity were assumed to be near 10 per cent, as in Fig. 10.8.

The results of these assumptions are the estimates of daytime systematic bias relative to the nighttime reference used for Fig. 10.6. These are shown in Figs 10.9 (a) to (f).

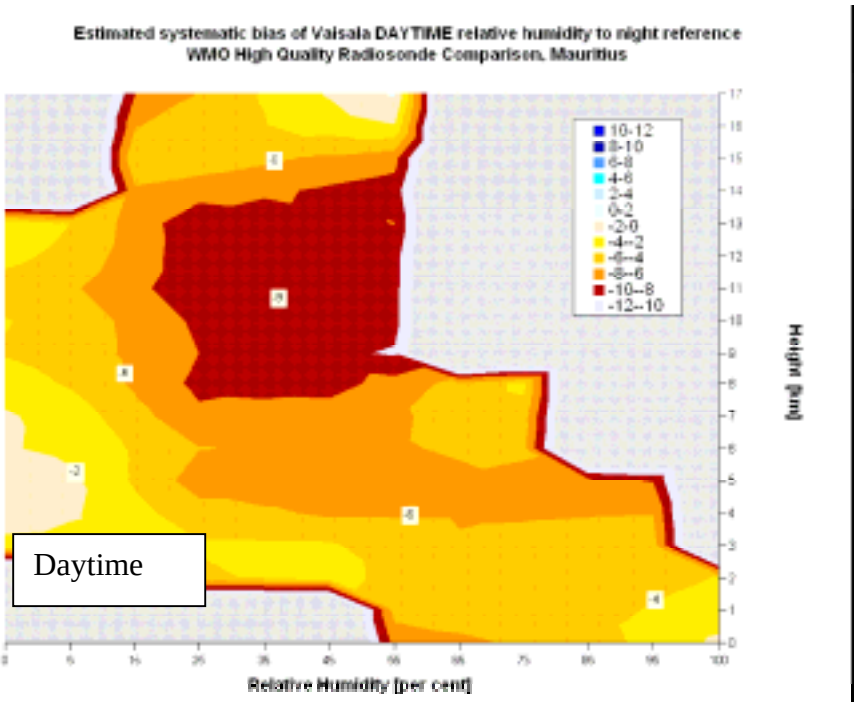


Fig. 10.9(a) Systematic bias for Vaisala daytime relative humidity.

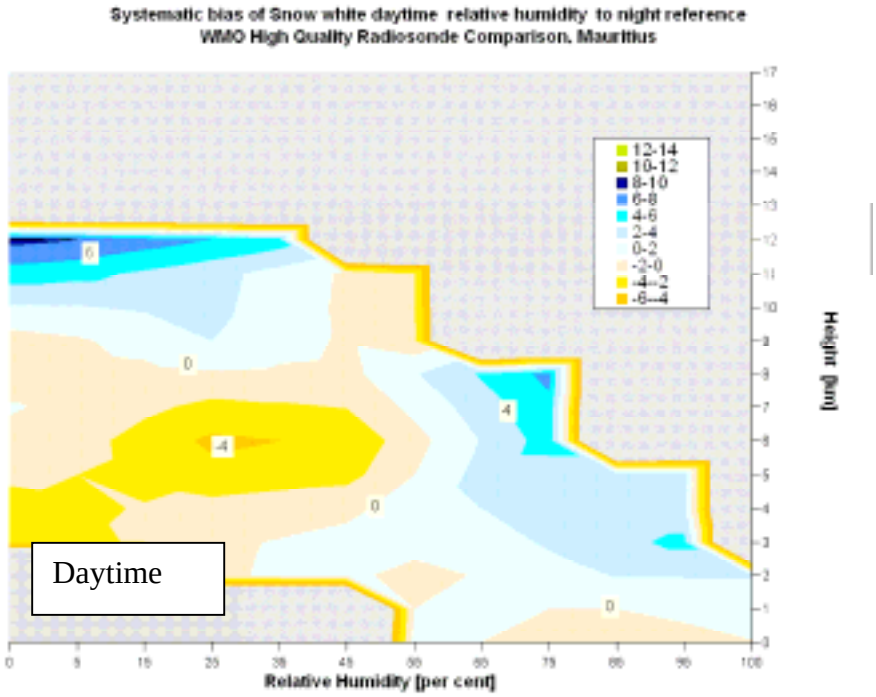


Fig. 10.9(b) Systematic bias for Snow White daytime relative humidity.

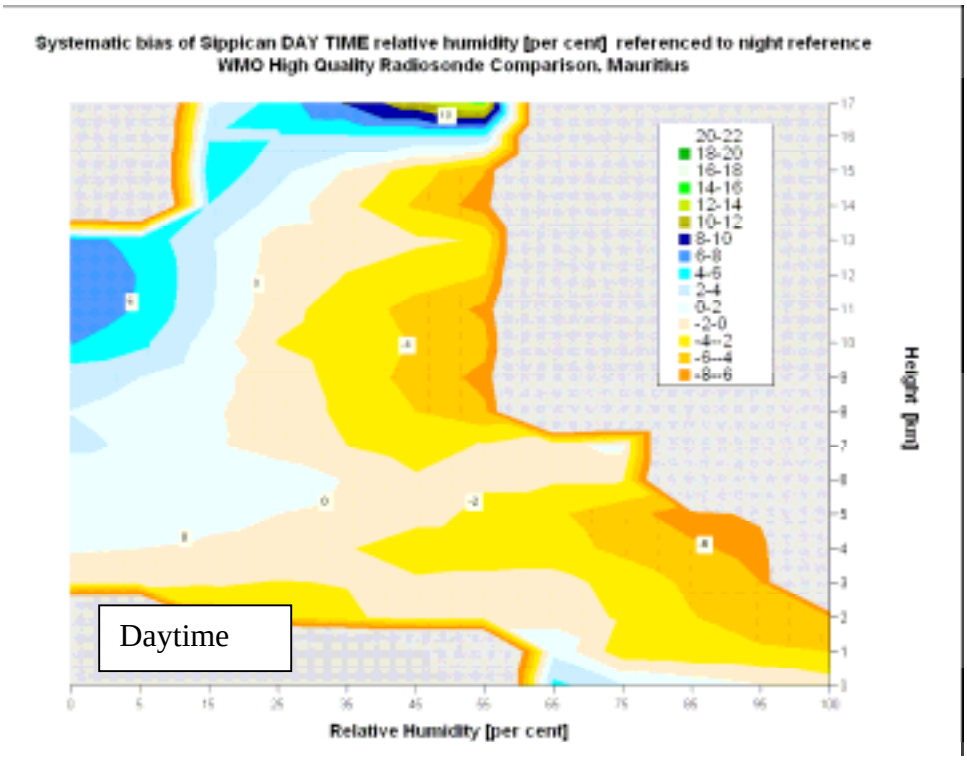


Fig. 10.9(c) Systematic bias for LMS-5 daytime relative humidity.

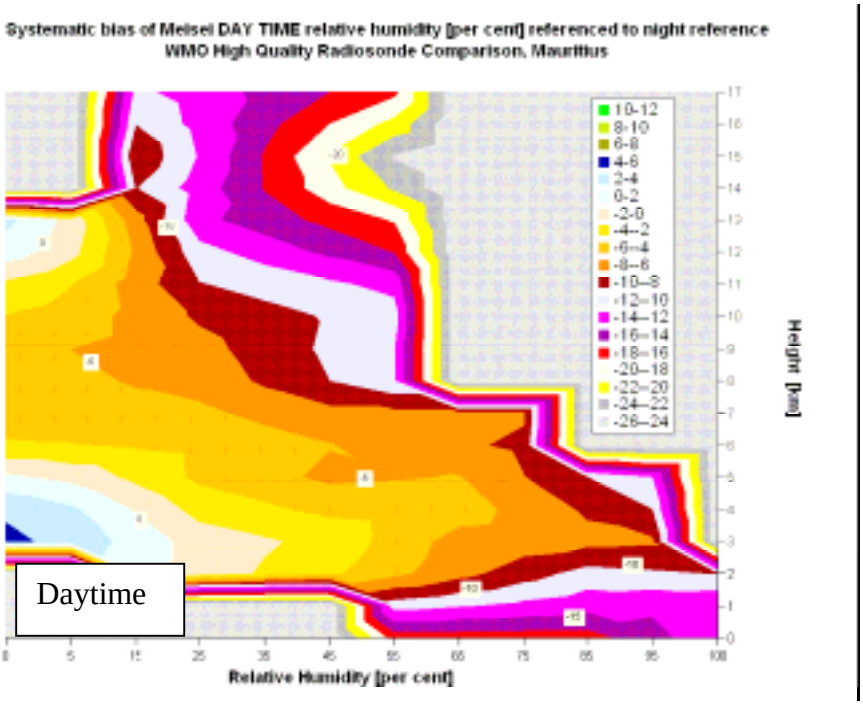


Fig. 10.9(d) Systematic bias for Meisei daytime relative humidity.

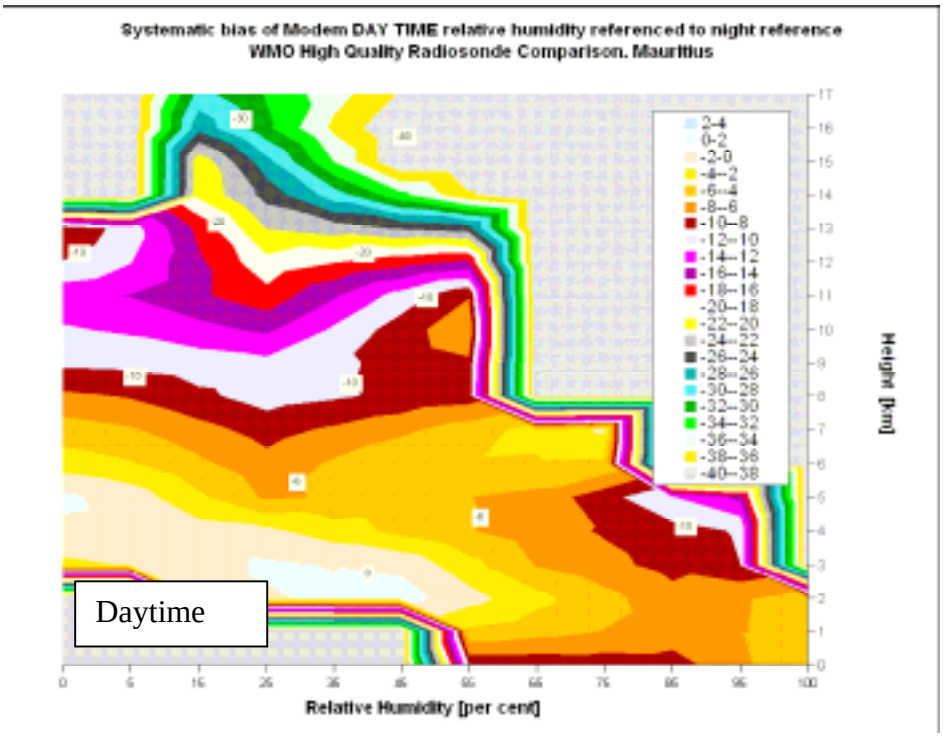


Fig. 10.9(e) Systematic bias for MODEM daytime relative humidity.

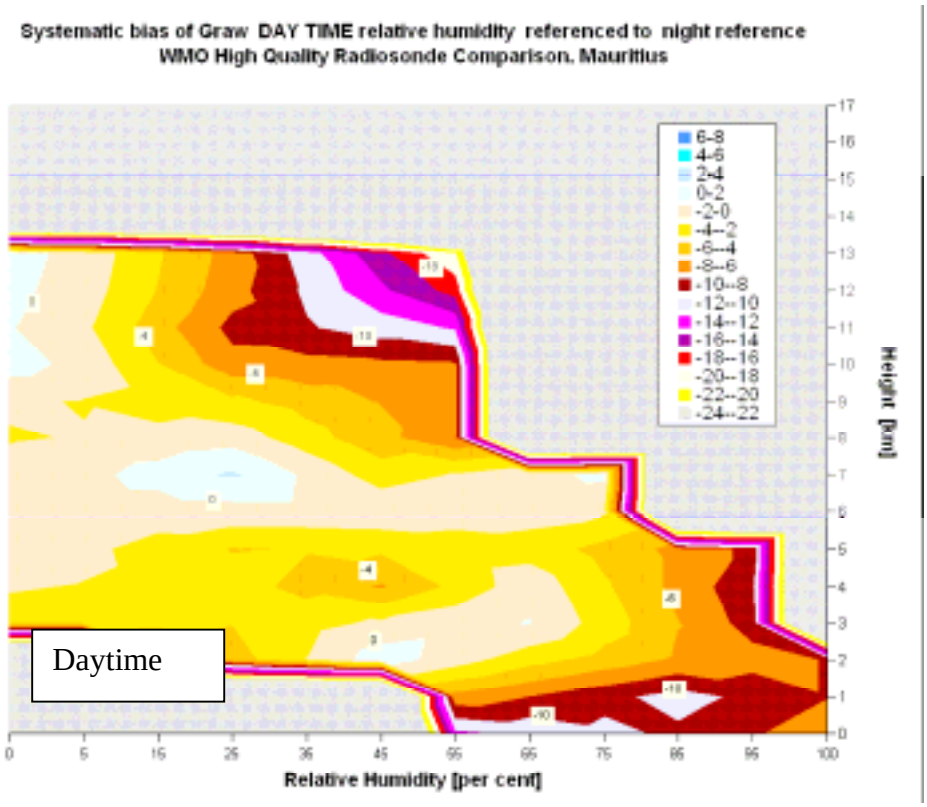


Fig. 10.9(f) Systematic bias Graw daytime relative humidity.

Fig. 10.9(b) shows the extent to which daytime Snow White measurements were assumed to be of similar quality to nighttime. Some positive bias relative to nighttime reference was starting to occur at heights of 12 km at low relative humidity, because of contamination in the daytime Snow White ducts.

Daytime Vaisala measurements, in Fig. 10.9(a), were shifted negative relative to nighttime measurements by between 3 and 7 % for heights up to 12 km; see Fig. 10.9(g). The values quoted for heights above 12 km were clearly less accurate and may be in error by several %. The results at lower levels which are constrained by the Snow White measurements should be reliable to about 1 %, in the lower troposphere, with slightly larger uncertainty (about 2 %) associated with the values in the middle troposphere. Vaisala relative humidity measurements at very low humidity had similar characteristics both day and night. Note: The Vaisala RS92 radiosondes used in Mauritius had improved protection against solar heating with an aluminized coating applied to the White glue and the bare copper on the sensor boom (as will be applied in current operational production models soon). However, the day-night difference remained similar to that observed previously in Brazil, suggesting that the heating problem is caused by direct absorption of sunlight on the surfaces near the sensors. Recent comparisons of Vaisala RS92 with the NOAA cryogenic hygrometer in Costa Rica (Vomel, et al, 2005) reported at AURA Validation Workshop, September 2005, show a day- night difference in the Vaisala RS92 measurements of about -7 % in the lower troposphere

Daytime Sippican relative humidity measurements, Fig. 10.9(c) were mainly within 5 % of the reference, and the problems with the positive bias above 15 km were less pronounced than at night. This may indicate that the problem at night is partially from contamination in the sensor duct.

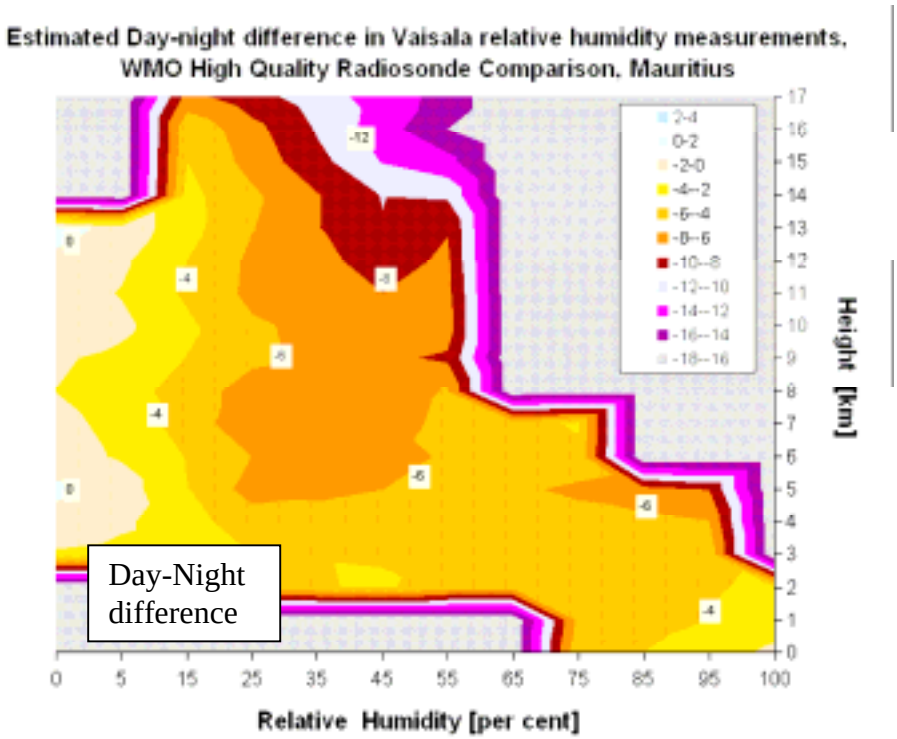


Fig. 10.9(g) Estimated Day- Night difference in Vaisala relative humidity.

Meisei and MODEM daytime relative humidity measurements, Fig. 10.8(d) and (e) both show very strong negative bias at heights above about 9 km and larger day-night differences than most of the other radiosondes at all levels. If the relative humidity sensor is not exposed high enough on the sensor boom to avoid air that has been heated by passing over the top of the radiosonde body, large day-night differences will result.

In night Graw measurements, there was a strong positive bias at 30 % relative humidity and height of 5 km, Fig. 10.6(e), but this bias is much less significant in the daytime Graw measurements Fig 10.9 (e). This would support the idea that the nighttime biases at midrange humidity were caused by contamination rather than by sensor calibration problems.

The magnitude of the random errors associated with the relative humidity measurements can be judged from the standard deviations associated with the systematic difference computed relative to Vaisala; see Figs 10.10 (a) to (e). Here, standard deviation values from day and night flights are combined together because in most cases there was little significant difference between day and night conditions. Fig. 10.10(a) shows that in situations where relative humidity was relatively stable with time, either moist or very dry, standard deviations between Vaisala and Snow White were in the range 1 to 4 per cent, suggesting the random errors in basic calibration were in the range 1 to 3 %. When rapid transitions in relative humidity were common the standard deviations went up to about 7 %, some of this caused by instability in Snow White measurements, but also with some limitations in the hysteresis/contamination after emerging from cloud of the Vaisala measurements. Here, the random errors in the relative humidity measurements may have increased up to 5 per cent. At heights above 12 km it is probable that the errors of both systems increased, and it would be unwise to assume that random errors were much lower than 10 per cent at 15 km for either system for the conditions in Mauritius.

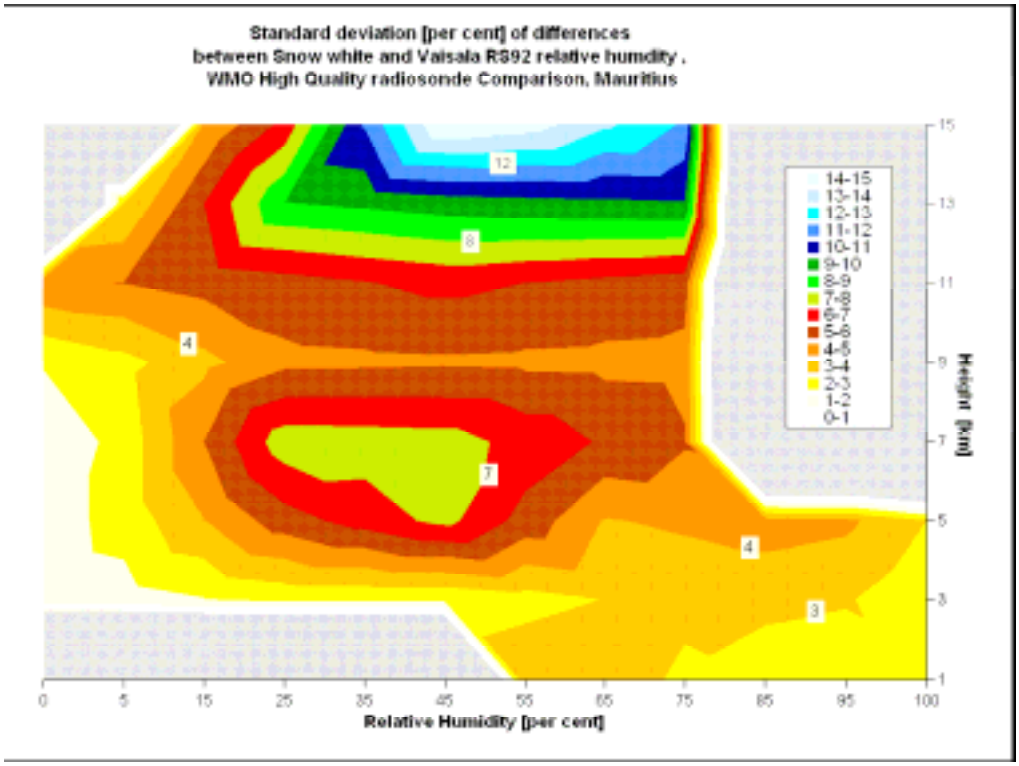


Fig 10.10(a) Standard deviations of differences between Snow White and Vaisala relative humidity.

The remainder of the relative humidity sensors had some functional similarity to the Vaisala sensors. Some errors may be common to both sensor types and may not show up in the standard deviations associated with the systematic differences. Thus, the standard deviations of these sensors relative to Vaisala are usually similar to or less than the values shown in Fig. 10.10(a).

Differences of Sippican LMS-5 relative humidity measurements with Vaisala showed smaller standard deviations than with Snow White,, Fig. 10.10(b).

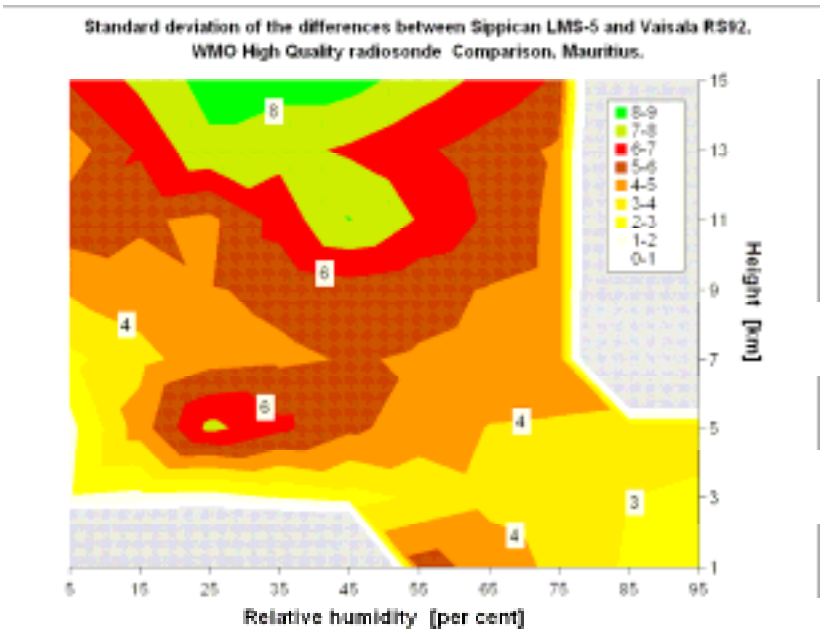


Fig. 10.10(b) Standard deviations of differences between Sippican LMS-5 and Vaisala relative humidity.

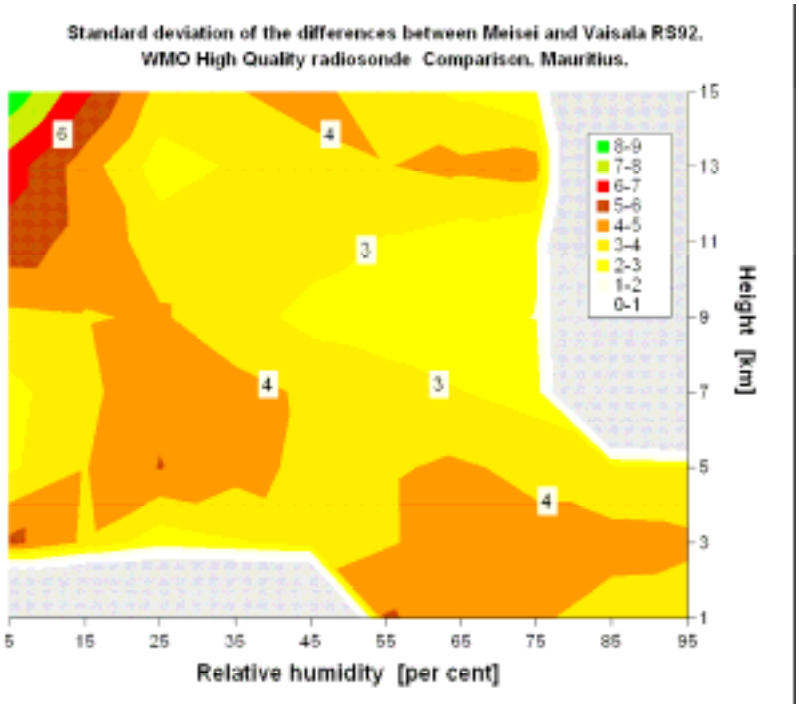


Fig 10.10(c) Standard deviations of differences between Meisei and Vaisala relative humidity.

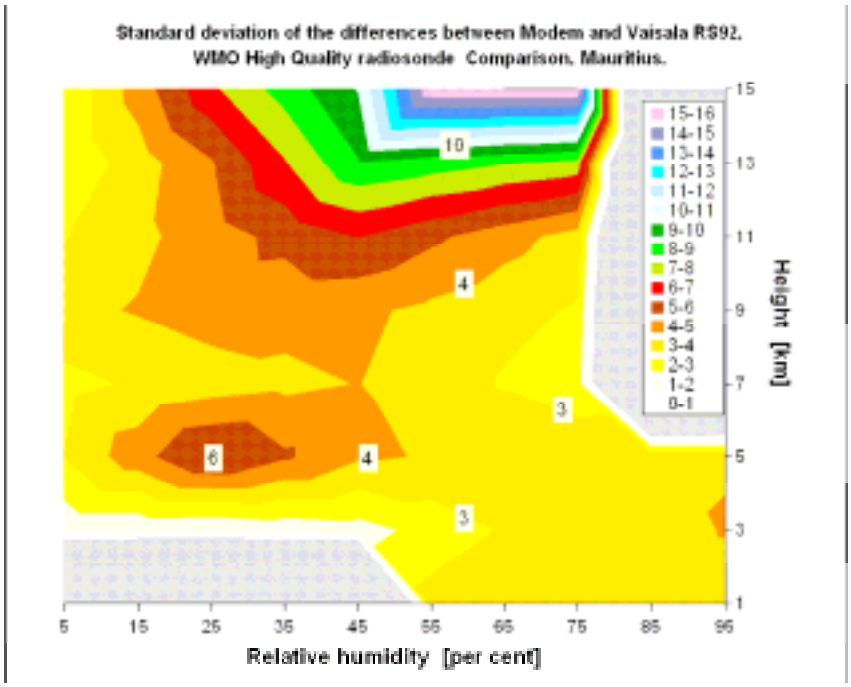


Fig 10.10(d) Standard deviations of differences between MODEM and Vaisala relative humidity.

Meisei relative humidity measurements, Fig. 10.10(c) had the smallest standard deviations relative to Vaisala at all levels. The random errors of Modem relative humidity measurements must have been similar to the other capacitative sensor at heights below 11 km, see, Fig. 10.9(d), but the random errors must have been larger than Meisei above 11 km.

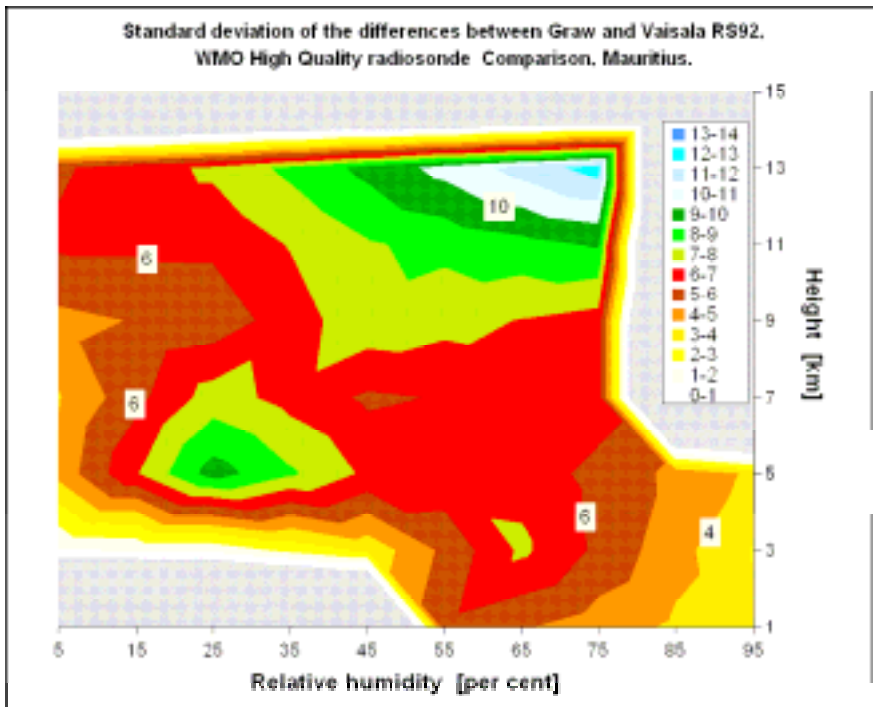


Fig. 10.10 (e) Standard deviations of differences between Graw and Vaisala relative humidity.

Graw relative humidity measurements; Fig. 10.10(e) had larger random errors than the other capacitance sensors between the surface and 12 km. Graw addressed this problem with a new relative humidity sensor that is available since October 2005.

Given that the relative humidity sensors have good reproducibility, more effort is required to minimize systematic sources of error associated with poor sensor exposure, failure to eliminate contamination from sensors in all of the troposphere, or failure to establish the correct temperature of the air where the relative humidity is measured.

11. RECOMMENDATIONS OF RADIOSONDES SUITED FOR GCOS AND SATELLITE CALIBRATIONS

In recent years there has been much criticism of radiosonde operations for changing equipment and hence disrupting traceable climate records since 1955.

This view ignores that:

- There is no point in attempting to standardize the equipment in use until it is capable of the performance requirements necessary for the task.
- The name of many radiosondes may stay the same, but the electronics always changes with time, because of the limited lifetime of modern electronic components.
- The radiosonde must be built in such a way that there is only one way to deploy the sensors, whoever is operating the system. If there are many ways of deploying the sensors then immediately the traceability is lost.

11.1 Temperature

In this test the temperature sensors were nearly all of the size to provide a high speed of response so that if:

- the sensor calibration was correct,
- the radiosonde signal channel electronics reliable, and
- data transmission and reception reliable,

then at night it should be possible that a long-term stability of measurement of ±0.1 K is potentially achievable. The small differences between the temperature measurements of most of the radiosondes in Fig, 9.6 indicates that many of the operational radiosondes were close to achieving the accuracy desired for long term climate monitoring, with problems mostly eliminated from the early design phases tested in the previous WMO intercomparison in Brazil.

The range of systematic bias at night in temperature measurements has reduced greatly compared to the previous WMO intercomparison in Brazil. So, please do not judge the capability of the future global radiosonde network by the less than optimum performance of radiosonde systems and software in countries where the equipment in use is well below the standard demonstrated here or from test results from older generation radiosondes.

However, only one radiosonde design had temperature sensor exposure in the daytime that should ensure the best accuracy for daytime measurements at the highest altitudes in the stratosphere. This means that there is still further room for improvement in daytime measurements quality for nearly all the daytime temperature measurements.

Pressure sensor errors have always limited the heights to which very stable temperatures could be reported. In this test, the GPS radiosondes have demonstrated that height assignment no longer needs to be a limitation on the heights to which radiosondes can usefully be used. Thus, reproducible heights with good long-term stability should be

possible with GPS radiosondes up to at least 40 km, given that the radiosonde batteries can sustain the longer flight duration.

Therefore, for the first time, most of the building blocks are in place to ensure optimum long-term stability in radiosonde temperature measurements, but some improvements in daytime measurements still need to be achieved. This is true for most of the radiosonde designs in this intercomparison and not just one. At the moment, the Mauritius results indicate quite clearly which radiosondes are closest to the time when the design could be standardized as satisfactory for climate work [i.e. producing temperature measurements of accuracy between 0.1 and 0.2 K], see Fig. 9.6, 9.9, 9.13 and 9.14.

11.2 Relative humidity/water vapour

In earlier WMO Radiosonde Intercomparisons, the only way to get close agreement between the sensors was to eliminate any flight that has passed through cloud or rainy conditions. This was because the carbon hygristor used in earlier USA radiosondes was not stable in these conditions and had negative errors on emerging from cloud and the Vaisala RS80 was often contaminated after passing through cloud and showed large positive errors on emerging from cloud.

Thus, if the old generation of humidity sensors had been tested in the intercomparison using the same methods of processing the systematic biases of many types would almost certainly have been 20 per cent or more from the reference in mid-range and low humidity at 5 km.

Here, the humidity measurements at night from Vaisala RS92 and Snow White chilled mirror hygrometer were in close agreement at heights up to 14 km, i.e. down to temperatures of -70°C. As most of the other radiosonde systems showed relatively small standard deviations relative to the Vaisala sensor, this suggests that if the problems with inadequate protection and or ventilation of these sensors in wet conditions can be overcome, most of the problems with large systematic bias at night can be overcome.

In daytime conditions, only Snow White appeared to make measurements close to the most reliable nighttime measurements. However, Snow White was unable to make useful daytime measurements at temperatures lower than -50°C, in the moist conditions prevailing in the Mauritius intercomparison.

It would appear that a stability of 2 per cent relative humidity should be achievable from radiosonde measurements at night at all temperatures down to - 70°C with more developments to the current sensor designs. This may also be possible in the daytime in future, since random errors in relative humidity seem similar day and night. In Mauritius the three most reliable humidity sensors were Vaisala RS92, Snow White and Sippican, but all three require more development to optimize performance.

It is also possible that the Vaisala RS92 and Snow White can be improved to produce reliable measurements to 5 per cent accuracy in relative humidity down to -90°C.

These accuracies seem to fall short of stated climatological requirements for measurement stability, but there is currently no other technique with all weather capability that can produce reliable relative humidity profiles.

11.3 Winds

All the GPS radiosondes in this test can measure winds accurately enough to any height to satisfy climatological requirements, given that the batteries are capable of sustaining the necessary flight durations.

11.4 Limitations on radiosonde sampling caused by small-scale atmospheric motion

The limitations imposed on each radiosonde sample by small-scale motions in the tropics can be illustrated by plotting all the temperature and humidity observations for one day as a function of height. Results for Vaisala measurements on February 8 and February 22 2005 are shown in Fig. 11.1 for temperature, 11.2 for relative humidity, 11.3 for wind, u component and 11.4 for wind, v component. There were no significant synoptic changes near Mauritius on 8 February and some small changes in tropospheric winds on 22 February.

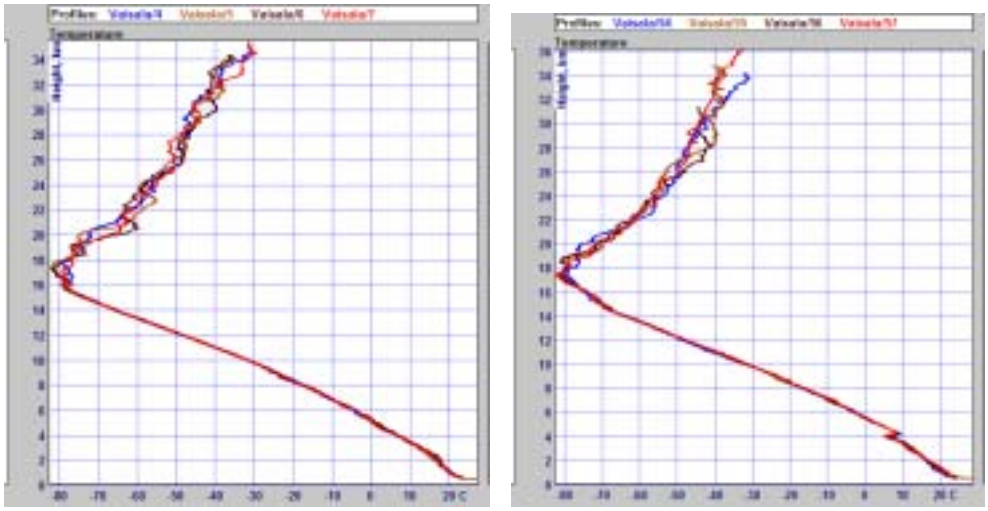


Fig. 11.1 Comparison of four radiosonde temperature measurements within 14 hours, demonstrating the influence of small scale atmospheric motions in the stratosphere.

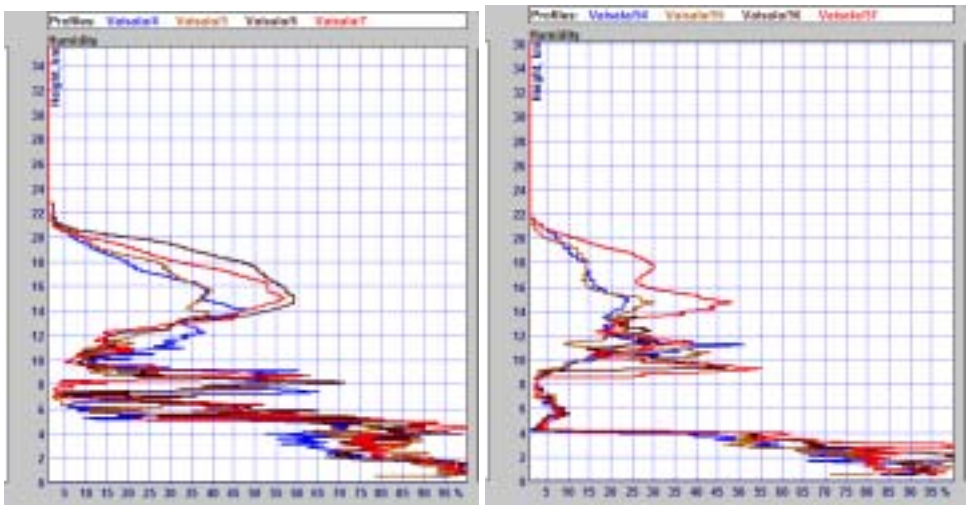


Fig. 11.2 Comparison of four radiosonde relative humidity measurements within 14 hours, demonstrating the large variability of relative humidity in some layers in the troposphere, and the small variability in others over relatively short periods.

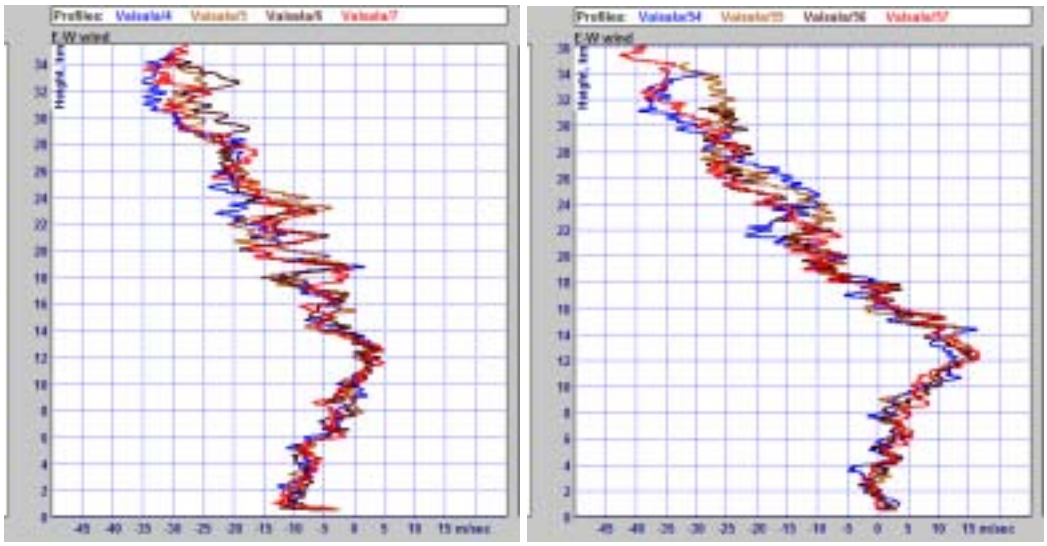


Fig. 11.3 Comparison of four radiosonde u component measurements within 14 hours, demonstrating the large variability of wind in some layers in the stratosphere.

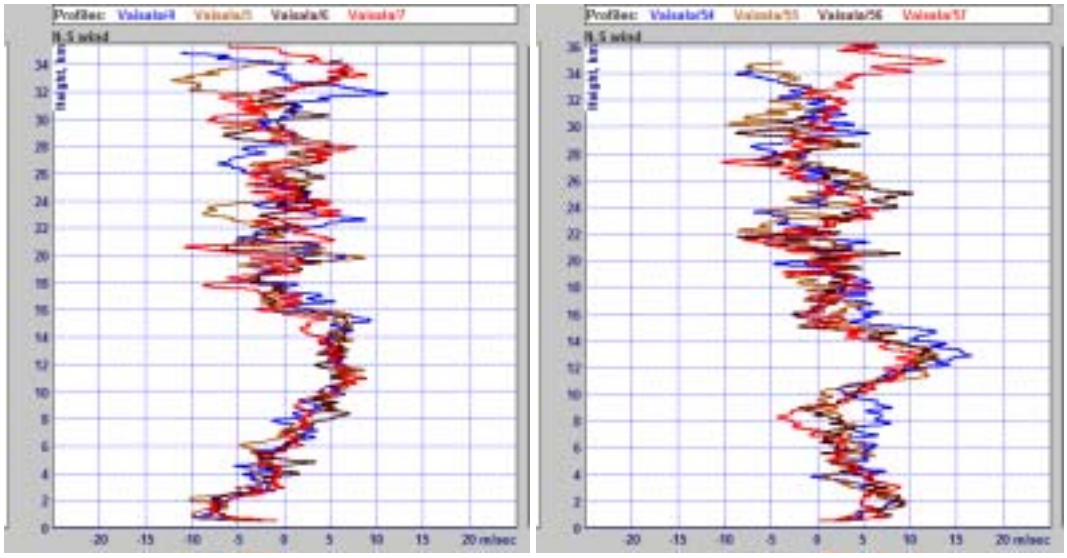


Fig. 11.4 Comparison of four radiosonde v component measurements within 14 hours, demonstrating the large variability of wind in some layers in the stratosphere.

The variations between the flights shown in Figs 11.1 to 11.4 are all real and not the result of measurement error, apart from the differences between nighttime and daytime relative humidity between 14 and 22 km in Fig. 11.2.

When designing observing networks, the magnitude of the perturbations in the radiosonde sample needs to be taken into account.

When samples are spread throughout the test, the influence of atmospheric variability on averages over longer time scales can be seen in all the examples from different radiosonde type measurements:

- Fig. 11.5 for Sippican daytime temperature measurements;
- Fig. 11.6 Snow White night relative humidity measurements;
- Fig. 11.6(a) Snow White night dewpoint measurements;
- Fig. 11.7 Modem daytime, u wind component measurements;
- Fig. 11.8 GRAW daytime, v wind component measurements.

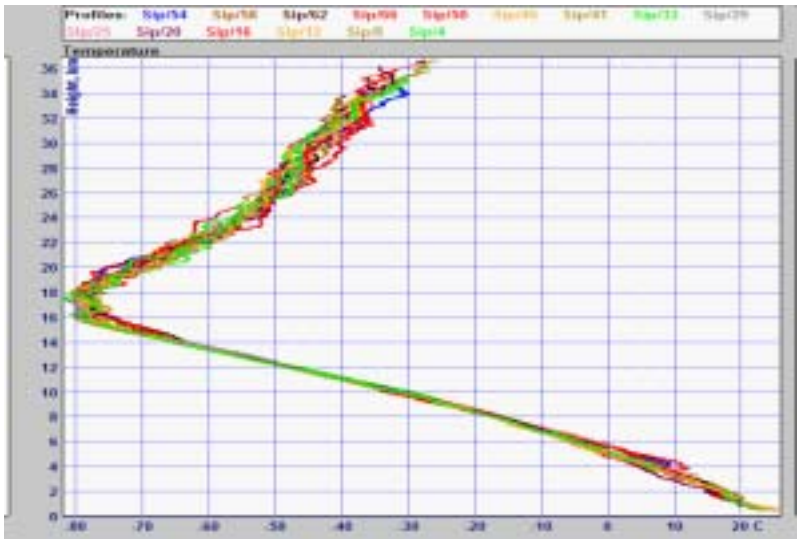


Fig. 11.5 All Sippican daytime temperature measurements.

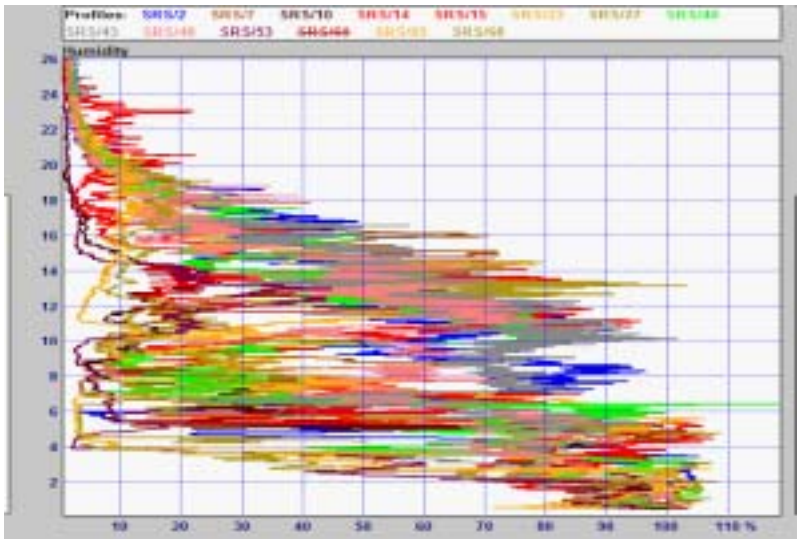


Fig. 11.6 All nighttime Snow White humidity measurements.

The dominance of short-term variations in temperature in the stratosphere on climatological averages in the tropics is clear in Fig. 11.5.

The very wide spread of relative humidity in Fig. 11.6 illustrates the difficulty of making representative climatological observations of water vapour in the tropical troposphere, even in the upper troposphere which clearly varied from very dry to saturation during this test..

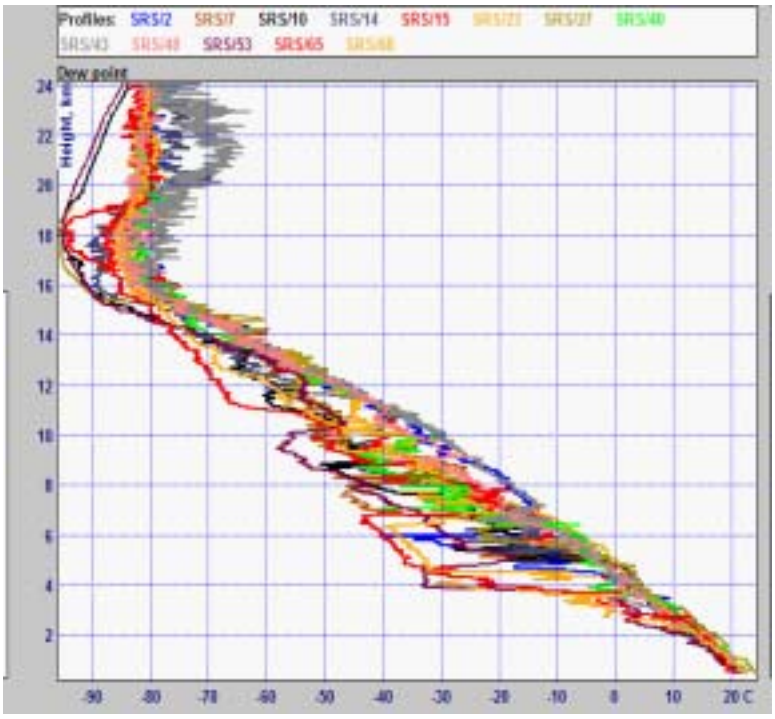


Fig. 11.6(a) All nighttime Snow White dewpoint measurements

Fig. 11.6(a) presents the summary of the Snow White dewpoint measurements with the large range of relative humidity at 15 km in Fig. 11.6 corresponding to a range of dewpoints of about 14 °C from -72 to -86°C.

Taking a longer sample with the wind components gives a similar level of variability in the stratosphere to the single day observations, but the variability in the troposphere becomes larger than in the stratosphere because there was significant long term synoptic scale variability in the troposphere, see Fig. 11.7 and 11.8..

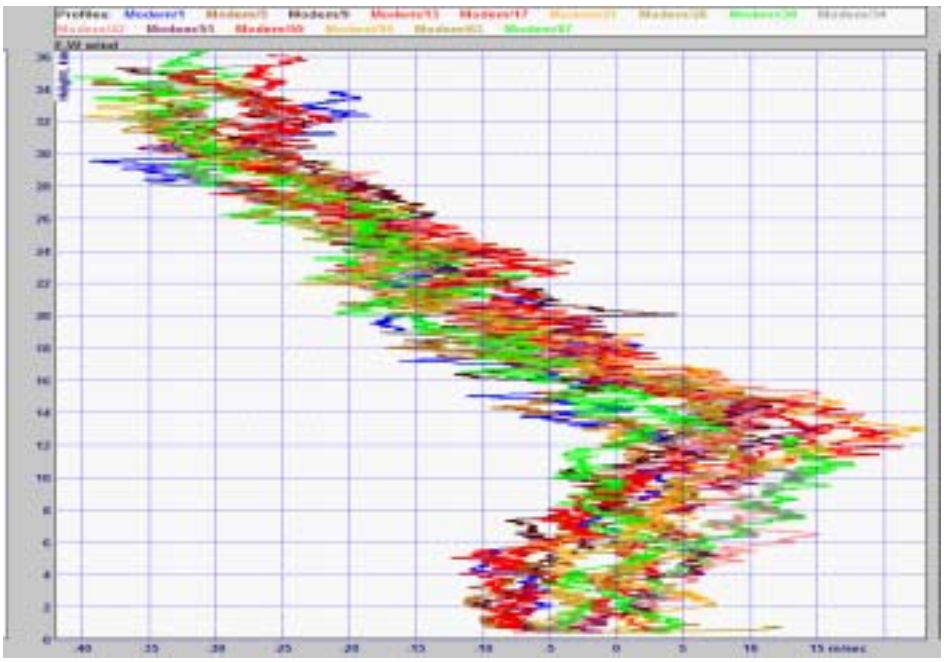


Fig. 11.7 All Modem daytime u wind component measurements.

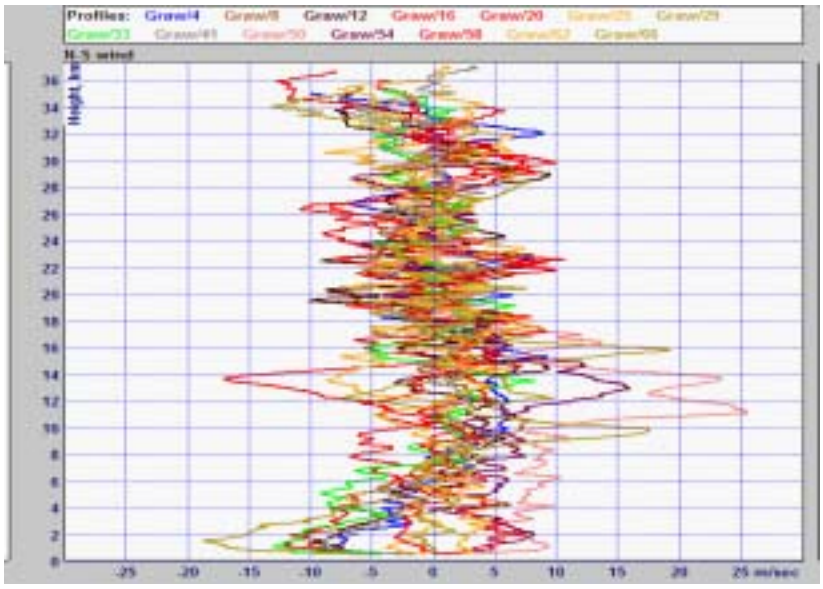


Fig. 11.8 All daytime GRAW v wind component measurements. Here, the outlying winds in the troposphere were associated with tropical storms passing close to Mauritius, and with similar winds observed by all systems on the flight.

11.5 Are special reference radiosondes required?

In the intercomparison in Mauritius, both 3-thermistor radiosondes and Snow White chilled mirror hygrometers proved useful in interpreting the results, but would not have given a reliable climatological sample without using the operational radiosondes to identify the anomalies and errors of the two working references.

Further deployment of improved 3-thermistor and chilled mirror hygrometers is recommended for future testing of radiosonde developments in support of climate observing networks.

Measurements of water vapour appear the least satisfactory compared to stated user requirements, so reference type developments would be best concentrated in this area, but there needs to be a review to identify user requirements that are realistic for climate observations.

If further improvement of the operational radiosondes is successful, the best radiosonde observing strategy for climate reference or satellite calibration reference sites may be to use two different operational types at the given reference site. This removes the dependence on one manufacturer and allows crosschecking between the two sets of measurements to identify possible drift. This cross-check could be performed by comparing standard level geopotential measurements 30 minutes apart, whilst combining the two measurements together to provide a more representative sample for satellite calibration activities.

These issues need to be discussed more deeply with the user communities now that the analysis of the test has been completed.

12. REMOTE SENSING

The remote sensing systems deployed at Vacoas to support the intercomparison were:

- Vaisala CT75K laser ceilometer, provided by Vaisala, with data logging supported by the Finnish team, see Fig 12.1(a)
- Rutherford Appleton Laboratory (RAL) 78 GHz fmcw cloud radar, supported by M. Oldfield (RAL) and D. Lyth (Met Office) with funding from COST secretariat in Europe.
- GPS water vapour sensor, installed by R. Smout (UK) and processed subsequently in the UK by J. Jones (Met Office), see Fig. 12.1(b)

Fig. 12.1(a) Vaisala CT75K lidar ceilometer plus Rutherford Appleton Laboratory 78 GHz fmcw cloud radar (centre of picture) operating in the wet towards the end of the intercomparison.

The lidar ceilometer and GPS water vapour sensors were available throughout the test. However, there were some periods when problems occurred with data logging and data are not available.

The cloud radar was only available from 16 February until the end of the intercomparison. A critical component in the cloud radar had failed in late 2004 and the Met Office was grateful to RAL for quickly acquiring a spare and shipping the system to Mauritius. The cloud radar suffered some system failures in shipment to Mauritius, and Dr. Pathack (computer faults) and the Mauritius technicians (power supplies) provided energetic support to Mr Oldfield in solving the problems.

Fig. 12.1(b) GPS water vapour sensor installed on the handrails of the staircase to the roof, Vacoas.

Although there were some problems with the availability of GPS water vapour measurements, there were sufficient to use in support of the estimation of day-night differences in the radiosonde relative humidity measurements, see Fig. 10.6.

The GPS water vapour antenna was installed at an early stage of the test, and been subsequently some other radiosonde antenna were installed nearby that interrupted the field of view and caused multipath problems under some conditions. Thus, certain parts of the GPS water vapour record were not reliable enough to be used. It would have been better if the sensor had been installed away from the other antenna. This would also have avoided confusion when the intercomparison finished, since it had been intended to leave the system in operation for a week after the test to reduce uncertainty in the location of the sensor, but the sensor was dismantled at the end of the test because it was thought to be a radiosonde system receiver.

The number of GPS water vapour sensors in the Indian Ocean was very limited and the quality of the GPS solutions would have benefited from one or two more receivers on Mauritius and possibly one on Rodriguez.

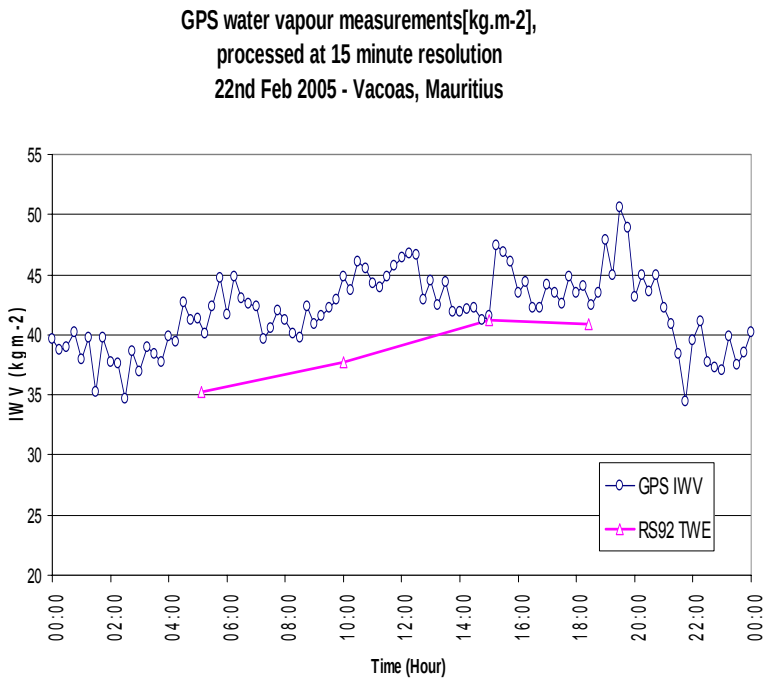


Fig. 12.2 Example of 24 hours of GPS water vapour measurements processed at 15-minute resolution, Vacoas, Mauritius compared with IWV from Vaisala radiosonde measurements. Time is UTC so that the radiosonde ascent just before 16.00 UTC was in the dark.

The performance of both the laser ceilometer and the cloud radar at Vacoas raised some questions, since most systems reported cloud in the lower and middle troposphere, but rarely (ceilometer) and never (cloud radar) at heights above 7 km. It is possible that this type of instrumentation has rarely been thoroughly tested in the wet conditions encountered in Vacoas. It is known that rain reaching the ground and wetting the cloud radar antenna can decrease the sensitivity by as much as 10 dB. This may have effect the radar measurements in Mauritius. The CT75K may not have been sensitive enough to detect high cirrus clouds especially in daytime. An example of the different information available from laser ceilometer and cloud radar in the lower troposphere is shown in Figs. 12.3(a) to (c). Fig 12.3 (a) shows a time versus height plot of basic laser ceilometer output (signal +noise) from 16 February 2005. Fig. 12.3(b) shows range corrected signal power output from the 78 GHz cloud radar. The cloud radar is extremely sensitive to back scattering from drizzle size drops. In the cloud shown here, the drizzle rate was probably just high enough to feel intermittent drops impacting an observer stood outside. This was a limited shower passing over Vacoas, not heavy rain. In Fig. 12.3(c), data from the radiosonde test flight at 10.16 has been superimposed on the cloud radar plot. The cloud top and base were probably as shown. The three relative humidity measurements on this test flight indicate some fluctuations in relative humidity within the cloud layer. Meisei relative humidity increased with time in the cloud, as the chemical contamination started to outgas, whereas both Modem and Vaisala relative humidity reduced as the radiosondes moved close to the cloud top. As this was a daytime ascent, it is probable that solar heating started to introduce a negative bias of 2 to 3 per cent in relative humidity for Modem and Vaisala in the upper part of the cloud. However, given the small-scale variability in cloud structure in the horizontal, this conclusion can only be validated if this type of pattern occurred on a large number of daytime ascents through cloud.

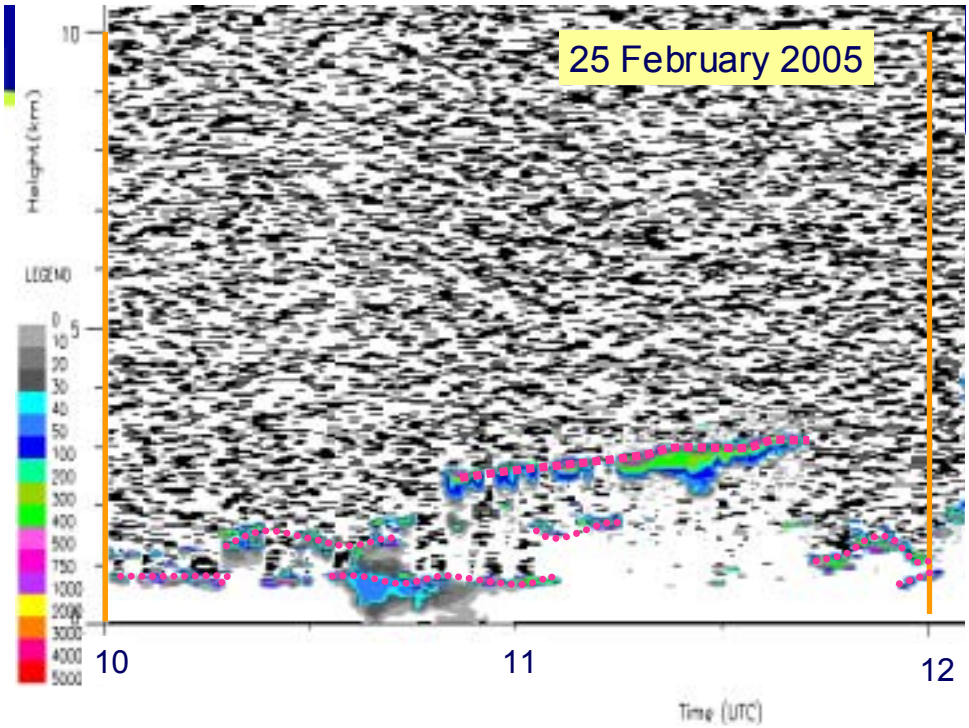


Fig. 12.3(a) Time v height cross-section, CT75K signal output, dotted and dashed on 25 February 2005, purple lines are for referencing position of ceilometer signals to cloud radar output in Fig. 12.3(b).

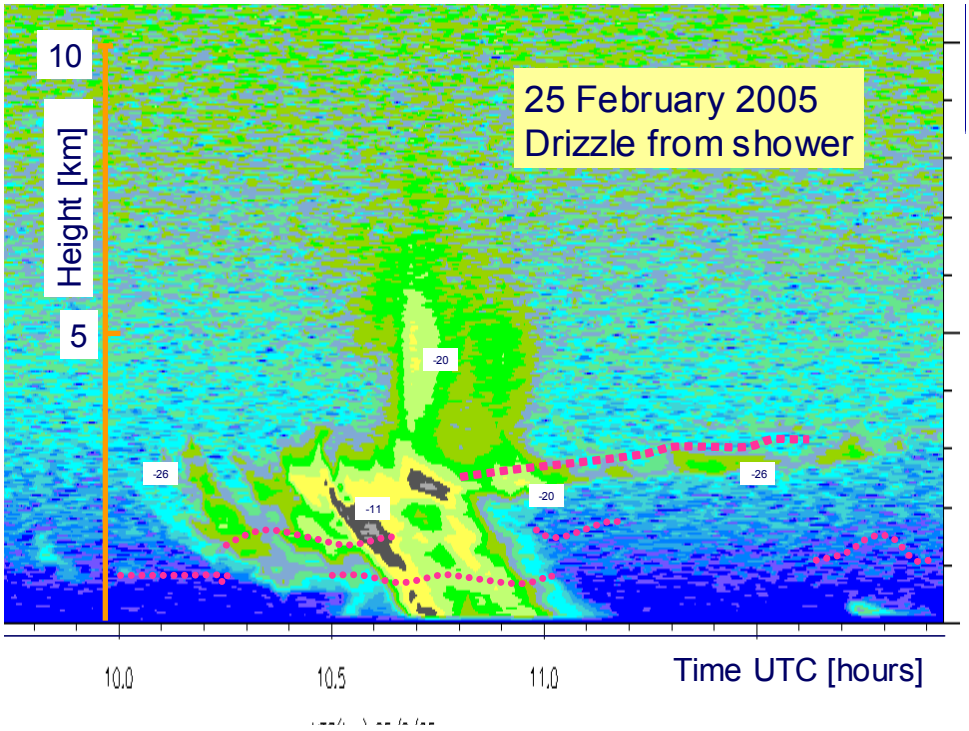


Fig. 12.3(b) Time v height of range corrected 78 GHz cloud radar output, backscatter contoured at 3 dB power intervals, absolute values are arbitrary, since the cloud radar appeared to have different sensitivity from earlier tests in Switzerland and UK.

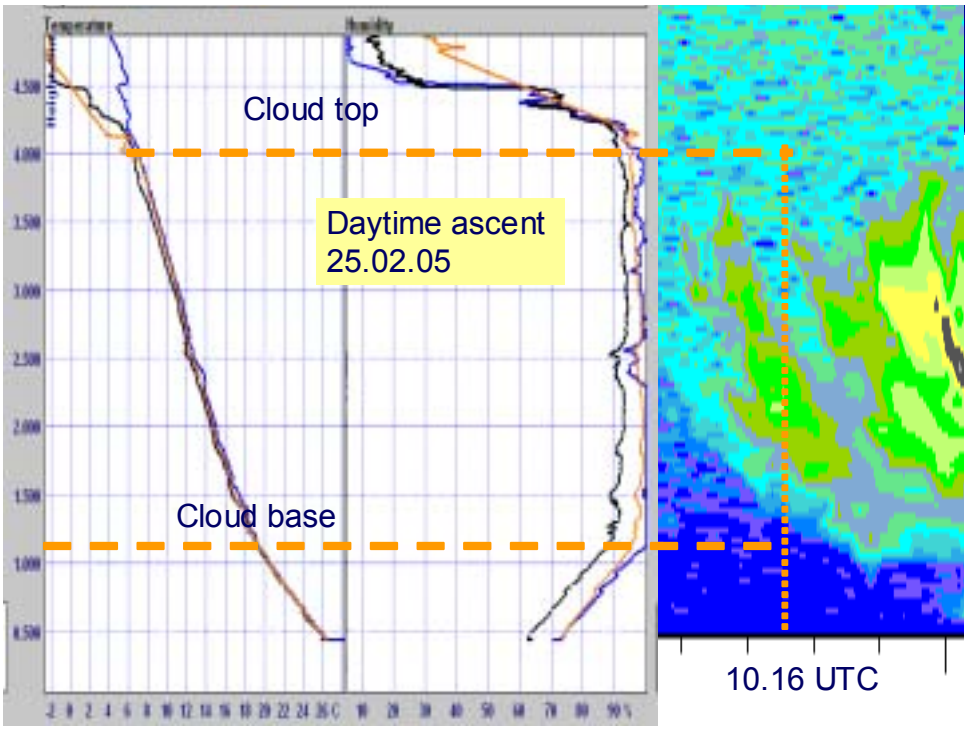


Fig. 12.3(c) Relationship between radiosonde test data from Flight 67, 10.16 hour on 25 February 2005 and cloud radar output.

In Fig. 12.4(a), GPS water vapour measurements at 15 minute intervals are superimposed on cloud radar measurements for 24 February 2005. Information from the laser ceilometer on cloud base and the lowest level of precipitation falling from the cloud is also plotted. In this example the cloud radar measurements have not been range corrected.

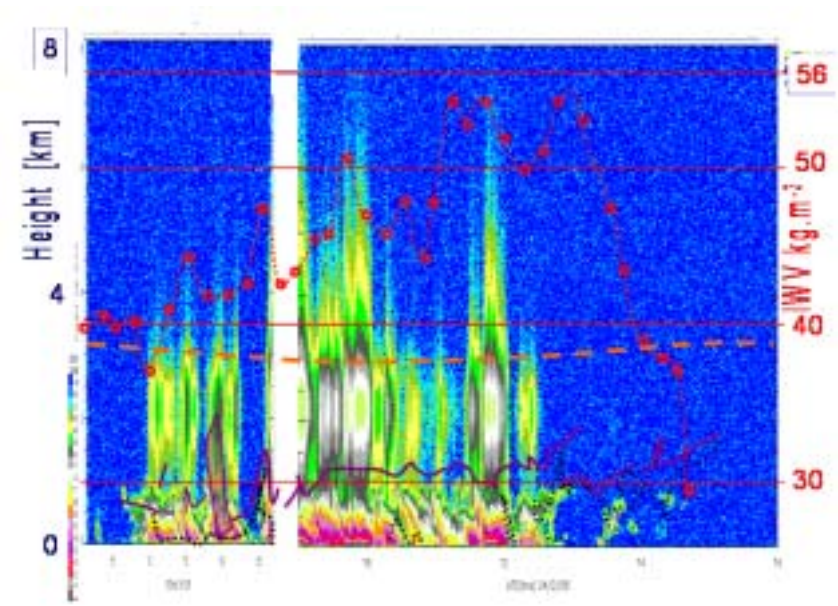


Fig. 12.4(a) Integrated water vapour from GPS superimposed on cloud radar measurements on 24 February 2005, showing the water vapour increasing with time during the day until the showers stop in the evening. The solid purple lines are strongest signals from the ceilometer (cloud base); the dotted block lines are the bottom of precipitation falling from the clouds as seen by the laser ceilometer. Dashed orange line estimated bottom of extremely dry layer from radiosondes.

Both cloud radar and ceilometer show precipitation falling from the cloud to the ground for much of the time from a succession of small showers. Here, the cloud radar sensed the precipitation at low levels earlier than the ceilometer at around 07.00 UTC, with drizzle near the ground probably advected by wind from an adjacent shower. At certain times, the cloud radar does not sense low cloud that is detected by the ceilometer, e.g. 8.30 and 13.00 to 15.00. This occurs when there are very few drizzle size drops in low cloud.

The dashed orange line indicating the bottom of a very dry layer was derived from the radiosonde ascents. Thus, in the regions where the cloud radar shows signal extending above this level, the cloud radar signals are likely to be anomalous. This type of artifact has been observed earlier in showery weather in England. The cloud radar signals near the ground are very strong relative to any upper signals between 09.00 and 11.00 and around 12.00. This led to suspicions that the optics in the cloud radar had become misaligned during shipment. Fig 12.4 (b) shows the radiosonde test flight at 10 through one of these occasions.

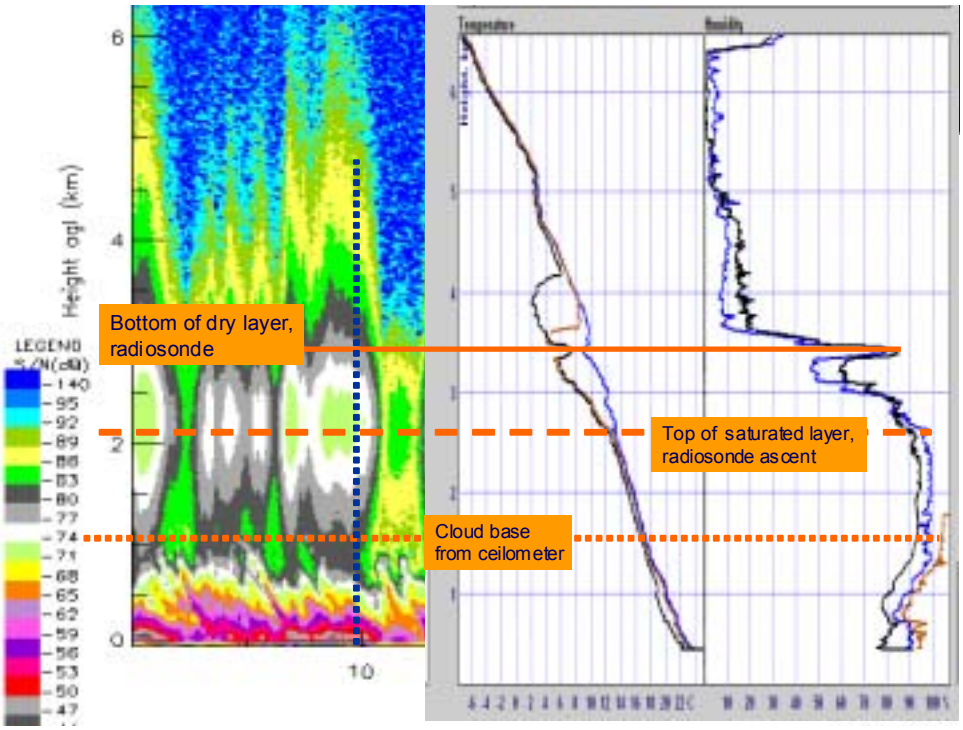


Fig. 12.4(b) Radiosonde test flight results from 10.00 on 25.02.05 superimposed on cloud radar measurement. Radiosondes reporting were Vaisala, blue, Meisei black and SRS (brown) but the SRS relative humidity became totally contaminated on entering cloud.

The radiosonde shows that there was a dry layer under the cloud. Near the ground a shallow layer, about 200 m thick, has much higher relative humidity than the layers above. This layer corresponds to the levels at which the cloud radar shows the very strong signal. Thus, there may be a meteorological reason why this shallow layer with enhanced drizzle size drops occurs with rain falling through a dry layer from a cloud higher up.

Fig. 12.5 (a) shows the laser ceilometer data displayed for two days on an occasion when the ceilometer was able to detect cloud between 5 and 10 km for the period 16 .00 on

18 February until 05.00 on 19 February, [note the ceilometer time in this figure was 2 hours in advance of UTC and 2 hours behind Mauritius local time]. Here the display software was provided by H. Klein Baltink. Pictures of the cloud conditions at 05 UTC [07 hours in Fig. 12.5(a)] 19 February and 14.48 UTC [16.48 hours in Fig. 12.5(a)] can be found in Annex C.

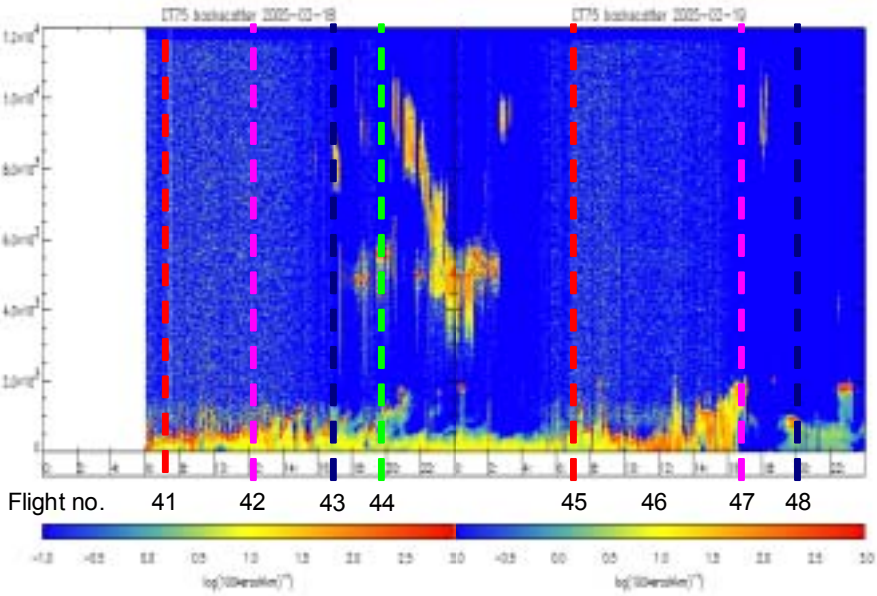


Fig. 12.5 (a) Two days data, near the end of the second week, from the Vaisala CT75 laser ceilometer, plotted using software provided by H. Klein Baltink. The times of the relevant radiosonde test flights are indicated by the vertical dashed lines. Height is above the surface.

The radiosonde relative humidity for ascents 41 to 44 are represented by Vaisala measurements in Figs 12.5(b). It is difficult to tell whether the ascents actually passed through low cloud, apart from Flight 44. Flights 42 to 44 probably passed through or close to cirrus at upper levels. The intermediate shallow cloud layers indicated by ascent 44 were supported by the laser ceilometer observations; see Fig. 12.5(c) for the laser ceilometer output plotted by Met. Office software.

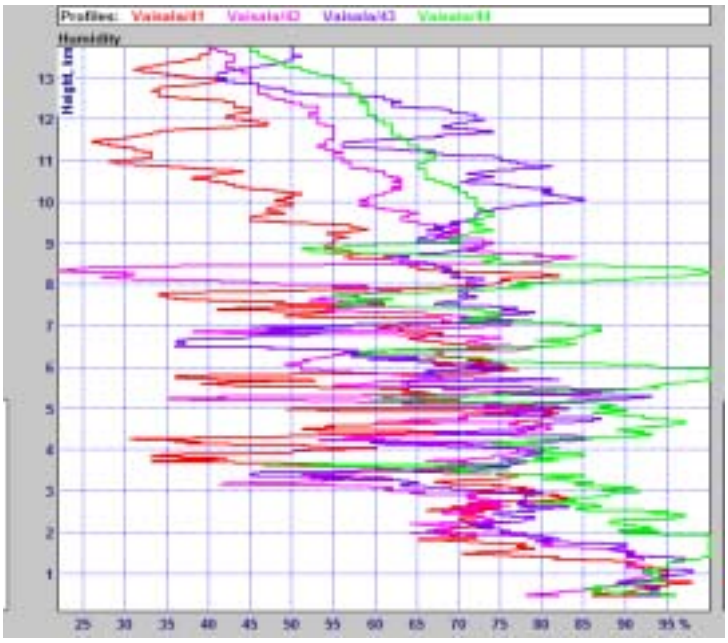


Fig. 12.5(b) Radiosonde relative humidity measurements on 18 February, 2005 Height above sea level

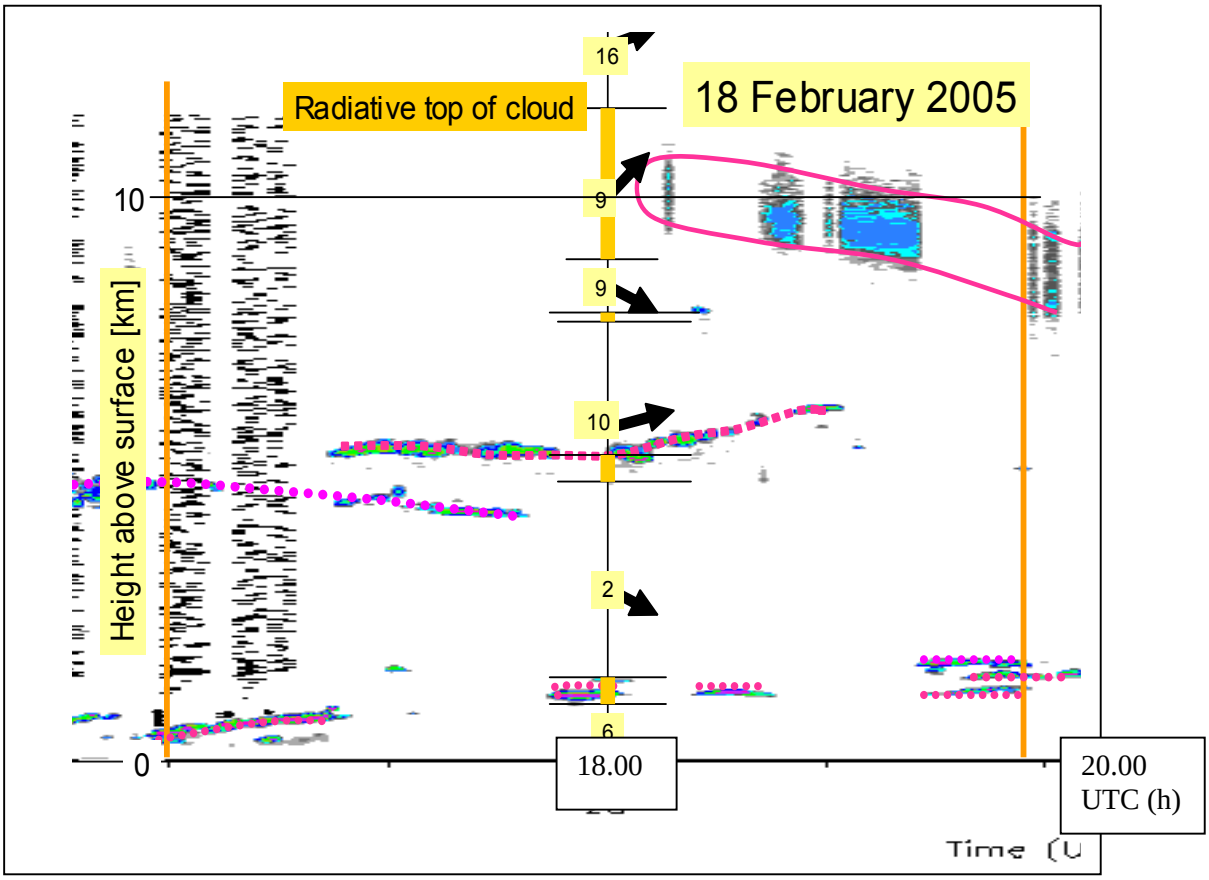


Fig. 12.5(c) Detailed comparison between Radiosonde relative humidity measurements on 18 February 2005 and laser ceilometer output, height above the surface. Radiosonde ascent indicated by black vertical line, thick gold line indicates layer near saturation. The arrow indicates wind direction [pointing to the right, westerly wind, pointing towards the bottom of the plot, northerly wind] number in yellow box wind speed in ms-1. All the moist layers are located near cloud, but not always at exactly the same height as indicated by the ceilometer.

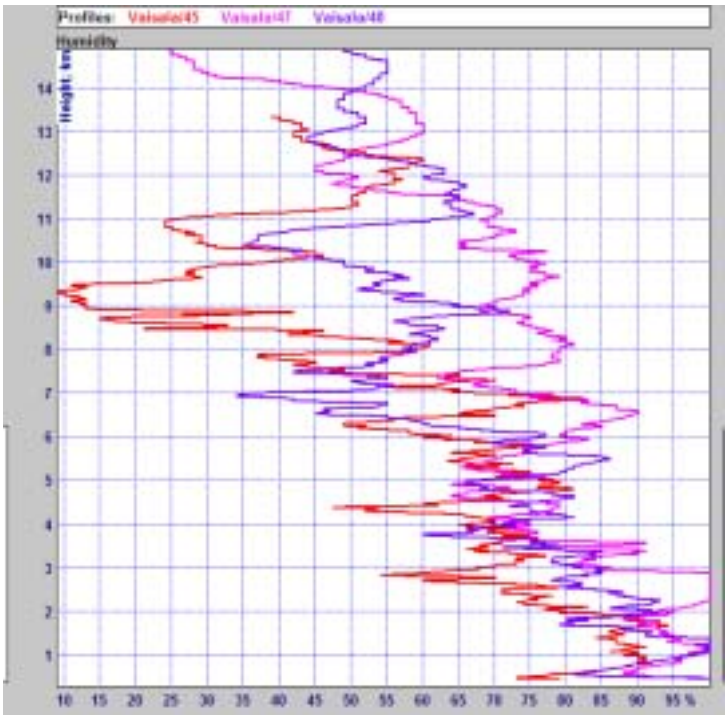


Fig. 12.5(d) Radiosonde relative humidity measurements on 19 February 2005, Height above sea level.

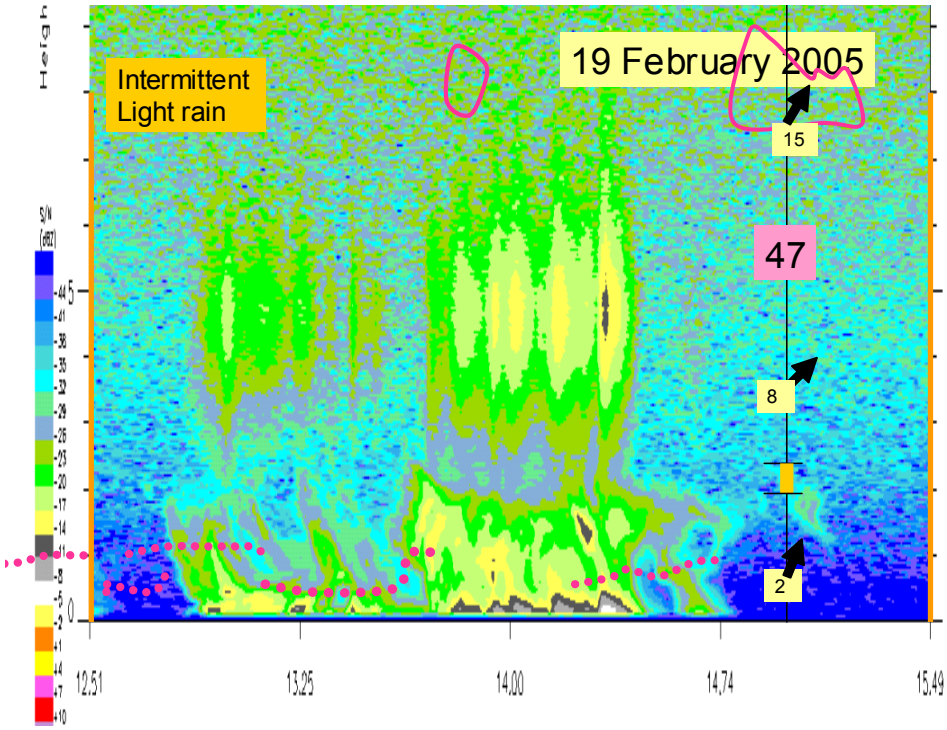


Fig. 12.5 (e) Range corrected fmcw cloud radar output showing the showers preceding Flight 47. The radiosonde ascent measurements are represented for Flight 47 using the same symbols as in Fig. 12.5 (c). Pink lines correlate to Laser ceilometer output as shown in Fig. 12.5 (c). Height is above the surface.

The radiosonde relative humidity for ascents 45 to 48 are represented by Vaisala measurements in Figs 12.5(b). Flight 45 did not pass through any cloud up till at least 11 km. On this day heavy rain was forecast to develop around Mauritius. By 4 hours later heavy localized showers had started near Vacoas and the heavy rain falling from mid-level cloud damaged the balloon so Flight 46 was abandoned. Flight 47 was launched during a period of intermittent light rain following a succession of less intense showers detected by the fmcw cloud radar; see Fig. 12.5(e). Flight 47 relative humidity indicates layers close to saturation with respect to ice from about 6 to 12 km. Most of the layers between 6 and 11 km had dried out significantly by the time Flight 48 was launched.

These examples show that by operating remote sensing during the test it is possible to gain a much better insight into the meteorological conditions. Possible problems with the radiosondes associated with cloud measurements and possible problems with the remote sensing instrumentation can be identified. The combination of the radiosondes and remote sensing gave a very much more comprehensive picture of the upper air-conditions above Mauritius, than is usually available.

A more detailed account of the remote sensing investigations in Mauritius will be published later.

The main success of this first attempt to utilize remote sensing directly in radiosonde testing was that the GPS water vapour measurements were useful in identifying day- night differences in radiosonde relative humidity.

The main lesson learned was that the remote sensing equipment needed to be established on the site for the intercomparison well before the radiosonde test began. It was too much work for the project team to concentrate on setting up both types of system at the same time. With the systems established well in advance it also allows anomalies in the remote sensing systems to be identified in advance, so that rectification or supporting experiments to understand limitations can be put in place before the test starts.

Prof. H. Richner (Switzerland), supported by COST funding, supervised the logging of all the remote sensing data and was responsible for assembling a database that could be used for comparison with CHAMP GPS occultation measurements of temperature and humidity profiles over Mauritius during the intercomparison; see Fig. 12.6. [Satellite-derived temperature and humidity profiles based on GPS occultation measurements by the CHAMP satellite; data provided by J. Wickert, GeoForschungsZentrum (GFZ), Potsdam, Germany].

He is in the process of assembling a database at the Institute for Atmospheric and Climate Science, ETH Zurich. It will contain all remote sensing data, and can be accessed using an Internet browser. In addition, he computed mean profiles for each of the multiple ascents, using a combination of those radiosondes that subjectively agreed best. These profiles are available both in graphic and numerical form. Naturally, all data files will be complemented by an appropriate description of the contents and formats.

There were a total of 27 temperature and humidity profiles derived from the CHAMP satellite. The separation between density (i.e. temperature) and humidity effect on the total observed GPS delay observed by the satellite, was made by using an iterative process, i.e., without resort to any other system or data. These profiles were kindly provided to us by the colleagues from the GeoForschungsZentrum Potsdam. See Fig. 12.7 for an example of a water vapour profile.

Studies will have to show whether humidity information in the upper troposphere and the lower stratosphere can be improved by combining radiosonde and satellite information: The observed radiosonde temperature profiles could be used when deriving the humidity profile from the occultation measurements, thus eliminating an inherent ambiguity. However, it must be born in mind that satellite data is averaged over a very large area (not necessarily

cantered at the location where the radiosonde ascent was made), while the radiosonde provides a local profile. On the other hand, the fact that the spatial variability of the atmosphere decreases with height alleviates the problems arising from this fact.

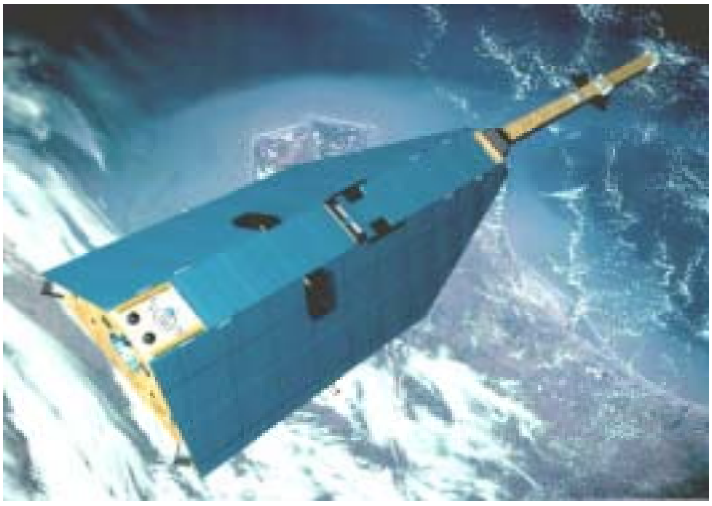


Fig. 12.6 CHAMP satellite which measures - among other geophysical parameters - the occultation parameters of GPS satellites.

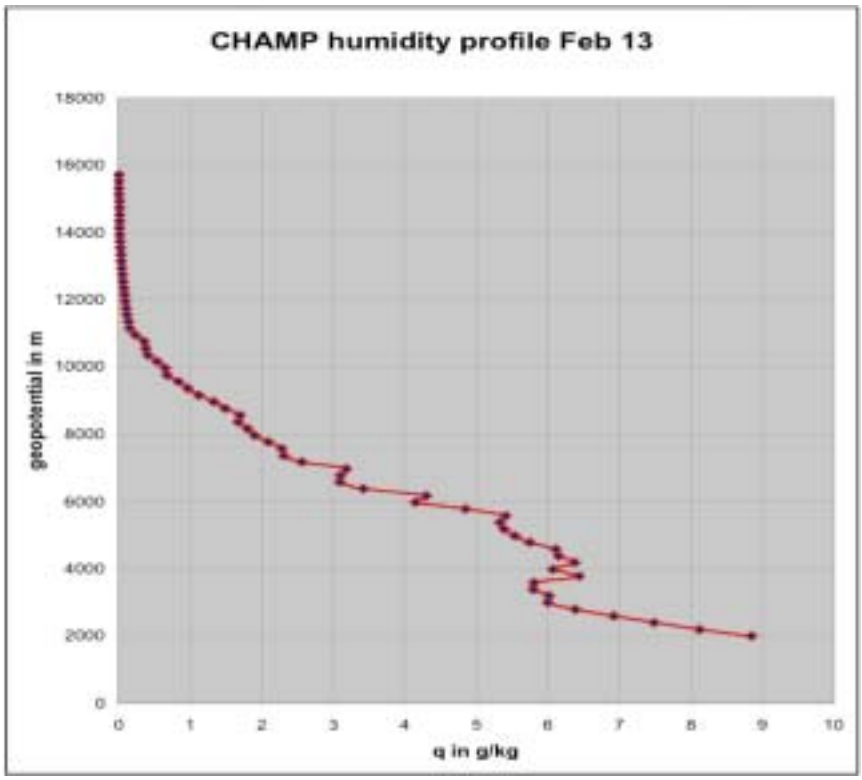


Fig. 12.7 Example of a satellite-derived humidity profile. This profile was generated without referring to any other data.

13. CONCLUSIONS AND RECOMMENDATIONS

13.1 Conclusions

13.1.1 Organization of the test

1. The WMO High Quality Radiosonde Intercomparison was completed successfully in February 2005. Many practical difficulties were solved because of strong teamwork between staff of the Mauritius Meteorological Services, participating manufacturers, and the WMO project team.

2. The financial investment in performing this intercomparison has been justified by the benefits obtained by manufacturers, radiosonde data operators, and data users. The results will inform radiosonde procurement activities in many parts of the world; however, there remains a clear mandate to minimize the expenditure on future intercomparison work as far as possible.

3. The knowledge obtained on the limitations of current radiosonde designs will help to target further developments in the directions required by customers and data users. For instance, most users of GPS radiosondes will now prefer less expensive GPS radiosondes without a pressure sensor.

4. The weather conditions in Mauritius were more difficult for radiosonde measurements than in the previous WMO Intercomparison of GPS Radiosondes in Brazil (2001). Rain impacted many more flights than in Brazil. However, the intercomparison data set obtained was larger than in Brazil, with the differences between radiosonde sensors more consistent in the vertical.

5. The balloon burst heights obtained in Mauritius were higher than in Brazil. The WMO project team provided basic training in balloon handling, and Richard Smout supervised improvements to balloon filling facilities. The new hydrogen generator installed several weeks before the start of the test provided sufficient gas for the large number of test flights, thus solving the outstanding logistics problem.

6. Balloon launch procedures needed to be modified to account for the erratic nature of low-level winds at the launch site. The frequency and erratic nature of downdrafts from passing convective activity caused problems not experienced in earlier intercomparisons. It became essential that each launch be supervised by at least one experienced member of the WMO project team. The consequence of this was that two persons were insufficient to manage the practical elements of the operation. The launch programme required three individuals to manage and supervise intercomparison activities. The problem was overcome for the later weeks of the intercomparison with the arrival of the UK participants supported by COST.

7. The Intercomparison identified limitations in most radiosonde types, which required resubmission or reprocessing of data to eliminate identified errors. All reprocessing of data required the approval of the IOC Chairman. Faults included errors in conversion of GPS heights to geopotential heights and incorrect radiation corrections for temperature measurements, many due to incorrect local time within the ground system. All three-thermistor radiosonde measurements were reprocessed at least once because of errors in the software originally supplied for processing. Resolving these problems more than doubled the workload of the WMO project team, both during the intercomparison and in the months that followed.

8. The drafting of two preliminary papers on the results of the intercomparison aided in the interpretation of the results and expressed their importance to the participants. These documents also led to rapid initiation of development efforts in eliminating outstanding problems identified in the intercomparison. Although beneficial, this effort required a substantial effort by the project team to inform and advise participants which had not been anticipated by the International Organizing Committee.

9. The analysis of this test relied very heavily on the presence of Vaisala radiosondes as a working link between all radiosondes on all flights. The working reference radiosondes were financed by the participants, but insufficient funds were available to have working references on all the test flights, as would have been the ideal situation. This highlights the need for working references to be as cheap as possible, if they are to be used in sufficient numbers to be really useful.

10. The two working references used have not yet achieved a level of performance where they can be used as a stand-alone reference.

11. Modern radiosonde systems are easy to install and can provide reliable results soon after installation.

12. Radio frequency characteristics of modern radiosondes are more reliable than the previous generation of systems and were proven more reliable when tracking large numbers of radiosondes on a single balloon.

13. The contribution of COST to the intercomparison was of great benefit, since the presence of additional experts to aid the project team allowed better use of remote sensing techniques during the test.

13.1.2 The most significant test results

1. The intercomparison demonstrated that all the participating radiosondes deserved to be considered as high quality radiosondes, and were generally of higher capability than earlier radiosonde designs.

2. In this report the differences between the radiosonde types are displayed against arbitrary references. The philosophy behind the references was to average the results from as many radiosonde types that did not have outstanding systematic errors. The quality of a given radiosonde design for all measurements can be judged by the number of meteorological variables where it has been included in the reference. A meteorological variable with large numbers of radiosonde types in the reference is likely to be measured well by all the radiosonde types, but the meteorological variables with only a few radiosonde types in the reference are likely to be much more difficult to measure accurately. Table 13.1 shows the meteorological variables judged to be of suitable quality for inclusion in a reference for each radiosonde type.

Table 13.1 Measurements of meteorological variables judged suitable for use as part of working references for radiosonde tests from the results of the WMO High Quality Radiosonde Comparison, Mauritius. The height ranges where values are judged of suitable quality are indicated for the relative humidity sensors.

Met. variable	Graw	Meisei	Meteo-labor	Modem	Sippican	Vaisala
Wind	yes	yes		yes	yes	yes
Height	yes	yes	?*	yes	yes	yes
pressure	yes	yes	?*	yes	yes	yes
Temperature night	?	yes	yes	?	yes	yes
Temperature day	?	?	yes -	?	yes	yes
Relative humidity night	? 0 - 4 km	? 3 -16 km	yes** 0-18 km	? 0 - 2 km	yes 0 - 13 km	yes 0 - 15 km
Relative humidity day	? 5 -11 km	? ## 3 - 8 km	yes** 0 -11 km	? 5 -11 km	yes 0 -15 km	yes 0 - 17 km

? *the question mark indicates where the variable might be of suitable accuracy in some other conditions than those encountered in Mauritius*

***** *conditions for preflight preparation in Mauritius caused some problems*

****** *indicates where some editing of faulty measurements is required*

*indicates Meisei will modify the protective cap on the humidity sensor to improve sensor ventilation and reduce solar heating of the protective cap by April 2006.*

Estimating suitable working references is most difficult for relative humidity. The core of the problem can be seen In Fig.10.8 where it cannot yet be established whether the nighttime or daytime humidity measurements were closer to the truth at temperatures below -30° C. Clearly, Snow White and Sippican measurements were the most consistent between day and night, and all the other radiosonde types require improvements to reduce differences between daytime and nighttime measurement quality.

Whilst Table 13.1 might be taken to indicate that the LMS Sippican was the best all round radiosonde, this was not the case. The LMS Sippican system in Mauritius was a prototype, which showed a great deal of potential. It was not a completed operational system with the high quality of radiofrequency transmission necessary for operations in some regions of the world.

3. The GPS radiosondes in the test could all produce geopotential heights of sufficient accuracy that it is no longer necessary to use a pressure sensor with a radiosonde. The GPS geopotential height were of much better accuracy than geopotential heights derived using a pressure sensor at all heights in the stratosphere.

4. GPS wind measurements were of a high enough quality to meet both operational and climatological user requirements. The agreement obtained between wind measurements was limited by differences in the filtering applied. GPS winds and heights require much less smoothing than might be applied to older generation radiotheodolite winds.

5. The temperature measurements of the seven radiosonde types agreed more closely together than in the previous radiosonde intercomparison in Brazil. This was true for both daytime and nighttime ascents. At night most of the temperature measurements fell on average within ±0.2K of the chosen reference. The range of the temperature measurements was similar in daytime measurements in the troposphere, but daytime measurements in the stratosphere were within ± 0.5K of the chosen reference.

6. A calibration error was identified in the SRSD-C34 thermocouple sensor observations at temperatures lower than -50°C and this has now been rectified.

7. Only one temperature sensor was painted white and this showed large negative temperature errors at heights around 30 km at night.

8. Temperature errors caused by evaporation of water from the surface of the temperature sensor, when the radiosonde emerged from cloud into a dry layer, were very common on all radiosonde types in Mauritius. The Vaisala sensor has a hydrophobic coating, and the magnitude and duration of the evaporation error was much smaller for Vaisala than the other radiosonde types.

9. The results from the specialized 3-thermistor radiosonde proved useful in interpreting the origin of the differences between the temperature measurements. At this stage of development of the Lockheed Martin Sippican version of the three-thermistor too many measurements had to be amended because of faults in the assembly or stability of the radiosonde temperature channels for the system to be considered as a stand-alone high quality reference.

10. At night the two most reliable relative humidity sensors agreed on average within ±2 percent relative humidity from the surface to 14 km (-70°) over the full range of relative humidity encountered in the intercomparison. This performance represents a large improvement on any relative humidity sensing system in previous WMO Radiosonde Intercomparisons.

11. Large systematic bias in relative humidity measurements occurred in nighttime measurements as well as in daytime measurements. At temperatures higher than -40°C, maximum bias from the chosen reference at night was + 10 per cent. With some radiosondes water/ice contamination errors seemed more persistent at night than in daytime conditions.

12. Estimates of Day-night differences in relative humidity were supported by comparison with GPS integrated water vapour measurements at Vacoas. This independent reference confirmed that day-night differences in Snow White measurements were small. It was concluded that, Snow White measurements were a good method of linking daytime to nighttime relative humidity measurements. However, contamination problems in the Snow White duct in moist conditions limited daytime Snow white measurements to a maximum height of about 12 km.

13. In the daytime, many radiosonde types had systematic biases in the range -10 to -20 percent relative humidity for temperatures lower than -40 °C. The problems of day-night differences in the relative humidity measurements of most operational radiosonde relative humidity sensors have not yet been fully addressed by the manufacturers.

14. Standard deviations of the differences between different relative humidity sensors were usually relatively small (less than 5 per cent) at temperatures higher than -40°C, so the random errors in relative humidity were usually much smaller than the large systematic biases. This suggests that many of the large systematic biases could be resolved by improved sensor mounting and exposure, plus improved estimation/measurement of the relative humidity sensor temperature.

15. Upper cloud conditions varied a lot throughout the intercomparison. Thus, at temperatures lower than -70°C, discrepancies between Snow white and the other relative humidity sensors increased rapidly because of the wide range of conditions. Contamination from upper cloud was a problem with many sensing systems, and it was difficult to discriminate the effects of contamination from the very low speed of response of the capacitative sensors at very low temperatures.

13.2 Recommendations

Here, recommendations are drafted in terms of potential CIMO Commission Recommendations.

13.2.1 Organization of Intercomparison and Associated Activities

Recommendation 13.2.1.1 Intercomparison Planning

Considerations:

1. Considerable financial and human resources were required for the WMO Intercomparison of High Quality Radiosonde Systems, Vacoas, Mauritius, 2-25 February 2005.
2. Resources required to conduct such an effort must be realistic if the desired results are to be achieved.
3. The estimate of human resources required must be an end-to-end process beginning with operational testing, analysis, and ending in a comprehensive report.
4. Historically, WMO International Radiosonde Intercomparisons are held every 4-5 years.
5. Participants agreed that as changes to these instruments are applied and new technologies evolve, another intercomparison should be held in 4-5 years.

The International Organizing Committee (IOC) / Expert Team (ET) recommended that:

1. CIMO prepare a document detailing lessons learned from this and past intercomparisons. This document must include details of how to conduct reasonable operations cost estimate.
2. CIMO, in its planning, needs to minimize the cost to manufacturers, while still producing a comprehensive data set on radiosonde performance.

Recommendation 13.2.1.2 Post Intercomparison Testing

Considerations:

1. As system manufacturers correct significant errors there must be a process by which these systems can be retested.
2. To accommodate such retesting small scale tests should be performed to demonstrate that the problem(s) have been rectified.

The IOC/ET recommended that:

1. CIMO develop a process for small-scale testing with the intended purpose of demonstrating that problems have been rectified.
2. CIMO should post test results of these small-scale tests to a suitable WMO information site.

Recommendation 13.2.1.3 Intercomparison Process

Considerations:

1. Not all radiosonde manufacturers participated in the most recent WMO Intercomparison.
2. The WMO Mauritius Intercomparison established verifiable performance results.
3. Regional or other large-scale tests need to be conducted to provide a verifiable link to the WMO Radiosonde Intercomparison series.

The IOC/ET recommended that:

1. CIMO develop a process whereby new radiosonde types can be evaluated during the period between WMO Intercomparisons.
2. CIMO should consider using a two-phase process; phase 1, conducting initial small-scale pilot intercomparisons performed with an accepted high quality radiosonde, and phase 2, follow on to a large scale regional intercomparison to provide a verifiable link to the WMO Radiosonde Intercomparison series.

Recommendation 13.2.1.4 Intercomparison and Capacity Building

Considerations:

1. It was clearly evident that the participants gained significant knowledge both in terms of basic radiosonde infrastructure and improved operational procedures.
2. The WMO Mauritius Intercomparison instilled morale, self-confidence, greater expertise and knowledge within the host country's meteorological staff.

The IOC/ET recommended that:

1. CIMO express to other Members the benefits of hosting or participating in WMO or regional Intercomparisons.

13.2.2 Technical Considerations

Recommendation 13.2.2.1 Pressure Sensors

Considerations:

1. The WMO Mauritius Intercomparison clearly demonstrated that GPS radiosondes provided an acceptable means for determining pressure values.
2. The accuracy of these derived pressures would allow for the elimination of pressure sensors on GPS radiosondes.
3. The elimination of the pressure component would reduce the cost of consumables.

The IOC/ET recommended that:

1. CIMO forward information to CBS on the improved ability of GPS radiosondes to provide accurate pressure reports from geometric height measurements, allowing for the elimination of pressure sensors on GPS radiosondes.

Recommendation 13.2.2.2 Temperature Sensors in wet conditions

Considerations:

1. The WMO Mauritius Intercomparison clearly demonstrated the need for hydrophobic coatings on temperature sensors. Sensors coated with these materials performed better in wetter conditions.
2. When applied these coating minimize temperature errors in wet conditions.

The IOC/ET recommended that:

1. CIMO provide advice to manufacturers and radiosonde operators on improving temperature measurements during wet conditions.

Recommendation 13.2.2.3 Temperature Sensor Exposure

Considerations:

1. The WMO Mauritius Intercomparison clearly demonstrated the need for reducing random errors and radiation corrections in daytime conditions.
2. To achieve these goals a concerted effort must be made by the manufacturers to improve the exposure of their radiosonde temperature sensors.

The IOC/ET recommended that:

1. CIMO continue to provide advice to manufacturers on temperature sensor exposure to reduce random errors and radiation corrections during daytime launches.

Recommendation 13.2.2.4 Relative Humidity Sensor Contamination

Considerations:

1. The WMO Mauritius Intercomparison clearly demonstrated the need to minimize chemical contamination of the thin film capacitance relative humidity sensor.
2. To achieve this and reduce the relative humidity errors manufacturers need to develop methods of driving off such contamination before launch.

The IOC/ET recommended that:

1. CIMO work with the manufacturers to provide guidance to radiosonde operators on how to minimizing the potential errors due to chemical contamination.

Recommendation 13.2.2.5 Water and Ice Contamination

Considerations:

1. The WMO Mauritius Intercomparison clearly demonstrated the need to minimize contamination errors from water and ice during flights.
2. To achieve this and reduce such errors manufacturers need to develop improvements to the radiosonde sensor exposure.

The IOC/ET recommended that:

1. CIMO work with the manufacturers in developing and testing improved sensor exposure and in-flight decontamination mechanisms for upper cloud in the tropics.

Recommendation 13.2.2.6 GPS Wind Measurements

Considerations:

1. During the WMO Mauritius Intercomparison and the following IOC some manufacturers indicated that improved guidance material was needed on methods to optimize upper wind measurement quality.

The IOC/ET recommended that:

1. CIMO survey the algorithms used for upper wind calculations and indicate suitable standards for the calculation of GPS winds.

Recommendation 13.2.2.7 Pre-Launch radiosonde checks

Considerations:

1. The results from the WMO Mauritius Intercomparison clearly supported the need to conduct preflight temperature and relative humidity checks prior to launch.
2. The application of rigorous preflight checks should identify faulty radiosondes before launch and problems with humidity sensor contamination..

The IOC/ET recommended that:

1. CIMO establish rigorous standards for preflight checks of radiosondes with the intent of minimizing the cost of lost labor and expendables.

14. ACKNOWLEDGEMENTS

We are very grateful for all the resources made available by the Director of Mauritius Meteorological Services, Dr. N. Sok Appadu.

The success of the test was mainly dependent on the facilities and staff provided by the Mauritius Meteorological Services, under the leadership of Dr. Beenay Pathack.

The UK Met Office provided most of the staff for the WMO Project team and thanks are due to the Chief Executive for authorizing the staff time to work on the project.

Miroslav Ondras, World Weather Watch department organized vital preparations for the test and encouraged the Project Team in some of the more difficult circumstances encountered whilst running the test.

Mr. Sergey Kurnosenko did an invaluable job in generating the Intercomparison database and processing software in difficult personal circumstances. We were very grateful that he persevered in supporting the work.

The test could not have been successfully completed without the funding and manpower resources provided by all the radiosonde manufacturers. We are particularly grateful to Vaisala for providing remote sensing equipment, and to MODEM for resolving a temporary financial problem in the middle of the test.

Support from the European COST organization financed the deployment and analysis of the fmcw cloud radar observations during the test and provided more staff to help with supervision of the Intercomparison. The Space Science Division of the Rutherford Appleton Laboratory, UK, facilitated the deployment of the fmcw cloud radar to Mauritius.

This report has benefited greatly from comments by the manufacturers and the IOC members and associated experts, especially H. Klein Baltink, C. Bauer, F. J. Schmidlin and Y. Lemaitre.

Finally, this report was extremely difficult to write, because it is fairly clear which was the most complete radiosonde system in Mauritius, and this can be judged by the reader from the plots of the results. However, the written words must be balanced so as not to damage unnecessarily the large progress made by all the manufacturers. In many areas the smaller manufacturers have forced progress for the customers, even though this may not have resulted in a large increase in sales of the lesser known radiosondes. We have tried our best to be fair. All these systems provide measurements of higher quality than those of the previous generations of radiosondes.

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16. ANNEXES

ANNEX A - Officers on Duty during the WMO Radiosonde Intercomparison

Mauritius Meteorological Services

PMT	A.Khayrattee
SMT	M.Y. Oozeer A.S. Deeda V.K. Goonjur B. Sok Appadu A. Vencadachellum J. Rugjee J.M.A. Bertrand S. Sowdagur A. Bhundoo P. Pathack A.N. Beeharry J. Madhoo B.Seeborun L.S.K.Ramtohul R.Gobin
MT	D. Dhurmea (Mrs.) V.Mungul A.K.Bachun H.D.Sewock(Miss)
Chief Electronic Technician	G. Muthu
Electronic Technician	Ibrahim Dhansa Damaree Ramaswamy Woomed Abdool

ANNEX B - List of International Participants

Chairman of ET/IOC	J. Nash	UK [WMO]
Project manager	B. Pathack	Mauritius
Flight manager	R. Smout	UK [WMO]
Data manager	S. Kurnosenko	US [supported by manufacturers]
Flight manager (2)	T. Oakley	UK [COST]
Remote sensing manager	H. Richner	Switzerland [COST]
Cloud radar operations	M. Oldfield	UK [COST]
	D. Lyth	UK [COST]
Graw	F. Schmidmer	Germany
Meisei	M. Fujita	Japan
	K. Hoashi	Japan
	K.Shimizu	Japan
	K. Hosoda	Japan
Meteolabor	P. Ruppert	Switzerland
	R. Maag	Switzerland
	T. Brossi	Switzerland
	R. Romanens	Switzerland
Modem	G, Ricaud	France
	P. Charpentier	France
Sippican	T. Degroot	USA
	M. Cardoza	USA
	B. Johnson	USA
Vaisala	H, Jauhiainen	Finland
	M. Svennas (Mrs)	Finland
	M. Markkanen	Finland
	S. Immonen	Finland
	E. Mattila	Finland
	J. Valle	Finland
	A. Rieppola	Finland

ANNEX C - Pictures of Systems and Testing

(This is only a limited sample of the personnel and equipment involved in the test)

Preparing Flight Log and surface observations for participants, Meisei pre-launch ground check equipment in the foreground.

Attaching Graw radiosonde to flight rig

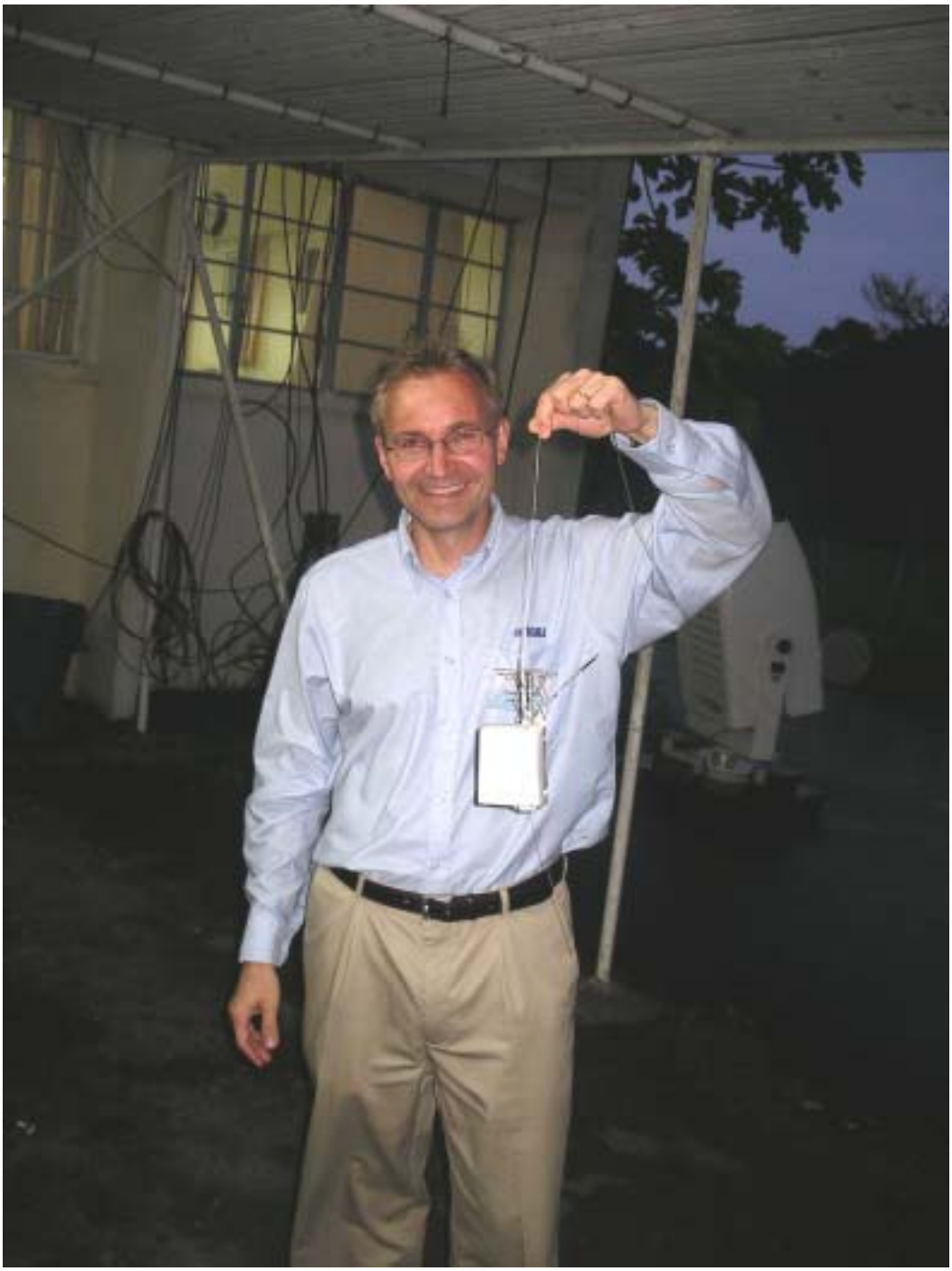
LMS-5 radiosonde + Sippican Multi-thermistor on stand.

MODEM radiosonde

Meisei radiosonde

Preparing “nighttime” SRS radiosonde +Snow White

“Daytime” SRS + Snow White, with entrance to internal duct through side pipe in order to alleviate rain /cloud contamination of the duct.



Vaisala RS92 radiosonde

Multi-thermistor radiosonde in wet pre-launch conditions. The thermistors were shielded from the rain until immediately before launch.

Graw ground system in right hand side foreground

Modem ground system + radiosonde pre-launch check unit.
Note Meisei ground system Fig. 3.2 (c).

LMS – ground system

Some of the ground reception system was shared with LMS for the multi-thermistor radiosondes, operated by UK Met Office staff

Operating SRS + Snow White ground system, cloud radar display to the right.

Vaisala ground system

The balloon shed was just large enough for the balloons. The balloon handling area had to be kept as clean as possible. Red gloves were used to emphasize the need to handle the balloons very carefully, avoiding manual contact.

GPS radiosonde antenna mounted on the roof of the radiosonde operations area

Balloon launch, 05.01 19 February

Cloud near the launch site, 14.48 UTC on 19 February

Graw and LMS-5 waiting for Snow –white.

Meisei, Modem and SRS Snow White preparing and ready for nighttime launch

Some of the technical support provided by Mauritius Meteorological Services

ANNEX D - Radiosonde Comparison Software (RSKOMP ©) for WIN32 Platform

Expert team has used the Radiosonde Comparison Software (RSKOMP©) which has been regularly used in radiosonde intercomparisons since 1990. It implements the well-established comparison methodology and provides multiple important features that make RSKOMP a powerful and complete tool for radiosonde data analysis.

In this comparison RSKOMP was used for the following tasks:

- To create a common data base of all intercomparison flights;
- To reconcile different entry data standards from different participants;
- To perform post-flight data quality analysis;
- To detect and eliminate missyncronizations;
- To hide data where measurements were judged atypical;
- To calculate and analyze statistical results;
- To produce other relevant reference materials for the report.

During its existence the RSKOMP has been thoroughly verified. History of major applications of RSKOMP includes:

- Phase 3 of WMO Radiosonde Intercomparison (1989, USSR)
- Potential Reference Radiosonde Test (1992, UK)
- Phase 4 of WMO Radiosonde Intercomparison (1993, Japan)
- WMO Intercomparison of Humidity Sensors (1995, USA)
- Flight Phase of Ozonesonde Intercomparison (1996, Switzerland)
- Phase 5 of WMO Radiosonde Intercomparison (2001, Brazil)
- WMO Intercomparison of High-Quality Radiosondes (Mauritius, 2005).

… plus many other tests / experiments of the smaller scale.

It should be noted that WRSKOMP applicability is not limited to radiosonde data neither to any particular manufacturer standard. **Practically any data that are represented in a form of vertical profiles may be analyzed with WRSKOMP**. So, the dataset may include radiosondes, ozonesondes, remote soundings data, theoretical models or combination of the above data sources.

The readers who are interested in more details may refer to the Web site:
www.rskomp.net

ANNEX E - Data Format Recommendations

One of the problems the expert team has faced during the intercomparison was substantial difference in the entry data standards. We anticipated this and were able to solve the problem, however, it was the essential additional workload and clearly increased the time needed to complete the post-flight analysis.

There were several sources of inconsistencies:

- Different units of measure and data reporting standards adopted by different manufacturers. For example:
  (i) Wind speed in knots and m/s.
  (ii) Standard and opposite wind direction conventions.
  (iii) Height above sea level and above surface.
  (iv) Geopotential and geometric height.
  (v) Time since start, time of day (in the both forms HH:MM:SS.hh and “seconds since midnight”).
- Numerous data separators, such as space, tab, comma, <, >, +.
- Including pre-flight data;
- Too many data columns (up to 80) most of which did not contain any information;

All of the above disagreements increase the risk of misinterpretation of the data and must be removed by the participants before the data are submitted to the common database.

It is understood that modern radiosondes have multiple channels with the specific housekeeping parameters, so we do not suggest that all data sources follow the same strictly defined data format. Nevertheless, based on our experience, we strongly recommend observing the following general requirements:

1. Participants should negotiate use of the same units of measure and interpretation of variables.
2. All data files from the same data source should have same number of header lines (which may be different for different data sources, of course).
3. Same variable is always reported in the same column (which may be different for different data sources, of course).
4. Clearly defined convention for the representation of the missed data. It is recommended that all data sources follow the same method.
5. There is no limitation imposed on the data precision but it is recommended to keep it reasonable (we sometimes observe precision of 0.001 in reporting, for example, relative humidity).
6. Pre-flight data should be removed; otherwise it creates additional synchronization problems.
7. Use the most common data separators such as Space and Tab characters to ensure readability by any software package.

These requirements will be helpful no matter what software is used to evaluate the combined dataset. If participants will choose to use RSKOMP software, they can further benefit by following rather flexible RSKOMP data formatting rules and using some optional possibilities (such as metadata), implemented in this package.