Initial Results from the WMO High Quality Radiosonde Test Mauritius,

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This paper provides a brief survey of the initial results from the WMO Intercomparison of High Quality Radiosonde Systems, Mauritius. All radiosondes that took part in the test proved to be of good quality; although problems were identified with some systems which if rectified will improve measurement quality in the long term. The most suitable contenders for climate temperature monitoring work to pressures as low as 5 hPa were the Vaisala and Sippican radiosondes. All radiosondes were suitable for use if balloons were only ascending to 30 hPa. Both specialised reference systems (Meteolabor Snow-White and Sippican 3-Thermistor) require further development to be fully reliable as working references.

1. Introduction

The WMO Intercomparison of High Quality Radiosonde Systems consisted of 62 successful multiple radiosonde comparison flights, performed between 7 and 25 February 2005 at the headquarters of the Mauritius Meteorological Services, Vacoas.

This test was organised by the CIMO Expert Team on Upper- Air Systems Intercomparisons, chaired by Dr. J. Nash. Mauritius Meteorological Services volunteered to host this test and February 2005 was chosen for the test by the Expert Team to allow the radiosonde relative humidity sensors to be tested in both wet and dry conditions.

B. Pathack performed a variety of tasks as Project Manager. Organising import and export of equipment proved a major effort, but all equipment was delivered on time. Provision of facilities for the test included the installation of a hydrogen generator to facilitate filling 2000g balloons, stabilised power supply for the ground system computers and Internet connections for the participants. The number of international participants present in Mauritius at any time during the test was about 15. The typical number of people from Meteorological Services Mauritius involved in the test during one week was more than 20. 4 teams of 3 persons were trained to prepare balloons, provide surface observations and manage the launch of the balloons. Radiosonde support rigs were assembled in advance from green bamboo canes obtained locally. Training in balloon handling and comparison launch procedures were provided by J. Nash and R. Smout.

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

2. Radiosondes tested

Six main radiosonde types were tested [method of height determination indicated]:

Vaisala RS92	(Finland)	[pressure sensor and GPS height]
Graw DFM-97	(Germany)	[pressure sensor and GPS height]
MODEM M2K2	(France)	[GPS height only]
Sippican LMS-5	(USA)	[GPS height only]
Meisei RS-01G	(Japan)	[GPS height only]
Meteolabor, SRSD-C34	(Switzerland)	[Hypsometer pressure sensor]

Vaisala, Modem and Meisei radiosondes and Vaisala, Graw and Sippican radiosondes were flown together as two groups with either Meteolabor or three thermistor radiosondes included as a reference. The use of two groups had been agreed at the International Organizing Committee by the HMEI representatives Fig.1 shows preparation for launching the Vaisala-Sippican-Graw group with a 3 thermistor radiosonde.

Fig.1 Graw and Sippican 3 thermistor radiosondes ready for a night time comparison 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.

Vaisala radiosondes were flown on all test flights, with 59 out of 62 successful. Thus, it is convenient to use the Vaisala 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 2000g balloons, but this separation was shortened at night in the second and third weeks. Thus, 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. Night time launches were at 19.00 and between 22.00 to 23.30 local time.

24 Sippican MKII, 3 thermistor radiosondes were flown, [5 at night, 19 in the day] to provide a "working reference" for temperature. The Snow- white chilled mirror hygrometer was successfully deployed as a "working reference" for dew point/ relative humidity measurements on 34 flights.

During the second half of the test MODEM flights were operated by staff from Mauritius, see Fig.2, and the Graw system was operated by staff from the UK at the request of the respective manufacturers.

Fig.2 Staff from the teams of Mauritius Meteorological Services working with the MODEM system during the second half of the test.

50 flights reached higher than 30 km and sufficient flights ascended to heights above 34 km to provide useful comparisons up to this level. The balloon performance was judged as good given the rainy conditions and the presence of thick upper cloud at night for part of the test. Local staff only received a short period of training before starting the test, but coped well with unpredictable launch conditions with low level winds varying significantly between launches.

3. Data processing

The processing software used for this test was provided by S. Kurnosenko. This was an updated version of the RSKOMP software used to analyse results from Phases III and IV of earlier WMO Radiosonde Comparisons.

Sergey Kurnosenko managed 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 test. The comparison data base consists of samples extracted at 1s intervals from the files provided by the manufacturers, using extraction software modified on site in Mauritius.

The attempt to use GPS timing as a method of synchronising samples did not work because of a lack of consistency in the use of GPS time between the systems. Thus, data samples were synchronised 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 sensed values may have been adjusted by software to a different value to be consistent with a different launch time.

Input data were checked by the WMO supervisory team as soon as possible following the flight. 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.

Launch procedures were modified to try and prevent damage to the more fragile radiosondes and to ensure that other systems did not lose GPS lock during the launch procedure.

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

Some other data problems were not recognised until close to the end of the trial and this required some rework of the observations after the final flight.

- Vaisala reprocessed daytime temperature measurements using a different editing filter.

- Meisei recomputed temperatures because incorrect corrections had been applied to night time measurements during the test.
- Meteolabor reprocessed geopotential heights because of errors in the height computation software.
- MODEM reprocessed geopotential height computations since an incorrect value of local g had been used for the geometric height to geopotential conversion.

Statistical processing was based on the WSTAT program supplied by S. Kurnosenko. The data were edited by the Chairman of the IOC, before the statistics were processed. Editing was required mostly by the two specialised sensing systems, where elimination of the various occasional Snow white failure modes [high instability in dewpoint measurement at upper levels in some flights, contamination in the Snow white duct leading to dewpoints that were higher than air temperature in upper layers in daytime, loss of the water film on the chilled mirror in very dry layers], and thermistor calibration errors/ inter-channel radiofrequency offset problems for the 3 Thermistor radiosondes.

When a temperature sensor becomes wet in passing through 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. The other manufacturers ought to consider using a hydrophobic coating on the temperature sensor to minimise the significant errors that follow sensor wetting. The measurements in the layers where the wetting error happened were hidden and not used in the following statistics.

4. <u>Simultaneous temperature comparisons</u>

Figure 3(a)) show the systematic differences referenced to the average of Meisei, Sippican and Vaisala in the dark. Meisei, Sippican 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 temperatures had calibration discrepancies of about +0.5 K. The Graw discrepancies were much smaller than in the previous WMO GPS Radiosonde test in Brazil, where errors had been larger than 1 K. All temperature sensors apart from MODEM had aluminised 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 2 K at 30 km, with at least 1K the result of cooling by infrared radiation.

The estimates of random error at night in Fig. 3(b) were derived from the standard deviations of the differences between sensor measurements on the assumption that the errors were not correlated between different sensor types. The values for Vaisala and Sippican 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 seem to be the result of changes in signal channel performance/ data reception [induced by battery output changes towards the end of the flight?] rather than changes in sensor performance. The exception to this was the MODEM sensor where variability in the infrared environment induces more variation than in the other sensors.

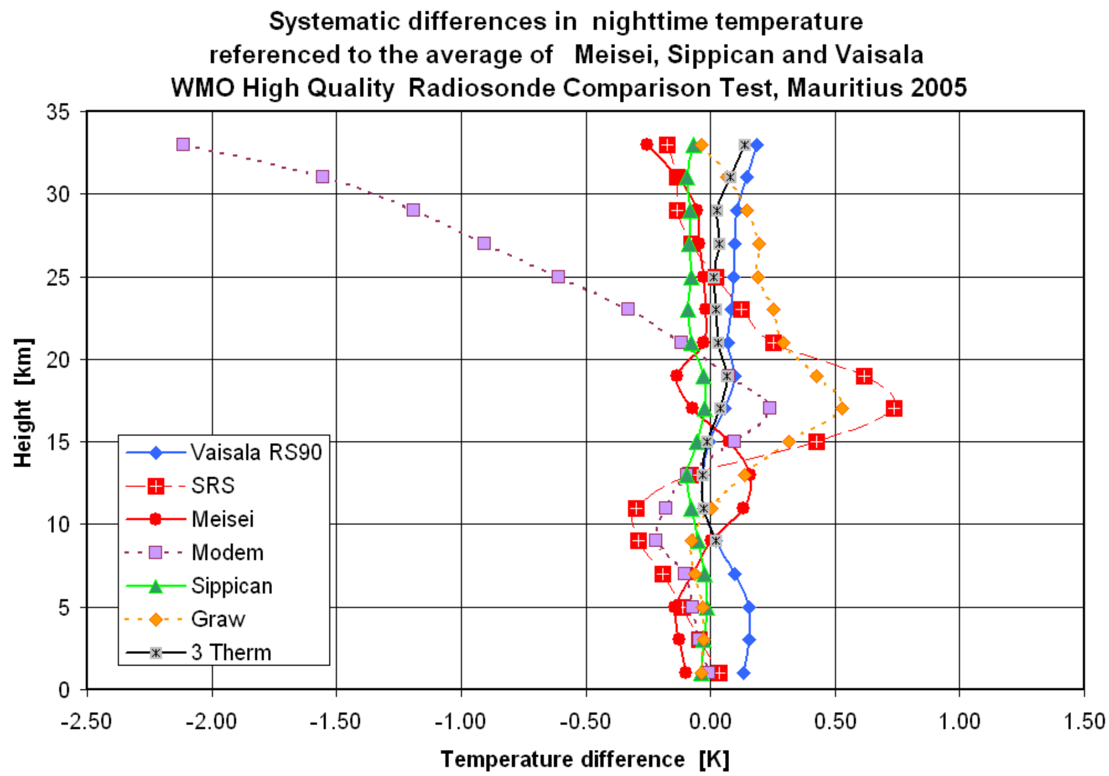

Fig.3 (a) Systematic bias between simultaneous temperatures [K] at night

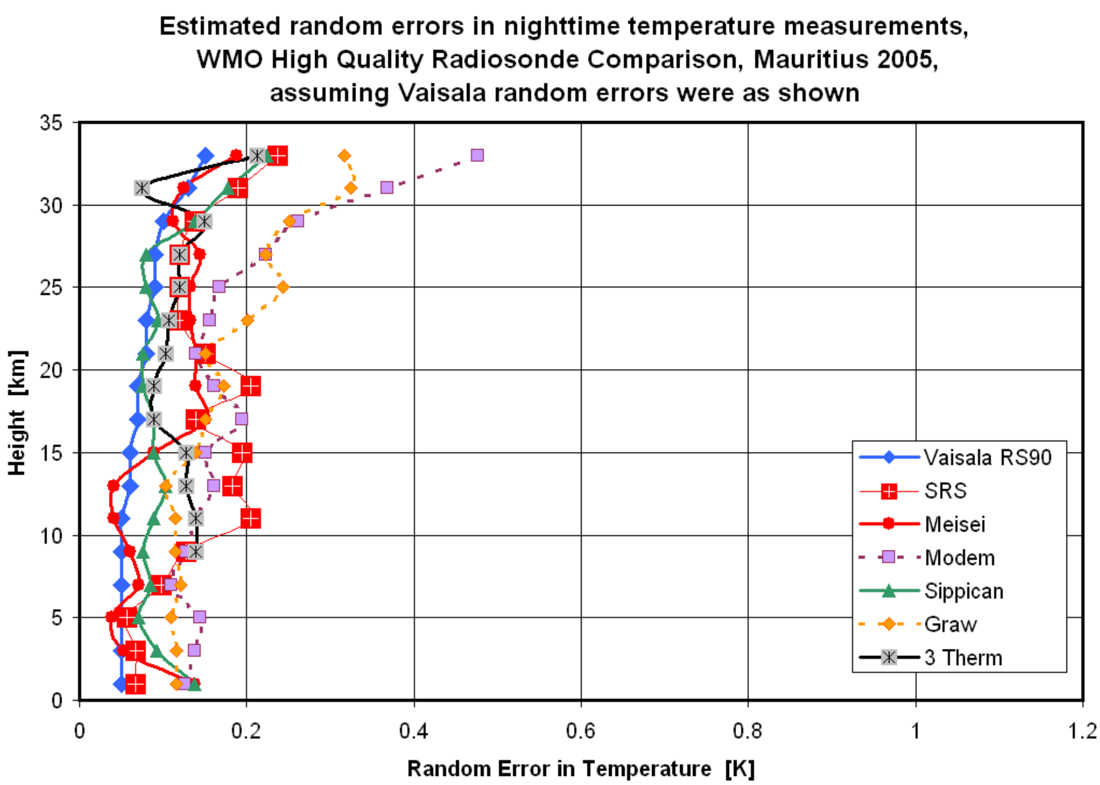

Fig. 3(b) Estimated random errors in temperature sensor measurements at night

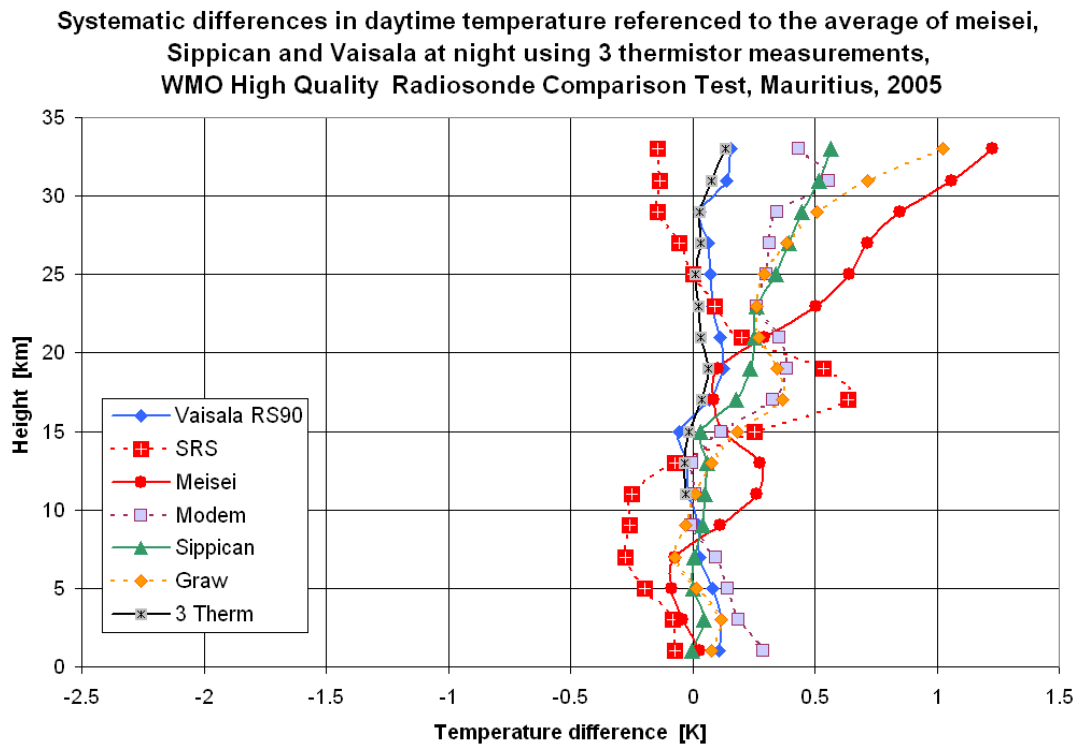

Fig.4 (a) Systematic difference between simultaneous daytime temperatures [K] referenced to the night time reference, using three thermistor measurements as a link.

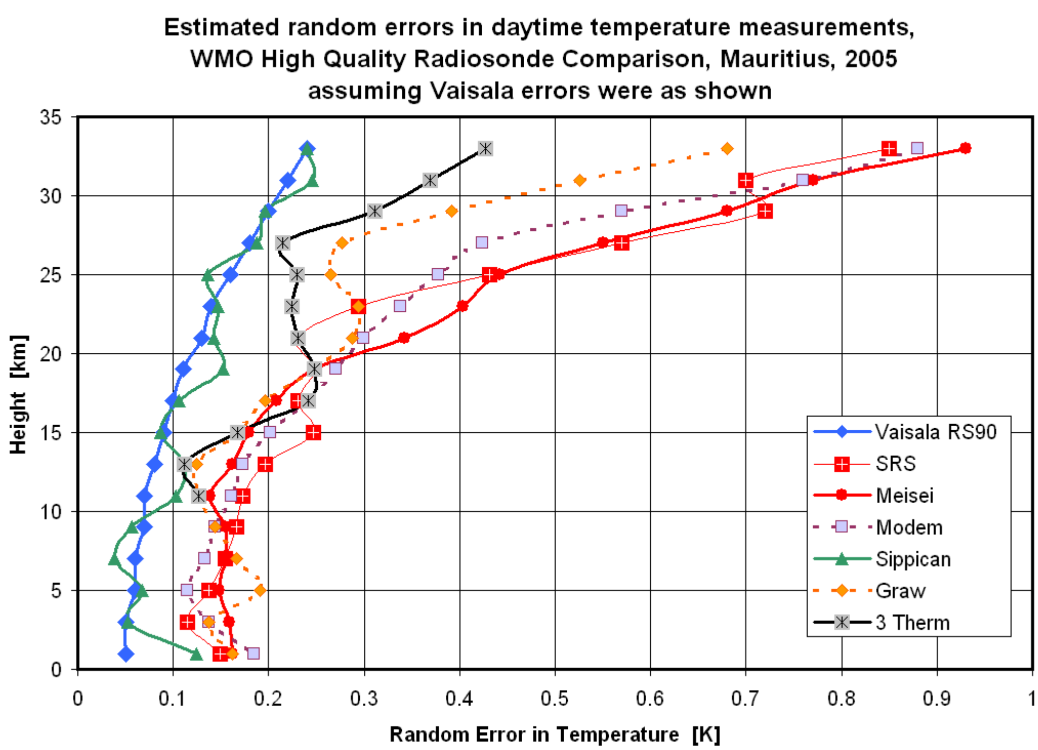

Fig. 4(b) Estimates of random error in daytime temperatures [K]

Figure 4(a) show the systematic differences for day time temperature comparisons. The absolute values of the three thermistor measurements may be offset by up to ± 0.2 K from truth, so this limits the accuracy to which night time and daytime temperature measurements can be compared together. The 3 thermistor measurements did provide an accurate representation of the variation in the vertical of the correct temperature in the stratosphere.

Vaisala made the smallest daytime temperature correction (about 0.6 K at 10 hPa). SRS and Sippican made corrections of just over 1 K at about 30 km. From Fig 4 (a), Vaisala and SRS corrections produce results closest to the three thermistors at upper levels. The Sippican measurements diverge from the three thermistors at 30 km so the Sippican corrections should probably be larger by at least 0.3 K at 30 km. 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.

Temperature errors in daytime measurements fluctuate in the short term as the radiosondes rotate in flight. The predominant period of rotation on the bamboo cross is between 10 and 15 s, and the effects of rotation can be identified in the detailed data sets. The temperature pulses in the comparison flights may be larger than occur in individual flights where the radiosonde motion is more random during flight.

Daytime temperature error fluctuations increase with height and affect all the radiosondes to some extent, including Vaisala. For instance, air passing over the current Vaisala. Modem , Graw and SRS sensor support/protective structures is warmed and may then pass over the temperature sensor producing positive temperature error pulses. These fluctuations are often but not always filtered out by the processing software. In Mauritius, the magnitude of the temperature pulses affecting daytime measurements was up to 1 K at 30 km. Vaisala used a new filter to process the final Vaisala data in Mauritius which is not yet in operational use. The original Vaisala data in Mauritius used the existing operational Vaisala filter. At heights above 28 km these original Vaisala temperatures showed larger standard deviations in the differences with Sippican and three thermistor than were found with the revised measurements. The random error estimates in Fig. 4(b) were deduced from the standard deviations of the differences between radiosondes and assume that Vaisala temperature fluctuations in filtered data were of similar magnitude to the Sippican fluctuations. Fig. 4(b) shows that random errors in Sippican and Vaisala daytime temperature measurements were less 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. It is expected that most of the temperature sensors with largest random errors at 10 hPa will benefit from a redesign of the temperature sensor mount to minimise the fluctuations from air that has passed over surrounding sensor support structures.

Overall, the two most suitable radiosonde temperature measurements for climate monitoring to pressures as low as 5 hPa both day and night were Vaisala and Sippican.

Three thermistor radiosonde measurements can also give very high quality measurements if the system is implemented carefully, but the Sippican system used in Mauritius needed further development to be reliable as an absolute reference. It would be difficult to build a cost-effective specialist reference radiosonde that would provide better temperature measurements than a combination of two of the best operational GPS radiosondes.

A combination of Vaisala GPS with a suitable operational version of the Sippican GPS radiosonde would be recommended for best measurement quality for high performance climate/satellite monitoring.

5. Simultaneous geopotential height comparisons

The simultaneous height comparisons from this test demonstrate that GPS height measurements give geopotential heights that are more accurate than the best pressure sensors at all heights above 16 km and are of similar accuracy to pressure sensor measurements at heights below 16 km. The systematic bias of all the geopotential heights relative to the Vaisala GPS height measurements are shown in Fig. 5 (a).

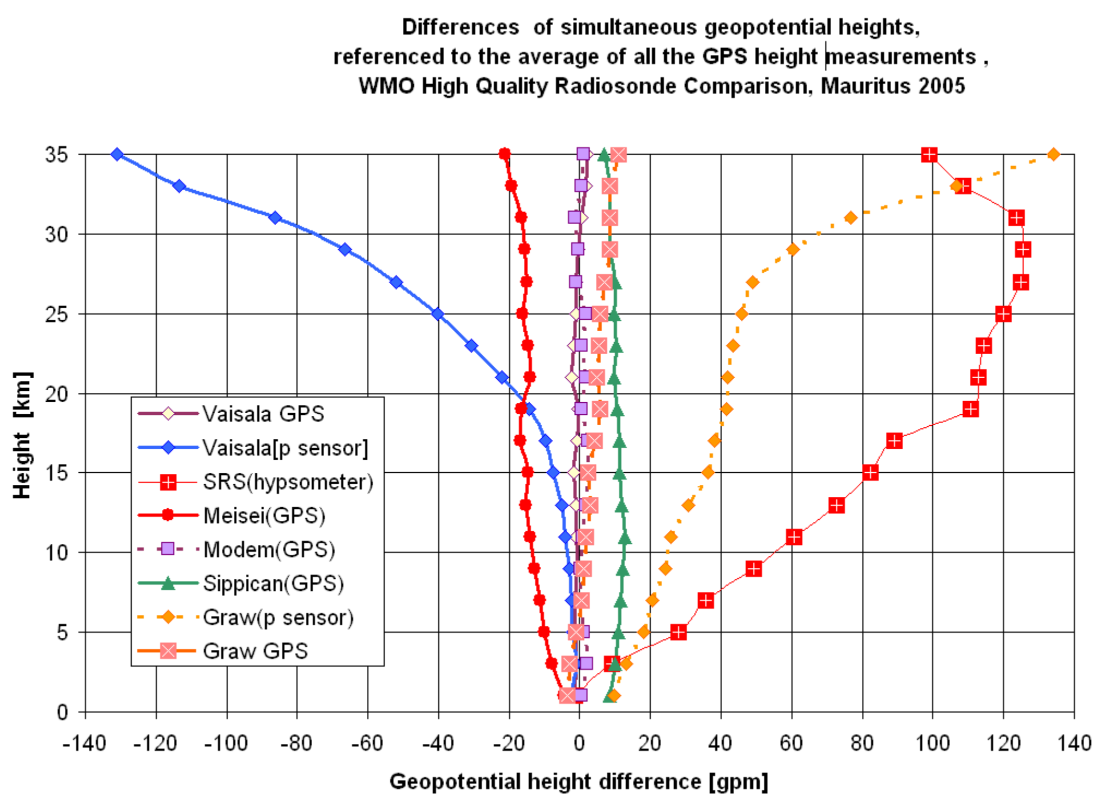

Fig. 5 (a) Systematic difference between geopotential height measurements [gpm], using average of all GPS measurements as a working reference, Vaisala, SRS and Graw heights derived from high quality pressure sensors

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 do not give very reliable heights at pressures lower than 10 hPa.

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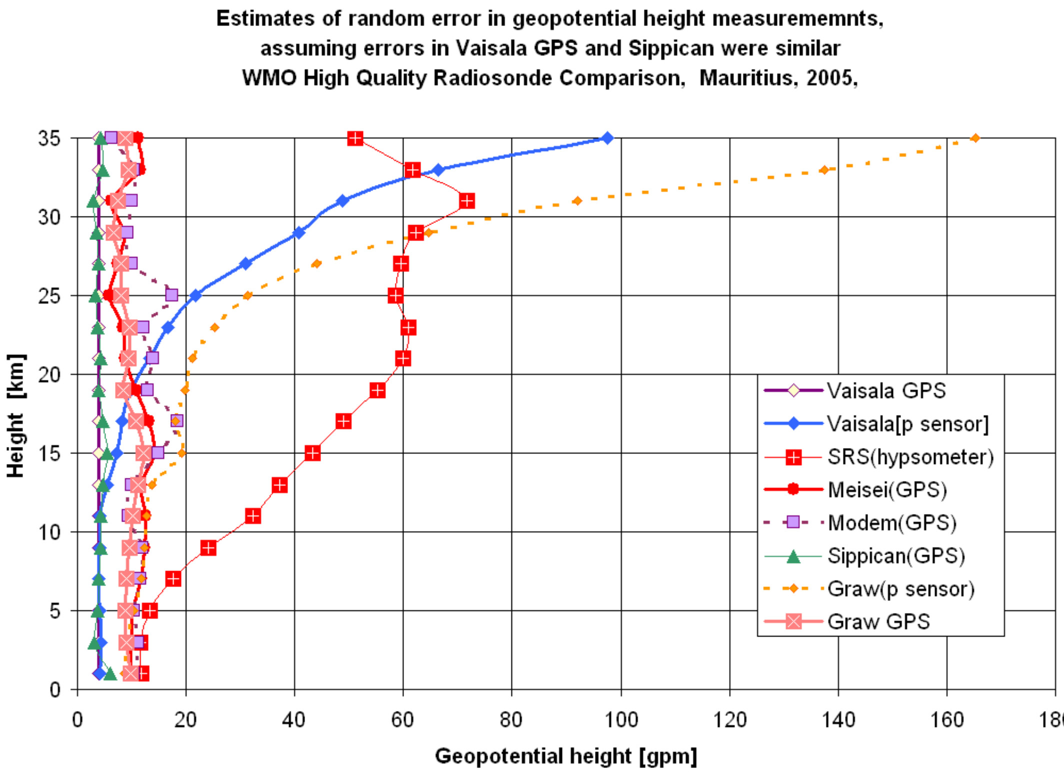

Fig. 5 (b) Estimates of random error in geopotential height measurements [gpm]. Vaisala, SRS and Graw heights were derived from high quality pressure sensors

Fig. 5(b) contains estimates of the random error in geopotential height measurements. 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 negligible with the new GPS height measurements, even at pressures lower than 5 hPa.

6. <u>Simultaneous pressure comparisons</u>

Fig. 6(a) shows the results of the comparisons between simultaneous pressure measurements. 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 and excluded, whilst another 5 did not appear to match to the surface pressure correctly and were excluded in the lower troposphere.

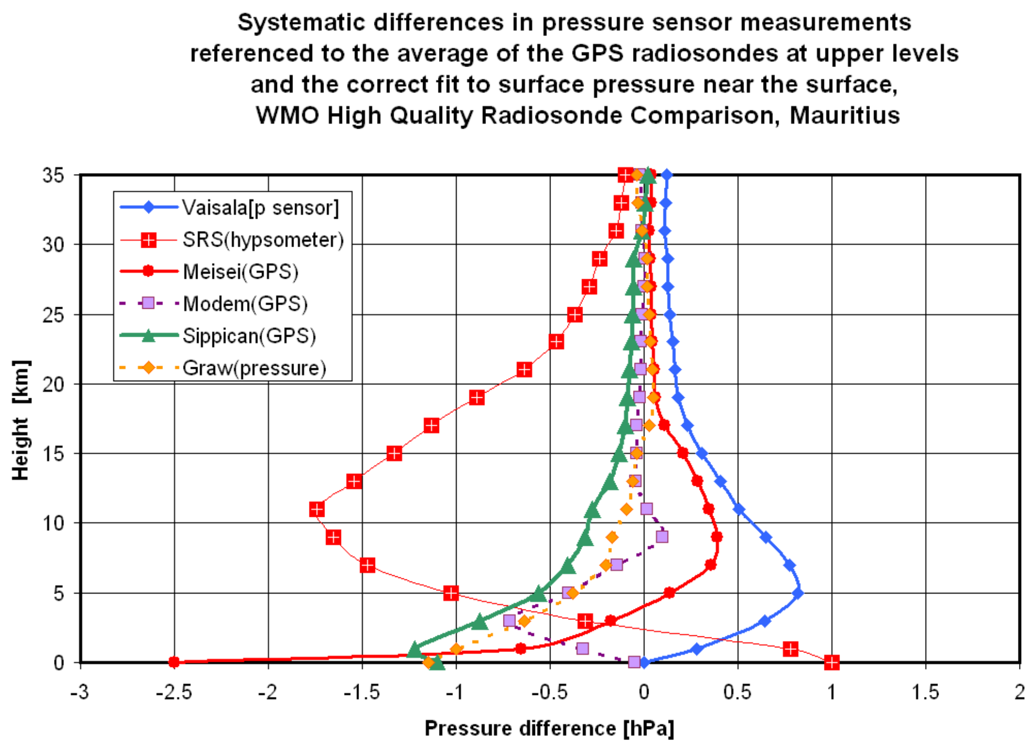

Fig.6 (a) Systematic differences of simultaneous comparisons between pressure measurements [hPa].

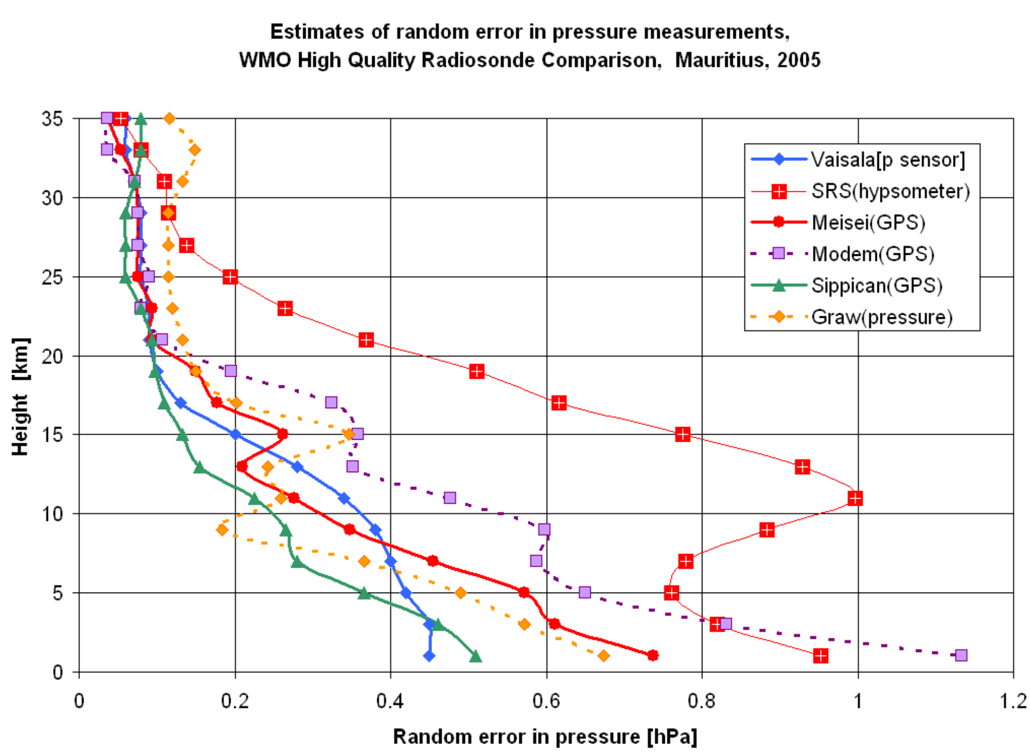

Fig.6 (b) Estimates in random error of pressure measurements [hPa].

The reference in Fig. 6(a) in the stratosphere and upper troposphere is the average from the three GPS systems. Near the surface the pressures of Vaisala and Modem were closest to the truth. The reference between 1 and 8 km was an arbitrary adjustment between the surface and the upper reference.

Fig. 6(b) contains the estimates of random error in the individual sensors. The assumed performance of the Vaisala pressure sensor takes into account that the standard deviations between Meisei and Modem pressures were smaller than those between Vaisala and Modem in the upper troposphere and at pressures lower than 10 hPa.

7. <u>Simultaneous relative humidity comparisons</u>

The systematic differences between the relative humidity sensors will be presented using contour plots of systematic difference plotted as a function of height and relative humidity for the individual sensor types in Figs. 7(a) to (f) for night time measurements and Figs8(a) to (f) for daytime measurements. The values presented were originally computed using Vaisala as the computational reference, and using relative humidity bands, 95 to 100, 75 to 95, 55 to 75, 35 to 55, 15 to 35 and 0 to 15 per cent. The night time reference used for presenting results was the average of Sippican, Snow White and Vaisala measurements. Sippican measurements were omitted above 14 km and were not used above 8 km for the band 55 to 75 per cent relative humidity.

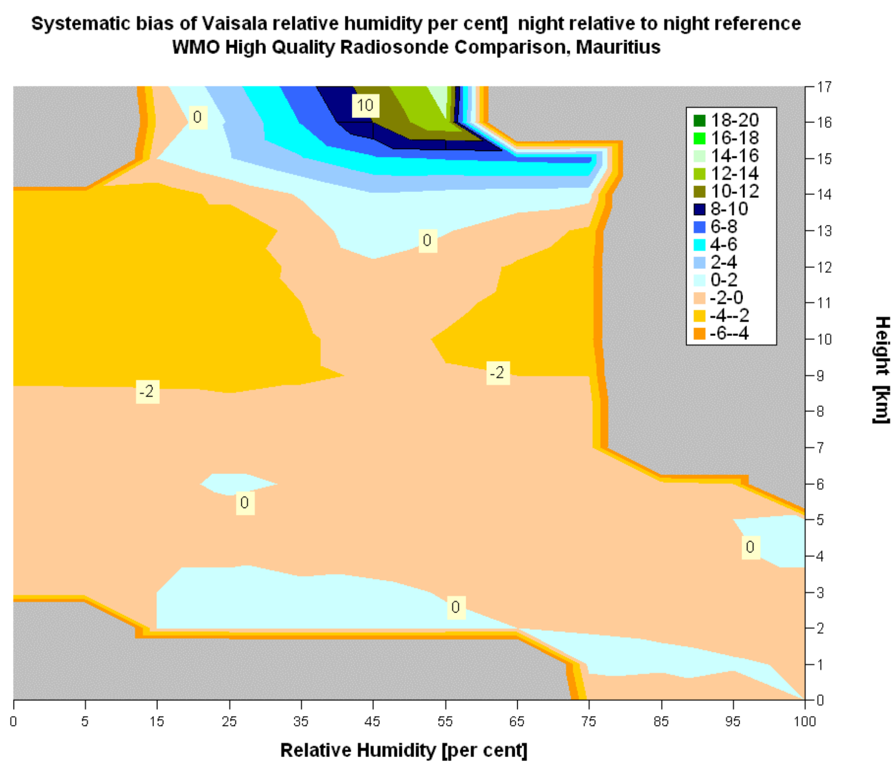

Fig. 7(a) Systematic bias for Vaisala night time relative humidity, referenced to the average of Vaisala, Snow white and Sippican.

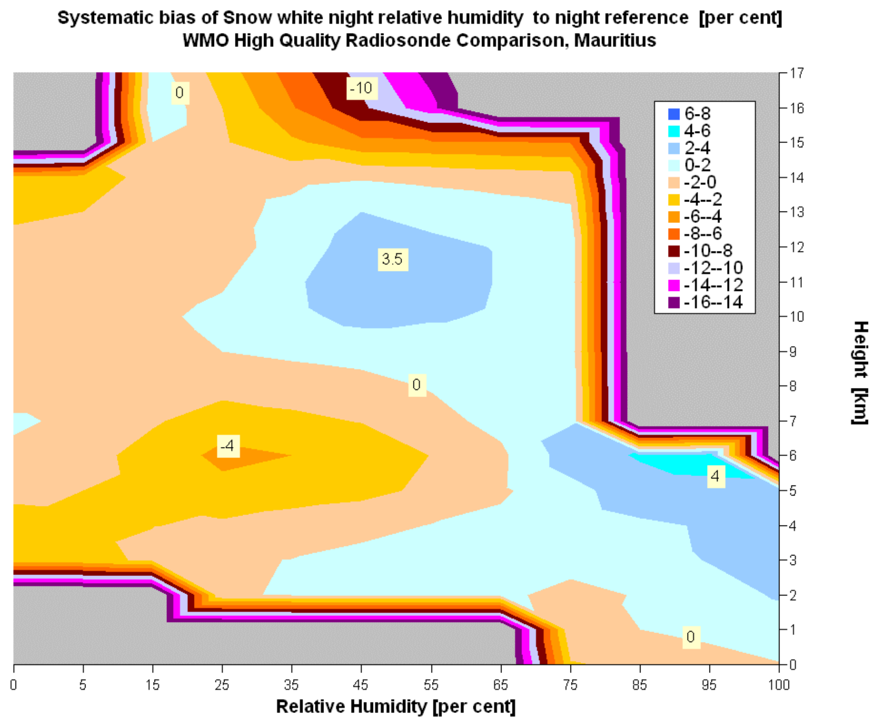

Fig. 7(b) Systematic bias for Snow White night time relative humidity, referenced to the average of Vaisala, Snow white and Sippican

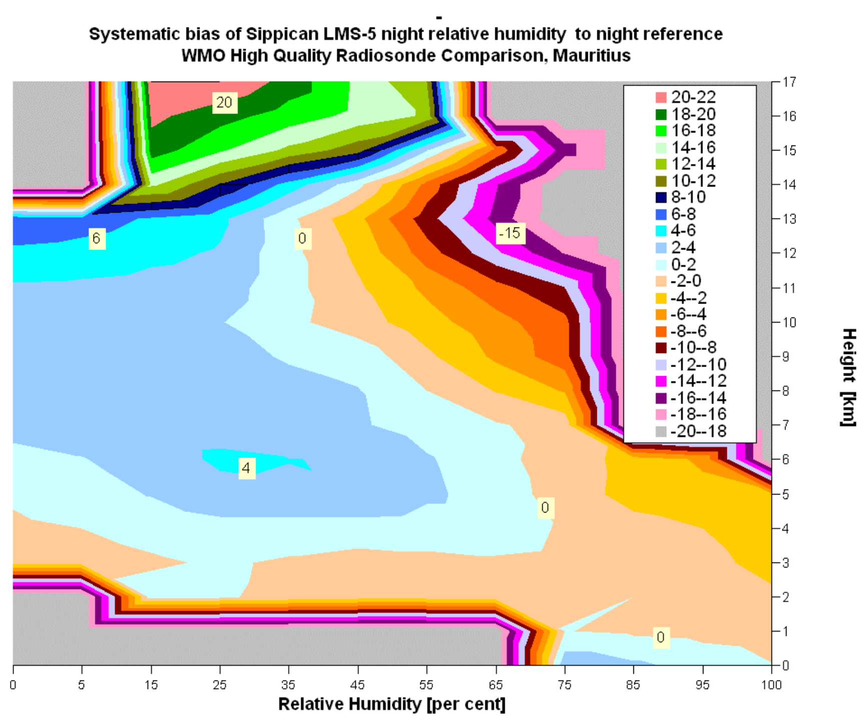

Fig. 7(c) Systematic bias for LMS-5 night time relative humidity, referenced to the average of Vaisala, Snow white and Sippican

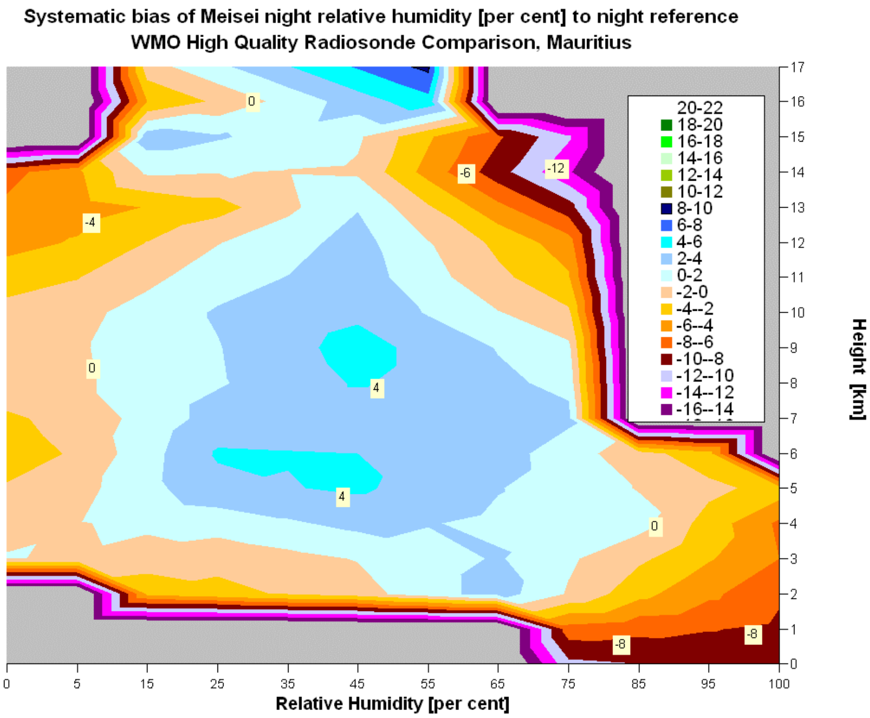

Fig. 7(d) Systematic bias for Meisei night time relative humidity, referenced to the average of Vaisala, Snow white and Sippican

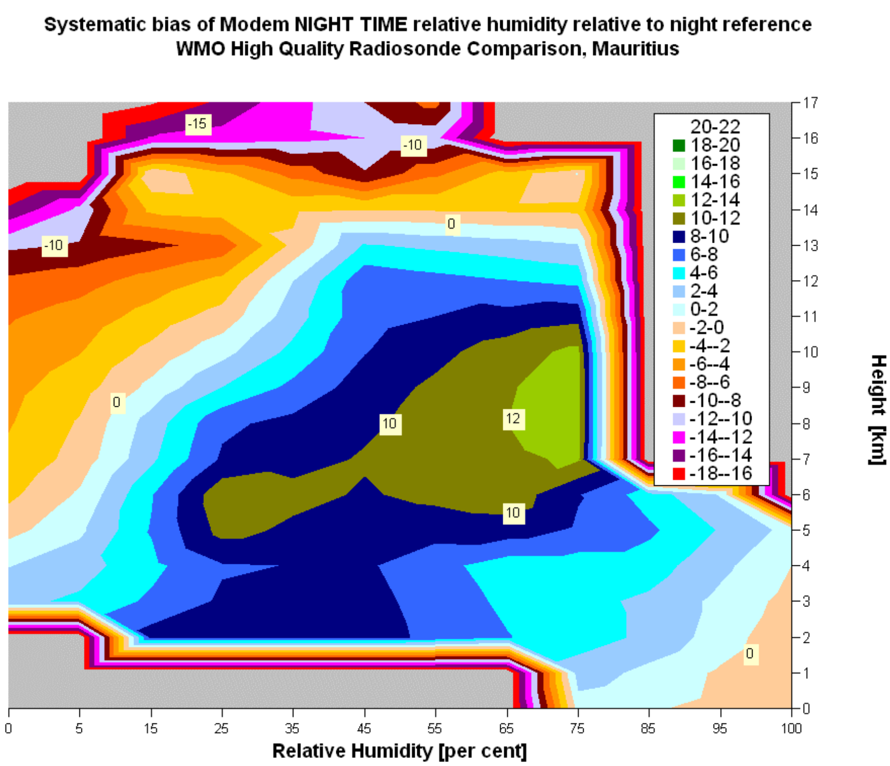

Fig. 7(e) Systematic bias for MODEM night time relative humidity, referenced to the average of Vaisala, Snow white and Sippican

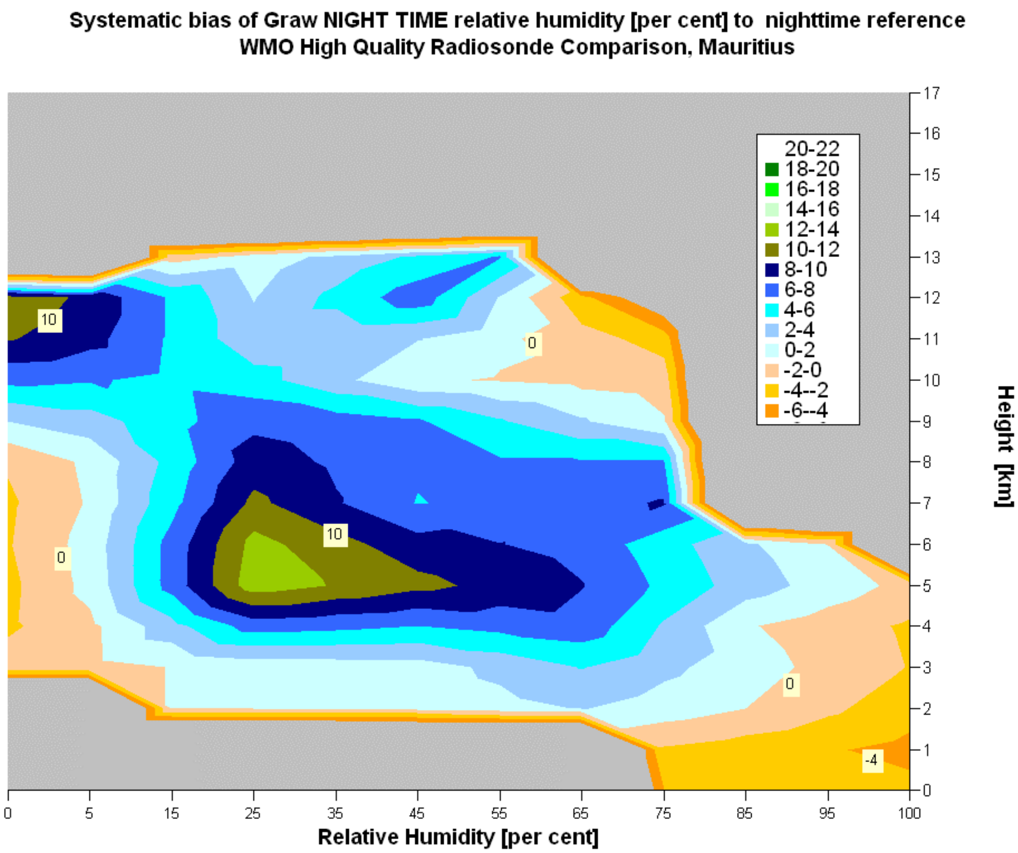

Fig. 7(f) Systematic bias for Graw night time relative humidity, referenced to the average of Vaisala, Snow white and Sippican.

Fig. 7 (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 deg C. Thus, Snow White showed much lower relative humidity than Vaisala at temperatures near -80 deg C, in the region above the top of most of the upper clouds encountered.

Sippican measurements at night, Fig.7(c), were generally within 5 per cent of the reference at heights up to 11 km, i.e. down to a temperature of -40 deg 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. 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 deg C is now being addressed by the manufacturer.

Meisei measurements at night, Fig. 7(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 may have been caused by chemical contamination of the sensors in shipment from Japan.

MODEM and Graw relative humidity measurements, Fig. 7(e) and (f) showed positive bias greater than 5 per cent 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 8(e) and (f). The positive bias persisted further in the vertical in the MODEM measurements than in the Graw measurements. Graw measurements were not considered below -60 deg C because of the slower response of this sensor at lower temperatures. MODEM measurements showed significant negative bias [15 per cent] at heights above 16 km where temperatures were as low as -80 deg C.

Day night differences in the radiosonde relative humidity measurements were checked against measurements of integrated water vapour by a GPS sensor installed at the site for the experiment. The preliminary results from this comparison indicate that the Snow-white measurements had small day-night difference and so the Snow White measurements have been used to refer the daytime systematic differences to the night time references, as far as possible. Unfortunately, the daytime Snow whites had a contamination problem which limited valid measurements to temperatures higher than -50 deg C.

Daytime Vaisala maximum relative humidity in moist layers in the upper troposphere had values about 10 per cent lower than similar measurements in the dark. Thus, 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.

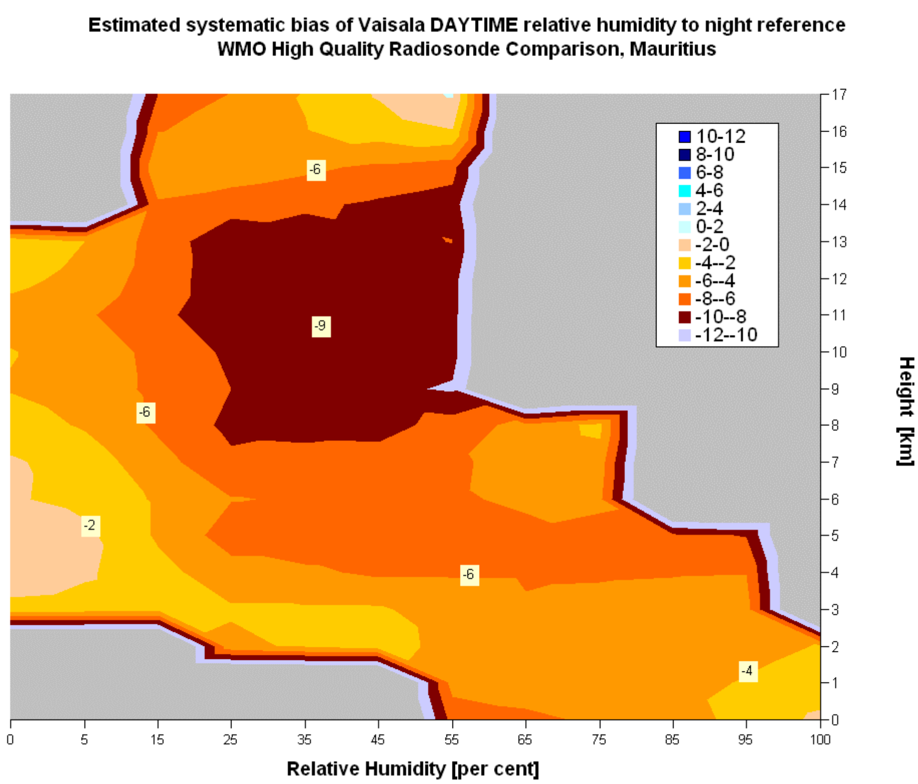

Fig. 8(a) Systematic bias for Vaisala daytime relative humidity

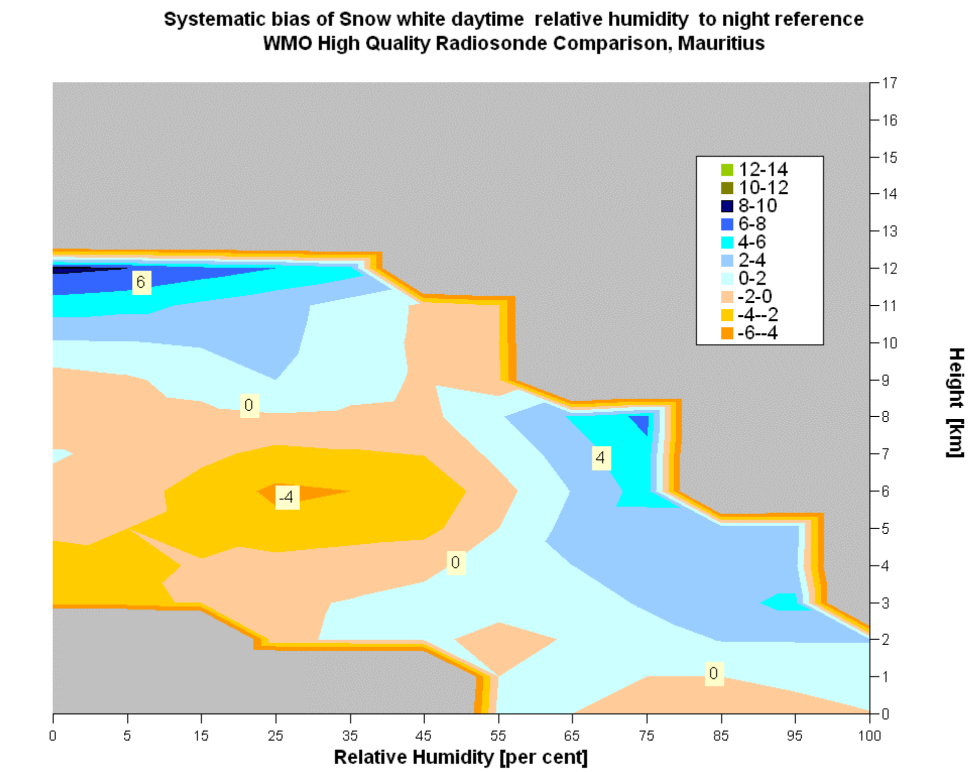

Fig. 8(b) Systematic bias for Snow White daytime relative humidity

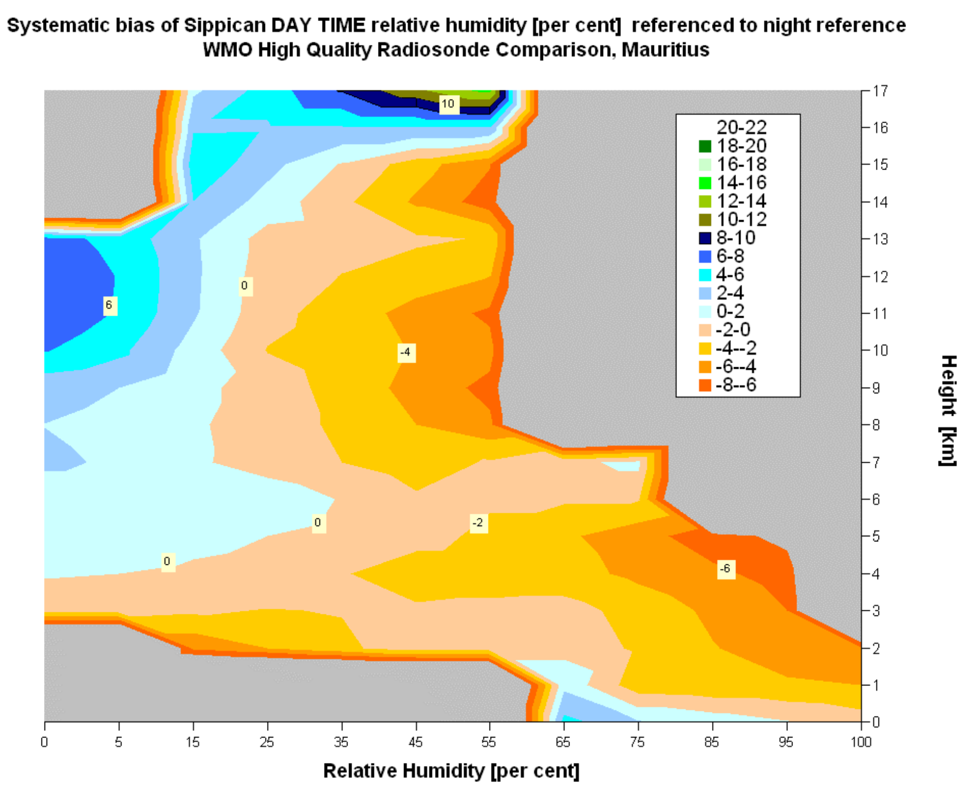

Fig. 8(c) Systematic bias for LMS-5 daytime relative humidity

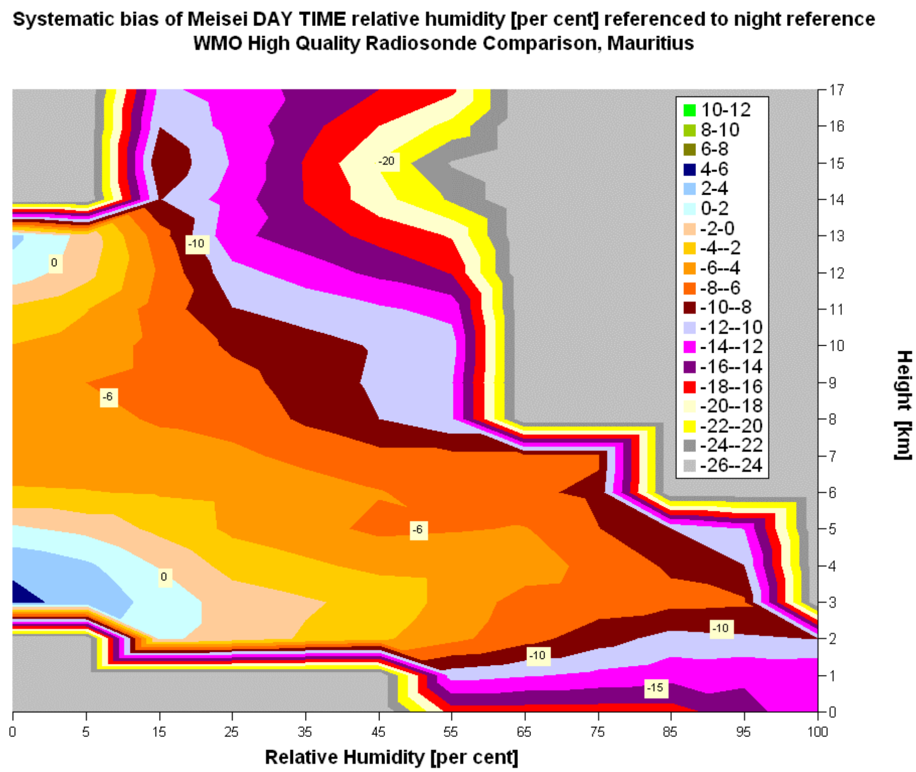

Fig. 8(d) Systematic bias for Meisei daytime relative humidity

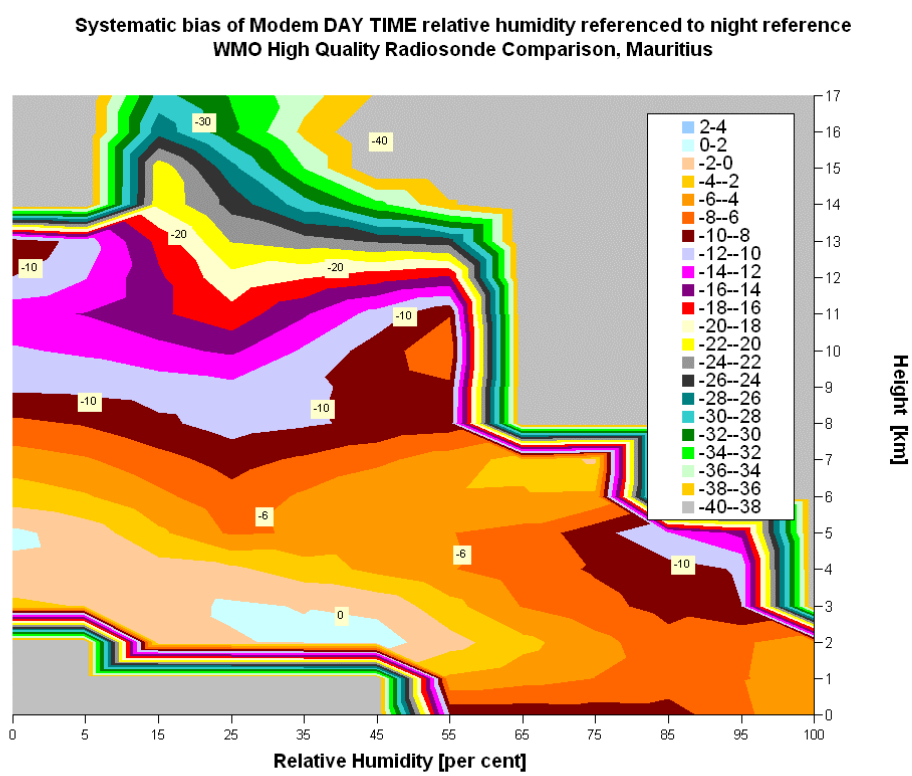

Fig. 8(e) Systematic bias for MODEM daytime relative humidity

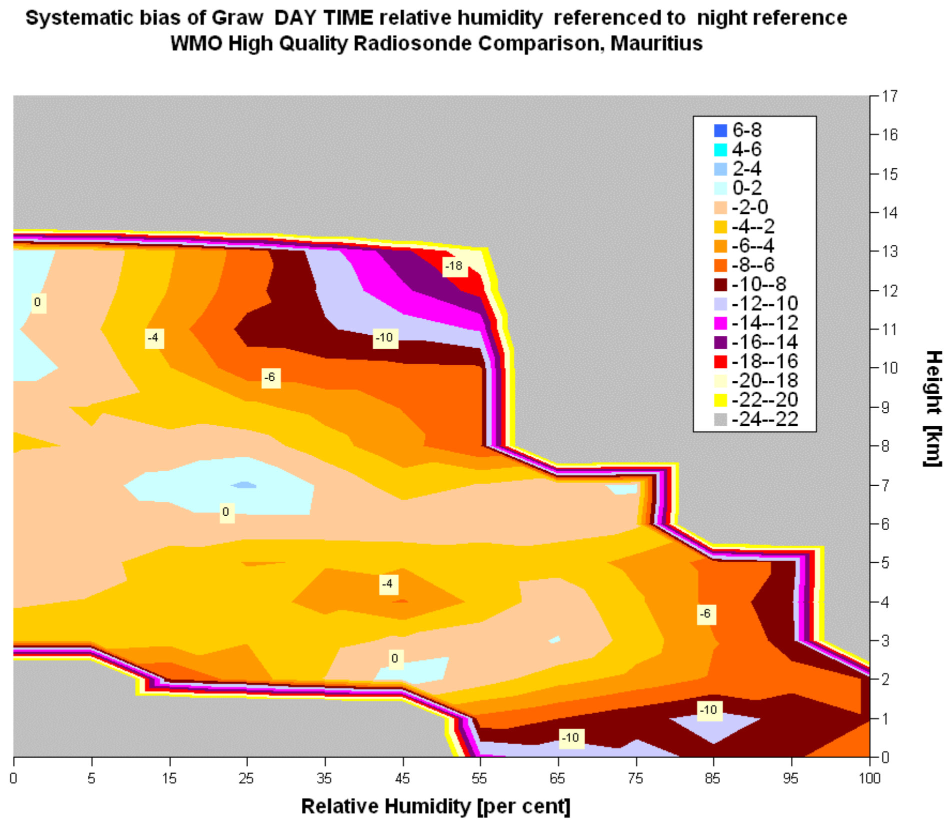

Fig. 8(f) Systematic bias Graw daytime relative humidity

Fig. 8(b) indicates the extent to which daytime Snow white measurements were assumed to be of similar quality to night time. Some positive bias relative to night time reference was starting to occur at heights of 12km at low relative humidity, because of contamination in the daytime Snow-white ducts.

Daytime Vaisala measurements, Fig. 8(a) were shifted negative relative to daytime measurements by between 3 and 7 per cent for heights up to 12 km, see Fig. 8(g). The values quoted for heights above 12 km were clearly less accurate and may be in error by several per cent. The results at lower levels which are constrained by the Snow White measurements should be reliable to about 1 per cent., in the lower troposphere, with slightly larger uncertainty [about 2 per cent] 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 in current production models.

Daytime Sippican relative humidity measurements, Fig. 8 (c) were mainly within 5 per cent 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.

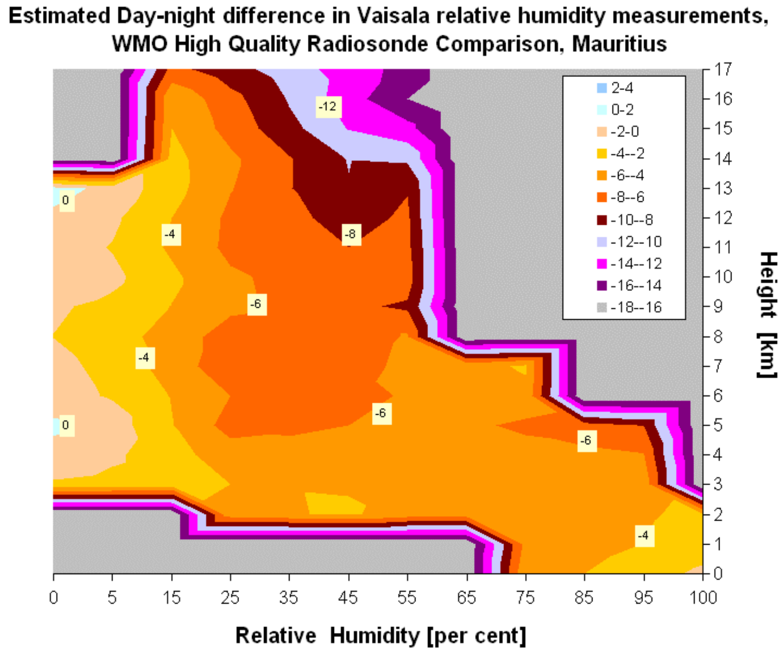

Fig. 8 (g) Estimated Day- Night difference in Vaisala relative humidity.

Meisei and MODEM daytime relative humidity measurements, Figs. 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.

The strong positive bias at 30 per cent relative humidity and height of 5 km relative to the lower troposphere measurements in night Graw measurements Fig. 7((e), is much less significant in the daytime Graw measurements Fig. 8(e). This would support the idea that the night time 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. 9(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. 9 (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 per cent. When rapid transitions in relative humidity were common the standard deviations went up to about 7 per cent, some of this caused by instability in Snow white measurements, but also with some limitations in the hysteresis/ contamination 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.

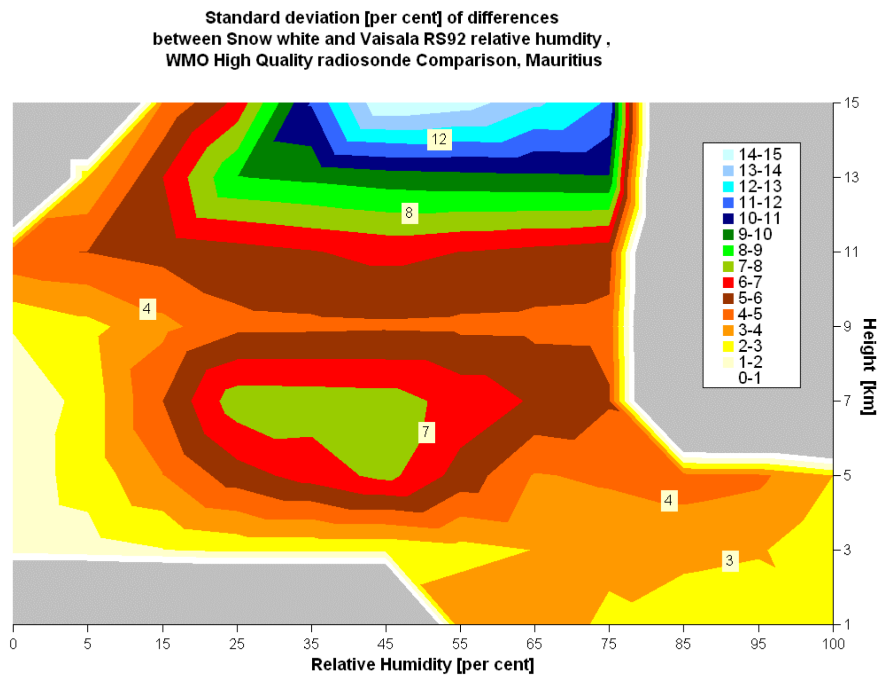

Fig 9(a) Standard deviations of differences between Snow White and Vaisala relative humidity

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.9 (a).

Sippican LMS-5 relative humidity measurements, Fig. 9(b), had quite similar standard Sippican contamination problems were more similar to Vaisala than Snow white.

Meisei relative humidity measurements, Fig. 9(c) had the smallest standard deviations relative to Vaisala at all levels.

Modem relative humidity measurements, Fig 9(d) had larger random errors than the preceding capacitative sensors above 11 km.

Graw relative humidity measurements, Fig 9(e) had larger random errors than the other capacitative sensors in the range 3 to 6 per cent for heights from the surface to 12 km.

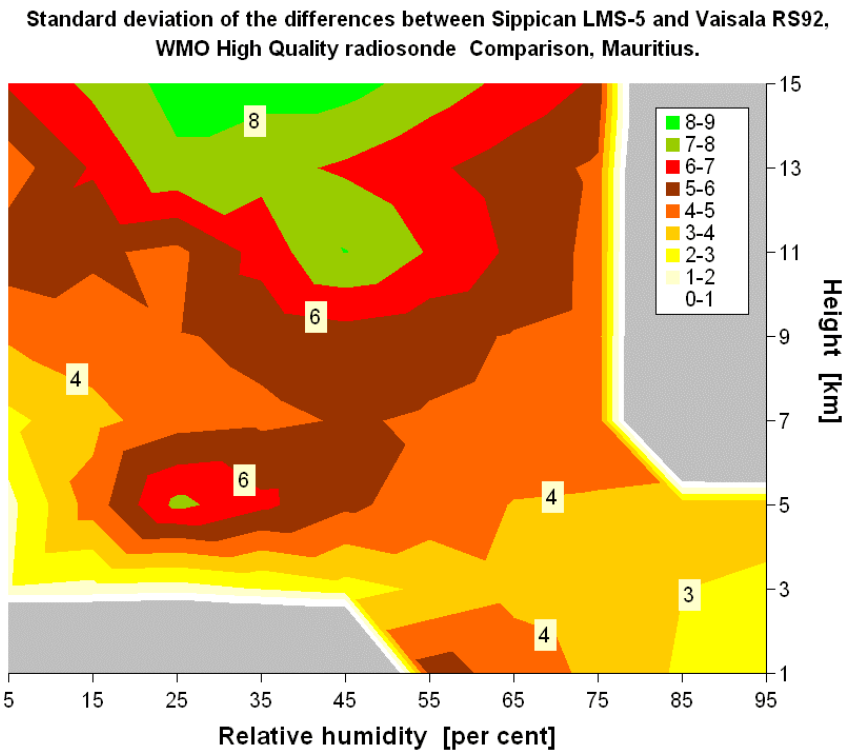

Fig 9(b) Standard deviations of differences between Sippican LMS-5 and Vaisala relative humidity

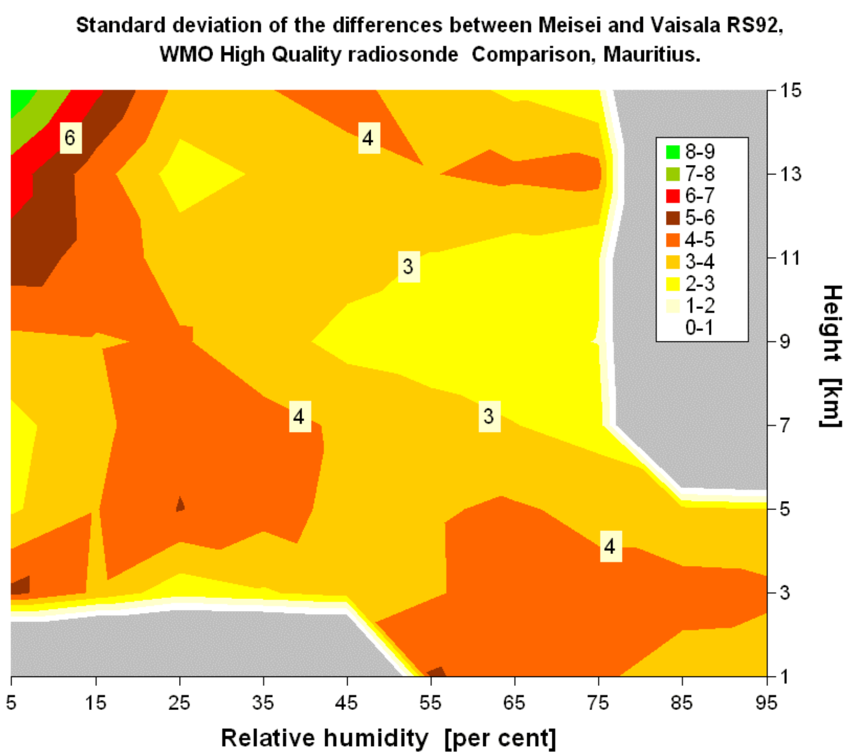

Fig 9(c) Standard deviations of differences between Meisei and Vaisala relative humidity

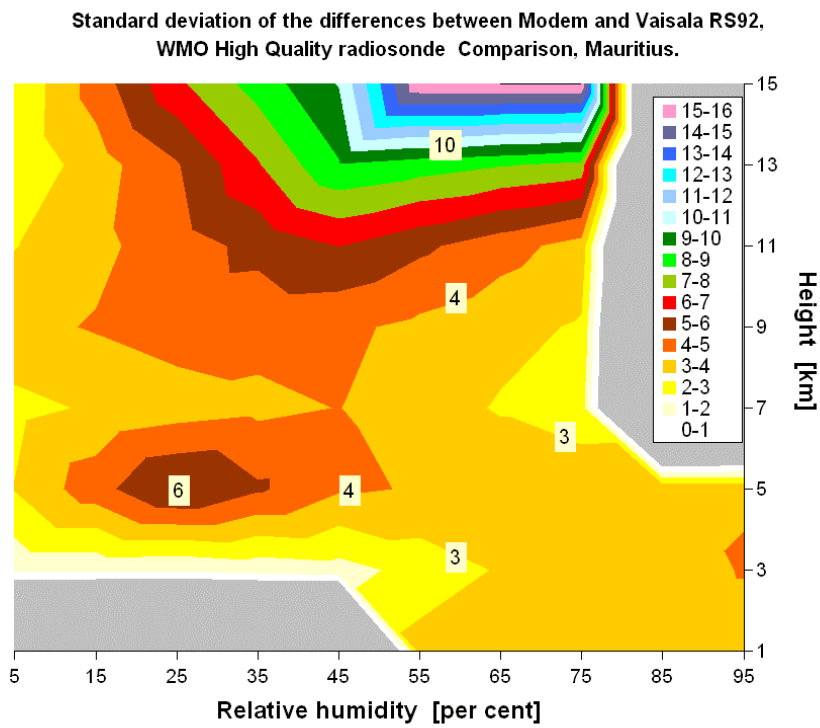

Fig 9(d) Standard deviations of differences between MODEM and Vaisala relative humidity

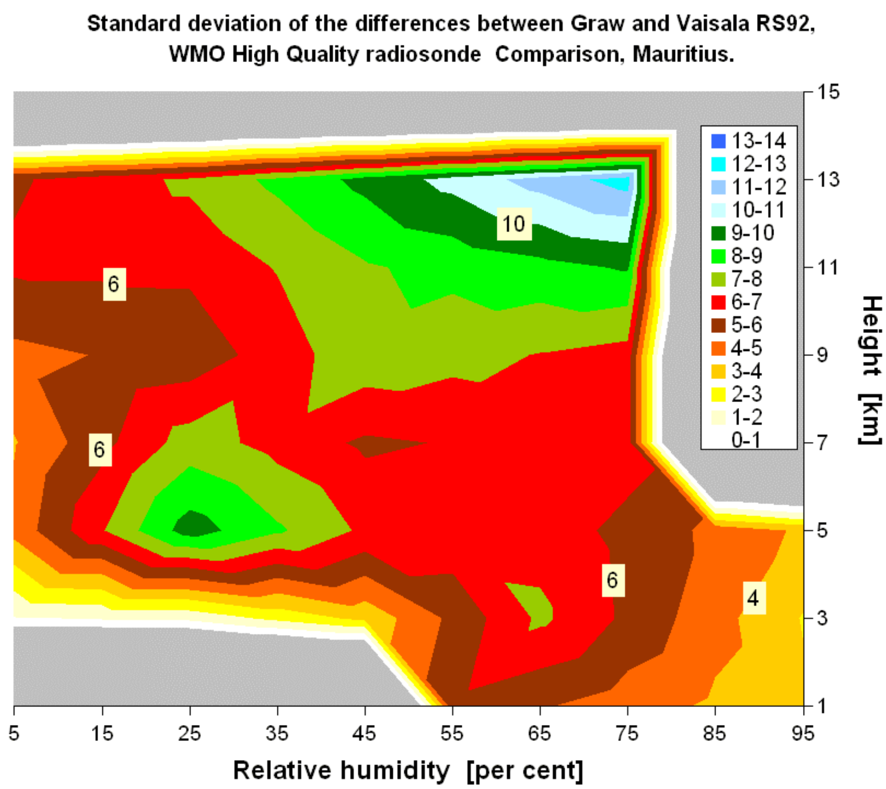

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Fig 9(e) Standard deviations of differences between Graw and Vaisala relative humidity

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

7. Simultaneous wind comparisons

There were no significant problems with this generation of GPS wind measurements. The main differences between the systems see Figs.10 (a) and (b) for comparisons between U and V wind components, arose from the different types of filtering used to remove the pendulum motion of the radiosonde under the balloon. The filtering of the Meisei measurements averaged over too long a period to give optimum performance in the stratosphere, and some of the test flights were too long for the battery design, so some Meisei measurements deteriorated in quality at the uppermost heights.

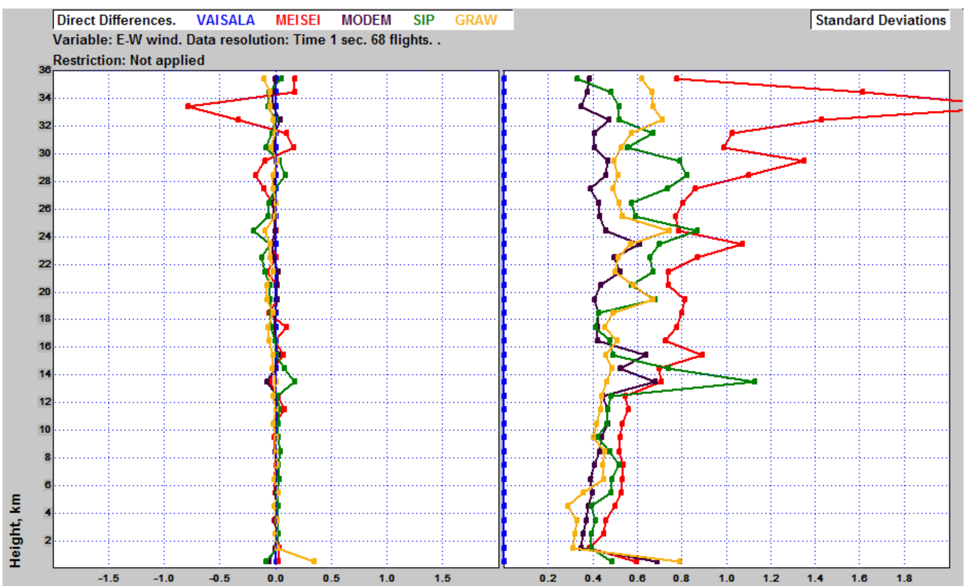

Fig. 10(a) Systematic bias and standard deviations of simultaneous comparisons between U components [ms^{-1}].

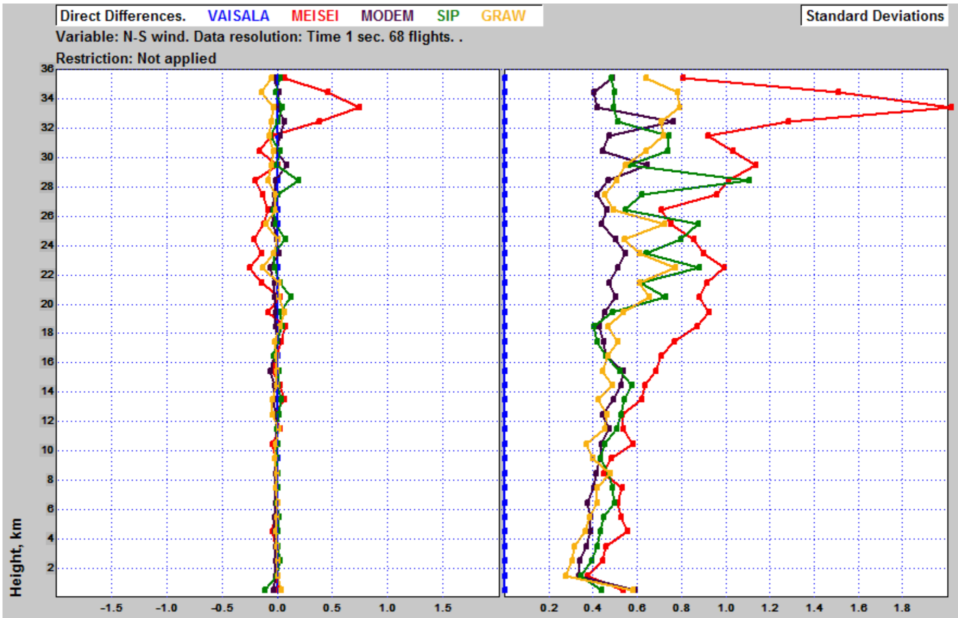

Fig. 10(b) Systematic bias and standard deviations of simultaneous comparisons between V components [ms^{-1}].

Typical random errors in wind component [u, v] measurements must have been less than or equal to 0.3 ms^{-1} for all systems at all heights apart from Meisei in the stratosphere. Systematic bias between measurements from different systems was negligible. These results were obtained with minimal editing of the wind profiles by the WMO Supervisors.

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

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