

NEW DEVELOPMENTS AND OPERATIONAL EXPERIENCE WITH UPPER-AIR OBSERVATION TECHNOLOGY

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ABSTRACT

Recent developments in the technology for conventional (in situ) observation have led to very large improvement compared to ten years ago in measurement, processing and transmission while reducing the expenditure and running cost of ground based upper air network. Uniformly high quality radiosonde measurements should be achievable worldwide soon, if manufacturers and customers improve working relationships. GPS radiosondes provide very reproducible height measurements. The number of winds from wind profilers assimilated into NWP model has significantly increased in the last 5 year. The first wind profilers have been successfully deployed in Africa. While already assimilated in NWP, the increase density of GPS integrated water vapour allows better identification of humidity fields associated with mesoscale phenomena. The concept of ground based integrated remote sensing starts to be applied to the design for the new generation of high resolution numerical weather prediction model, and for physical process understanding for climate parameterization.

1. INTRODUCTION

Climate and weather observations are essential for the development of climate change policies and weather services securing the safety and quality of life of the public. Progress and reliability in upper air measurements are important in the improvement and the validation of climate model and numerical weather prediction.

Recent developments in the technology for conventional (in situ) observation have already led to very large improvement in measurement, processing and transmission while reducing the expenditure and running cost of ground based upper air network. Improvements in numerical weather and climate models need observations of atmospheric variables such as clouds, winds, temperature and humidity at increasingly high resolution in space and time. Met services are already working toward 1 km resolution regional models and will be able to update some of their control variables every 15 minutes. Measurement of the variability of the observed quantity at the models' resolved scales allows an optimal assimilation of the information by giving an estimate of the representativeness error as well as the measurement. Interaction of different scales from global to convective scale is important in the understanding of atmospheric and climate physical process. Information on these interactions needs to be provided by data with high spatial and time resolution from many regions. For the future, the needs of weather forecasting and climate modelling can only be covered at a reasonable cost by mixing some existing in situ measurements (balloon-borne radiosondes, aircraft) with integrated ground-based remote sensing systems that provide more continuous sampling of the essential atmospheric variables in complement to satellite observation. In the long run this mix will probably need to be implemented in all regions of WMO.

In this paper progress in operational radiosonde technology is reviewed. Then recent development in remote sensing technique is presented. In this context, deployment of wind profilers in West Africa is shown. Maturity of the operational implementation of GPS water

vapour is examined. Progress of development of integrated profiling systems is illustrated with examples from the COST 720 project in Europe.

2. PROGRESS IN RADIOSONDE TECHNOLOGY

Modern radiosonde systems are much more sophisticated systems than the best radiosondes in use 20 years ago. The WMO GPS Radiosonde comparison in Brazil, da Silveira, et al (2005) began systematic testing of not only GPS wind finding systems but also a new generation of radiosonde temperature and relative humidity sensors. These new temperature sensors were mostly small thermistors or thermocapacitative devices and relative humidity sensors were mostly thin capacitance sensors, but a practical chilled mirror hygrometer also became available for testing water vapour measurements.

2.1. Temperature Comparisons

The night-time comparison between the temperature measurements from Brazil can be seen in Figure 2.1.1. Most of these measurements fell within $\pm 0.5\text{K}$ of the reference used, with only the two white painted temperature sensors (Modem, Sippican rod) showing larger cooling above 25 km and the Graw radiosonde showing a strong positive bias at the lowest temperatures between 14 and 21 km. The origin of the Graw problem was traced to temperature dependence in the signal channel electronics and was not a sensor problem. Graw redesigned the electronics and in the Mauritius test the strong positive bias had been eliminated, see Fig. 2.1.2. However, the Modem temperature sensor still showed the strong negative bias above 25 km in Mauritius, Nash et al (2006). The liaison between the manufacturer and the WMO Scientific team was faulty following the test in Brazil and the problems associated with infrared cooling of white paint were not explained adequately to Modem. This was rectified following the test in Mauritius where there was much more follow-up activity. In Fig. 2.1.4 it can be seen that Modem has now eliminated the white paint from their operational product.

Temperature differences with respect to night reference similar to Mauritius test,
NIGHT TIME, WMO Radiosonde Comparison, Brazil, 2001

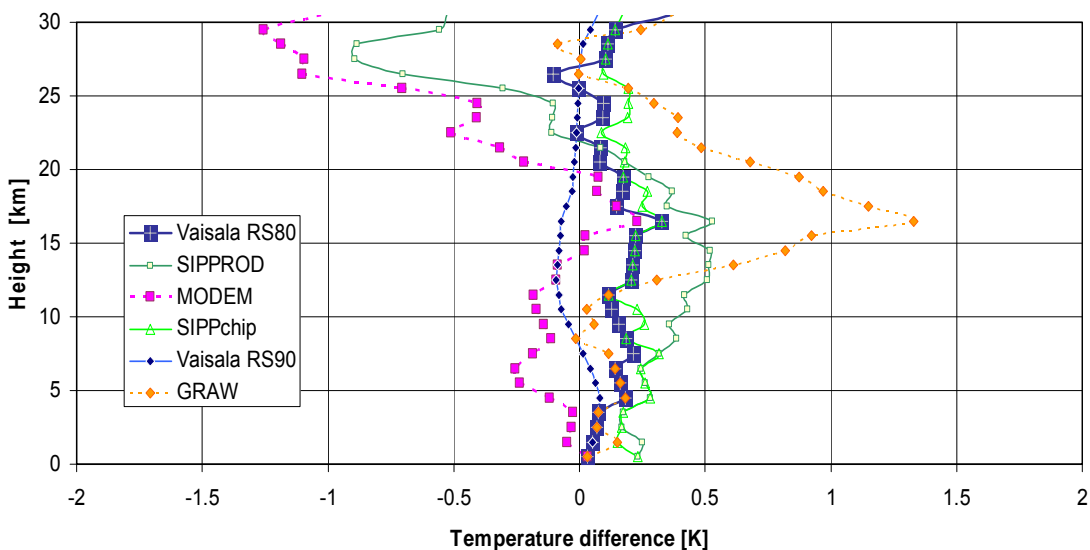


Figure 2.1.1 Systematic differences between radiosonde temperature measurements at night, using a reference expected to be similar to the reference in the WMO High Quality Radiosonde test In Mauritius.

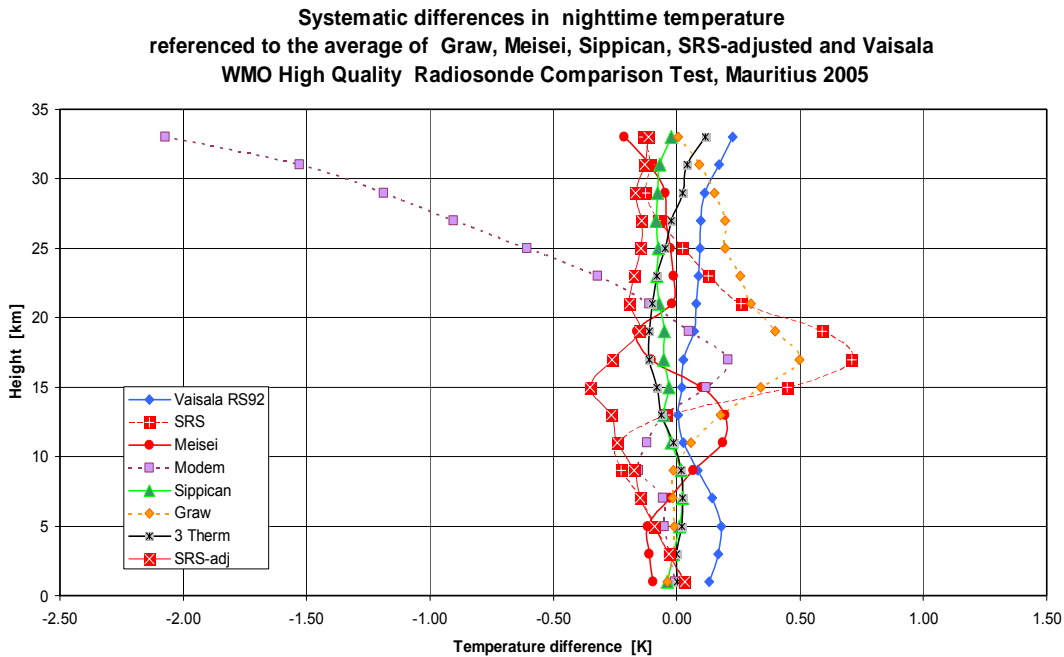


Figure 2.1.2 Systematic differences between radiosonde temperature measurements at night, WMO High Quality Radiosonde test In Mauritius.

At night the reproducibility of all the temperature measurements in Mauritius was estimated to be less than or equal 0.2K for all the radiosonde types between the surface and 30 km, see Figure.2.1.3(a). The degradation in reproducibility above 30 km was most probably the result of poor data reception at the longest ranges, but in the case of Modem this was probably due to variation in the infrared errors from flight to flight.

In the daytime the situation was different, with most temperature sensors showing much larger variation in random errors at heights above 16 km. In nearly all cases the heating of the temperature sensor was either sensitive to the orientation to the sun, i.e. coatings or shape were non-uniform or the support structure to the temperature sensor extended above the sensor and so air passing over the support structure could then flow over the sensor from time to time giving rise to intermittent positive bias. In one case editing software was used to eliminate many of the positive pulses, but this is not desirable for a high quality measurement. Thus, for climate monitoring it is important that manufacturers improve these aspects of sensor design and exposure.

Estimated random errors in nighttime temperature measurements,
WMO High Quality Radiosonde Comparison, Mauritius 2005,
assuming Vaisala random errors were as shown

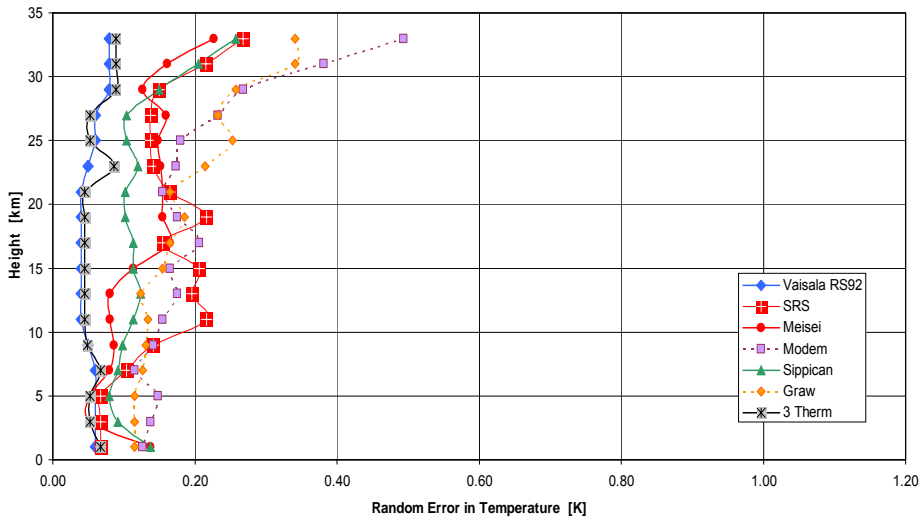


Figure 2.1.3 (a) Estimated random errors in night time temperature measurements, WMO High Quality Radiosonde Test, Mauritius.

Estimated random errors in daytime temperature measurements,
WMO High Quality Radiosonde Comparison, Mauritius, 2005
assuming Vaisala errors were as shown

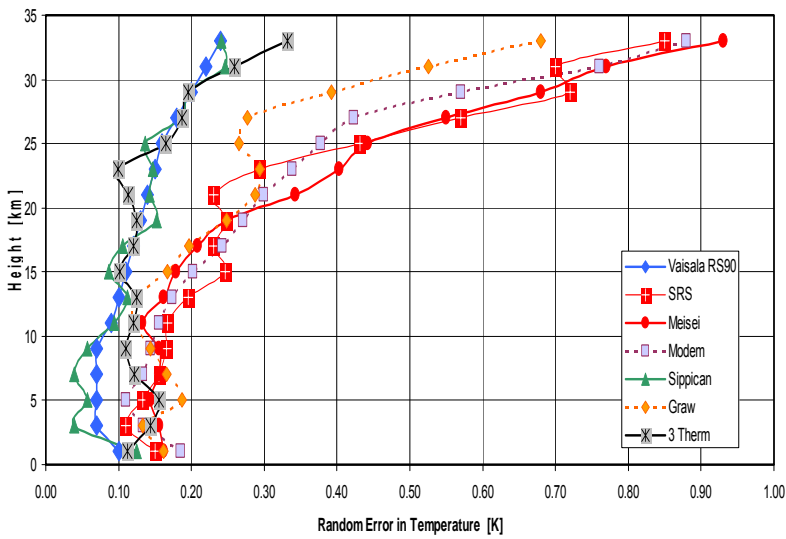


Figure 2.1.3(b) Estimated random errors in daytime temperature measurements, WMO High Quality Radiosonde Test, Mauritius.



Figure 2.1.4 New Graw DFM-06 radiosonde + temperature mount from previous DFM-97 radiosonde

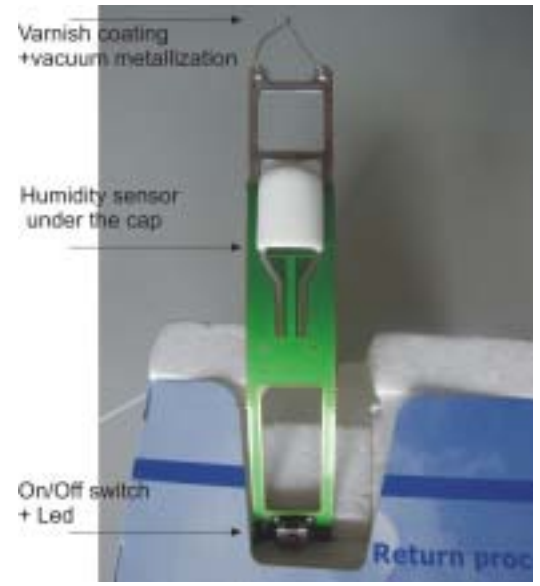


Figure 2.1.5 Modem temperature sensor from Mauritius test plus new modem temperature sensor mount in 2006

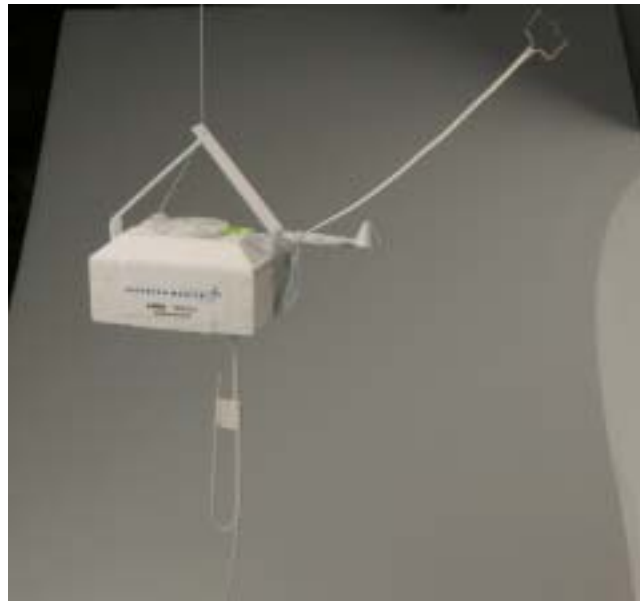


Figure 2.1.6 Lockheed Martin Sippican radiosondes, MKIIa as used in Brazil intercomparison, LMS-6 designed following the WMO high quality Radiosonde Intercomparison in Mauritius

Figures 2.1.4 to 2.1.6 show how the design and exposure of three temperature sensors have evolved since inter-comparison in Mauritius, with cleaner exposure in each case.

2.2. Geopotential height comparisons

In many radiosonde designs height assignment errors in the stratosphere often introduced larger errors in the reported temperatures than the sensor error.

In Mauritius the systematic offsets between most of the GPS geopotential height measurements were small [within 10 m for all but Meisei] see Fig. 2.2.1. These systematic differences were very much smaller than the differences between heights computed from the best pressure sensors at heights above 25 km. Similarly, the reproducibility of the GPS geopotential height measurements was also low [less than or equal to 10 m] see Fig.2.2.2. These values were much better than those achieved by the best pressure sensors at heights above 25 km. Thus, for the higher troposphere/stratosphere GPS radiosondes should no longer need to use a pressure sensor and this could lead to a reduction in the cost of GPS radiosondes in the long term. However, with the use of non-hydrostatic model for mesoscale forecasting (MesoNH), it is suggested that the possible benefit of using a pressure sensor to assign pressure to the GPS height directly in the lower and middle troposphere [and so not assuming hydrostatic balance in the vertical] should be investigated. This possible benefit seems the only possible reason to retain the pressure sensor on GPS radiosondes.

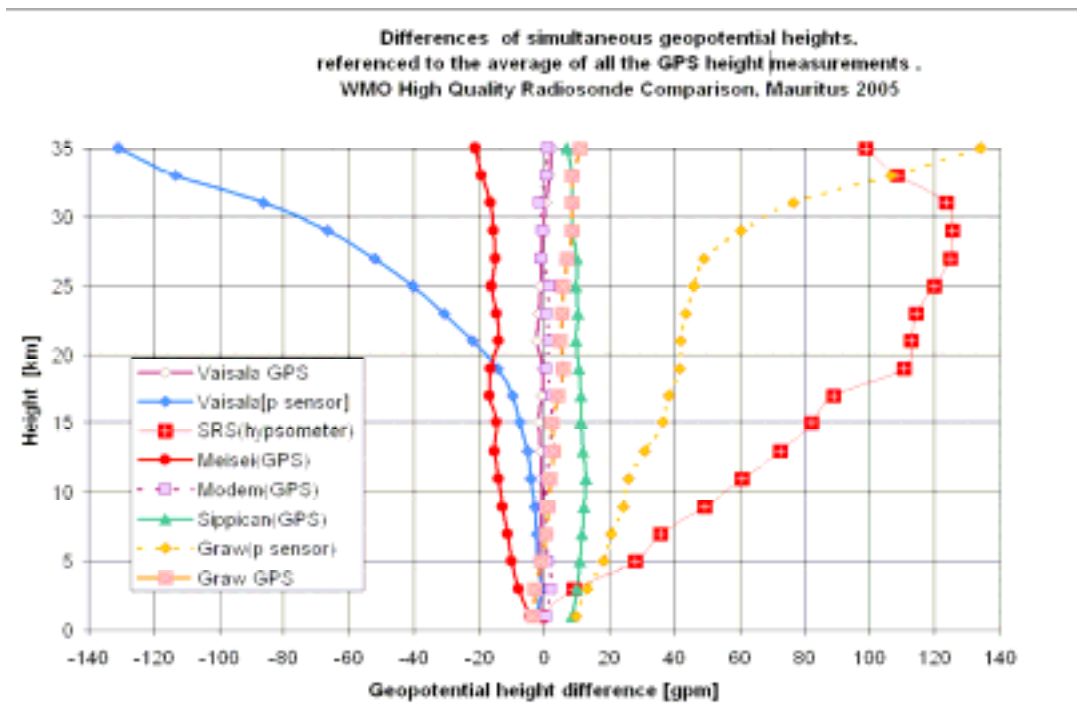


Figure 2.2.1 Systematic differences between radiosonde geopotential height measurements, WMO High Quality Radiosonde test In Mauritius.

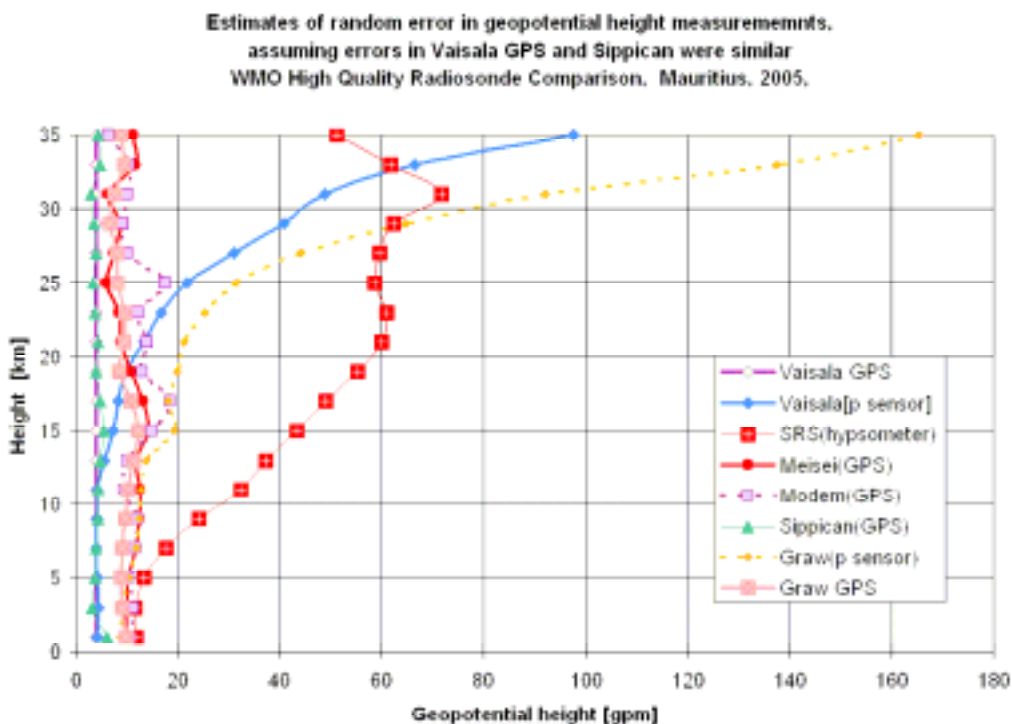


Figure 2.2.2 Estimated reproducibility of geopotential height measurements, WMO High Quality Radiosonde Comparison, Mauritius.

2.3. Relative humidity sensor comparisons.

Relative humidity systematic differences from the WMO GPS Radiosonde Intercomparison, Brazil as analysed by Nash are shown in Figs 2.3.1 for Vaisala Radiosondes and Fig.2.3.2 for Sippican MKIIa radiosondes. It should be noted that the temperature at a height of 11 km was usually about -40°C . Thus, the RS80-A radiosonde clearly had calibration problems at temperature lower than this at high humidity.

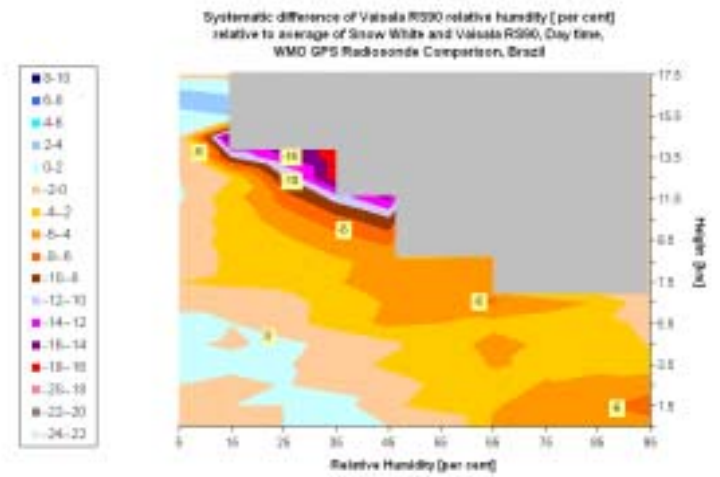
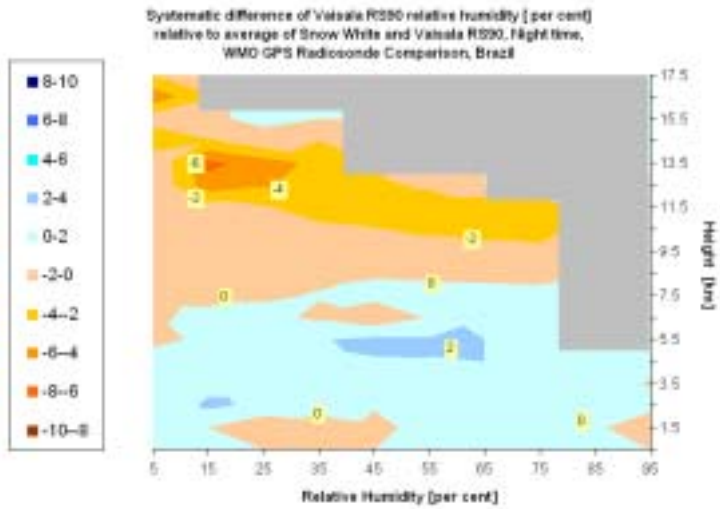
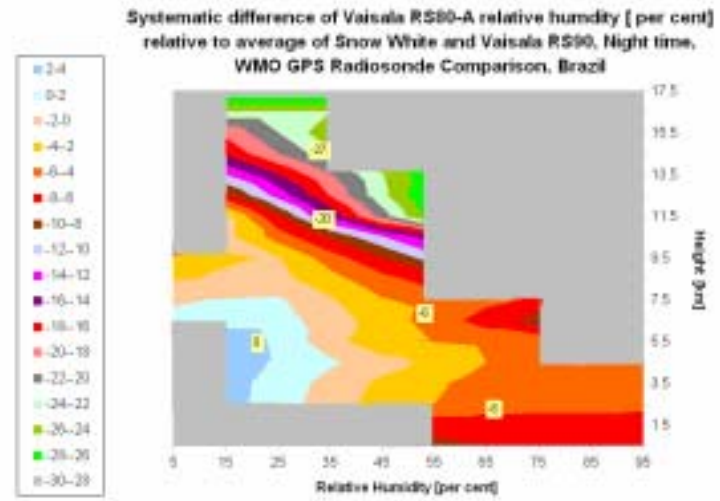
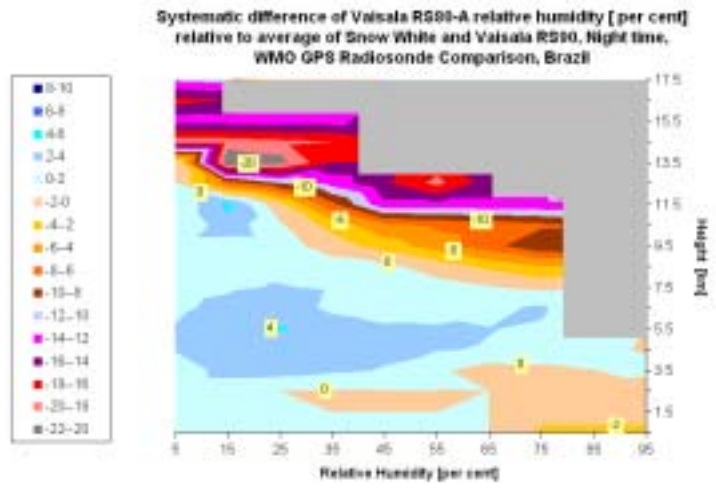


Figure 2.3.1 Systematic differences in relative humidity presented as a function of height and relative humidity for Vaisala RS80 and Vaisala RS90, day and night, WMO GPS radiosonde Comparison, Brazil. Data only presented for categories where sufficient samples were available.

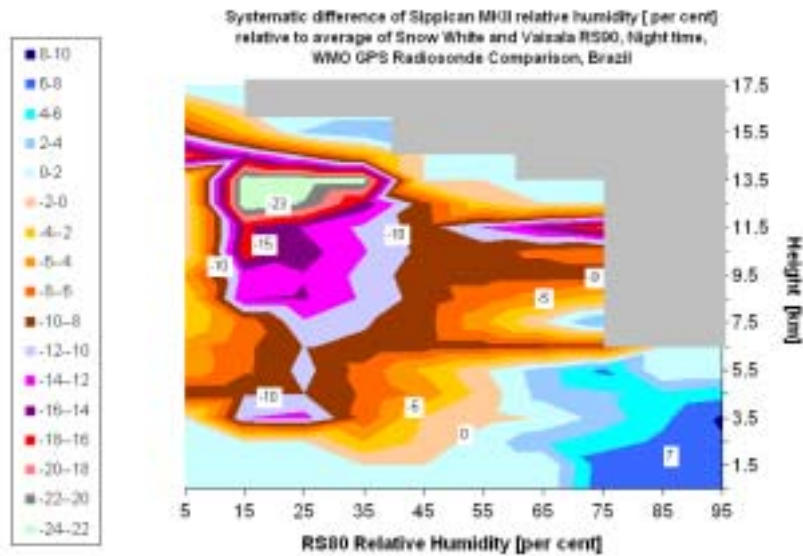


Figure 2.3.2 Systematic differences in relative humidity presented as a function of height and relative humidity for Sippican MKII radiosonde night, WMO GPS radiosonde Comparison, Brazil.

This problem was known for many years, but the manufacturer has not provided much guidance about this to the customer. Without admission of problems, progress in improvement becomes extremely slow and operational measurements are left to be substandard for many years. As far as relative humidity measurement, this criticism probably applies to nearly every manufacturer in the last decade, and the problem with substandard temperature measurements from some radiosonde types has also persisted for too many years. It is a challenge to HMEI and CIMO to rectify this situation.

Figure.2.3.1 also shows that Vaisala daytime measurements were not of the same quality as nighttime measurements with daytime measurements at least 5 per cent low relative to nighttime measurements at high relative humidity.

The carbon hygistor sensor used in the Sippican MkII showed larger departures from the reference at nearly all humidities, particularly when temperatures were less than 0 °C [heights greater than 5 km].

In the WMO High Quality Radiosonde Comparison in Mauritius, the Vaisala RS92 radiosonde showed small differences relative to the reference at night, except at the coldest temperature, heights near 16 km, where contamination probably caused the positive bias seen, see Fig.2.3.3 (a). In the daytime, the RS92 relative humidity measurements at high humidity again have a negative bias of at least 5 per cent relative to Night-time measurements, see Fig.2.3.3 (b). In this case, the negative bias in upper moist layers was not so large as in Brazil, because Vaisala had changed the coatings around the sensor mounts to minimise heating of the humidity sensors. However, it is clear that the sensors are heated directly to a temperature above ambient atmospheric temperature, and there has yet to be a response to the customers as to what will happen in future about this problem. This day-night difference in relative humidity is important when attempting to integrate radiosonde measurements with remote sensing measurements in the techniques described later.

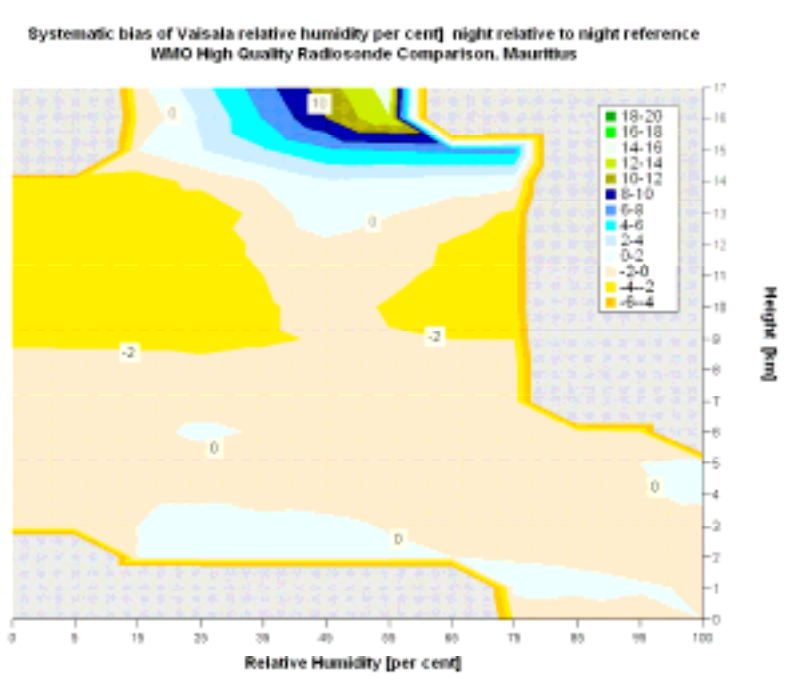


Figure 2.3.3(a) Systematic differences in relative humidity presented as a function of height and relative humidity for Vaisala RS92 radiosonde night, WMO High Quality Radiosonde Comparison, Mauritius

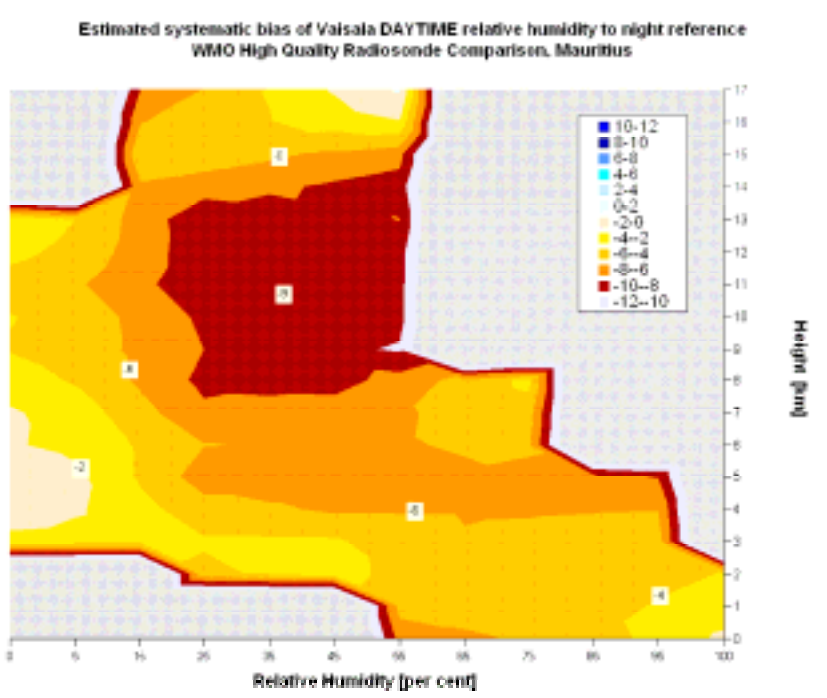


Figure.2.3.3 (b) Systematic differences in relative humidity presented as a function of height and relative humidity for Vaisala RS92 radiosonde day, WMO High Quality Radiosonde Comparison, Mauritius.

2.4. Other issues

Wind measurements with the new generation of code correlating GPS wind systems are much more accurate than any of the earlier operational wind systems. The capability of GPS radiosondes has been improved so that systems are now available that synchronise

rapidly during radiosonde preparation with minimal requirement for exposure outside before launch.

The new generation radiosonde transmitters are much more stable in frequency and as such cannot be criticised by the ITU for wasting radiofrequency spectrum. This also leads to very good data reception in the ground system with relatively low power radiosonde transmissions.

Ground systems associated with GPS radiosondes have become so small that it is easy to transport them around with minimal time necessary for installing an upper air station.

At this time a large scale changeover to the new generation radiosondes is starting to occur in the global network. Fig.2.4.1. shows the extent to which new radiosondes from Vaisala and Modem have now spread into the global observing system. China is also introducing a new radiosonde design that gives radiosonde temperatures of much higher reproducibility than the system that has been in use for many years; see the report of the CIMO Rapporteur on Radiosonde performance.

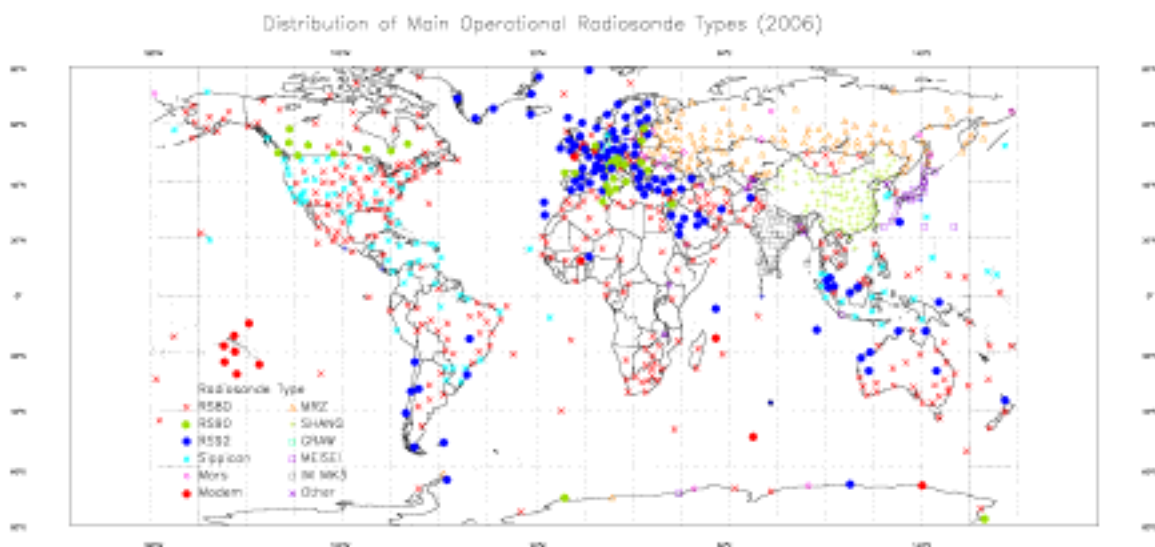


Figure 2.4.1 Radiosonde types in use in the Global Observing Network, early 2006, taken from the Report of CIMO Rapporteur on Radiosonde Compatibility [T.Oakley]

3. RECENT DEVELOPMENT IN REMOTE SENSING TECHNIQUE

3.1. Microwave Radiometer

Ground-based multi-channel microwave radiometers measuring brightness temperatures around the 22 GHz water vapour absorption and around the 60GHz oxygen complex are now commercially available. These radiometers are robust enough to run completely unattended (Gaffard and Hewison 2002). They can measure with a good accuracy the integrated water vapour and liquid water in all weather conditions except during rain (Crewell et al 2002). They can provide temperature profiles in the lower troposphere up to 3 km with vertical resolution that gradually degrades with height and some indication of the vertical humidity structure in the lower troposphere. They can also provide cloud base height indication if an upward pointing infrared radiometer is incorporated with the system.

In the last 5 years, interactions between users and manufacturers have led to significant improvement in the design of radiometer. High time sampling rate (better than 30 s) are

now available on most of the commercial available radiometers. Such sampling rate allows a characterisation of the atmospheric variability from convective scale to synoptic scale. Inter-comparison campaigns allowed bias identification on some of the channels. Fig. 3.1.1 shows the bias between the observed brightness temperature and those modelled from in situ radiosonde for the channels of 2 radiometers. The inter comparison was done over 7 weeks in Camborne UK in winter – only clear sky condition were selected. The Rosenkranz 1998 radiative transfer model was used to compute the brightness temperature from the radiosonde. In the oxygen complex, in particular when the effect of water vapour is negligible, (i.e. from 54 to 60 GHz) this model is considered as unbiased in typical near surface conditions (Hewison et al 2006). The corresponding channels are sensitive to the temperature in the first 3km where the radiosonde temperature is very accurate. So the 1K bias observed in the 4 channels (from 54 to 58 GHz) for one of the radiometer is an instrumental bias. The origin of the bias was identified by the manufacturer and corrected. However, elimination of bias between radiometers still poses one of the main practical problems to be examined in pilot network operations.

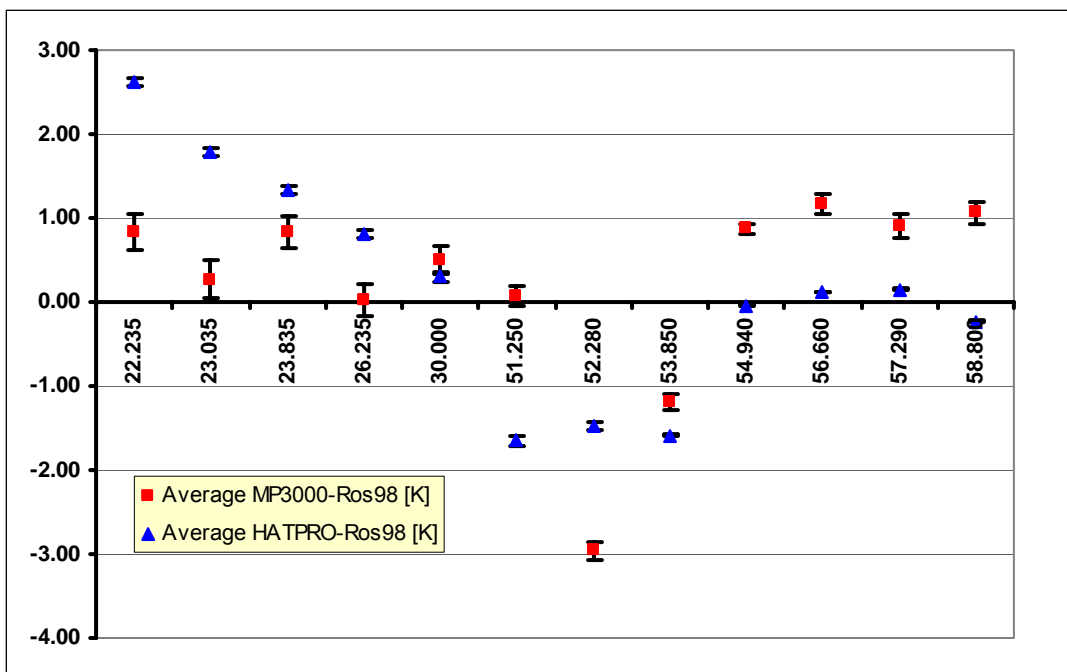


Figure 3.1.1 Observed –modelled brightness temperature for different channels for two commercial radiometers

The competition between manufacturers has led to a significant fall of the market price of radiometer while the instruments performance has improved.

Figure 3.1.2 shows one example of monitoring of the lower troposphere by a radiometer during the Convective Storm Initiation Project (CSIP) experiment at Linkenholt, South East UK. The microwave radiometer retrieval showed a strong temperature inversion in the lower 1 km between 0500 and 0700 UTC. This was due to radiative cooling from the surface during the previous night. This inversion was eroded as the surface temperature climbed rapidly to 20°C by 0600 UTC. This was associated with an unusually low relative humidity near the surface, Figure 3.1.2 b.

In addition to the atmospheric profile retrieved by the radiometer at Linkenholt, the atmospheric profile was measured by a radiosonde at Larkhill, 35 km away, at 0600 UTC 24 June 2005, Figure 3.1.3. Both profiles show a similar vertical structure, but the radiometer does not retrieve as much detail in the relative humidity profile as the

radiosonde. The radiosonde measured a higher relative humidity at the surface than the radiometer, 60 % compared to 35%. The radiosonde profile shows a stable structure between the surface and the top of the inversion at ~500 m, similar to that shown by the radiometer in Figure 3.1.2.

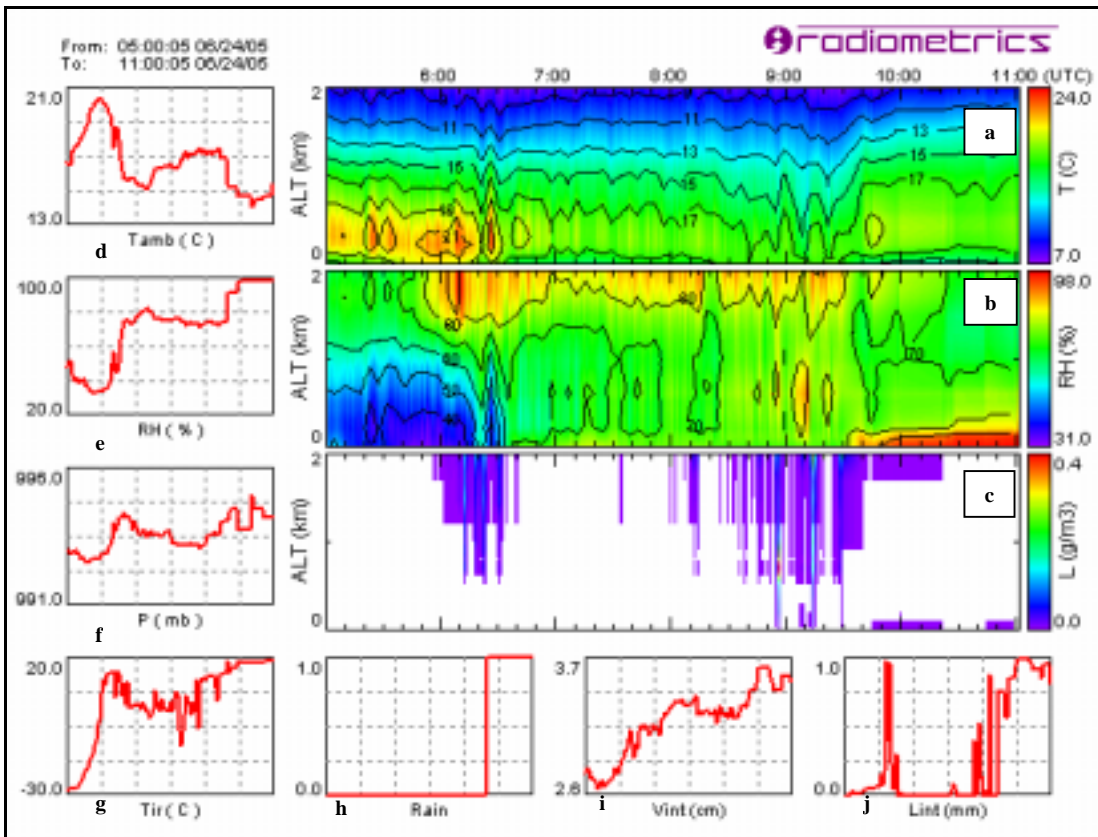


Figure 3.1.2 Microwave radiometer retrieval showing (a) temperature, (b) relative humidity and (c) liquid water time-height cross sections for 0-2 km height, 24 June 2005, 0500-1100 UTC. Time series of scalars are also shown in red for (d) surface temperature, (e) surface relative humidity, (f) pressure, (g) infrared brightness temperature, (h) rain sensor, (i) integrated water vapour and (j) integrated liquid water.

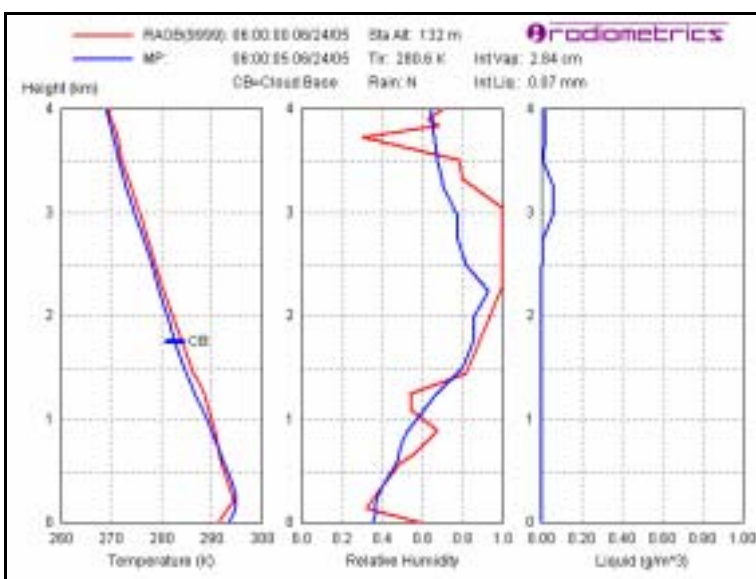


Figure 3.1.3 Atmospheric profiles of temperature, relative humidity and liquid water measured by a radiosonde launched from Larkhill (RAOB, red line) and retrieved by microwave radiometer at Linkenholt (MP, blue line). 6 June 2005, 0600 UTC.

3.2. Wind profiler and weather radar VAD wind

A wind profiler is a ground-based Doppler radar with 3 or more beams which measures clear air signals backscattered from refractive index fluctuations associated with turbulence. The Doppler shift of the signal measured from different beam directions is used to estimate profiles of the wind vector. Typically wind profilers operate in the UHF band for profiling the boundary layer, while VHF systems can be used to profile most of the troposphere. In addition to measuring the wind vector, the signal to noise ratio from wind profiler radars is sensitive to the magnitude of the gradients in the refractive index. These provide indications of the height of temperature inversions (for VHF systems in the upper troposphere) and hydrolapses (for UHF systems in the lower troposphere), which can be used to monitor the height of the top of the boundary layer. The spectral width can also be used to give an indication of the turbulence. Only the wind information is actually used operationally.

Wind profiler winds are used by weather centres for NWP and nowcasting, for airport safety, and by universities for atmospheric research. In Europe, a network of wind profiler, CWINDE, provides wind observations onto the GTS. This network was initiated through the COST 76 action, and further developed under EUMETNET by the WINPROF project. While the network remains heterogeneous (a mix of research and operational instruments observing either in the UHF or VHF), the centralisation of the data allows a systematic monitoring of the profiler winds. Collection of VAD winds from Doppler weather radars in Europe are also centralised by the CWINDE hub. Figures 3.2.1(a) and (b) show the locations of wind profilers, and weather radars reporting wind respectively. All winds considered of acceptable quality are assimilated by ECMWF and the Met Office.



Figure 3.2.1 a) Wind profiler location contributing to the CWINDE network



Figure 3.2.1 b) Doppler weather radar location contributing to the CWINDE network

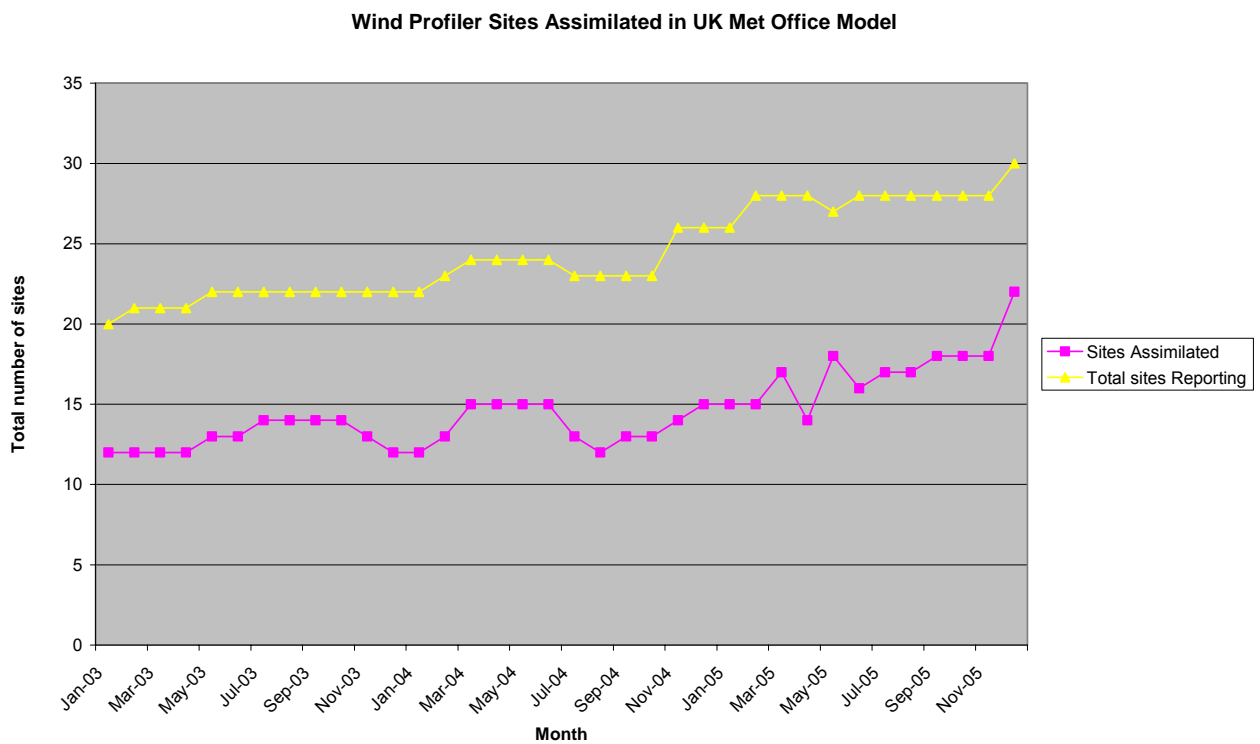


Figure 3.2.2 a) Yellow curve shows the time evolution of the number of sites of wind profiler in Europe and the pink curve indicates the number of sites that deliver winds which are assimilated.

Weather Radar Wind sites being Assimilated in UK Met Office Model

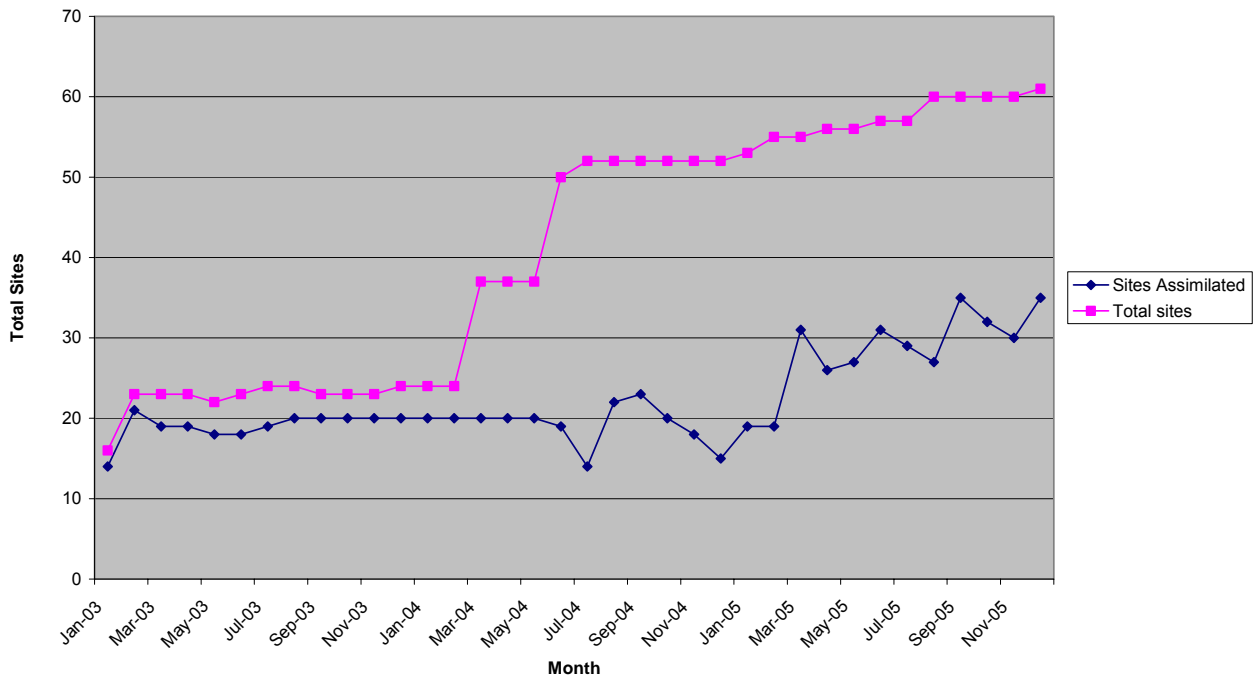


Figure 3.2.2 b) Pink curve shows the time evolution of the number of sites weather radar in Europe and the blue curve indicates the number of sites that deliver winds which are assimilated.

The wind profilers are continuously monitored against the model. Depending of the bias and rms against model value wind profiler data are accepted or not for assimilation. Each level in the profile is separately monitored, only certain wind from selected height in the profile are accepted. Table 3.2.1 shows the list of data accepted for assimilation in the UK Met Office model for September 2006. This list is updated every month. Only few wind profilers are fully blacklisted in the assimilation scheme, they correspond to profiler located in mountainous area where the real topography is quite different from the model representation of orography.

WIND PROFILER DATA ASSIMILATION

September 2006

Wind Profiler Sites Used at UK Met Office from 19th Sep 2006

WMO	Profiler Site	Type	Frequency *	Assimilated Now	Restrictions	Previous Month **
01012	Andenes			No		No
02043	Kiruna	MST	30 mins	Yes	Reject above 500hPa and below 850hPa	Yes
03019	South Uist (Low Mode) -	TROP	30 mins	Yes		Yes
03020	South Uist (High Mode)	TROP	30 mins	Yes	Reject above 150hPa	Yes
03203	Isle of Man	BL	30 mins	Yes	Reject above 400hPa	Yes
03501	Aberystwyth	MST	12 mins	Yes	Reject above 350hPa	Yes
03591	Wattisham	BL	30 mins	Yes	Reject above 500hpa	Yes
03807	Camborne	BL	30 mins	Yes	Reject above 500hPa	Yes
03840	Dunkeswell	BL	30 mins	Yes	Reject above 500hPa	Yes
06348	Cabauw	BL	1 hour	Yes		Yes
06610	Payerne	BL	30 mins	No		No
07112	La Ferté Vidame	TROP	1 hour	Yes		Yes
07453	Clermont Ferrand	TROP	1 hour	No		No
07626	Lannemezan	TROP	1 hour	Yes	Reject above 250hPa and below 700hPa	Yes
07650	Marignane	BL	30 mins	Yes	Accept some between 08-18Z. Reject above 500hPa and below 950hPa	Yes
07690	Nice	BL	15 mins	Yes	Reject above 500hPa and below 950hPa	Yes
10135	Nordholz	TROP	30 mins	Yes	Reject above 250hPa	Yes
10266	Ziegenderf	TROP	30 mins	Yes	Reject above 250hPa	Yes
10391	Lindenberg SODAR	BL	30 mins	Yes		Yes
10394	Lindenberg 482MHZ	TROP	30 mins	Yes	Reject above 150hPa	Yes
10636	Frankfurt	TROP	30 mins	Yes	Reject above 7000hpa & below 950hpa	Yes
10678	Bayeuth	TROP	30 mins	Yes	Reject above 250hPa	Yes
11036	Vienna	BL	30 mins	No		Jun 06

11120	Innsbruk			No		No
12842	Budapest	BL	15 mins	Yes	Reject above 500hpa & below 950hpa	Yes
12982	Szeged	BL	15 mins	No		Aug 06
16228	L'Aquila	BL	1 hour	No		No
16300	Torino	BL	30 mins	No		No

Total Currently Assimilated= 20

Total Currently Rejected= 8

* Not all messages will contain Wind Data.

** Where station was assimilated in the previous month, yes is stated. If not the month last assimilated is noted. (2006 only)

Some stations are on the boundary between being Accepted or Rejected, this is reviewed every month.

Table 3.2.1 Operational blacklist report of European wind profiler data for September 2006

In the last 5 years Japan has also developed a full network of 31 wind profilers. The profilers observe from near the ground up to about 5km in dry condition and up to 10 km in precipitation. The frequency used is in the range 1300 -1375 MHz. This network operates well and delivers the measurement required, i.e. wind in the lower and middle troposphere. Their operational assimilation in the JMA 4 D-Var assimilation scheme has shown positive impact in particular in the rainfall over Japan. These data are available on the GTS and are also assimilated operationally by ECMWF and the Met Office.

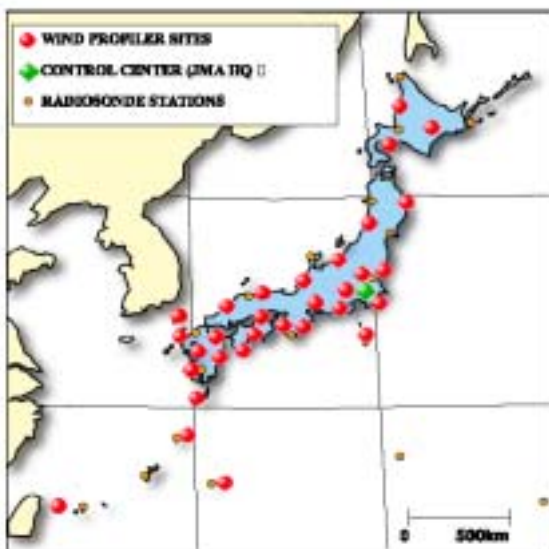


Figure 3.2.3 Wind profiler network in Japan

3.3. Wind profiler in West Africa

AMMA (African Monsoon Multidisciplinary Analysis) is an international project to improve knowledge and understanding of the West African monsoon (WAM). In situ and remote sensing networks have been deployed in West Africa. The network has been designed in such way that in association with satellite data a multi-scale observation approach can be achieved: from global to convective scale.

3.3.1. Wind profiler deployment for AMMA

An impressive network of 4 UHF and 1 VHF wind profilers have been deployed for AMMA. Their location is shown on the map in Fig.3.3.1.1. Two UHF profilers at Bamako (Mali) and Ouagadougou (Burkina-Faso) belong to ASECNA (African civilian aviation). They have been operating in a continuous survey mode since March 2005 for Bamako airport and since June 2006 for Ouagadougou airport to monitor strong nocturnal low level wind shears that regularly affect the safety of aircraft landing and take-off. These are the first operational wind profilers installed in Africa.

Two other UHF profilers have been specifically installed for AMMA at Niamey (Niger) and Doug (Benin). A VHF wind profiler was also installed at Djougou, these 3 wind profilers will be returned to country of origin after AMMA.



Figure 3.3.1.1 Wind profiler map for AMMA.

3.3.2. First results (Campistrion et al 2005)

At Bamako, the dry period is associated with a rather simple meteorology characterised by a remarkably regular diurnal cycle of all the radar observables.

The regular diurnal cycle allows merging observations from all the days into a composite mean day (as a function only of the hour). The cost is an amplitude reduction for the parameters, compensated by advantages such as better vertical coverage and less sensitivity to measurements errors and small scale processes. It was verified that the resulting picture was in agreement with the general pattern of the month. Figure 3.3.2.1 shows mean day time-height sections based on high-mode profiler measurements collected during 26 days of March 2005. The parameters are wind velocity, dissipation rate of turbulent kinetic energy ϵ , reflectivity ($Cn2$), and vertical velocity. ϵ is deduced from the median value of the Doppler spectral width measured on the three beams (Jacoby-Coaly et al, 2002). A 1-hour running average was applied on the pictures.

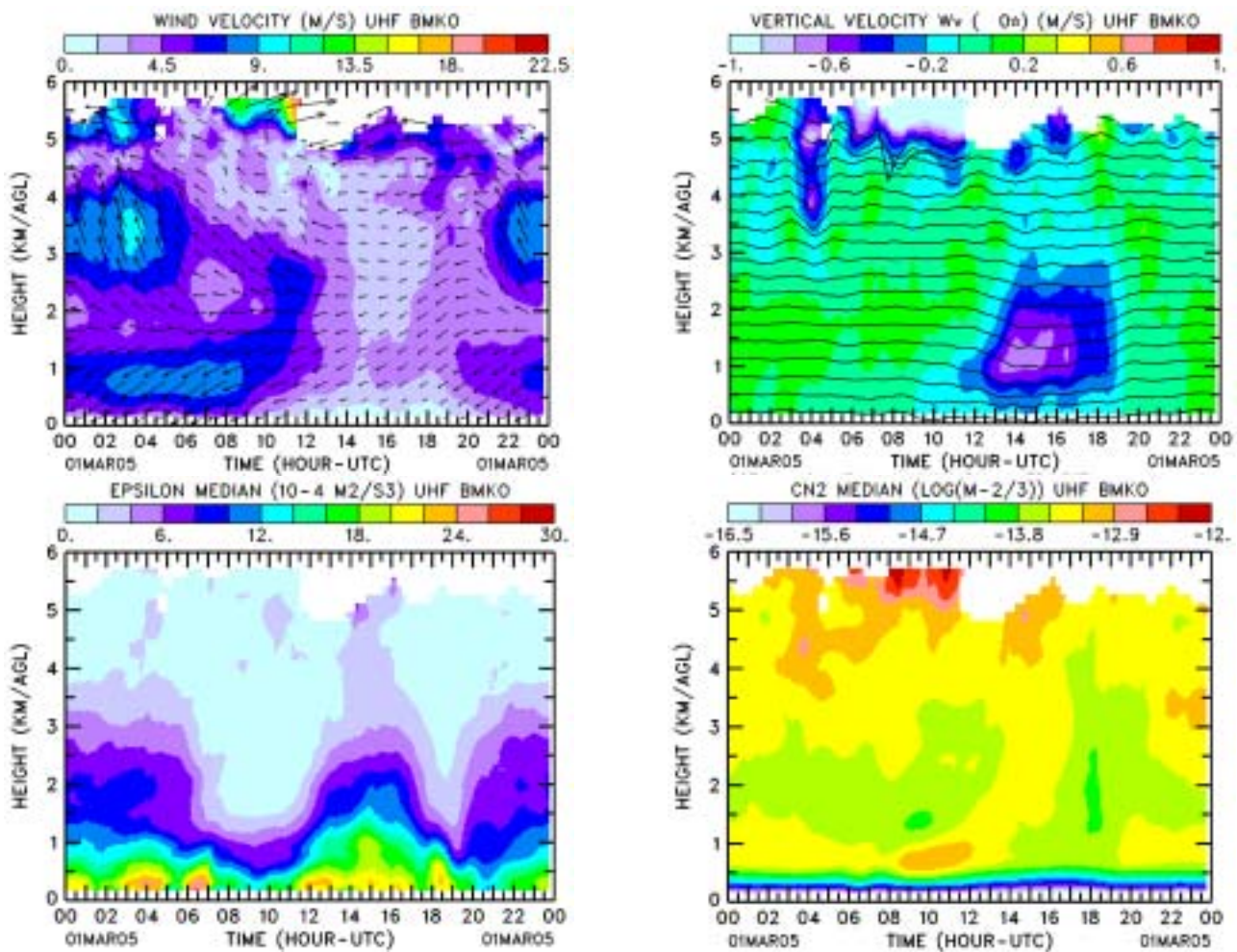


Figure 3.3.2.1 Time-height sections of wind velocity (top left), dissipation rate of turbulent kinetic energy (ϵ) (bottom left), median reflectivity (bottom right), and vertical velocity (top right) for a composite day made of high-mode profiler observations collected in March 2005 at Bamako.

The main key in the understanding of the diurnal circulation comes from the time and height evolution of turbulence through ϵ . During the afternoon the wind is weak (less than 4 ms^{-1}) and vertically quite homogeneous, slightly turning with height from north-easterly to easterly. The thermal turbulent mixing is responsible for this homogeneity. It is mainly confined below 3 km agl which is the level previously defined as the atmospheric boundary layer (ABL) top, with an extension of weaker intensity up to 5.5 km agl. This height is the base of a cloud layer giving light precipitations discernable by negative vertical velocity in Fig .3.3.2.1 and enhanced reflectivity.

Note: the north-easterly nocturnal low level jet (LLJ) below 1 km agl reaches its maximum value near sunrise nearby the 500 m agl level. This inertial circulation develops after sunset and is maintained as long as the surface turbulent friction is absent. Another nocturnal jet, but of south-easterly origin, is present at middle level between 3 and 4 km agl. This is the layer of the summer African Easterly Jet. This middle level jet (MLJ) disappears as for the LLJ during day time when thermal turbulence develops.

During the afternoon, Figure 3.3.2.1 shows that the vertical velocity is mainly negative, especially inside the ABL. This negative vertical velocity is considered to be a bias attributed now to a UHF measurement artefact the most probable cause of which comes

from the detection of particulate matter such as insects transported by convective turbulent motion (Lothon et al, 2002). The most unexpected result was the existence during the night of a turbulent field as intense as in the afternoon, see Figure 3.3.2.1. A measurement artefact is possible, but with the same type of profiler, nocturnal jets have been already observed in France but none of them were associated with turbulence. So the reliability of this observation will have to be checked with other means.

The deployment of wind profiler in Africa is successful. It demonstrates the maturity of the infrastructure for this remote sensing technique.

3.4. Cloud radar

Cloud radars are used to measure cloud top, internal cloud structure and cloud distribution in the lower, middle and upper troposphere. They provide a continuous stream of data and usually operate at frequencies near 35 GHz or 94 GHz. There are two variants of cloud radars. 'Pulsed' versions have been deployed at several cloud observing sites in Europe including Cabauw, Netherlands, Lindenberg, Germany, Palézieau, France and Chilbolton, UK and ARM sites in North America. FMCW (Frequency Modulated Carrier Wave) cloud radars have not yet been deployed at regular observing sites. Pulsed cloud radars are extremely expensive i.e. in the region of £400k to £1000k, whereas FMCW cloud radars can be made available for under £100k.

In 2003 the UK Met Office and the Rutherford Appleton Laboratory (RAL) started evaluation of a prototype cloud radar. This evaluation has proved very successful, but has also highlighted several areas that require further development. Thus a new project has been set up at the Met Office to develop with the RAL a prototype operational cloud radar observing at 94 GHz.

Cloud radars can measure the top of deep fog, but in the early stages of development or thin fog the prototype system observing at 78 GHz lost sensitivity at heights lower than 100 m due to the geometry of transmitter and receiver antennae.

Figure 3.4.1 shows the evolution of fog during a test day at Payerne In Switzerland. At 05:00, the fog thickened with larger water drops within the fog giving higher cloud radar signals. At 07:00 UTC (8:00 local) the fog start to lift, with cloud dissipated due to solar heating. However the fog layer formed again in the evening. At 10.00 drizzle from a very small shower gave a very much larger signal for a short period. The top of the fog has been verified in various experiments and was found to be reliable consistent with the vertical resolution of the radar, (15 m) in this mode.

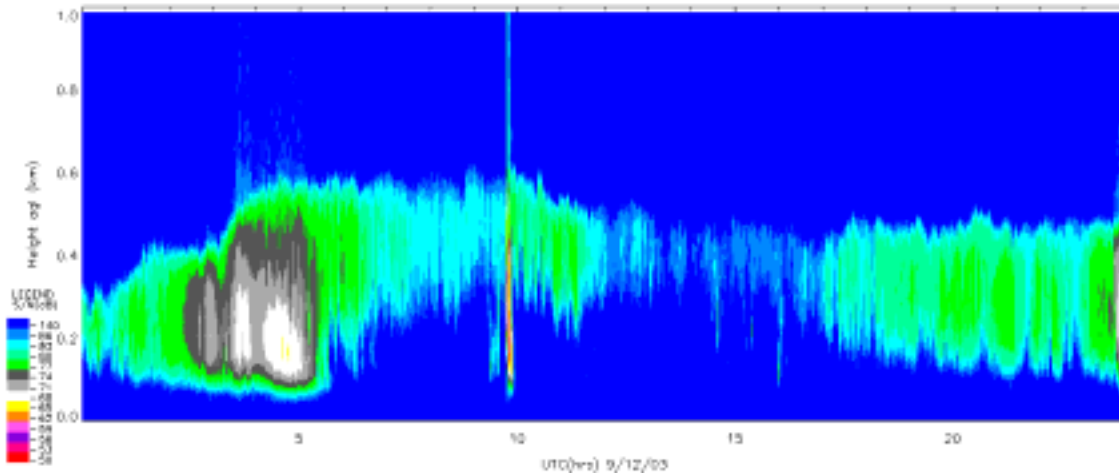


Figure 3.4.1 Example of low stratus/fog evolution captured by the cloud radar.

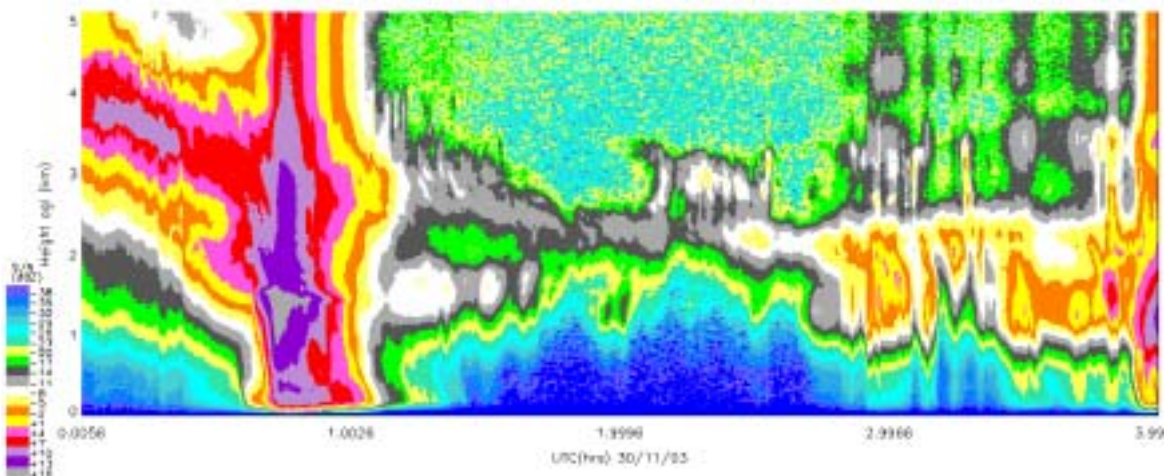


Figure 3.4.2 Example of frontal cloud from 30 November 2003, Payerne, Switzerland.

In Figure 3.4.2., the cloud radar is detecting cloud which lowers with time between 00 and 03:00 UTC. Precipitation is falling from this cloud, some as drizzle. The drizzle can give signals as strong as the signals received in heavier rain. The structures at 4 km and above from 03 to 04 UTC on this day are judged to be artifacts caused by a radar fault which allows strong signals between 1 and 2 km to give false signals in the higher range gates. The generation of the false echoes seems most pronounced when real signals are found in the lowest range gates, e.g. see the shower at 10:00 UTC in Fig.3.4.1. Rectification of this fault is to be addressed. The judgments about the cloud radar on this day are based on collocated measurements by laser ceilometer and wind profiler radar, together with surface observations. In future operational applications, the cloud radar will have to be used with a collocated laser ceilometer, see section 4.2.

3.5. GPS water vapour networks

The problems of performing rapid real time processing of the time delays of GPS signals to compute zenith time delay and/or integrated water vapour have largely been resolved, although there are a variety of methods of computing the results. For instance, in Europe there is still no consensus as to the best methods to be used, with several different schemes producing results of acceptable quality and plans are being made to resolve the issues by collocating sensors with microwave radiometers and radiosonde stations.

Siebrén de Haan has produced a report on national / regional operational procedures for GPS water vapour networks and agreed operational practices, [prepared for the CIMO Remote Sensing Expert Team, and to be published as IOM, No, 92, WMO T/D- 1340].

Computation of results with fifteen minute resolution and small time delays seems possible and has started in KNMI, see http://www.knmi.nl/research/groundbased_observations/gps/processing_gps/near_real_time_IWV.html

Several national networks are now progressing towards this type of operation, as the customers require quicker delivery for nowcasting applications. Inexpensive access to suitable networks of GPS receivers is being negotiated by different methods according to the situation in each country. The GPS results are now being used operationally in the numerical weather prediction forecasts of several countries in Europe and North America. Africa also plan to develop GPS sensor. The map there after show the actual site already set up on the African continent.

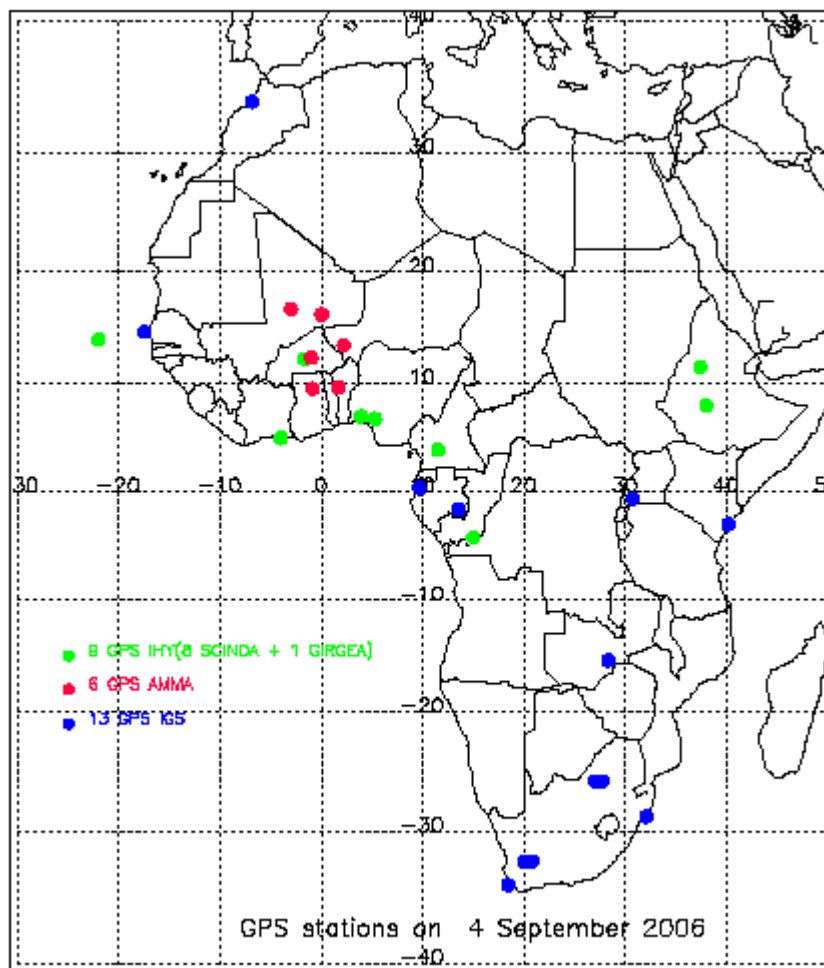


Figure 3 5 1 Actual GPS sensor sites used to measure IWV in Africa

In the UK a large network of sensors is available from the UK mapping agency, and these data are supplied for Met Office processing under a memorandum of understanding between the two government agencies. The GPS processing system will be handed over to full Met Office operational control in 2007 and at that time investigations will start as to whether a higher network density may be required in certain areas of the country. Figure

3.5.2 shows a plan view plot of the data available across the UK on a day when thunderstorms were spreading north from France. Notice the pronounced variation of water vapour with longitude in southern England. The very narrow band of dry air which becomes even drier when thunderstorm activity is at its highest and moistens once the thundery area moves east occurs in some types of thundery conditions in the UK. In 2005 several days were seen where a similar very dry layer was oriented east-west at about 54°N. Resolving structures in the water vapour fields such as this requires a spacing of better than 50 km in the horizontal. The relationship between severe thunderstorms and the water vapour fields is complex and it will take several years before forecasters can be thoroughly briefed as to how to use the information in improving short term forecasts of severe weather.

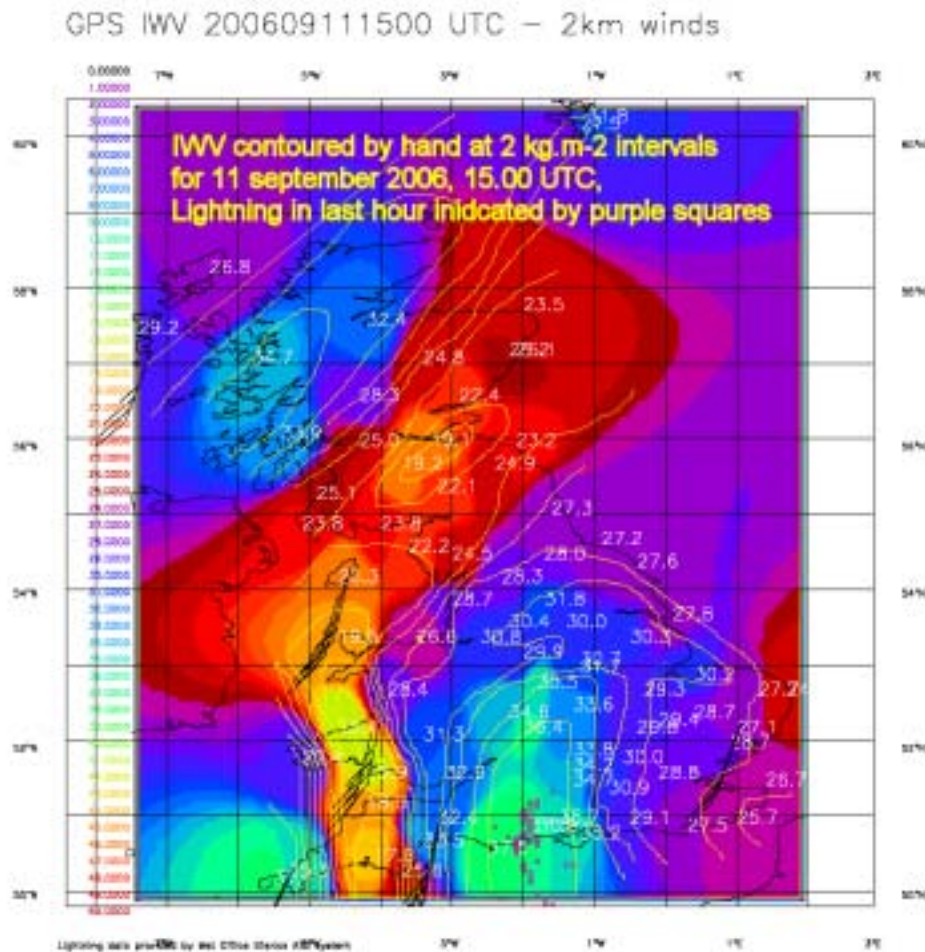


Fig. 3.5.2 GPS water vapour plot from operational testing of the UK network

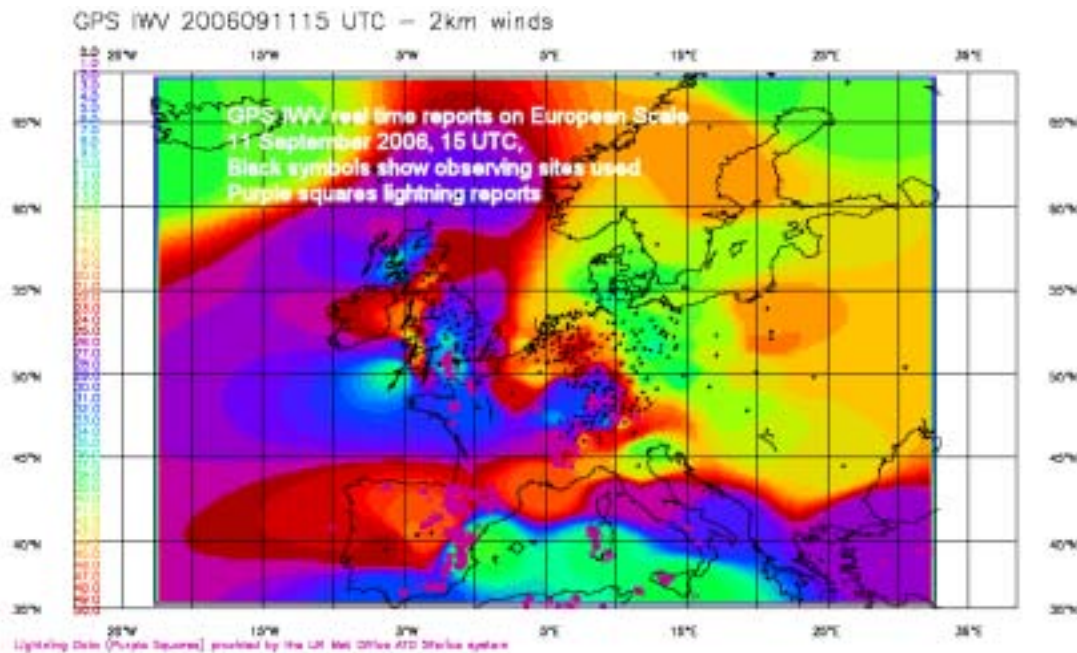


Fig.3.5.3 GPS water vapour plot for Europe, showing current sites supplying data to E-GVAP hub in near real-time.

Figure 3.5.3 shows a more extensive water vapour plot across Europe for the same time and it can be seen that the integrated water vapour northern and eastern Germany is much lower than near the Alps and in the UK where thunderstorms were occurring. This plot comes from the hub of the EUMETNET water vapour project E-GVAP. It is expected that observations will be added from France and Ireland within about a year.

4. Integrated profiling systems

While a number of existing remote sensor and in situ instruments deliver measurements of moisture, temperature, cloud, and wind, no one sensor or instrument by itself is sufficient to provide all the required measurement.

- Radiosondes do provide high quality measurements of temperature, humidity and wind; however those measurements are sparse, in time and space, and only represent a spot measurement. Operational radiosondes do not provide cloud information. Satellite observing systems used to retrieve thermodynamic profiles provide global coverage, but they do not provide the necessary vertical, horizontal and temporal resolution to characterize variation in the planetary boundary layer. Satellite systems don't have the vertical and horizontal resolution necessary for cloud property estimation.
- Ground based remote sensing instrument such as microwave radiometers can measure with a good accuracy the integrated water vapour and liquid water in all weather conditions except during rain. They can also provide temperature and humidity profile. All these measurements can be done with a 30s time resolution. However the vertical resolution is poor and above 3km microwave radiometer profile have no vertical skill.
- Raman Lidars have proved to be an effective tool for retrieving water vapor profile with high temporal and vertical resolution under clear sky conditions. Their use however is limited at the moment, by cost, the relatively short life of some

components and complexity and remains more research tool than operational unattended monitoring instrument.

- Wind profilers (UHF and VHF) have been designed for winds measurement. The radar technology allows good vertical resolution ranging from 50 m in the boundary layer up to 500 m in the upper troposphere. Several works have shown that other parameters like turbulence information and refractive index variations could be extracted from the signal to noise ratio. Such information combined with passive instrument like microwave radiometer can improve the vertical resolution of the retrieve profile (Bianco et al. (2005)).
- Ceilometers operationally provide cloud bottom height, the use of the measured extinction profile combined with cloud radar measurement allows a classification of the hydrometeors of the cloud and thus improve the retrieved liquid profile.

The Integrated Profiling Technique, developed by Löhnert et al [2004], uses at the moment cloud radar, radiometer and radiosonde to derive accurate liquid profiles. Such techniques can be further developed to include other information, such as significant level in the humidity structure estimated by the wind profiler. Integrated profiling systems will also allow the development of multi-instrument quality control procedures. To facilitate the cooperation between several countries in Europe a COST Action has worked on the development of cost-effective integrated ground-based remote sensing stations for atmospheric profiling and the assessment of their use for meteorological analysis and forecast as well as climate research and climate monitoring. The following sections use examples from the COST720 to illustrate recent progress in the development of integrated profiling systems.

4.1 Wind profiler and radiometer integration example of case studies

4.1.1 Layer identification

Several tests in the UK have shown that 1 GHz wind profiler is, in most conditions, able to measure the height of refractive index discontinuity which most of the time is not detected by a radiometer. Figure 4.1.1.1 shows one example of time-height evolution of the range-corrected wind profiler signal to noise ratio (SNR) at high time resolution (5 minute) for the vertical beam. Each point represents 30s of acquisition time. The layer of stronger signal between 200 and 300m is the result of ground clutter contamination and measurements at these heights should be ignored. The cloud base detected by the ceilometer was superimposed in white circles. Strong signal to noise was mostly limited to the region between 200m and 600m, with variable signal to noise structure above 1000 m. Hourly radiosondes were launched at the site.

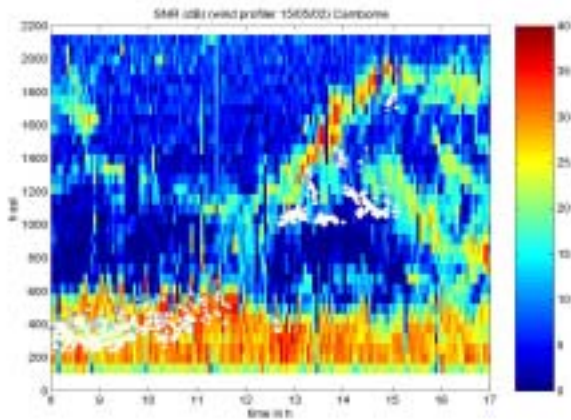


Figure 4.1.1.1 Signal to noise ratio of wind profiler (dB scale) on 15/05/2002 at Camborne. White and blue circles show cloud base reported by ceilometer.

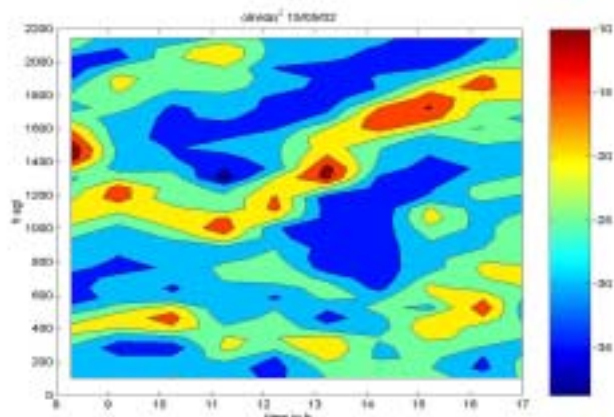


Figure 4.1.1.2 Time-height series of square gradient of the refractive index (dB scale) computed from hourly radiosonde on 15/5/02, Camborne.

The evolution of the square of the refractive index $(dn/dz)^2$ computed from the radiosondes during the day shown in Figure 4.1.1.2 is in very good agreement with the evolution of range-corrected signal to noise ratio. All the hydrolapses and temperature inversions which make strong discontinuities in the refractive index correspond to enhanced signal in the radar data. A collocated microwave radiometer reported a similar tendency to the radiosondes for the temperature between the surface and 1 km, see Figure 4.1.1.3, but the humidity from the two systems was only similar in the layers below 500m, and shown in Figure 4.1.1.4. The microwave radiometer could not resolve the temperature inversion and the associated dry layer shown by the radiosondes. In this case, incorporation of information from the wind profiler signal to noise in a retrieval method should improve the vertical structure reported from the radiometer.

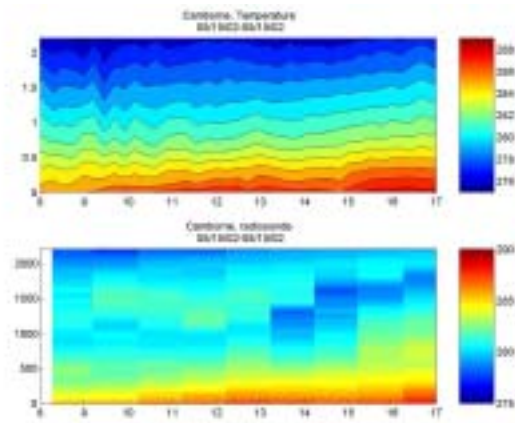


Figure 4.1.1.3 Time-height series of temperature profile from radiometer (upper panel) and radiosonde (lower panel) Camborne 15 May 2002 0800-1700 UTC.

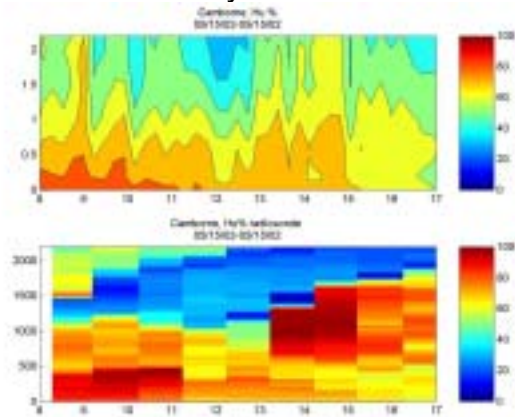


Figure 4.1.1.4 Time-height series of humidity profile from radiometer (upper panel) and radiosonde (lower panel) Camborne 15 May 2002 0800-1700 UTC.

4.1.2 Convective conditions

Figure 4.1.2.1 and 4.1.2.2 show examples of convective scale phenomena resolved by a radiometer and wind profiler observing at high temporal resolution. Profiles were retrieved using commercially available software. The wind profiler showed a thermal plume. The vertical wind speed measured by the wind profiler on 29 June 2005 1600-1700 UTC shows ascent of about 0.5 m s^{-1} from the surface to about 1.3 km, lasting about 10 min, as shown in Figure 4.1.2.2.a. On either side of this, vertical wind speeds of about -0.6 m s^{-1} were measured in the downdraughts. Above the top of the thermal, the vertical speed was also negative as air from above was probably being pulled into the downdraught. The signal to noise ratio produced by the wind profiler shows the change in humidity occurring between the boundary of the updraught and the surrounding downdraughts, Figure 4.1.2.2.b. The surface temperature gradually increased from 18.2 to 19.3 °C at 1628 UTC, which may have triggered convection, forming the updraught, see Fig. 4.1.2.1(d). The temperature profiles in Figure 4.1.2.1(a) show unstable conditions – a large temperature gradient – near the surface at 1633 UTC, before the updraught occurs. The temperature profiles then show neutral, well-mixed conditions within the thermal updraught – a smaller temperature gradient. The relative humidity was lower within the thermal (60-75 %), due to its higher temperature, see Fig. 4.1.2.1(b).

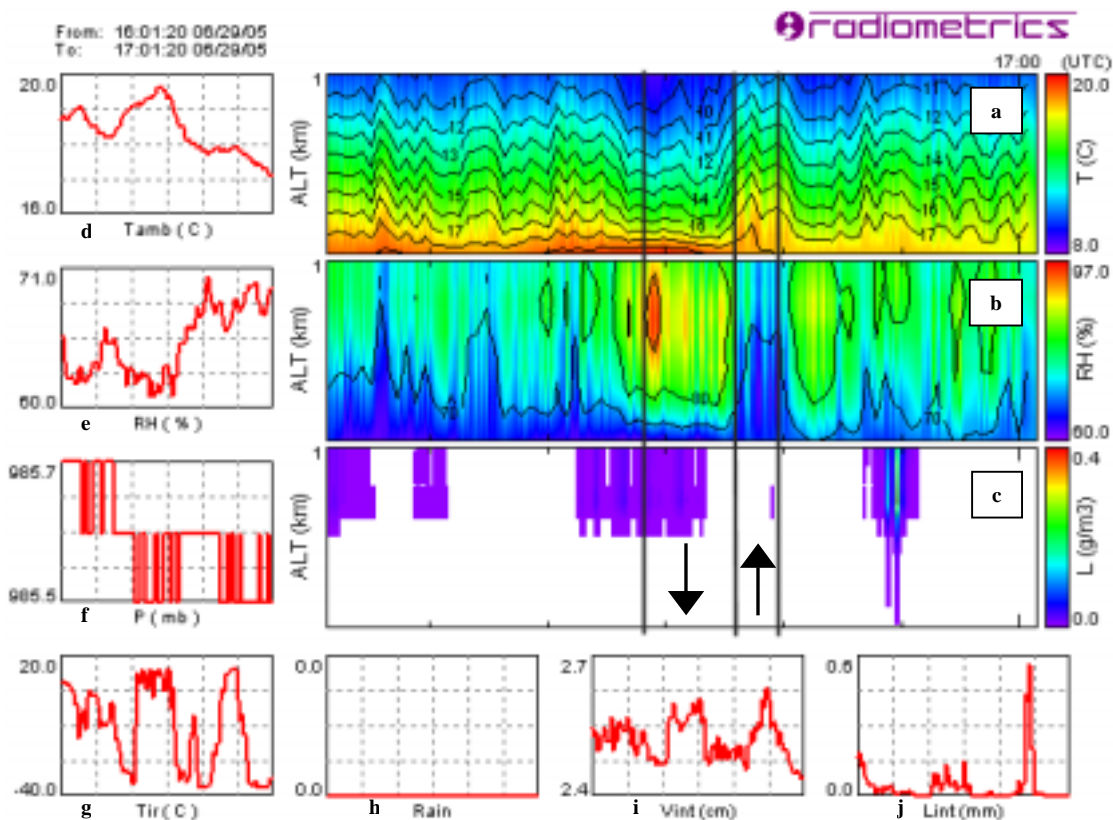


Figure 4.1.2.1 Microwave radiometer retrieval showing (a) temperature, (b) relative humidity and (c) cloud liquid water time-height cross sections for 0-2 km height, 29 June 2005, 1600-1700 UTC. Time series of scalars are also shown in red for (d) surface temperature, (e) surface relative humidity, (f) pressure, (g) infrared brightness temperature, (h) rain sensor, (i) integrated water vapour and (j) integrated liquid water. Arrows indicate updraught and dowdraught.

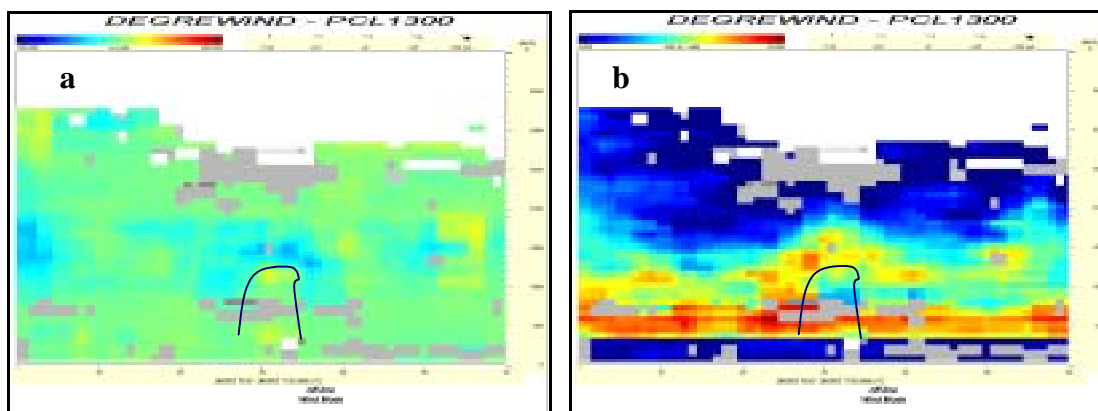


Figure 4.1.2.2 (a) Vertical speed and (b) signal to noise ratio, from wind profiler at Linkenholt 29 June 2005 1600-1700 UTC.

The profile remained closely adiabatic until the end of the updraught at 1639 UTC. Figure 4.1.2.1(i) also shows that the IWV built up before the thermal updraught, then reduced, although the higher IWV could be associated with the presence of low clouds (Figure 4.1.2.1(j)). At 1631 UTC this low cloud cleared, allowing solar heating of the surface to initiate convection. The other periods in Figure 4.1.2.1 showing warm plumes of low RH also correspond to periods of ascent in the wind profiler data, but with weaker vertical velocities.

When looking at the radiometer on its own, the validation of the measurement is difficult. It is not easy to be sure that the variations seen in the profile are real; they could be the result of noise. The same difficulty occurs in the wind profiler measurement. The vertical speed is noisy and the signal to noise ratio too. However when combining the two sources of information, the thermal is very well described, validating the 2 sets of observations. Furthermore, the use of the vertical structure seen by the wind profiler could be used once again to improve the vertical resolution of the profiles produced by the radiometer.

This example indicates how integration of observations from different system can be used to study in detail atmospheric processes important for various scales of numerical weather prediction.

4.2 Cloud radar Ceilometer integration

The work presented here has been performed and documented by Oleg A. Krasnov and Herman W. J. Russchenberg in the COST720 final report.

The physical mechanism involved in the backscattering process for cloud radars is mainly a Rayleigh scattering from hydrometeor. The location and vertical extension of a cloud can then be measured by cloud radar. Calibrated radars give a measurement of the reflectivity. The reflectivity is a function of both the size and the concentration of water droplets. The size dependency is very strong (D^6 where D is the drop diameter) while the concentration is linearly linked with the reflectivity. The liquid content is function of the drop volume (D^3 dependency) and the concentration. So we need to know either the size or the concentration to estimate the liquid content. The Ceilometer backscatter signal is approximately proportional to the second power of the diameter so the ratio of the radar to lidar backscatter power is a very sensitive function of mean size. The Figure 4.2.2.1 shows the ratio of the radar reflectivity factor and extinction of the Ceilometer signal in the radar volume. The observed tendency reflects the process of drizzle formation in the cloud. This behaviour of the radar-lidar ratio can be used to classify the cloud into three regimes: non-drizzling clouds, clouds in transition in which drizzle is being formed, and clouds containing mature drizzle. In first approximation, these regimes can be matched with the appropriate relationship between the radar reflectivity factor and the liquid water content.

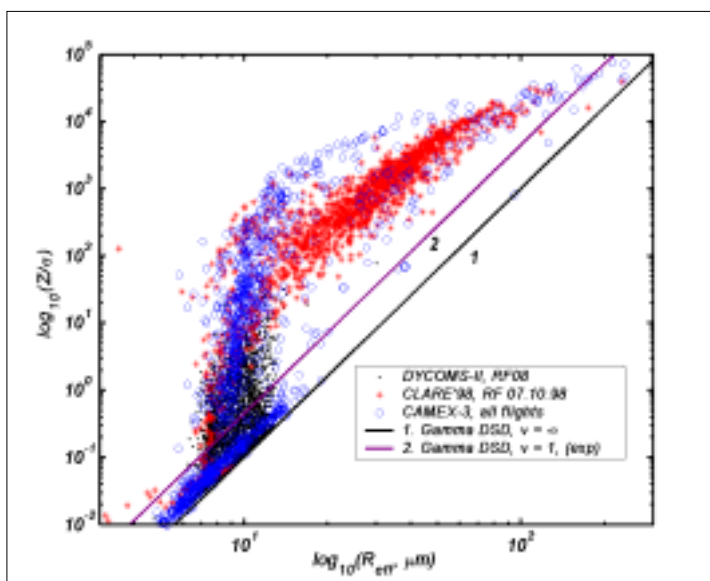


Figure 4.2.2.1 Simulated radar-lidar ratio versus the effective radius. Both plots are based on in-situ data taken during the CLARE 98, DYCOMS-II, and CAMEX - 3 campaigns

The algorithm produces vertical profiles of the liquid water content. These profiles can be integrated over a height to get the liquid water path. This can be compared with retrievals from a microwave radiometer for validation (Figure 4.2.2.2). This method remains limited by the strong extinction of the ceilometer signal inside the cloud. Drizzle detection then has to be based on an empirical threshold of reflectivity measured by the cloud radar.

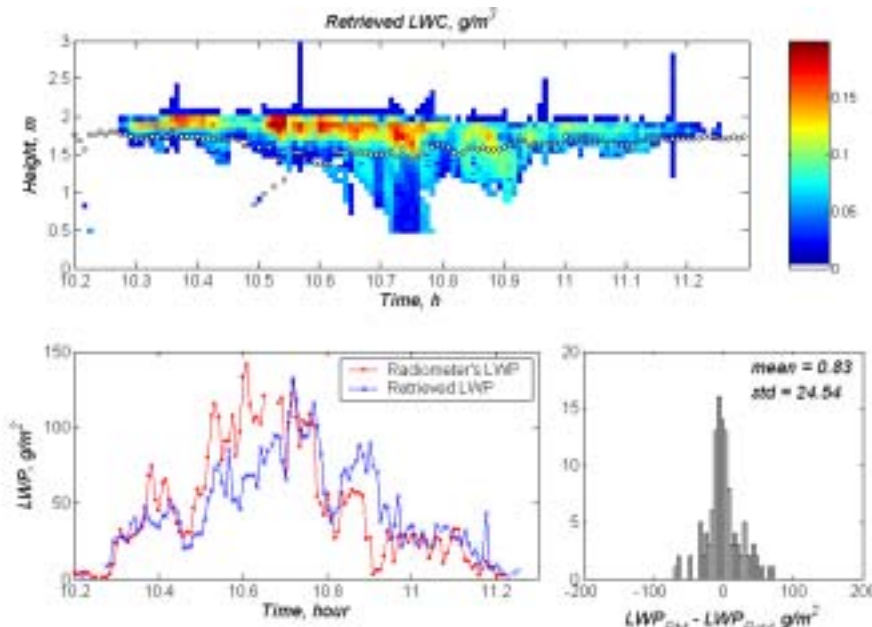


Figure 4.2.2.2. Top cloud liquid profile, the dots indicate the cloud base. Bottom left comparison of integrated liquid content obtained cloud radar ceilometer techniques with radiometer retrieval. Bottom right distribution of the difference.

5. CONCLUSION AND FURTHER DEVELOPMENT

Radiosondes are the only instrument that can currently give detailed profiles of humidity and temperature collocated with wind measurements. However sondes have to be carefully designed to avoid bias and contamination – the size, the orientation, the coating of the sensors are important. It is essential for climate references that such bias is minimised and kept stable. Homogeneity in the radiosonde measurement quality over the world is also desirable. In China a new generation of radiosonde is going to provide good quality measurements and the radiosondes tested in the WMO High Quality Radiosonde Inter-comparison like in Mauritius are now being deployed around the world.

The need for weather forecasting and physical process understanding for climate prediction, requires data at high temporal and spatial resolution. This can only be achieved by a mixture of in situ and remote sensing

With the help of European funding, the development of a European network of wind profiler has maximized the use of wind profiler and VAD wind.

During AMMA, the deployment of wind profiler in Africa was successful, demonstrating the maturity of this remote sensing technique. Help from international funding will lead to

sustainable development of wind profiler network, including training for technicians supporting the systems.

With the evolution in the software and network architecture, GPS integrated water quantities are now available within 15 min. Several national met services are working toward this goal as this makes this measurement very valuable for nowcasting. Integrated water quantities are now assimilated operational into NWP. This information is cheap and funding to help various regions to expand their actual networks is desirable.

While having a limited vertical resolution, radiometers have the potential to be useful for high time resolution description of physical processes.

FCMW cloud radars are becoming affordable as operational instruments.

An integrated approach has the prospective to deliver better product than independently retrieved quantities. However the actual cost of such integrated remote sensing station might remain too high unless customers work with the manufacturers to reduce costs.

At the Met Office we are currently working on costed options of a new upper air network that can deliver the required information for the new generation of NWP. A mixture of in situ and ground based remote sensing observing systems (possibly including wind profilers, microwave radiometers and cloud radars coupled with laser ceilometers) has the potential of producing continuous monitoring of upper winds, temperature, humidity and cloud around the British Isles on a network spacing of less than 100 km for the first time.

In this project a fundamental change in the design of the upper air network is being evaluated with the intention of reducing the number of radiosonde consumables purchased each year. This is driven by the user requirement for upper air measurements at higher spatial resolution than is affordable with current network in order to satisfy future NWP models. This is to be coupled with an integrated approach to exploiting the various remote sensing technologies that are reaching maturity for operations, e.g. GPS water vapour, weather radar winds, wind profiler, microwave radiometer, cloud radar observations combined with laser ceilometers. Assimilation and integration methods will be developed to fully exploit the information content of the synergy of instruments.

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REFERENCES

Bianco, L., D. Cimini, F. S. Marzano, and R. Ware, 2005: *Combining microwave radiometer and wind profiler radar measurements for high-resolution atmospheric humidity profiling*, J. Atmos. Oceanic Technol., 22, 949-965.

Campistron B., F. Saïd, S. Madougou, C. S. Sow, D. Badiane, C. F. Kébé, and F. Traoré. *Dry and humid period at Bamako (Mali) observed in 2005 with an UHF wind profiler radar*. AMMA, first international conference, Dakar, November 28th – December 4th 2005

- Crewell, S., M.Drusch, E.van Meijgaard, and A.van Lammeren, 2002: “*Cloud observations and modeling within the European BALTEX Cloud Liquid Water Network*”, Boreal Env. Res. 7: 235–245.
- Gaffard, C. and T.J.Hewison, 2003: “*Radiometrics MP3000 Microwave Radiometer Trial Report*”, Observations/Development Technical Report TR26, Met Office, UK, Available from <http://tim.hewison.org/TR26.pdf>.
- Jacoby-Koaly, S., B. Campistron, S. Bernard, B. Benech, F. Ardhuin-Girard, J. Dessens, E. DuPont, and B. Carissimo, *Turbulent dissipation rate in the boundary layer via UHF wind profiler Doppler spectral width measurements*, Boundary layer Meteorol., 103, 361-389, 2002.
- Löhnert, U., S.Crewell and C.Simmer, 2004: “*An Integrated Approach toward Retrieving Physically Consistent Profiles of Temperature, Humidity, and Cloud Liquid Water*”, J. Appl. Meteor., Vol.43, pp.1295-1307.
- Nash, J, R Smout, T Oakley, B Pathack, S Kurnosenko, *WMO intercomparisons of High Quality radiosonde Systems, Vacoas, Mauritius, 2-25 February 2005*, Instrument & Observing Methods, No 83,WMO/TD 1303
- Hewison, T.J., D.Cimini, L.Martin, C.Gaffard and J.Nash, 2006: “*Validating clear air absorption model using ground-based microwave radiometers and vice-versa*”, Meteorologische Zeitschrift, Vol.15, No.1, pp.27-36,
- Lothon,M., B. Campistron, S. Jacoby-Koaly, B. Benech, F. Lohou, and F. Girard-Ardhuin.:”*Camparison of radar reflectivity and vertical velocity observed with a scannable C-band radar two UHF profilers in the Lower Troposphere*”. 2002, J. Atmos. Oceanic Technol., 19,899-910.
- da Silveira R. B, G.F.F Fish, L.A.T.Machado, A M,Dall Antonia, L F Sapucci, D Fernandes, R Marques *Report of the WMO RSO Inter-comparison experiment- Brazil* Instrument & Observing Methods report No 90 WMO/TD 1314 2005
- Stankov, B. B., E. E. Gossard, B. L. Weber, R. J. Lalatis, A. B. Withe, D. E. Wolfe, and D. C. Welsh, 2003: *Humidity gradient profiles from wind profiling radars using the NOAA/ETL advanced Signal Processing System (SPS)*,