WORLD METEOROLOGICAL ORGANIZATION

COMMISSION FOR BASIC SYSTEMS
OPEN PROGRAMME AREA GROUP
ON INTEGRATED OBSERVING SYSTEMS

EXPERT TEAM ON OBSERVATIONAL DATA REQUIREMENTS
AND REDESIGN OF THE GLOBAL OBSERVING SYSTEM

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Plans for updating of the observing system technologies available in the next decade

(Submitted by the Chairman)

Summary and Purpose of Document

In accordance with assigned responsibilities, the Expert Team has started to explore observing systems that will be available in the next decade with the goal to develop a strategy for a composite upper-air observing system that best utilizes the strengths of *in situ* and satellite observing systems. The attached report published as WWW Technical Report No.20 (WMO/TD No.1040) was the first outcome of the ET efforts in this area. The ET felt that further evolution of this document should be achieved through periodic updates and invited broader community to offer additions and improvements.

ACTION PROPOSED

The meeting is invited to review WMO/TD No.1040 and decide on any amendments, if necessary.

Appendix: **OBSERVING SYSTEMS TECHNOLOGIES AND THEIR USE IN THE NEXT DECADE (WMO/TD No. 1040)**

WORLD METEOROLOGICAL ORGANIZATION

WORLD WEATHER WATCH
TECHNICAL REPORT NO. 20

OBSERVING SYSTEMS TECHNOLOGIES AND THEIR USE IN THE NEXT DECADE

Prepared by the Expert Team on the Observational Data Requirements and Redesign of the Global Observing System of the CBS Open Programme Area Group on Integrated Observing Systems

WMO/TD No. 1040

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EXECUTIVE SUMMARY

The Expert Team on the Observational Data Requirements and Redesign of the Global Observing System (ET-ODRRGOS)[1] within the Open Programme Area Group on Integrated Observing Systems has started to explore observing systems that will be available in the next decade. The current as well as alternative systems are described with introductory detail. It is the goal of this Expert Team to develop a strategy for a composite upper-air observing system that best utilizes the strengths of in situ and satellite observing systems.

This report includes several different technologies; they are presented to different levels of detail. Balance is yet to be achieved through further evolution of the document. The Expert team invites the broader community to offer additions and improvements. It is the intent of the Expert Team within the Open Programme Area Group for an Integrated Observing System to maintain and update this "living" document.

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1. INTRODUCTION

1.1. Background

The CBS Technical Conference on Integrated Upper-air Observing (Karlsruhe, September 1998) encouraged further exploration of the availability of alternative systems and the development of a strategy for a composite upper-air observing system. An Expert Team within the Open Programme Area Group on Integrated Observing Systems has started annual updating of the report on "Candidate Observing System Technologies and Their Use". The following information is the first update and it is generally considered valid for the time period 2000-2004 although possibly for longer.

2. IN SITU UPPER AIR MEASUREMENTS

2.1 Automated aircraft reporting *(main source - AMDAR, 2000)*

Some existing and virtually all new commercial wide-body aircraft can be equipped with avionics that provide automatically both meteorological information (wind speed and direction, temperature and four-dimensional position) and the means to communicate the information to ground stations. The maximum operational altitude of such aircraft is *circa* 15km, with most of the observations being captured between 7 and 11km, within designated flight corridors.

Two separate approaches are in use; ASDAR, which uses a dedicated on-board processor connected to the aircraft avionics system and transmits observations automatically via the meteorological geosynchronous satellites of the IDCS (International Data Collection System); and ACARS (Aircraft Communication Addressing and Reporting System). These are collectively named AMDAR (Aircraft Meteorological Data Relay). ACARS is the standard aircraft data-link system used world-wide. ASDAR was developed by specially established WMO consortium in the 1980's and entails relatively expensive and time-consuming certification and installation. It has the important advantage of using the meteorological satellite communications facility that is free for this type of message. However, some airlines impose expensive carriage charges making the system less cost-effective. On the other hand, ACARS uses the plane's own avionics system thus requiring no additional hardware to be installed and carried. It does, however, use the airlines' communications system that can entail considerable communication costs. The major communications providers are cooperating in a WMO led attempt to minimise these costs. Special software developed by some meteorological services or alternatively by some avionics manufacturers, and installed in the aircraft avionics system is all that is needed for a fully functional AMDAR system.

ASDAR measures wind speed, wind direction and air temperature up to 15 km. (although limited by cruise altitudes which rarely exceed ~12km). An observation is reported every 7 minutes in level flight (from ~500hPa to 120hPa) and observations at selected pressure levels in ascent (10 at 10hPa intervals initially and then every 50hPa up to 500hPa) and descent (every 50hPa below 500 hPa and every 10 hPa below 700hPa). The wind speed is accurate to +/- 1.8m/sec; the temperature to +/- 1°C. AMDAR measures the same parameters with roughly the same accuracy; AMDAR is planning to add humidity in the future as well as turbulence.

The WMO AMDAR Panel was established in March 1998 to coordinate exploitation of this technology. The Panel encourages improvements to existing AMDAR systems and the development of new ones in an attempt to supplement conventional upper air observations in data sparse areas of the globe. Areas in particular need have been identified through impact studies by a number of weather services and reported at recent CGC-WMO workshops.

The ASDAR system has made a major contribution to the World Weather Watch programme by providing *in situ* observations over data sparse regions, which were unobtainable any other way. The number of ASDAR units reporting at any given time peaked at 20 for a short period in early 1998 but generally had remained fairly steady since 1996 at an average of 18 units providing around 1800 reports per day. As of 30 July 1999, 17 ASDAR units were operational and providing air reports but this has declined to 12 units of which 10 are actually operational as at 8 June 2000. Data quality had remained high although a loss of data occurs through maintenance down time, aircraft avionics and ASDAR hardware faults. The number of ASDAR units reporting was expected to decline as faults occur in the ASDAR hardware which is becoming increasingly obsolescent.

2.1.1. Operational AMDAR Programmes

Operational programmes based on ACARS exist in Australia, Europe, the USA and more countries are setting up programmes with encouragement from the AMDAR Panel. They have the following characteristics:

Australia

The Australian AMDAR system became operational in 1985 on a small number of Ansett domestic aircraft that quickly increased over the first few months of operation. A considerably improved system was installed on part of the Qantas international fleet in 1991. Data transmissions from all aircraft are limited to the VHF-ACARS system, although there are clear benefits to be gained from the much more expensive SATCOM system to collect data from long over-ocean tracks. From January to June 1999 a total of 116,958 observations per month were made by 25 Ansett aircraft and a total of 43,878 observations per month by 21 Qantas aircraft. AMDAR data have made a significant impact on Australian meteorological operations in forecasting support for aviation, severe and public weather programmes. The benefits arise from the frequent, near-real-time characteristics and proven accuracy of these observations. Continuous monitoring quickly detects bad data and poor performing aircraft using two, and very soon three, independent systems. Information is rapidly passed to the airlines for prompt corrective action.

Europe
(source: www.meto.govt.uk/sec5/obs_land/ol6/amdar_programme.html)

The EUMETNET-AMDAR Program has been set up to maximise the cost/benefit ratio of AMDAR systems operated by the participating members by reducing duplication and seeking to meet requirements in the most cost effective manner. The participating members are as follows:

> Austria, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom

To date, AMDAR programmes have been set up by KNMI (The Dutch Meteorological Service), SMHI (The Swedish Meteorological Service), Météo-France, DWD (The German Meteorological Service) and the Met Office of the United Kingdom. New programmes are likely to develop in Portugal, Spain, Finland and Ireland.

This programme started on 1 January 1999 and represents a short-term operational programme with duration of three years. It is hoped that it will deliver an AMDAR programme to meet the following objectives:

- To provide ascent/descent measurements over the territory of EUMETNET members, aiming at an average spacing of 250 km and a time spacing of every 3 hours, to be adjusted as necessary according to the results of the EUCOS design studies;

- To provide measurements from data sparse areas having an impact on short-range forecasts in Europe, to be adjusted as necessary according to the results of the EUCOS design studies;

- Measurements from data sparse areas world-wide, representing about 20% of the data collection effort of the Programme.

New Zealand

The Meteorological Service of New Zealand Limited (MetService) has recently commenced a formal agreement with Air New Zealand (AirNZ). AMDAR reports from selected AirNZ aircraft within a geographical box 155°E to 180°E and 25°S to 50°S will be delivered to the MetService and relayed to the GTS following quality control procedures.

USA

The United States AMDAR programme consists of 2 components. A research and development programme was commenced by the Forecast Systems Laboratory (FSL) in the late 1980s and has continued to develop in a non-operational mode providing services to the airlines and the global research community. The operational programme called MDCRS (Meteorological Data Communications and Reporting System and involving the FAA and NWS, commenced in 1992. It grew slowly in the first few years, but has grown very rapidly since. There are close to 40,000 wind and temperature reports every day provided by four airlines: Delta, Northwest, United and UPS. Profile data are available from some 40-50 airports. American Airlines has just joined the programme providing the full suite of data, and Federal Express Airlines has agreed to supply its flight following data, that contain weather information, and are transmitted every thirty minutes.

2.1.2 AMDAR Expansion

There are AMDAR programmes being set up in Canada, Southern Africa led by South Africa, and the Middle East led by Saudi Arabia with proposals being considered for further expansion in the Asia-west Pacific rim, Southern America and the Caribbean-Central American region. Coordination of these expansion programmes is being assisted by the AMDAR Panel.

2.1.3 New AMDAR Measurements

The first-generation of water vapour sensing system (WVSS) using a thin-film capacitor was fitted on six aircraft in the US producing over 1,200 observations per day in real-time. In a number of comparisons between WVSS and radiosonde data, the WVSS data were shown to be consistent with itself and with the radiosonde. Preliminary conclusions from comparisons between WVSS and radiosonde showed that the WVSS had comparable accuracy with the radiosonde in the region below 20,000 feet. It was pointed out, however, that the unique disadvantage in measuring relative humidity on a commercial aircraft came from the definition of relative humidity that included the saturation vapour pressure that was a strongly non-linear function of temperature. The FAA/NOAA evaluation should be completed in 2000. The AMDAR Panel met in 1999. However, this system has several operational disadvantages with regard to routine sensor calibration, maintenance and replacement, which make it difficult to work with. The sensor is also known to produce substantial errors under certain operational conditions.

A new WVS technology under development uses a single-mode diode laser to obtain a potential accuracy down to one part per million for water vapour mixing ratio. The second generation of WVSS fits into the existing temperature probe aperture on all aircraft thus making retrofit of this sensor easy. Future plans included the increase of the number of first generation WVSS units expected as part of a formal FAA evaluation to 62 units with at least 30 units to be fitted to UPS aircraft. Four second-generation WVSS prototypes would be evaluated on National Centre for Atmospheric Research (NCAR) aircraft and on selected commercial aircraft.

The inclusion of turbulence reporting has already produced useful operational results. The routine reporting of Derived Equivalent Vertical Gust on Australian and some European aircraft is being used by the ICAO World Area Forecast Centres to upgrade SIGMETs and warnings for air navigation and passenger safety purposes. These observations are also used for forecast verification and the location of known turbulent areas such as sub-tropical jet streams. The USA has developed another turbulence measurement called Eddy Dissipation Rate (EDR). This is to be introduced operationally in the near future and has been under trial for several years by one airline. Development is being undertaken to assimilate EDR directly in to regional and global models to improve forecasts generally and aviation forecasts in particular. Additional graphical displays of observations have been developed for trial by airlines and forecasters.

ICAO has adopted EDR as its preferred measure of turbulence and is in the process of developing specifications and regulations for processing and reporting systems as part of the Automatic Dependence Surveillance System (ADS).

2.2 Automated Shipboard Aerological Programme (WMO, 1997b)

The Automated Shipboard Aerological Programme (ASAP) measure wind speed and direction, temperature, humidity, and pressure with accuracies similar to the radiosonde. Spatial resolution depends on ship routes; temporal resolution is 12 hours. The ASAP provides high quality upper-air data comparable to those of an ocean weather ship, but at a cost per sounding of approximately 15% of the latter.

The deployed systems in 1997 were operated by: Denmark (2 units), France (4 units), Germany (5 units), Japan (5 units), Russia Federation (1 unit), Spain (1 unit), Sweden/Iceland (1 unit), the UK (1 unit), and the USA (2 units). Globally, around 5700 ASAP soundings were taken in 1996 and reported to the ACC, and of these, over two-thirds were taken in the COSNA area. This corresponds to the number of soundings from around 8 ocean weather ships taking 2 soundings/day. The average network efficiency is about 50%, meaning that the units are taking soundings about half of the time.

2.3 GPS signal monitoring - ground-based

(source: http://metix.nottingham.ac.uk/wavefron/index.html)

The measurement of vertically integrated atmospheric water vapour (IWV) is feasible using ground-based Global Positioning System (GPS) receivers. The delay in the GPS signal due to atmospheric water vapour can be converted to equivalent water vapour content with little uncertainty. The principle is that the troposphere delays microwave signals, with 90% of the delay attributed to the dry component and 10% due to water vapour. The dry delay can be modelled adequately with surface pressure and temperature measurements leaving the magnitude of the wet delay to be converted to precipitable water vapour. Present methods of measuring water vapour (e.g., radiosondes, water vapour radiometers) are limited in temporal and spatial resolution. GPS offers a distinct advantage over traditional meteorological sensors in that it is a moveable, all-weather system that can provide continuous measurements with little or no need for calibration checks. These systems are also used by other agencies for non-meteorological purposes. Accuracies of 1-2kg per m^2 for IWV (comparable to radiosondes) can be obtained if collocated surface pressure and temperature are available. Potential applications include forecasting, using real time data, and climate studies, using a database of continuous IWV estimates produced over time scales from every few seconds to monthly.

GPS appears to be a reliable and cost-effective method of obtaining sub-hourly integrated water vapour estimates over land under virtually all weather conditions with an accuracy that is comparable to radiosondes. The technique is complementary to satellite derived integrated water vapour, as satellites provide high spatial resolution in cloud-free regions, whereas GPS is useful in cloudy regions.

A major operational difficulty with this measurement is the timeliness. Currently, there is a delay of up to two weeks in order to obtain the highest measurement accuracy (1 kg per m^2) because of the inherent delay in obtaining the sufficiently accurate satellite orbit details. Research is being directed to this and accuracies have improved (e.g predicted orbit ephemerides are now available which give accuracies of about 1.5-2 kg per $m^{2)}$. Real time processing could be available by 2002 that provides operational data within 3 hours.

2.4 Radar systems

The Doppler capability (measuring the Doppler frequency shift caused by the radial movement of hydrometeors in relation to the radar location and thus measuring the radial velocity) is now standard on any new radar purchased. Doppler radars provide rainfall intensity, mean radial velocity from each radar sample volume and spectral width (a variance measure in the mean velocity). The radial velocity can be used directly by the NWP models if required, however this only provides one component of the velocity field. These observations can also be used to retrieve a vertical profile (VAD), together with a measure of the error characteristics of these winds. Radial velocities are measured to a calibration accuracy of 1 m/sec. The retrieval of a field of three-dimensional winds from single Doppler radars is still an area of active research. In terms of VAD profiles, previous studies have demonstrated that VAD wind speeds can be retrieved within 2 m/sec and direction within 5-18^o of radiosonde observations. This is still under review. The base resolution of the radial velocity and related data is 150 m. However, this is processed (for independent sampling) to 750 m in range by 1^o in azimuth as the highest resolution polar data. In VAD mode one profile is produced for the coverage area of each radar. The vertical resolution is only constrained by range resolution and beamwidth at that point. The temporal resolution of the VAD profiles in a normal network operational mode would be 5 minutes (and could be less).

For those nations with weather radar networks a number of upgrade paths are available. In particular, the addition of a Doppler capability can provide radial wind estimates at a number of altitudes when scatterers in the form of precipitation are present. When such radars have sufficient power, scattering from dust, insects and cloud droplets may also be detected. The addition of dual polarisation schemes may provide better precipitation estimates, discrimination of ice in cloud and reduction of the impact of beam blockage. Traditionally the cost of a retrospective Doppler upgrade is approximately $400US. However new digital IF receivers (installed to replace obsolete receiver technology) can also provide as an added benefit a Doppler capability for as little as $80K. A technical assessment of this technology is currently underway.

2.5 Radiosonde system

Radiosonde refers to a balloon-borne package of instruments that can be launched, manually or automatically, to a fixed schedule or on demand. Measurements of pressure, temperature and humidity are made and wind data may be obtained by tracking the position of the balloon. The height range is from the earth surface to 35 km maximum, depending upon the balloon used and the station status. Observations are made every 2 secs (approx. 10m of ascent). The temperature accuracy RMS errors range from 0.2 to 1.5 C; these numbers depend on the central calibration of the element, the sensor response time, and accounting for the effects of solar radiation. The humidity accuracy RMS errors range from 2 to 20%; large differences in performance have occurred between 1 batch of radiosondes and another, especially in measurement performance in water droplet clouds, and accuracies at low temperatures and high humidities are still under investigation. Geopotential heights absolute accuracy RMS errors range from 5m low in the atmosphere to 200 m high in the atmosphere; height errors are caused primarily by errors in pressure measurements which vary between 1 hPa decreasing to 0.5 hPa from surface to 200 hPa. Wind finding depends on Loran or GPS technology; Loran accuracy is 0.5 m/s in each component near the surface decreasing to about 1.0 m/s at 20 hPa and GPS accuracy is 0.3 m/s in each component near the surface decreasing to about 0.8 m/s at 20 hPa.

There are a number of drivers for radiosonde modernization. Some, such as the cessation of the Omega network and pressure on the RF spectrum are external, others derive from the desire to reduce operational costs. The measurement of thermodynamic parameters is being improved by the efforts of manufacturers to upgrade instruments. Unfortunately most manufactures are lagging particularly in moisture measurement. Recent corporate take-overs have seen the choice of manufacturer decline to a potentially unhealthy number.

There has been a search for alternative tracking options for wind finding. These include the use of LORAN-C, VLF radio navaids, GPS tracking and radiotheodolite. In general, the effective coverage of the ground-based navaids is limited and uncertain and the cost of a GPS radiosonde is some 1.4 times that of an Omega radiosonde. The sudden demise of Omega forced GPS radiosonde technology onto the global networks in a prototype form. The problems are slowly being resolved. The USA has successfully implemented radiotheodolites in the Caribbean, however the system is not suited to locations outside the tropic zone (20N-20S) because of reflected beam interference when the balloon is at low elevations. Manufacturers are working on solutions to this problem, however these are yet to be tested. Even in tropical regions, many developing countries would be struggling to maintain the ground stations due to lack of funds and technical expertise.

Further cost savings may be made if the GPS engine on the radiosonde can be used to calculate the 3D position of the radiosonde. This will allow the elimination of an on-board pressure sensor, pressure can be calculated from height and temperature and humidity profiles) using the reverse of the current procedure of calculating height from pressure. The recent removal of degradation from the civil GPS signal by the US Government may mean that derived height values will be improved.

There has been a push for automated launches to help reduce manpower costs. Vaisala have produced the autosonde, a PC controlled, electro-pneumatic device which can fill balloons and launch up to 24 pre-loaded radiosondes to a pre-arranged and programmed schedule. Flights can be pre-determined (e.g. 6 hourly) or done on request. It takes 3-4 hours to fill and costs about $400K USD. So far the equipment has shown good reliability. However, the site needs to be carefully chosen in terms of the proximity of obstructions (e.g. buildings, high ground) and the local wind climate. There is a strong correlation between failure rate and the gust structure on the site, with ascents being lost when the gust speed exceeds 33 knots. These conditions occur ~3% of the time in the Midlands but up to 17% of the time in the Shetlands. Currently, autosondes also have difficulty selecting the turning points from the data to create the WMO message describing the mean data profile. There is a significant risk of a biased selection, which is addressed by tasking a manned radiosonde site to remotely access and clean up the data in real time. To date, they are deployed in a number of countries including Sweden, Australia, the United Kingdom and Canada.

There is no standing body such as the ACC, AMDAR Panel and DBCP to provide an international focus and forum for the development and use of radiosonde systems. However, internationally coordinated trials have been conducted on an *ad hoc* basis.

2.6 Radiosonde supplements

2.6.1 Dropsonde

A dropsonde is like a radiosonde, except deployed from above. It takes measurements of the atmosphere as it descends towards the surface. This eliminates the need for a balloon, however deployment is very expensive. Currently it involves the use of specially equipped aircraft. Deployment from routine aircraft is not feasible without expensive modifications. At present dropsondes are only used in specific experiments and by the USA for hurricane tracking.

To overcome the cost of deployment planes and crew, GAINS is a programme developed by the Forecast Systems Laboratory (part of NOAA) that would develop the systems needed for an operational global *in situ* observing system. The operational programme, which would begin later in this decade, is conceived as a network of high-technology balloons that could be evenly distributed over the global stratosphere at altitudes from 60,000 to 90,000 feet. The balloons would drift with the wind, but could be located as desired by a technique called "shear direction". The balloons are to be large, over 30 m in diameter, and could carry payloads of over 250 kg. They would typically carry small packages, "sondes" of many different types, which could be dropped on command to measure important atmospheric and ocean parameters. While the feasibility of the balloon hardware may be well advanced, the proposed radiosonde the size of a golf ball will require significant technical advances in most systems currently on a radiosonde. (http://www-frd.fsl.noaa.gov/mab/sdb/)

2.6.2 Glidersondes

The National Severe Storms Laboratory (of NOAA) is examining a system called a ‘Glidersonde’, which is effectively a re-usable radiosonde. The Glidersonde is deployed like a radiosonde attached to a weather balloon, however the radiosonde is housed in a small glider (1m wingspan). The meteorological measurements are made during ascent like a normal radiosonde, however at a predetermined height (~25,000ft), the glider is released and it will travel back to one of a number of set landing locations. The use of the system may be limited in strong wind situations. (http://www.nssl.noaa.gov/teams/western/glidersonde/)

2.6.3 Unmanned aerial vehicle (UAV)

The use of UAVs with on-board sensors can be used to measure meteorological parameters and chemical composition of the atmosphere. UAVs are a rapidly developing technology as the uses for these devices are extensive, i.e. the future is bright for the viability of these platforms. There are some regulatory problems; permission to fly and licensing required by air traffic authorities will restrict the use of UAVs in many locations. Currently, most UAV systems being developed are very expensive – often targeted to military applications. The most promising system for meteorological systems is the 'Aerosonde'.

An instrumented aerosonde with wingspan ~3m and weighing less than 20kg has been developed by the Australian Bureau of Meteorology specifically for Meteorological operations and research. The GPS is used for autonomous navigation and satellite relay for data return. A pitot tube is used for wind and standard Vaisala sensors for other elements (however there is some concern about the humidity sensor). With a top airspeed of 32 m/s, it has a range of 3500 km and a ceiling of 5 km. Flights can last one to two days and can be extended longer with the expected new engine. It supplies wind, temperature and moisture measurements and can operate either autonomously or by remote control. Performance parameters are expected to improve with the next version. Each Aerosonde costs about $25K USD and each flight hour has costs that are in the tens of dollars range. Regular aircraft cost $4.8K USD per flight hour. Once operational, the cost per sounding for this system would be comparable to radiosondes. This cost-effectiveness, however, is based on a presumption of high recovery rates for the Aerosonde. (http://www.aerosonde.com/aerora_home.htm)

2.7 Atmospheric profiler systems (radar laser and acoustic systems)

2.7.1 Profilers

Profilers are essentially vertically pointing Doppler radars. Doppler returns from moving particles in the beam are processed to provide four dimensional wind structures in the vertical. The profilers operate continuously, in an automated, unmanned mode. The data are averaged over specified time intervals (from 6 minutes to an hour) to reduce noise and to increase their representativeness. Lidar systems can also perform similar tasks, however are obscured by cloud or fog. Sodars are limited to boundary layer measurements.

Wind Profilers are ultra-sensitive, upward-looking Doppler radars generally operating at frequencies between 40 and 1400 MHz. They were designed primarily to measure winds in all weather conditions, by detecting signals backscattered from turbulence-induced refractive index fluctuations. As the turbulent eddies drift with the mean wind, their translational velocity provides a direct measure of the mean wind vector. Typically profilers are designed to operate in two modes, one for low-altitude sampling with high vertical resolution and another for higher altitude sampling with reduced vertical resolution. The main advantage is that profiles of 3 dimensional wind speed and wind direction data are produced with a high temporal resolution. The wind data include orthogonal components e.g. for easterly and northerly winds. RMS vector error is between 1 and 2 m/sec for 15 minute winds, and around 1 to 1.5m/sec for 30 minute winds (WMO, 1998).

2.7.2 Sodars

Acoustic sounders are also known as acoustic radars or *sodars* ('radar' based on sound waves rather than radio waves). By emitting a powerful transmitted sound pulse and receiving a weak backscattered pulse, they are able to observe the fine detail of wind, turbulence and, to some extent, humidity fluctuations. Displayed return signal power patterns may give insight into features within the boundary layer such as inversions, convective plumes and wave motions. A major factor is the advent of cheap, powerful personal computers which has made commercial sodar versions possible. Reliable wind measurements will not be obtained in strong wind or rain. Systems can only be operated on sites where noise pollution from the measurement is tolerated. The technique known as Radio Acoustic Sounding System (RASS) involves both the propagation of acoustic pulses and the measurement of pulse velocity which is temperature-dependent, hence leading to temperature measurements.

RASS can measure horizontal and vertical wind, turbulence; the useful height range depends upon meteorological conditions, transmitted power, the chosen acoustic frequency and the background noise level. A typical height range expected from a commercial sodar is from near the surface to between 500 m and 1 km. Resolution depends on design and height range. Systems with low height range may use 10m, but the resolution of systems working to 1 km height will usually be between 50m and 100m. RMS vector error in horizontal wind is about 1 to 2 m/sec.

Wind profilers with an associated RASS can provide virtual temperature measurements with reasonable vertical resolution and accuracy up to heights of a few km (if based on VHF radars, the height range extends to the tropopause). However, there is a considerable noise pollution problem that limits the choice of sites where RASS can be deployed. Measurements of the vertical velocity of precipitation and the vertical distribution of return signals from precipitation allow the height of the ‘bright band’ to be determined for weather radar network applications.

A quasi-operational network of 30 radar wind profilers is in service through the central portion of the United States. Wind profilers are also deployed in many countries including Australia, France, Germany and the United Kingdom. About 23% of the US Profiler network uses RASS. The wind profiler technology has now reached a stage where viable operational systems are being implemented. The major problem faced when installing radar-based profilers is RF frequency band limitations.

2.8 Ground Based Radiometers

Ground-based zenith-pointing radiometers observe radiation emitted by the atmosphere and measure the brightness temperatures which are converted to path-integrated water vapour and liquid water. Microwave radiometers offer some chance of all weather observing capability. Infrared interferometers may provide slightly more accurate profile information in cloud free conditions, but cannot observe through cloud or in fog. Integration of measurements by these systems with information on the heights of discontinuities in humidity or temperature from wind profilers, cloud radars or sodars is expected to lead to an improved output.

Temperature, relative humidity, and liquid water content are measured in the lower troposphere, 200 m to 5 km (best skill expected up to ~3 km); high temporal resolution, and expected vertical resolution likely to reduce from around 250 to 500 m near the ground to 1 km at upper levels (although it is expected that the instrument could be optimised to give higher resolution). Accuracy is better than 1^{o}C for temperature, but there is the possibility for trade off between vertical resolution and accuracy.

2.8.1 Atmospheric Emitted Radiance Interferometer (AERI)

(source: http://cimss.ssec.wisc.edu)

An ongoing program at the University of Wisconsin – Madison exists for using ground based interferometric atmospheric radiance measurements to calculate the temperature and water vapor structure of the Planetary Boundary Layer (the first three kilometers of the atmosphere). A two channel interferometer system has been developed and is called the Atmospheric Emitted Radiance Interferometer (AERI), which produces high spectral resolution radiances in the 3 to 20 μm region of the infrared spectrum at less than one wavenumber resolution. The instrument is portable, robust, field hardened, and is monitored remotely using the internet. The AERI instrument detects vertical and temporal changes of temperature and water vapor in the planetary boundary layer. High temporal and moderate vertical resolution in the lowest three kilometers of the atmosphere allows meteorologically important mesoscale features to be detected. AERI participation in the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program at the Southern Great Plains Cloud And Radiation Testbed (SGP CART) has allowed development of a robust operational atmospheric temperature and water vapor retrieval algorithm in a dynamic meteorological environment at five sites in Oklahoma and Kansas. Operating in a continuous mode, AERI temperature and water vapor retrievals obtained through inversion of the infrared radiative transfer equation, provide profiles of atmospheric state every ten minutes to three kilometers in clear sky or below cloud base. Boundary layer evolution, cold/warm frontal passages, drylines, and thunderstorm outflow boundaries have been observed, offering important meteorological information. With important vertical thermodynamic information between radiosonde locations and launch times, AERI retrievals provide data for stability index monitoring, planetary boundary layer research, mesoscale model initialization, verification, and nowcasting. The AERI system represents an important new capability for operational weather and airport monitoring applications. RMS differences with respect to multiple radiosonde launches at the SGP CART central facility are 1 K for temperature and 1 g/kg for water vapor over a one year period.

Ten minute monitoring of convective available potential energy (CAPE) and convective inhibition (CIN) is possible with the AERI system since these values are very dependent on the average temperature and moisture parcel characteristics within the first one hundred millibars of atmosphere. Mesoscale moisture advection tendencies and thermal advection tendencies are capable of being monitored with the AERI radiance information. This is important for monitoring the warm air advection severity into Mesoscale Convective Systems. Cold/warm frontal passage, development, and depth within the boundary layer can be monitored. The AERI system can not produce retrievals during precipitation and fog. It is equipped with a precipitation monitoring hatch and automatically closes during the onset of rain/snow. During periods of low clouds the retrieval algorithm is able to retrieve a temperature and water vapor profile to cloud base, however a full retrieval is possible between clouds.

AERI systems located next to Doppler Radars/wind profilers would allow the capability for observations of VAD wind, AERI temperature, and AERI moisture vertical profiles at high time resolution. With these measurements, moisture flux and convergence could be monitored and important nowcasting and model validation information is provided. Satellite active and passive sounding systems would be complemented exactly where the information detected from space begin to get ambiguous within the boundary layer due to water vapor, surface emission, and aerosols.

2.9 Lidar aerosol detection

(source: http://www2.etl.noaa.gov/)

A lidar transmits short pulses of laser light into the atmosphere, some of the light is backscattered, resulting in a profile of atmospheric scattering. Analysis of this signal can yield information about the distribution of aerosols in the atmosphere. The amount of backscatter indicates the density of the scatters. This can be used to measure cloud base height or track plumes of pollution. Other properties of the atmosphere can also be deduced from the lidar return signals. A frequency shift in the light because of the Doppler effect permits measurement of wind speeds. By detecting the amount of depolarization, one can discriminate between liquid droplets and non-spherical ice particles. Differential Absorption Lidar (DIAL) uses absorption, as evidenced by reduced backscatter from greater distances, to measure the concentration of atmospheric gases. A Raman lidar detects particular atmospheric components (such as water vapour) by measuring the wavelength-shifted return from selected molecules.

Currently, lidar applications are mostly restricted to research and non-meteorological agencies.

2.10 Lightning Detection

There are three main types of lightning detection. These are; stand alone sensors, lightning location networks and satellite sensors. The location networks and satellite systems have allowed for the widespread observation of lightning. The GPS system has allowed for very accurate clocks at sensors to make lightning detection networks based on time of arrival of RF signal from the lightning to be viable. These networks now are appearing in many countries, but the US NLDN system *(*http://www.glatmos.com/nldn/nldn.html*)* has been in place for many years and has proved the value of such systems. Unfortunately private corporations are running many of these networks hence data access is limited.

Two longer range networks using time of arrival method to locate lightning have been developed by the UKMO (called 'ATD Sferics Lightning Detection System') and NASA/RDI (Resolution Displays Inc.). These systems detect Sferics in the VLF band which travel great distances. While the detection efficiencies may be lower, the greater range allows for the possibility of global coverage with limited sensor numbers. The network would detect the thunderstorms without necessarily detecting all strokes.

The satellite technologies are still being developed. The current LIS sensor, being on a low orbit satellite means that it can only view a part of the globe once a day. (http://thunder.msfc.nasa.gov/)

3. IN SITU MARINE SURFACE MEASUREMENTS

Drifting and moored data buoys, ice floats, and sub surface floats are now generally accepted as a very cost-effective means for obtaining meteorological and oceanographic data from remote ocean areas. As such, they form an essential component of marine observing systems established as part of the World Weather Watch, the World Climate Research Programme, the Global Ocean Observing System, the Global Climate Observing System, the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology and other meteorological and oceanographic operational and research programmes.

Unfortunately in order to reduce costs, most data buoys now being deployed do not have pressure sensors. This will cause the number of active buoys that measure pressure to decline significantly in a few years.

3.1 Drifting buoy systems

Drifting buoys have a long history of use in oceanography, principally for the measurement of currents by following the motions of floats attached to some form of sea anchor or drogue. Since 1988, over 2500 Lagrangian drifters have been deployed in the world oceans in the context of the Surface Velocity Program (SVP) of the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere Program (TOGA) and then of the Global Drifter Program. These buoys were standardized in 1991, with small spherical hull and floats, and large Holey-Sock drogue centred at 15 metres below the surface. They are very reliable, with half lifetimes greater than 450 days (with drogue still attached).

In 1993, Lagrangian Drifters with barometer ports also called SVPB drifters were tested in the high seas (more than 20 prototypes) and proven reliable. The Lagrangian

Barometer Drifter, designed at the Scripps Institution of Oceanography for WOCE, is now commercially available at low cost, and meets both oceanographic requirements (research: measurements of sea surface currents) and meteorological requirements (operational: air pressure).

3.2 Ice Buoys

Ice buoys have been used extensively in Arctic and Antarctic regions to track ice movement and are available commercially for deployment by ships or aircraft. Such buoys are equipped with low temperature electronics and lithium batteries that can operate at temperatures down to -50°C. In addition to the regularly computed Argos locations the ice buoys can be equipped with satellite navigation receivers (e.g. Global Positioning System (GPS)), which can compute even more accurate positions for transmission through the Argos system.

3.3 Moored buoys

Moored buoys are normally relatively large and expensive platforms. Data are usually collected through geostationary meteorological satellites such as GOES, GMS or METEOSAT. If a moored buoy goes adrift it represents a potential loss of costly equipment and a possible hazard to navigation. For these reasons the Argos system has been used for location determination for moored buoys. In addition, some WMO Members use the Argos system for normal transmission of meteorological observations from moored buoys.

The Tropical Atmosphere Ocean (TAO) array of ATLAS Moorings: About every four to seven years there is a significant disruption of the atmospheric and oceanographic circulation patterns in the equatorial Pacific. These changes have complex effects on global scale weather. The disruption's two components, El Niño and its atmospheric component, the Southern Oscillation, were the focus of the international Tropical Ocean and Global Atmosphere (TOGA) programme. Through an ambitious programme in the equatorial Pacific, TOGA investigated the oceanic and atmospheric dynamics relating to the El Niño/Southern Oscillation phenomenon and its importance in the year-to-year variability of global climate.

The ATLAS mooring is a taut wire surface mooring with a toroidal float. It is deployed in depths of up to 6000 meters. Measurements from the mooring include surface variables (wind, air and sea surface temperature), as well as subsurface temperatures down to a depth of 500 metres. These data are transmitted to shore in real time using Argos System, processed by CLS or Service Argos Inc., and placed on the GTS. Post recovery processing and analysis of the data is performed at PMEL. This array and its planned expansion is the result of international collaboration between scientists from France, Japan, Korea and the USA.

3.4 Sub-surface floats

Sub-surface floats are autonomous free-drifting platforms gathering data at mid-depth and surfacing from time to time to transmit via Argos. Argos both locates the float at the surface and collects the data stored in their memory. The two main floats are ALACE (Autonomous Lagrangian Circulation Explorer) and RAFOS (SOFAR (SOund Fixing And Ranging) spelled backwards since RAFOS is the reverse concept of SOFAR where signals are emitted from the float and then received at moored buoy sites for location computation; SOFAR floats are no longer used).

ALACEs are autonomous floats that are repeatedly located when they pop up to the surface for satellite location through the Argos system. While they are at the surface their drift gives a measurement of the surface current. The cycling time is adjustable. The instrument is designed for 50 cycles. The basic cycling time used is 36 days, to provide a five-year lifetime.

PALACEs, (Profiler ALACE) are special ALACE floats capable of making water temperature and/or water conductivity measurements while popping up or down. They have shorter cycles of 5 to 15 days and a lifetime of about 100 cycles. They can dive as deep as 1500 metres. Some 3000 PALACE floats are planned for deployment in the next few years in the ARGO programme.

RAFOS floats are drifting listening stations that record the time of arrival of acoustic signals from moored sound sources and at the end of their lives pop up to report the recorded data through Argos. Present recording lifetimes are roughly 2.5 years. MARVOR floats work on the same principle as RAFOS. In addition, they can pop up and down several times during their lifetime and transmit data collected each time they surface.

Sub-surface floats are used in the World Ocean Circulation Experiment (WOCE) to measure the global distribution of current velocity below the high eddy noise region near the surface, to provide an accurate mean velocity. The mean velocity is combined with hydrographic data to compute water mass transport in the major ocean basins. The WOCE goal is to compute a five-year mean velocity on a 500 x 500 km2 scale. The requirements translate into the following number of five-year lifetime floats in the oceans: Atlantic: 225, Indian: 180, Pacific: 495, Southern (south of 45°S): 114.

Sub-surface float data are not disseminated onto the GTS principally because the data are not available in real-time.

Argo is a globally coordinated, pre-operational project within the Global Ocean Data Assimilation Experiment (GODAE) for the deployment of an array of up to 3000 sub-surface profiling floats, in support of GOOS, GCOS and the WCRP.

3.5 Ship based systems

3.5.1 Voluntary Observing Ships (VOS)

A fleet of some 7000 Voluntary Observing Ships (VOS) makes a significant contribution in the form of marine meteorological and surface oceanographic observations. About 40% of the fleet is at sea at any time making the necessary measurements, manually and automatically, at 6-hourly intervals. Data are communicated, primarily via the International Maritime Satellite System (INMARSAT), in real-time and in delayed mode by the collection of logbooks. Ships are recruited by some 50 WMO Members and coordinated by the Joint WMO IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). Members also operate an international network of ~ 200 Port Meteorological Officers, to commission and decommission equipment, collect logbooks and provide training and feedback to improve the quality of data. Lead centres monitor the performance of the real-time data stream.

3.5.2 Ship of Opportunity Program (SOOP)

(Source: http://www.brest.ird.fr/soopip/index.html)

The primary goal of the Ship-of-Opportunity Programme (SOOP) is to fulfill upper ocean data requirements which have been established by GOOS and GCOS, based on the results of programmes of the World Climate Research Programme (WCRP), and which can be met at present by measurements from ships of opportunity (SOO).

Approximately 100 dedicated SOO, operated by 7 Members, report upper ocean temperature along specified routes at sampling intervals developed under the Tropical Ocean and Global Atmosphere (TOGA) and WOCE programmes of WCRP. These sampling requirements have been designed for climate monitoring and prediction applications, and which have been endorsed by the WCRP Ocean Observing System Development Panel (OOSDP). Each vessel is equipped with a data acquisition system provided by the operating agency. These systems vary depending upon the agency, but generally meet agreed standards. Observations (such as the deployment of expendable bathythermographs - XBTs) are made normally by ships officers on a voluntary basis, though there is increasing automation in some underway systems such as used for measuring sea surface temperature and sea surface salinity. Observations are also utilized from other "opportunistic" vessels (navy, fishing, research, etc.) not formally participating in the programme. Interface between oceanographic agencies and met services and the ships is through designated Ship Greeters from the contributing national agencies and occasionally the international network of Port Meteorological Officers.

4. SATELLITE MEASUREMENTS

The current operational meteorological satellite observing system comprises a constellation of geostationary and polar orbiting satellites operated by various space agencies (see Figure 1). Each satellite has a payload of instruments including as a minimum a multi-spectral imaging radiometer. The various geostationary satellites, which operate in an equatorial belt, provide a continuous view of the weather from roughly 70°N to 70°S. At present there are satellites at 0° longitude and 63°E (operated by the European Organisation for the Exploitation of Meteorological Satellites - EUMETSAT), a satellite at 76°E (operated by the Russian Federation), a satellite at 105°E (operated by the People's Republic of China), a satellite at 140°E (operated by Japan), and satellites at 135°W and 75°W (operated by the USA). The polar-orbiting satellites are operated by the Russian Federation and the USA and more recently China. The METEOR-3 series has been operated by the Russian Federation since l991. The polar satellite operated by the USA is an evolutionary development of the TIROS satellite, first launched in April l960. The present NOAA series, based on the TIROS-N system, has been operated by the USA since l978. In the past decade, China has been flying the FY 1 series also. These spacecraft provide coverage of the polar regions beyond the view of the geostationary satellites and fly at altitudes of 850 to 900 km.

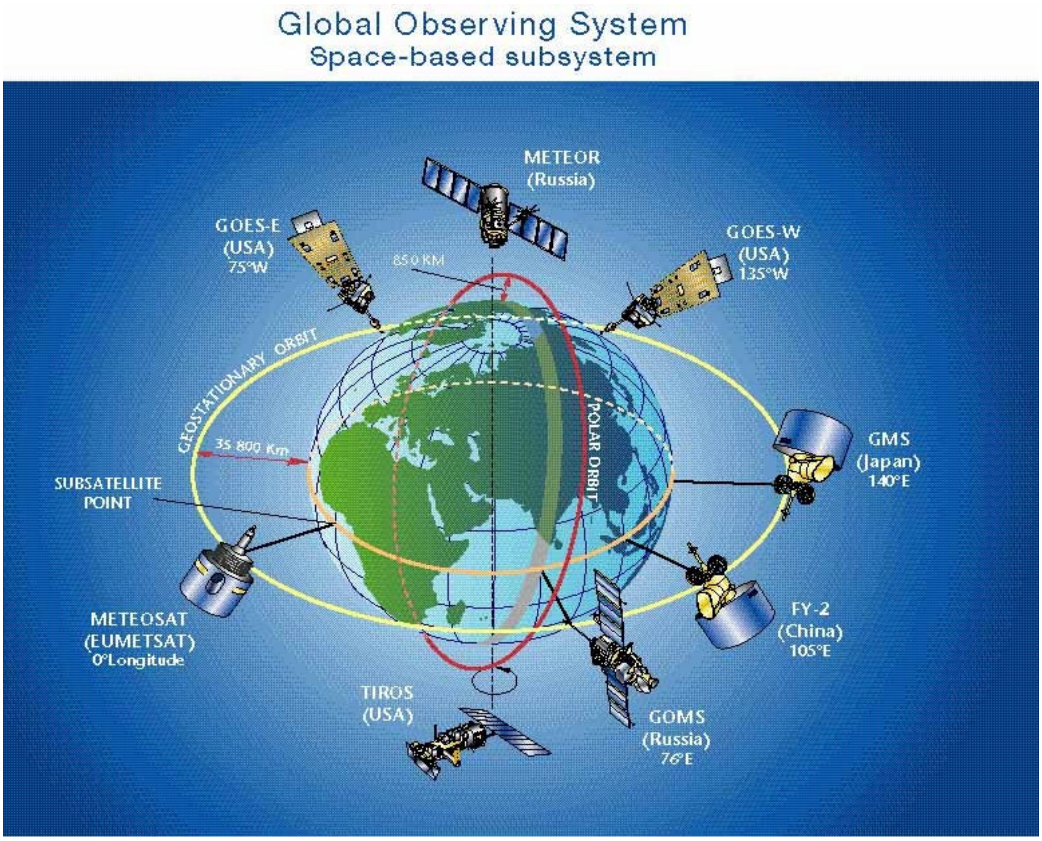

Figure 1 – The nominal configuration for the space-based Global Observing System

The ability of geostationary satellites to provide a continuous view of weather systems make them invaluable in following the motion, development, and decay of atmospheric phenomena. Even such short-term events such as severe thunderstorms, with a life-time of only a few hours, can be successfully recognized in their early stages and appropriate warnings of the time and area of their maximum impact can be expeditiously provided to the general public. For this reason, its warning capability has been the primary justification for the geostationary spacecraft. Since 71 per cent of the Earth's surface is water and even the land areas have many regions which are sparsely inhabited, the polar-orbiting satellite system provides the data needed to compensate the deficiencies in conventional observing networks. Flying in a near-polar orbit, the spacecraft is able to acquire data from all parts of the globe in the course of a series of successive revolutions. For these reasons the polar-orbiting satellites are principally used to obtain: (a) daily global cloud cover; and (b) accurate quantitative measurements of surface temperature and of the vertical variation of temperature and water vapour in the atmosphere. There is a distinct advantage in receiving global data acquired by a single set of observing sensors. Together, the polar-orbiting and geostationary satellites constitute a truly global meteorological satellite network.

Current upper-air observations from satellites include temperature and humidity profiles from infrared and microwave radiometers, and upper winds by tracking the movement of cloud and water vapour features. Some estimated accuracies, resolutions, and cycle times are summarized in the following table. Infrared radiometers provide the highest quality profiles but only in clear sky conditions. Microwave radiometers provide data under cloudy conditions but have lower vertical resolution. Observations from both are currently widely available over the oceans, but the retrieval of soundings over land is limited in the lower atmosphere because of varying surface emissivity. Improvements in this area are an ongoing research activity. Upper wind observations are provided on a global basis but only where suitable tracers are available and usually only at one level in the vertical. Improvements in resolution and capability are expected over the next 5-10 years.

Element and Instrument	Horiz Res[1]	Vert Res[2]	Cycle [3]	Delay[4]	Accuracy
	(km)	(km)	(hr)	(hr)	(rms)
Humidity Sfc – 300hPa					
NOAA & METOP (ATOVS)[6]	50	3	6	2	15%
METOP (IASI) & NPOESS (CrIS)	15	1	12	2	10%
Humidity below 50hPa					
METOP(GRAS) & NPOESS (GPSOS)	500	~1	12	2	10%
Temperature Sfc - 10hPa					
NOAA & METOP (ATOVS) [6]	50	3	6	2	1.5^oK
METOP (IASI) & NPOESS (CrIS)	15	1	12	2	1^oK
Temperature 500hPa – 10hPa					
METOP(GRAS) & NPOESS (GPSOS)	500	~1	12	2	1^oK
Wind Sfc – 200hPa					
MSG (SEVIRI) & GOES (Imager)	50/100	One level[5]	1	2	2-5m/sec

Notes:
1. The horizontal interval between consecutive measurements (sampling distance).
2. The vertical interval between consecutive measurements.
3. Cycle is time interval between measurements and assumes 2 satellites in polar orbit.
4. Delay is the time delay between the observation and receipt of data by the end user.
5. Satellite winds are single level data with vertical sampling typically ~1km.
6. For ATOVS, 1-4 profiles are provided per second per satellite (per $100km^2$).

4.1 Polar platforms

Polar orbiters allow a global coverage to be obtained from each satellite twice a day. To provide a reasonable temporal sampling for many applications at least two satellites are required, thereby providing 6-hourly coverage. A backup capability exists by reactivating 'retired' platforms and this has been demonstrated recently. Since 1979, coverage with two polar orbiting satellites has been achieved most of the time. The orbital altitude of 850 km makes it technically feasible to make high spatial resolution measurements of the atmosphere/surface.

Current operational polar orbiters include the NOAA series from the US and the METEOR, RESURS, and OKEAN series from Russia and the FY-1 series from China. They provide image data that can be received locally. The NOAA satellites also enable generation of atmospheric sounding products that are disseminated to NWP centres on the GTS. In the future, the NOAA AM satellite will be replaced by the METOP satellites provided by EUMETSAT and the NOAA PM satellite will transition to the NPOESS series.

Instruments that have been or will soon be a part of the polar orbiting series of satellites include:

4.1.1 Visible and Infrared Radiometers

The Advanced Very High Resolution Radiometer (AVHRR), flown in October 1978 on TIROS N, measures radiation in five visible and IR windows at 1 km resolution. This will transition to a more capable visible and infrared imager called the Visible Infrared Imaging Radiometer Suite (VIIRS), when the NOAA satellites become the NPOESS series, starting with a demonstration program in 2005, called the NPOESS Preparatory Project (NPP). VIIRS will be better calibrated than the AVHRR, have higher spatial resolution (400 meters vs. 1 km at nadir), and have additional spectral capability including channels that can be utilized to determine ocean color. Parameters that may be derived from the VIIRS for use in operational as well as climate monitoring include sea surface temperature, aerosols, snow cover, cloud cover, surface albedo, vegetation index, sea ice, and ocean color.

The Along Track Scanning Radiometer (ATSR), flown on ERS-1 and –2 in the 1990's, has been providing multi-view multi-spectral measurements enabling accurate determinations of sea surface temperature. This enhancement to the operational AVHRR has been embraced by the ocean community. The Advanced ATSR (AATSR), to be launched on ENISAT in 2001, will expand upon these capabilities.

4.1.2 Atmospheric Temperature and Humidity Sounding

An important development was the remote sounding of vertical temperature and humidity profiles in the atmosphere on a worldwide basis with the TIROS Operational Vertical Sounder (TOVS). TOVS has evolved to an advanced version in 1998 and consists of the High resolution Infrared Radiation Sounder (HIRS) and the Advanced Microwave Sounding Unit (AMSU). These IR and microwave sounders can produce soundings in clear and cloudy (non-precipitating) skies every fifty kilometers. NOAA will be transitioning to more capable sounders in the NPOESS series, starting with a demonstration program in 2005, called the NPOESS Preparatory Project (NPP). HIRS will be replaced by the Cross Track Infrared Sounder (CRIS), a Michelson interferometer that is designed to enable retrievals of atmospheric temperature profiles at 1 degree accuracy for 1 km layers in the troposphere, and moisture profiles accurate to 15 percent for 2 km layers. This is accomplished by the CRIS working together with the Advanced Technology Microwave Sounder (ATMS), being designed to be the next generation cross track microwave sounder. Comparable sounding capability will be realized on the METOP series by the Infrared Atmospheric Sounding Interferometer (IASI) in conjunction with the advanced microwave temperature sounding units (AMSU-A) and microwave humidity sounders (MHS / HSB). CRIS/ATMS will fly on afternoon (1330 ascending) and IASI/AMSU/MHS will fly in the morning (0930 descending) orbit.

4.1.3 Microwave All-Weather Radiometers

A complementary series of DMSP satellites in polar orbit fly a scanning microwave radiometer called the Special Sensor Microwave Imager (SSM/I), flown since June 1987. These provide night-day, all-weather imaging of the land and ocean surface because of the ability of microwave radiation to penetrate clouds. NOAA has used the DMSP SSM/I data extensively. A conical scanning version of the microwave sounder will be flown on NPOESS. The Conical Microwave Imager Sounder (CMIS) will combine the microwave imaging capabilities of Japan's Advanced Microwave Scanning Radiometer (AMSR) on EOS PM-1, and the atmospheric sounding capabilities of the Special Sensor Microwave Imager / Sounder (SSMI/S) on the current DMSP satellites. Polarization for selected imaging channels (vertical, horizontal, and +/- 45 degrees) will be utilized to derive ocean surface wind vectors similar to what has previously been achieved with active scatterometers. Although demonstrated on airborne platforms, space based validation of the passive microwave technique for wind vector derivation will await the Windsat Coriolis mission in late 2001. CMIS data can be utilized to derive a variety of parameters for operations and research including all weather sea surface temperature, surface wetness, precipitation, cloud liquid water, cloud base height, snow water equivalent, surface winds, atmospheric vertical moisture profile, and atmospheric vertical temperature profile.

4.1.4 Monitoring Ozone

Another important sounding approach used the ultraviolet portion of the electromagnetic spectrum to sound atmospheric ozone. The Solar Backscatter Ultraviolet (SBUV), which provides information on ozone amounts for atmospheric 7 to 10 km layers, was incorporated into the operational series of NOAA polar satellites (POES) beginning with NOAA-9 in 1984. The Total Ozone Mapping Spectrometer (TOMS) flew on Nimbus-7 and provided critical image data that first identified the Antarctic ozone hole, but it has not been made operational. The Nimbus-7 TOMS lasted into the 1990s and was replaced subsequently by TOMS sensors flying on a Russian Meteor spacecraft, the Japanese ADEOS, and a NASA Earth Probe. The TOMS equivalent capability will be continued with the flight of the Dutch provided Ozone Mapping Instrument (OMI) on NASA's Chemistry mission in 2002 and subsequently the Ozone Mapping and Profiler Suite (OMPS) on NPOESS, being developed for flight on afternoon (1330 ascending) NPOESS platforms. It consists of a nadir scanning ozone mapper similar in functionality to TOMS and a limb scanning radiometer that will be able to provide ozone profiles with vertical resolution of 3 km. Depending upon its ultimate design, the OMPS may be able to provide some of the same capability as limb scanning sensors on NASA's UARS and EOS Chem. However in the near term, there is concern about a possible gap in TOMS type data coverage.

4.1.5 Scatterometers

The first active radar scatterometer to determine wind speed and direction over the ocean surface was flown on Seasat in 1978. Great progress in this area was possible in the 90's with the SCAT data on ERS-1 and –2; the SCAT on ERS-2 is still providing quasi-operational data. A NASA scatterometer termed NSCATT flew on Japan's ADEOS from August 1996 to June 1997; scientists were able to show a significant positive impact in predicting marine forecasting, operational global numerical weather prediction, and climate forecasting. A follow-on mission, Quickscat, launched in 1999, carries the NSCATT successor instrument, Seawinds. Another Seawinds sensor is scheduled to fly on ADEOS-2 in 2000. No additional U.S. scatterometer missions are planned before NPOESS, which plans to use a passive microwave approach to determining the ocean vector wind field. This passive microwave technique will be tested as part of the Windsat Coriolis mission scheduled for late 2001. Europe's METOP series of satellites, scheduled to begin flying in 2003 include an ASCAT sensor, but ASCAT alone may not be able to provide the required geographic coverage and frequency of observation needed for operations and research. The Japanese have offered to fly an ADEOS-3 with a U.S. provided scatterometer, but a decision is still pending.

4.1.6 Radiation Budget

The Earth's radiation budget and atmospheric radiation from the top of the atmosphere to the surface will be measured by the Clouds and Earth Radiant Energy System (CERES) on its afternoon (1330 local time ascending orbit) NPOESS platforms. The predecessor Earth Radiation Budget (ERB) sensors flew on Nimbus in 1978, as well as on a free flyer and on NOAA-9 and -10 in the mid 1980s. The first CERES is currently flying on the Tropical Rainfall Measuring Mission (TRMM) which was launched in November 1997. Two CERES scanners (one each working in the biaxial and cross track mode) will be in orbit with EOS Terra in December 1999 and EOS Aqua in December 2000.

4.1.7 Altimetry

Altimeters flew on the European ERS-1 and –2 satellites in the 1990's and provided a major quasi-operational contribution. NOAA is planning to manifest a dual frequency microwave radar altimeter for its morning (0530 descending) NPOESS platforms. The type of altimeter, planned for JASON-1 in 2000, measures the ocean topography which provides information on the ocean current velocity, the sea level response to global warming/cooling and hydrological balance, the marine geophysical processes (such as crustal deformation), and the global sea state

4.1.8 Positioning Sensors

(source sites: http://www.cosmic.ucar.edu/cosmic/index.htm)

Geometric determinations of location depend on inferences about the atmospheric temperature and moisture concentrations; they provide valuable complementary information to tropospheric infrared and microwave sounders about the tropopause and stratosphere. Ray bending and changes in the phase and amplitude of the transmitted signals allowing inference of the upper atmosphere temperature profile to the order of 1 deg K or better between altitudes of 8 to 30 km in layers (with footprints ranging between 1 km x 30 km to 1 km x 200 km extent) with near global coverage. The coverage would be expected to be evenly spread over the globe, excepting polar regions. The system measures upper atmospheric virtual temperature profiles so data from the lower atmosphere would require alternate data to separate vapour pressure and temperature traces.

The Global Positioning System Occultation Sensor (GPSOS) will measure the refraction of radiowave signals from the GPS constellation and Russia's Global Navigation Satellite System (GLONASS). This uses occultation between the constellation of GPS satellite transmitters and receivers on LEO satellites. The GPSOS will be used operationally for spacecraft navigation, characterizing the ionosphere, and experimentally to determine tropospheric temperature and humidity. A similar system, GPSMET, flew in 1995. A GPS occultation system was recently provided for launch on the Oersted / Sunsat mission and variations will also be included on CHAMP, SAC-C and GRACE, all scheduled to be launched before 2001. NOAA is planning to manifest a GPSOS on all NPOESS platforms.

The European Polar-orbiting Satellite (METOP), due to be launched in 2004, will fly a GPS Radio occultation Atmospheric Sounder (GRAS). GRAS will provide 'all weather' temperature profiles with high vertical resolution in the upper troposphere and stratosphere, and humidity profiles in the lower troposphere.

A promising research GPS system is COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate). The National Space Program Office (NSPO) in China, the University Corporation for Atmospheric Research (UCAR), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), the University of Texas at Austin, the University of Arizona, Florida State University and other partners in the university community are developing COSMIC, a project for weather and climate research, climate monitoring, space weather, and geodetic science. COSMIC plans to launch eight LEO satellites in 2002, each COSMIC satellite will retrieve about 500 daily profiles of key ionospheric and atmospheric properties from the tracked GPS radio-signals as they are occulted behind the Earth limb. The constellation will provide frequent global snapshots of the atmosphere and ionosphere with about 4000 daily soundings.

4.2 Geostationary Platforms

The geosynchronous orbit is over 40 times higher than a polar orbit, which makes measurements technically more difficult from geostationary platforms. The advantage of the geostationary orbit is that it allows frequent measurements over the same region necessary for now-casting applications and synoptic meteorology. A disadvantage is that a fixed full disk view of the Earth is viewed from one satellite. Thus, five equally spaced satellites around the equator are needed to provide global coverage; polar regions are reviewed poorly at large zenith angles.

Currently, there is global coverage from geostationary orbit (>5 operational satellites for image data and products (e.g., cloud motion winds) and 2 satellites are providing a sounding capability as well. Reactivating 'retired' platforms provides backup and there have been several examples of this.

Some of the satellites provide a real-time reception capability to allow immediate access to the imagery for real-time applications. Products are disseminated on the GTS by the satellite operators for near real-time applications.

Instruments that have been or will soon be a part of the geostationary series of operational satellites include:

4.2.1 Visible and Infrared Radiometers

The Visible and Infrared Spin Scan Radiometer (VISSR), flown since 1974, has been the mainstay of geostationary imaging on GOES, Meteosat, and GMS. Changes are underway. Europe is moving to SEVIRI with 12 channels of visible and infrared measurements at 3 km resolution full disk every 15 minutes. Japan will embark on the MTSAT with 5 channels of visible and infrared measurements at 5 km resolution full disk every 30 minutes. China has the FY 2 series of imagers that will be adding several spectral channels to their current visible and infrared window measurements. USA will evolve from their current Imager with 5 channels of visible and infrared measurements at 5 km resolution full disk every 30 minutes to an Advanced Baseline Imager (ABI) that makes full disk images in 8 to 12 spectral bands in 5 minutes at 2 km infrared and 0.5 km visible resolution. ABI offers improved performance over current GOES in all dimensions (routine full Earth disk imaging while enabling mesoscale sub one minute interval imaging, better navigation, more noise free signals, and additional spectral bands for improved moisture feature detection).

4.2.2 Infrared Sounding

With the three axis stable platform on GOES-8, NOAA was able to introduce geostationary infrared sounders. Measuring the infrared radiation in 18 spectral bands, these sounders provide temperature and moisture sounding over North America and nearby oceans every hour every 30 km (in clear skies). A variety of products and applications are described in the literature (Menzel et al., 1998). NOAA plans to evolve to the Advanced Baseline Sounder (ABS) in 2009, using an interferometer, focal plane detector arrays, and on board data processing to cover 3.7 to 15.4 microns with 2000 plus channels measuring radiation from 10 km resolution; contiguous coverage of 6000 by 5000 km will be accomplished in less than 60 minutes. NASA will be demonstrating the technology necessary for ABS, with the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) in 2004. GIFTS will improve observation of all three basic atmospheric state variables (temperature, moisture, and wind velocity) with much higher spatial, vertical, and temporal resolutions. Water vapor, cloud, and trace gas features will be used as tracers of atmospheric transport. GIFTS observations will improve measurement of the atmospheric water cycle processes and the transport of greenhouse and pollutant gases (more details are available on http://its.ssec.wisc.edu/~bormin/GIFTS/). GIFTS and ABS represent a significant advance in geostationary sounding capabilities and brings temporal and horizontal and vertical sounding resolutions into balance for the first time ever.

4.2.3 Radiation Budget

Europe will be flying the Geostationary Earth Radiation Budget (GERB) starting on Meteosat Second Generation in 2004. This will enable hourly measurements of the Earth's radiation budget and atmospheric radiation from the top of the atmosphere to the surface.

4.3 Research and applications satellites

Research systems are valuable for demonstrating new instruments for possible future operational systems. To date, research satellites have been flown by several agencies of which TRMM and ADEOS are examples. The recently launched EOS and soon to be launched ENVISAT platforms are another. Applications satellites with a limited number of missions, such as ERS, also provide important contributions. More recently, measurements based in radio occultation technology such as the GPS/GLONASS have been added to the database of satellite capabilities. However, a long-term commitment to providing research and applications data routinely is necessary to increase the utility of all these data.

Some of the instruments and spacecraft involved in the research opportunities are spelled out in alphabetical order below.

4.3.1 Array MLS Light

The Array Microwave Limb Sounder (MLS) Light evolves from the EOS 2002 Chemistry Mission. Array MLS Light monitors the following processes and parameters vital to global change research. a) MLS measures lower stratospheric temperature and concentrations of H_2O, O_3, ClO, HCl, HNO_3, and N_2O, for their effects on (and diagnoses of) transformations of greenhouse gases, radiative forcing of climate change, and ozone depletion. MLS measures upper tropospheric H_2O and O_3 for their effects on radiative forcing of climate change and diagnoses of exchange between the troposphere and stratosphere. b) MLS monitors ozone chemistry of the middle and upper stratosphere by measuring radicals, reservoirs, and source gases in chemical cycles which destroy ozone. c) MLS measures the effect of volcanoes on global change by monitoring SO_2, and other gases mentioned above, as they are injected into the atmosphere by volcanic activity.

4.3.2 Cloudsat and PICASSO

Cloudsat will take a revolutionary global look at clouds with a new space-borne radar capable of peering deep into their interior to study their structure, composition, and effect on climate. It will fly in formation with PICASSO-CENA, (Pathfinder Instruments for Cloud and Aerosol Space borne Observations - Climatologie Etendue des Nuages et des Aerosols) which will use a lidar, an oxygen A-band spectrometer, a visible wide field camera, and an imaging infrared radiometer to study the role of transparent, thin clouds and aerosols, small atmospheric particles, and their effect on solar-energy transfer. These systems will allow determination of cloud height / base, profiles of cloud optical depth, ice and liquid content, along-track visibility, sub-visual cirrus, precipitation occurrence, aerosol optical depth and layer thickness. These missions will serve as a demonstration of key technologies that may lead to future operational systems for generating global three-dimensional images of cloud fields for weather forecasting.

4.3.3 Doppler Wind Lidar

Direct measurement of tropospheric winds would potentially provide the most significant contribution satellite remote sensing could make to the existing global meteorological observing system. At present tropospheric wind profiles represent the number one unaccomodated data product requirement for the NPOESS program. Direct measurement of horizontal wind vectors in clear air has been demonstrated using lidar from the ground and from aircraft, based on the wind-induced Doppler shift in the backscatter signal. The first spaceborne demonstration of the technique is being prepared for a shuttle mission in 2001; the project name is SPARCLE (Space Readiness Coherant Lidar Experiment). Adoption of a Doppler wind lidar to be flown on the NPOESS operational mission beginning in the 2009-2011 time frame is a goal.

4.3.4 EOSP (Scanning Polarimeter)

The NASA Earth Observing Scanning Polarimeter (EOSP) will provide global maps of cloud and aerosol properties from retrieval of 12-channel radiance and polarization measurements in the visible and near-infrared. The objective is to characterize the global aerosol distribution, the spatial and temporal variability, and the corresponding impact on climate. It will also be used to provide atmospheric corrections for clear sky ocean and land observations. It is planned for 2001.

4.3.5 GLAS (Laser Altimeter)

The NASA Geoscience Laser Altimeter System (GLAS) will measure ice sheet topography and associated temporal changes, cloud and atmospheric properties, and along-track topography over land and water. It will support prediction analyses of cryospheric response to future climate changes.

4.3.6 HydroStar

Determination of soil moisture and salinity, which is of great interest to both the research and operational communities, requires deployment of passive microwave instrumentation sensitive in the 1 GHz range. A spaceborne demonstration of this capability is awaiting development of antenna technologies that would allow for a viable, affordable mission. Techniques involving the use of Synthetic Aperture Interferometric Radiometry (SAIR) were proposed under the title of HydroStar. Concepts using inflatable and large aperture mesh antennas have also been studied and proposed. Technologies for these approaches are currently being funded under NASA's Instrument Incubator Program (IIP) and hopefully will lead to a research/operational demonstration mission in the future.

4.3.7 JASON-1 Follow-on

A radar altimeter for use in measuring ocean surface topography, circulation, and significant wave height, was flown on Seasat in 1978. Fourteen years later NASA / French TOPEX / Poseidon was launched in 1992. Data from these missions are being used to measure global mean sea level at accuracies approaching 2 to 3 centimeters, with a goal of 1 centimeter. The TOPEX data were also used in monitoring the advent and impact of the Pacific Ocean El Nino event. A follow-on to TOPEX/Poseidon, termed JASON-1, is planned for flight in 2000 with a dual frequency solid state altimeter (SSALT). However, with the exception of a single frequency altimeter on the European Space Agency's polar orbiting ENVISAT also scheduled for launch in 2000, no other altimeter missions are scheduled before NPOESS. The French Space Agency, CNES, has indicated a willingness to partner on a JASON-1 follow-on mission.

4.3.8 Landsat-7 Follow-on

The first Landsat mission termed the Earth Resources Technology Satellite (ERTS-1) was launched in 1972. These high resolution multispectral data are used for a multitude of applications encompassing global change related climate research, operational resource monitoring (renewable and nonrenewable), and national security purposes. Landsat 7, launched in April 1999, is continuing providing these data. NASA plans to launch in 2000 an Advanced Landsat Imager (ALI) which will fly in formation with Landsat 7 as a technology demonstration. Data from these missions will be analyzed together with value-added users and potential commercial providers.

4.3.9 LightSAR

Synthetic Aperture Radar (SAR) have applications in the areas of natural hazards (crustal deformation, volcanic), ice sheet mass balance and sea level (glacier and ice sheet velocities, ice surface topography and boundaries), the carbon cycle (forest regrowth and biomass), the hydrologic cycle (soil moisture and snow properties), and the role of ocean in climate change (air-sea interaction and ocean climate dynamics). A report entitled "The Operational Use of Civil Space-Based Synthetic Aperture Radar (SAR)" issued in 1996 (JPL 96-16) lists potential operational applications of SAR grouped under the headings of mapping and charting, resource monitoring and management, pollution and waste threats, natural hazards mitigation, oceans and ice, and enforcement and surveillance. Many operational and research requirements can only be satisfied through exploitation of SAR technologies. The National Research Council has noted that because of their all-weather, day-night capability, active microwave systems may represent the only reliable approach to collecting data on a given region at a given time. In addition, the signals returned by radar systems are sensitive to the physical structure and moisture content being sensed, and may offer avenues to obtaining results that are important for research and applications but are not otherwise obtainable. Although NASA has flown radars on shuttle missions, it has not yet deployed such an instrument on a free flying spacecraft. Recent technological advances have allowed NASA to plan for a LightSAR mission in 2002, in which a commercial teaming arrangement is being sought with industry (NASA AO-99-OES-01). This mission may become the pathfinder for both the research and operational communities in applying SAR technologies.

4.3.10 LIS

Lightning Imaging Sensor (LIS) is a small, highly sophisticated instrument that detects and locates lightning. It is operating on the TRMM mission and is providing information on the dynamics and physics of clouds. The LIS instrument examines the distribution and variability of lightning and thunderstorm activity. A higher number of lightening strokes is directly related to the intensity of storms. The Lightning Sensor is a compact staring imager capable of locating and detecting lightning within individual storms day and night.

4.3.11 MLS

The Microwave Limb Sounder (MLS) instrument on the EOS 2002 Chemistry Mission will study and monitor the following processes and parameters vital to global change research. a) Chemistry of the lower stratosphere and upper troposphere - MLS measures lower stratospheric temperature and concentrations of H_2O, O_3, ClO, HCl, OH, HNO_3, and N_2O, for their effects on (and diagnoses of) transformations of greenhouse gases, radiative forcing of climate change, and ozone depletion. MLS measures upper tropospheric H_2O and O_3 for their effects on radiative forcing of climate change and diagnoses of exchange between the troposphere and stratosphere. b) Chemistry of the middle and upper stratosphere - MLS monitors ozone chemistry by measuring radicals, reservoirs, and source gases in chemical cycles which destroy ozone. c) The effect of volcanoes on global change - MLS measures SO_2, and other gases mentioned above, in volcanic plumes to investigate the effects of volcanic injections into the atmosphere.

4.3.12 m MAPS

µ MAPS is a smaller version of the Measurement of Air Pollution from Satellites (MAPS) instrument. It was built for the Clark mission and is now looking for a flight of opportunity. The instrument is a nadir pointing gas filter radiometer that can obtain a 3-dimensional map of the CO content of the middle and upper troposphere as well as to provide N_2O cloud mapping.

4.3.13 SABER

Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) is to be used to study the energetics, chemistry, dynamics, and transport of the atmospheric region extending from 10 km to 180 km on the TIMED mission in the year 2000. It is a Earth limb scanning infrared radiometer with 10-channels from 1.27 µm to 15.2 µm. The instrument will be used to study CO_2, O_3, O_2, OH, NO, and H_2O.

4.3.14 TSIM

The Active Cavity Irradiance Monitor (ACRIM) was flown on Solar Max in the 1980s and again on the Upper Atmosphere Research Satellite (UARS) in 1991. The instrument is needed to determine the amount of incident solar radiation reaching the Earth's atmosphere, a major driver in climate and meteorological studies. NASA plans to fly a dedicated ACRIMSAT in 2000 and a follow on Solar Radiation and Climate Experiment (SORCE) in 2002. The SORCE mission will carry a payload consisting of a Total Irradiance Monitor (TIM), Solar Irradiance Monitor (SIM), and a Solar Stellar Irradiance Comparison Experiment (SOLSTICE). NPOESS plans to manifest TIM and SIM (together called TSIM) on its morning, 0530 descending platforms. However the NPOESS morning platforms will likely not be launched before 2010, causing a possible gap in solar measurements needed for earth system studies.

4.4 Satellite Capabilities

Summary statements on satellite capabilities in various applications areas can be found in the WMO Statement of Guidance document (WMO 2000). A major conclusion from this document is that there is a continuing need in all application areas for operational continuity of a suite of instruments deployed from at least two polar orbiting platforms and at least five geostationary platforms.

5. BASIC CLIMATE MONITORING NETWORK

For climate purposes, continuity of the data record is of primary importance. This demands a regular observing schedule. If observation schedules are made weather dependent serious biases are likely to be introduced into the record. It has been suggested, (NAOS, 1997) that reducing the sampling of benign weather systems such as anticyclones will increase the apparent water content of the atmosphere in the long-term record.

To avoid the possible degradation of the climate record there needs to be a network of observations maintained that are always made regardless of prevailing weather conditions. The GCOS, GTOS and GOOS networks serve this purpose on a global scale, however a greater network of stations would be required for detailed regional climate monitoring.

Separate to this network, an integrated adaptive observing system can be developed that allows for a targeted use of resources for a more effective GOS. Data obtained from adaptive observing systems would not be the primary basis for climate studies.

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