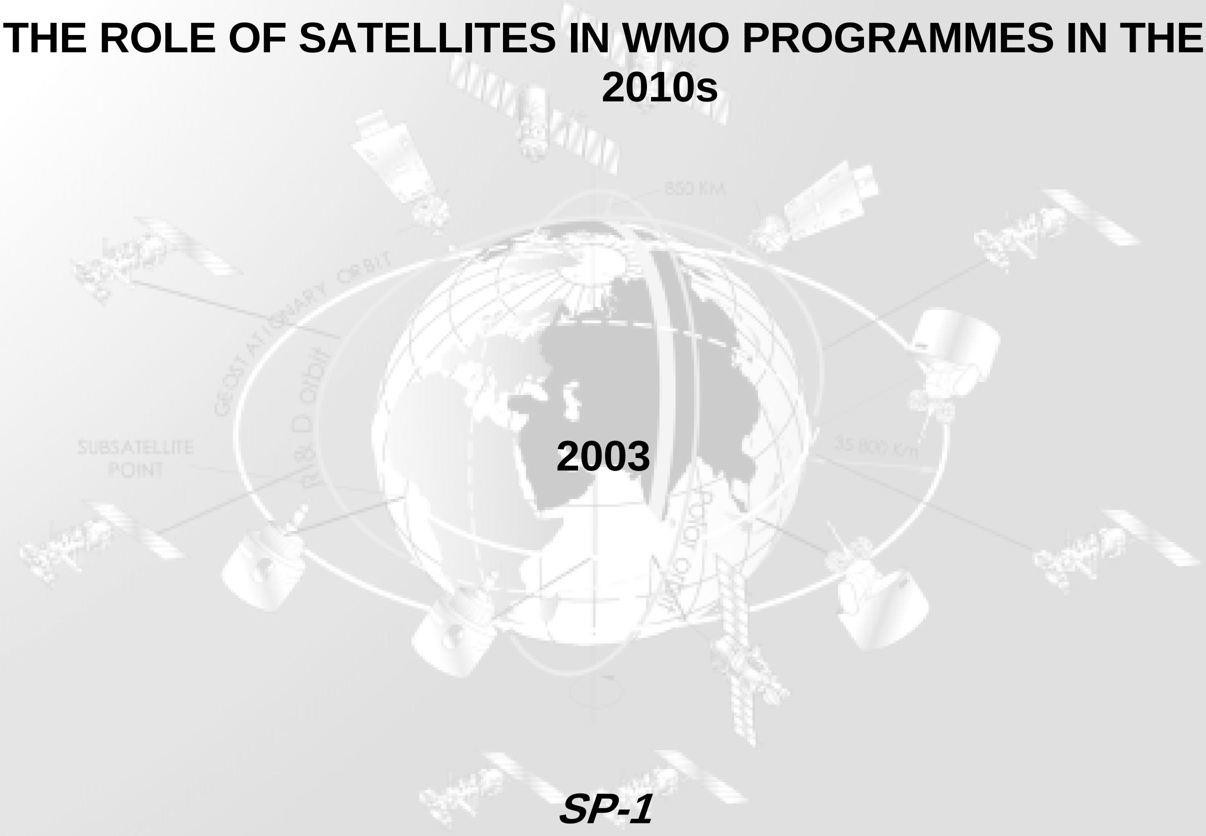
WORLD METEOROLOGICAL ORGANIZATION

# WMO SPACE PROGRAMME

SATELLITE REPORTS

# THE ROLE OF SATELLITES IN WMO PROGRAMMES IN THE 2010s



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# FOREWORD

In the 1970s, the space-based component of the Global Observing System (GOS) of WMO's World Weather Watch experienced a major expansion. Meteorological satellites - the first one was launched in 1960 - were starting to provide data, products and services on a global operational basis from both geostationary and polar orbits. At the invitation of the World Meteorological Organization (WMO), two visionary scientists, Dr D. Johnson (USA) and Dr I. Vetlov (former USSR), prepared a technical document for WMO Members. The document not only highlighted the potential contributions of meteorological satellites to all WMO Programmes, but also proposed a future configuration for the space-based component of the GOS.

The proposed configuration was finally realized in the mid-1990s. Over the period, especially since 1977, marked advances in remote-sensing and in computer capabilities, communications and space-based technology had revolutionised our ability to observe the Earth and its atmosphere from space. In addition the number of space-faring nations has grown. These developments further accelerated and extended the global monitoring and applications capabilities to domains beyond weather. As a result, the expectations and requirements of the world community from WMO Programmes grew considerably, especially in a number of areas of concern to humanity related to sustainable development such as climate change and its impacts, the negative impacts of natural disasters, dwindling water resources, monitoring of oceans, land and ecosytems, increased pollution and depletion of the ozone layer.

Over the next 25 years, the anticipated advancements in space-based observing systems, computers, data handling and information and communications technology are expected to further eclipse the recent achievements. In particular, we should expect considerable improvements to the global space-based observing system based, among others, on very high spatial and spectral sampling from ultraviolet to microwave wavelengths, with both active and passive sensors. By 2025, and likely before then, operational and research satellite systems from a variety of orbits will provide a spectral shell of real- and near-real time information that will be used to address societal and environmental problems in an increasing number of application areas. However, over a shorter time scale, especially in only the first decade of this 21st century, we must prepare ourselves to develop new approaches to data handling and applications through international partnerships. This is essential if the international community is to benefit fully from the growth, of several orders of magnitude, in the volume and content of satellite data which will be available from systems!

In recognition of these developments and the corresponding challenges and opportunities to WMO and the National Meteorological and Hydrological Services (NMHSs), the Organization has again felt the need to share and reflect on the potential contributions from present and future satellite systems. In this regard, WMO is indeed fortunate to receive the contributions of three eminent scientists, namely, Dr Ghassem Asrar, Dr Tillmann Mohr and Mr Greg Withee. In this technical document, they have provided their considerable expertise in highlighting the new and exciting potentials for observations from space. They have also proposed their vision of the future space-based component of the GOS. This document offers a view towards identifying the best approach in achieving and managing these developments, especially in the context of the new technological advances and environmental concerns. In the 2025 timeframe, WMO Members will certainly regard this document as having been a guiding light in expanding upon the challenges articulated over 25 years ago. I am therefore thankful to the three authors for this valuable contribution to WMO's Global Observing System in support of the NMHSs of Members, the Programme and activities of WMO and in addressing the challenges facing humanity over the next decades.

(G.O.P.Obasi)
Secretary-General

# EXECUTIVE SUMMARY

This document, a WMO publication on “The Role of Satellites in WMO programmes in the 2010s” is intended to update the last comparable publication entitled: “The Role of Satellites in WMO programmes in the 1980s” by D.S. Johnson and I.P. Vetlov published in 1977. This update was prepared by three primary authors: Dr G. Asrar, Dr T. Mohr and Mr G. Withee, with assistance from additional experts as identified and recruited by the primary authors. WMO Members involved in the Consultative Meetings on High-Level Policy on Satellite Matters felt strongly that the new publication would be of great importance to WMO Members, not only to the NMHSs but also the larger communities among the Members. For example, such users would include policy decision-makers or those involved with the IPCC assessment process. It is envisioned that there will be widespread use of the new publication by many user communities as nations progress into the new century and prepare for a new set of societal and environmental challenges across the globe.

Over the last four decades, since the launch of TIROS-1, satellite data have progressed from the era of simply “pictures” to high resolution digital renderings from a variety of spectral bands that provide both qualitative and quantitative information about the atmosphere, clouds, and land and sea surface properties. Today, environmental satellites are used for a variety of applications that span scales from now casting to climate, and include land, ocean, atmosphere and ecological applications. It is well recognized that meteorological satellites provide essential data for weather forecasting to national weather services across the globe; indeed it would be difficult to find an area of operational meteorology that had not come under satellite influence. Simultaneously, new instruments on research satellites are providing insights into future satellite systems to the extent that a variety of environmental applications are growing vigorously. The science and applications that develop from space-based observing systems will have far reaching impacts on WMO Members and programmes. This document focuses on the role of environmental satellites as part of a Global Observing System (GOS) as we rise to meet the challenges of the 21st century.

The document is divided into five Chapters with supporting Annexes. Chapter 1 addresses Meteorological Satellites and WMO programmes, and traces the history and development of the space-based portion of the GOS from its inception to where it is today. Chapter 2 presents the reader with a synopsis of current capabilities and how they meet WMO observational requirements for the Global Observing System and WMO supported programmes. It then provides a brief description of why they are important, trends for possible future requirements, and how these requirements are developed, reviewed, and assessed. Chapter 3 addresses the role of future technology for satellite systems in meeting the science challenges of both today and 20 years hence, and looks to observing system technology, from both operational and experimental satellites, that is expected to become available during that time period. Chapter 4 addresses the future evolution and challenges of the space-based portion of the GOS to meet the needs of WMO programmes. Annex I addresses the science of remote sensing. Annex II presents Observational requirements for WMO programmes. Annex III deals with processing, dissemination and storage of satellite data and how it will evolve to a data and information delivery system. Annex IV provides information regarding the near-term improvements expected in the space-based component of the GOS.

While Johnson and Vetlov focused on the potential contributions by operational meteorological satellites, this publication covers the spectrum of operational and experimental environmental satellites. The tremendous impact experimental satellites have had in providing new data and products in support of the WMO and WMO supported programmes is profound, wide-spread, and continues to increase. During the next few decades, the integration of experimental satellites with the evolving operational satellite systems will lead to a comprehensive space-based observing system that will have the potential of meeting many of the needs of WMO and WMO supported programmes. Through integration and exploitation of the strengths of each satellite system, maximum utilization can be realized.

The international realization of new environmental data through satellite space and ground systems brought to all members of the WMO, when combined with selected quality Earth-based observations, bode well for helping WMO users to be prepared to answer the pressing environmental and societal questions of tomorrow.

(Authors Signatures here)

# CHAPTER 1

# HISTORY AND DEVELOPMENT OF THE SPACE-BASED PORTION OF THE GLOBAL OBSERVING SYSTEM

## Meteorological Satellites and WMO Programmes

Barely 40 years after the launch of the first meteorological satellite in 1960, it is difficult to find any WMO programme or project that does not use or depend on satellite data. Uses of satellite data include training, operational meteorology, climate studies and modelling, agro-meteorology and oceanography. During these first decades of the 21st Century, WMO Members will continue to exploit operational meteorological satellite systems, while also expanding utilization to include experimental satellites[1]. During the next decades existing capabilities will be refined and improved, while new applications and advanced technology will migrate from the experimental realm to full operational use.

The potential for satellites to contribute to WMO programmes is truly remarkable, with observations that have the potential to satisfy many of the WMO requirements. As can be seen throughout this technical document, satellites provide a wide variety of essential data for use by WMO Members. For the atmosphere they measure cloud cover, temperature and humidity from the surface of the Earth to over 40 km in altitude, winds, precipitable water, precipitation, as well as ozone and other trace gases. They also observe aerosols, dust and volcanic ash. Over the oceans they measure surface temperature and winds, ocean levels and waves, ice cover and sea-surface biology. Over land they observe vegetation and snow cover, floods, forest fires and many other parameters, including monitoring of crops and drought conditions. Additional products are designed specifically for monitoring global climate and detecting climate change.

Satellites provide data that complement *in situ* observing systems and, in many cases, are the only source for observations. They provide global data coverage on a timely basis (Figure 1), which is only one of their advantages. There are few conventional observations from the world's oceans, which cover some 70% of the planet. Additionally, few observations are available from deserts, forests, polar regions or other sparsely inhabited parts of the planet. Global data are essential for many disciplines, and satellites offer the only practical solution to meeting the requirement for global coverage. In many cases measurements by satellites are made with remarkable accuracy: surface winds over the oceans can be measured with accuracy comparable to that of ship observations, ocean levels can be determined with an accuracy of a few centimetres, the temperature of any part of the atmosphere, anywhere in the world can be measured with accuracies that are useful inputs to numerical models. In many cases these levels of performance have been reached with first or second-generation instruments; even greater precision and usefulness is expected from instruments on future satellites.

These remarkable capabilities call for constant algorithm review, development and innovations. Some capabilities still require further improvements in order to meet the demanding and stringent WMO requirements for accuracy, coverage, resolution or timeliness. It is important to realize that satellite data are totally different in character from *in situ* data and have to be used in ways that reflect their characteristics. This means adapting the application methodology to suit the data, rather than the reverse. For example, atmospheric models are now adapted to use the radiances directly, instead of inverting satellite radiances into atmospheric temperatures as if they came from balloons.

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[1] For this document the definition of experimental satellites is defined in the 1993 edition of the “Manual for the Global Observing System (WMO Publication No. 544):

“An environmental observation satellite with the primary purpose of acquiring a defined set of research data; testing new instrumentation and/or improving existing sensors and satellite systems; and/or it may provide information for operational use, but has limitations due to the lack of a commitment to ensure continuity of service or a reliable satellite replacement policy; and also due to non-consistent modes of operations.”

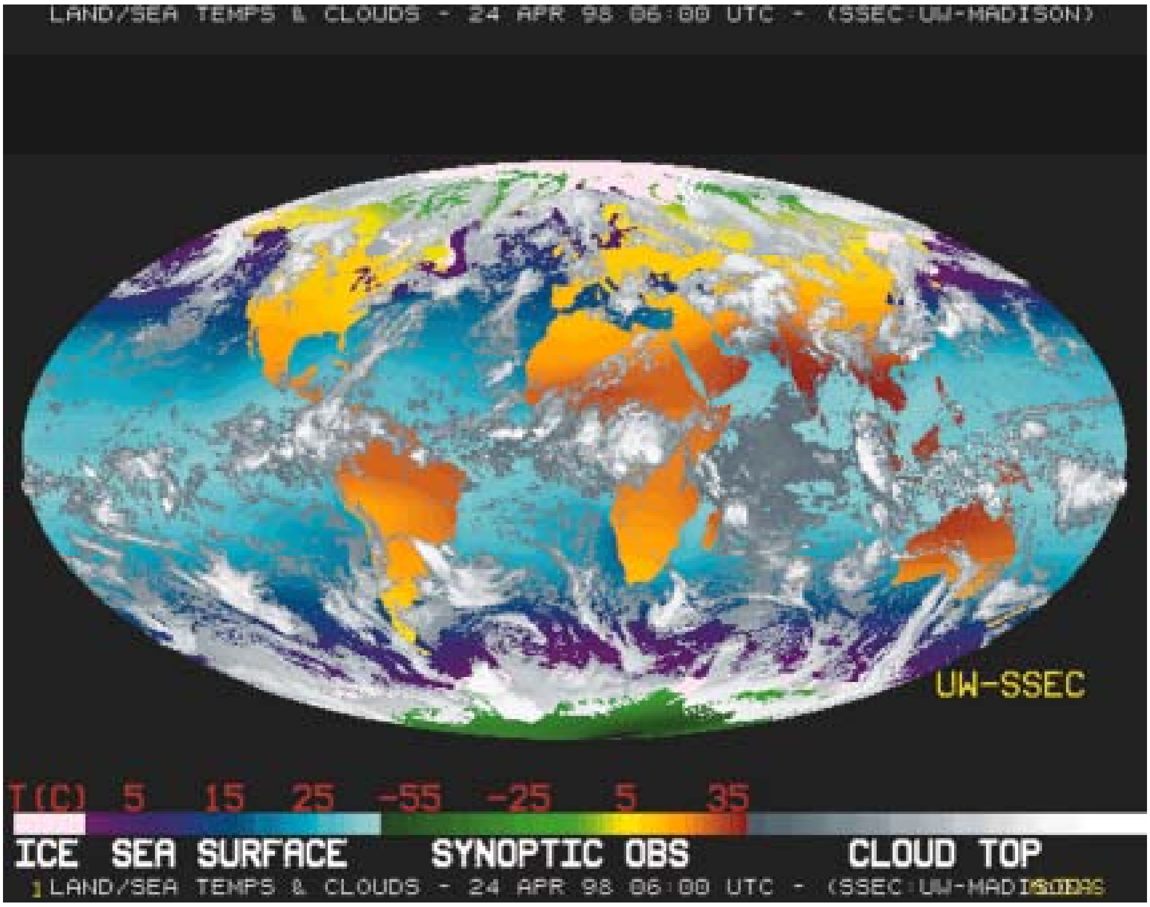


**Figure 1** - Composite image obtained from the global system of operational meteorological satellites in polar and geostationary orbit. It shows global cloud cover, sea surface temperatures, land surface temperatures and ice cover. Global images such as these are generated on a routine basis, and are updated every three hours**.**

The flight of pre-operational or demonstration satellite missions provides the opportunity to evaluate data in a research environment before they are placed into full operational use, but it is important to recognize that new techniques and completely new applications are often discovered only after many years of operational use. New uses for cloud imagery are still being developed after four decades of routine use.

The ability of geostationary satellites to provide a continuous view of weather systems makes them invaluable in following the motion, development, and decay of extreme meteorological phenomena. For example, short-term events such as severe thunderstorms, with a life-time of only a few hours, can be successfully recognized in their early stages of development and appropriate warnings of the time and area of their maximum impact can be provided to the general public. Hurricanes, typhoons and tropical storms can be monitored continuously, providing important information on their location and movement, placing the geostationary satellite at the heart of the warning process. Derivation of atmospheric winds from the analysis of successive satellite images has become an important product especially for NWP. Thus, the capability to provide timely information to improve warnings has been the primary justification for the geostationary spacecraft.

Flying in a near-polar sun-synchronous orbit, the polar orbiting spacecraft provides both day and night coverage of the entire globe once every 24 hours. The polar-orbiting satellites are principally used to obtain: (a) daily global cloud cover; (b) accurate quantitative measurements of surface temperature; and, (c) information on the vertical profile of atmospheric temperature and water vapour for use in a variety of application areas, most notably numerical weather prediction.

Together, the polar-orbiting and geostationary satellites constitute a global meteorological satellite network, providing valuable information to WMO Members for a variety of applications, including global and regional NWP.

A particular advantage of the polar orbiting satellite is that one instrument can observe the entire planet once or twice within a period of 24 hours. This has the important benefit that there are no inter-regional calibration errors. Satellite instruments are extremely sensitive and are able to detect and measure reflected or thermal radiation from an altitude of around 800 km for polar and 36,000 km for geostationary orbit. Instrument calibration stability over time is carefully monitored in order to provide continuity between instruments on successive satellites. This is of crucial importance for climate measurements.

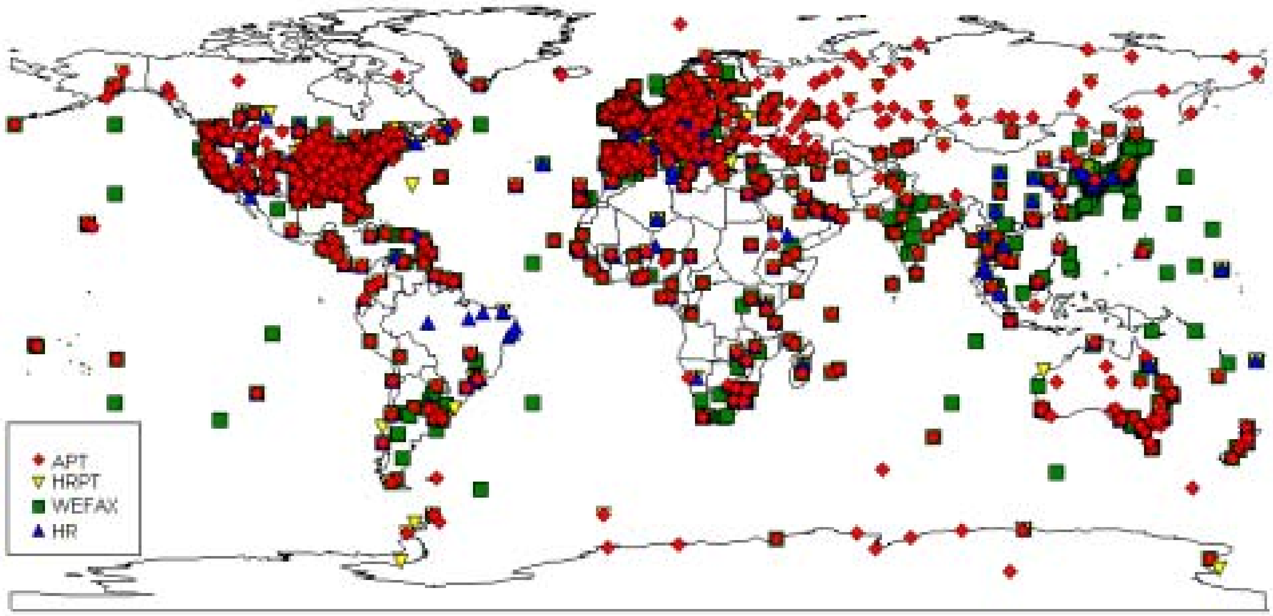


**Figure 2 -** Distribution of user stations of WMO Member States showing more than 1,300 stations located in 125 countries.

Although all satellite data must be used with due caution and proper regard for what they represent, this does not alter the fact that these data have become essential tools for many programmes. This offers encouragement to the development of further improvements over the coming decades, many of which are described in other chapters of this document.

The thrust of the current generation of meteorological satellites is aimed primarily at characterizing the kinematics and dynamics of the atmosphere. The ability to achieve such objectives was demonstrated during the Global Weather Experiment in 1979. This capability is now part of the global operations of the World Weather Watch. The existing network of meteorological satellites, which form part of the Global Observing System (GOS) of the World Weather Watch, produces real-time weather information on a regular basis. Today's operational meteorological satellites have comprehensive data broadcast capabilities. Virtually every meteorological centre in the world has at least one receiver for the direct reception of satellite data (Figure 2). With those facilities, transmissions can be received directly from the nearest geostationary satellites, providing quasi-continuous cloud imagery. These transmissions often include other types of meteorological data as well as imagery from other satellites. Operational polar satellites also broadcast data continuously as they orbit the Earth, providing local high-resolution data as they pass within view of the receiving. Reception of data from experimental satellite missions have generally been restricted to one central ground station and a few licensed sites, but increasing amounts of processed data are being made available over the WMO's Global Telecommunications System (GTS) and over the Internet. This is a welcome development, but there is certainly room for further improvements in early utilization of new forms of data. One such improvement has been instituted by NASA, through the direct broadcast of high resolution digital image data from MODIS, along with the provision of an applications processing package for data users; however, those data are transmitted at X-band frequencies. The cost of such receiving and processing ground stations is considerably more than that for the current operational meteorological satellites stations receiving data transmitted in S-band.

For most WMO programmes data continuity is essential. Increasing reliance on satellite data for operational applications means that gaps in the supply, due to a failed satellite for instance, could have very serious impacts. Continuity of observations for climate monitoring is also of great importance. In many cases great efforts have been made to ensure continuity through contingency plans and in-orbit spare satellites, but this is not invariably the case. Furthermore, research satellite data are playing increasingly important roles within the global observing system: this is evident in the area of ocean surface wind and height observations, as well as planned uses of high spectral resolution data for NWP applications. Continuity of operational satellite data is a must, pathways from research to operational satellite systems is most desirable.

## Rationale for the Technical Document

In 1977, a prophetic report, *The Role of Satellites in WMO Programmes in the 1980s by D.S. Johnson and I.P. Vetlov* [5], described the future space-based component of the Global Observing System. Through the efforts and commitments of a few space-faring nations and organizations, Johnson and Vetlov's vision was realized in the mid-1990s. Since 1977, the radical growth in computer capability, communications and space- based technology has revolutionized our ability to observe the Earth and its atmosphere from space. Continued growth in these basic technological areas during the new millennium make the outlook for even greater advances and capabilities achievable through space based remote sensing enormously positive. This technical document reflects on past achievements and looks to the future space-based component of the Global Observing System. The horizon for this technical document is the first two decades of the 21st Century: a new era in which WMO Members will continue to exploit operational meteorological satellite systems, while expanding their capabilities by taking advantage of information provided by experimental satellite systems.

While Johnson and Vetlov focused on the potential contributions of operational meteorological satellites, this technical document will address the spectrum of operational and experimental environmental satellites. The tremendous impact experimental satellites have made in providing new data and products in support of WMO and WMO supported programmes is wide spread, profound and continues to increase. During the next few decades, the integration of selected experimental satellites with the evolving operational satellite systems will lead to a comprehensive space-based observing system that will have the potential for meeting many of the needs of all WMO and WMO supported programmes. Through integration and exploitation of the strengths of each satellite system, it will be possible to achieve maximum utilization. Such exploitation bodes well in helping today's users be prepared to answer the pressing environmental and societal questions of tomorrow.

## Historical Review of the Global Observing System

Since the inception of the World Weather Watch (WWW), the space-based component of the Global Observing System (GOS) has had a profound impact on WMO Members. Its observational capabilities have led to data and information that permeate almost all products and forecasts provided by the National Meteorological and Hydrological Services (NMHS). Indeed, as has been pointed out by WMO's Secretary General, Professor G.O.P. Obasi, meteorological satellites provide essential data for weather forecasting to NMHSs across the globe. Indeed, the space-based component of the GOS marked the genesis of the WWW. The WWW brings new and exciting possibilities for observations from space. It serves as the catalyst, to bring together some of the world's leading experts to provide a blueprint for international cooperation that is unparalleled within the meteorological communities. The vision and genius of such a small select group has produced reverberations across the world that have stood the test of time and foretold the role of satellites in the global observing system.

WMO was formally established on 23 March 1950. At that time, and for nearly the next two decades, there were still large areas of the Earth's surface without adequate observational systems [6]. All this was soon to change in a profound and explosive fashion with the beginning of the space age.

The then USSR launched the first Earth-orbiting satellite, Sputnik-1, on 4 October 1957. The USA launched its first satellite, Explorer I, on 2 January 1958. First light at the new day's dawn for meteorology occurred with the launch of TIROS-1 on 1 April 1960. TIROS-1 was a low Earth orbiting satellite with a television camera that provided the first pictures from space of the Earth, revealing the distribution and the complexity of its clouds and cloud systems. The potential for such a new observing system was immediately obvious.

On 20 December 1961 the United Nations General Assembly (UNGA) unanimously passed Resolution 1721 (XVI) on the "International Co-operation in the Peaceful Uses of Outer Space". The UNGA noted the exceptional potential afforded to meteorological science and technology by observations of the Earth from outer space and was convinced of the worldwide benefits to be derived from international cooperation in weather research and analysis. In the light of developments in outer space, it recommended to all United Nations Member States, to WMO and other appropriate specialized agencies the early and comprehensive study of measures: to advance the state of atmospheric science and technology in order to provide greater knowledge of basic physical forces affecting climate and the possibility of large-scale weather modification; to develop existing weather forecasting capabilities and to help UN Member States make effective use of such capabilities through regional meteorological centres [1]. The resolution further requested WMO, in consultation, as appropriate, with the United Nations Educational, Scientific and Cultural Organization (UNESCO) and other specialized agencies, governmental and non-governmental organizations, such as the International Council of Scientific Unions (ICSU), to submit a report to WMO Members and to the United Nations (UN). This report would become the bellwether for WMO. The UNGA requested the report for earliest consideration six months later in June 1962!

WMO quickly agreed upon a course of action to meet such a demanding deadline. Two world recognized leaders in the young science of satellite meteorology, Dr H. Wexler from the USA and Academician V.A. Bugaev from the USSR worked together in Geneva, Switzerland to prepare the *First Report of the WMO on the Advancement of Atmospheric Sciences and Their Application in the Light of Developments in Outer Space* [1]. Eventually, there would be four more such reports but the first was to have the greatest impact on WMO Members. Sir Arthur Davies, the Secretary-General of WMO, at the time declared, "The First Report undoubtedly ranks as one of the major documents in the history of WMO" [6].

Wexler and Bugaev highlighted potential benefits of satellite data to both operational and research communities. Having laid the foundation, they then proposed a new structure, the WWW. The WWW was established in response to the emergence of the meteorological satellite and was based on an observing system comprised of meteorological satellites and conventional observations. Wexler and Bugaev went further to describe, in general terms, the space-based component of a global observing system (Figure 3). One of the new observing system's main requirements was the continuous existence of one or more satellites [1]: at the time of the First Report only polar-orbiting satellites existed and the space-based component of the GOS needed only one or more such satellites.

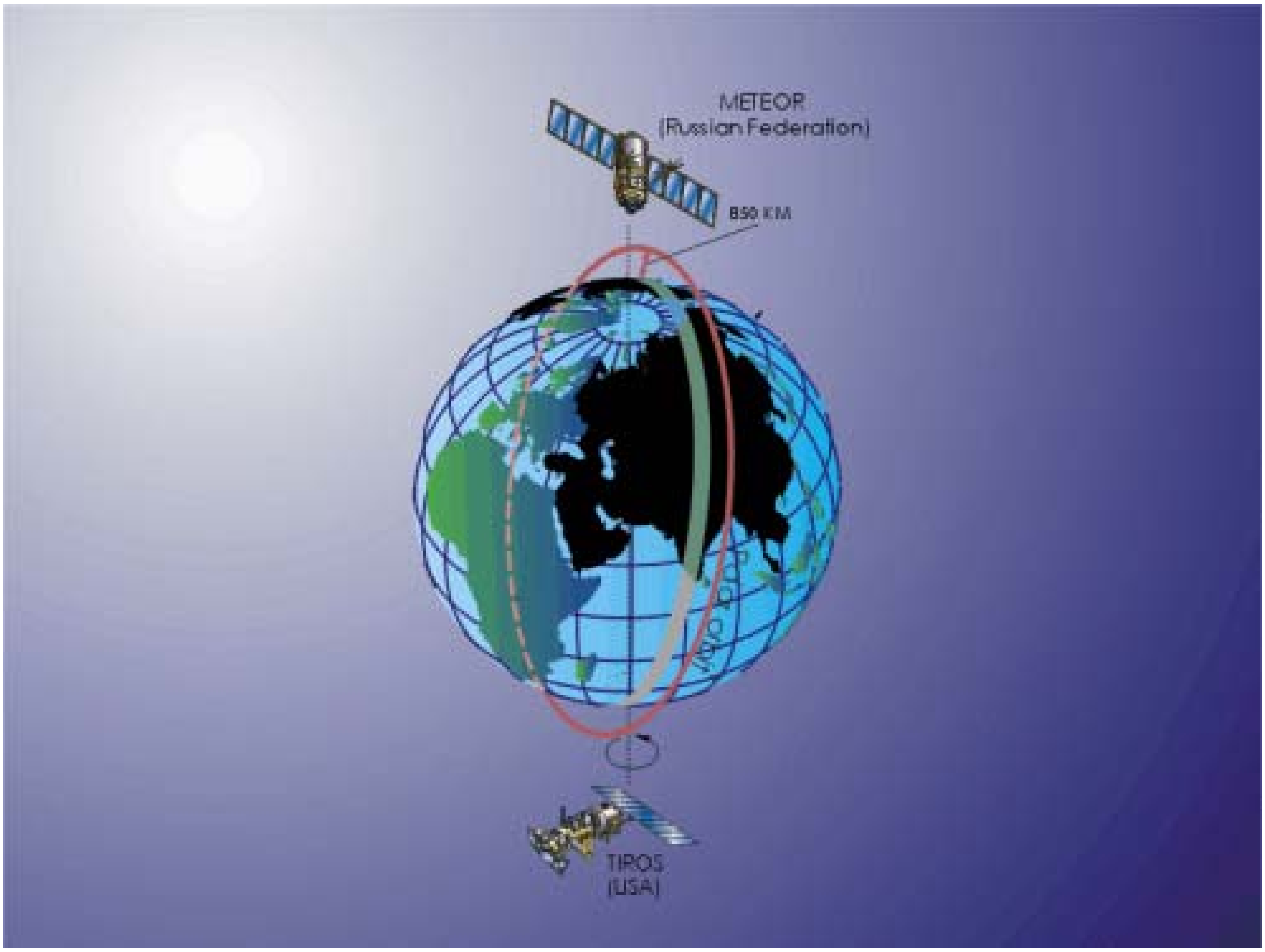


**Figure 3** - The first space-based component of the Global Observing System, 1961

In the course of the evolution of the space-based component of the GOS, a slow and steady increase in scope has occurred and this evolution has been guided by user requirements, compelled by technological advancements and made possible by the few space-faring nations and organizations in the world.

The Fourth WMO Congress, in April 1963, endorsed the First Report with appreciation, in particular with respect to the concept of the WWW. Thus, WMO established the WWW in less than two years after the first request from the UNGA. In 1966, the *Fifth Report of the WMO on the Advancement of Atmospheric Sciences and Their Application in the Light of Developments in Outer Space, WWW – Phase II, August 1966* [2] formally refers to the GOS for the first time:

“It follows that the essential elements of the WWW are: the observational networks and other observational facilities, hereafter called the Global Observing System;” [2]

In 1966, a technology demonstration communications satellite, ATS-1, flew in geostationary orbit with a meteorological payload, the spin scan cloud camera (SSCC). Repeat imaging from ATS’ SSCC allowed meteorologists for the first time to monitor continuously cloud and weather system development. Guided by the acknowledged father of satellite meteorology, Dr V. Suomi - winner of the WMO IMO award in 1993 for his leadership in this field - the geostationary satellite emerged as a vital and necessary component of the GOS. The *WMO, WWW, The Plan and Implementation Programme, 1972 – 1975*, *July 1971* [3] contained a new and more formal description of the space-based component of the GOS:

Meteorological satellites can be divided into two groups, those in polar or near-polar orbits and those in geostationary orbit. With the former it is possible to choose the orbit altitude within a wide range, while with the latter it must be approximately 36,000 km. A satellite in near-polar orbit at an altitude of, approximately 1,000 km, has a big advantage over a geostationary satellite as regards the resolution that can be obtained with a particular optical system. The near-polar orbiting satellite has the further advantage of being able to observe the whole globe whereas a geostationary satellite can only provide useful cloud cover information in an area within a range of about 60-65 degrees from the sub-satellite point. In contrast, geostationary satellites are able to provide much higher temporal coverage of the surface.

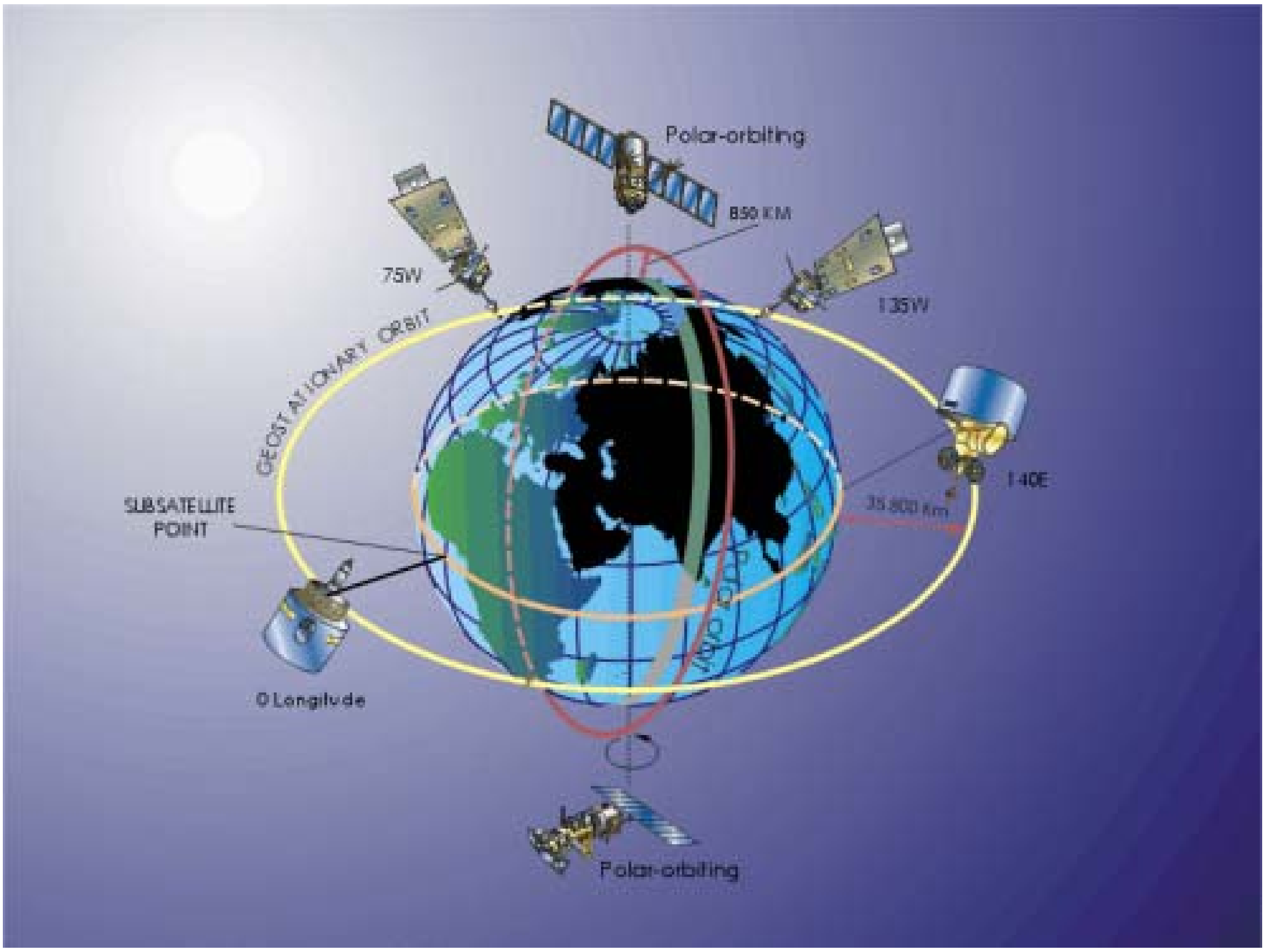


**Figure 4** - The 1978 space-based component of the Global Observing System

During the 1970s (Figure 4), satellite operators were steadfastly implementing a space-based component of the Global Observing System. The *WMO, WWW, Third Status Report on Implementation, July 1970* [4] described the European Space Research Organization (ESRO) project to launch a geostationary satellite in 1977 over approximately the 0° longitude, and also the Japanese plan to establish a geostationary meteorological satellite (GMS) at 120°E as part of its contribution to WWW and the Tropical Cyclone Project [4]. The *WMO, WWW, Sixth Status Report on Implementation, July 1973* [7] noted that the USA was developing a Geostationary Operational Environmental Satellite (GOES) service to be inaugurated late in 1973. The Sixth Status Report also recorded that the USSR had announced its plans for setting up a geostationary meteorological satellite at approximately 70°E longitude.

By 1977, the space-based GOS was well established in terms of plans and implementation. However, the pace of development and implementation had not kept abreast of the rapid advances being made in space based observing technology. The introductory chapter for the *WMO, WWW, Planning Report No. 36, The Role of Satellites in WMO Programmes in the 1980s, 1977 by D.S. Johnson and I.P. Vetlov* [5] heralded an impending change of major significance.

"Until quite recently this early planning for WWW served as a useful guide for the development of a global satellite observing system. However, satellites will soon play a far greater role than was originally anticipated in 1961. Satellites will play an increasingly important role not only in obtaining observational data, but also in providing a capacity for the collection and distribution of information in support of various WMO programmes." [5]

The defining phrase "in support of various WMO programmes" greatly extended the scope of responsibility for the space-based component of the GOS. Not only the WWW but also almost all WMO programmes would be served. This expansion would require a review of the definition at the time of the space-based GOS. Johnson and Vetlov would propose a possible constellation of satellites consisting of three to four satellites in quasi-polar orbits and four to five geostationary satellites (Figure 5).

Johnson and Vetlov alerted the meteorological community to the potential for a rapid increase in new data sets, by listing a number of expected parameters for the atmosphere, clouds, ocean surface and land surface. Thus, the technology pillar was again urging user requirements to be responsive to new capabilities. This urging would culminate in a concerted effort during the 1980's of the WMO Technical Commission to define its user requirements.

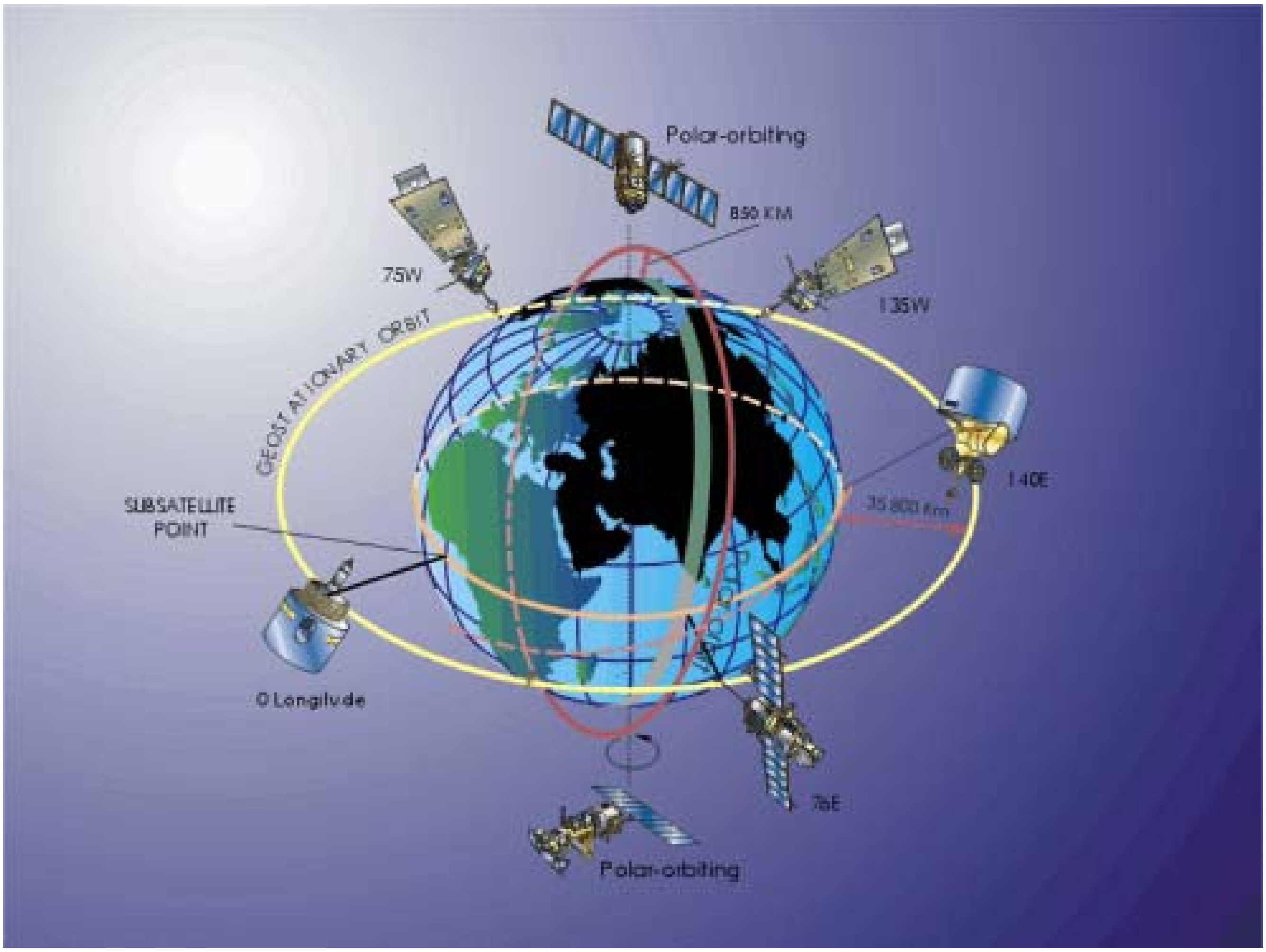


**Figure 5 -** The nominal configuration of the space-based component of the Global Observing System in the 1990s

**Present system**

The evolution to today’s constellations of satellites that comprise the space-based portion of the GOS fulfils the vision of Johnson and Vetlov (Figure 6). The geostationary satellite constellation operates in the equatorial belt and provides 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), 76°E (operated by the Russian Federation), 105°E (operated by the People's Republic of China), 140°E (operated by Japan), and 135°W and 75°W (operated by the United States of America (USA)). The second, and oldest constellation is comprised of polar-orbiting satellites operated by the Russian Federation, the USA and the People’s Republic of China. The METEOR-3 series has been operated by the Russian Federation since l991. The polar satellites operated by the USA are 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. FY-1C, the third in the series of China’s polar-orbiting satellites, is now operational. From altitudes of 850 to 900 km, these spacecraft provide coverage of the polar regions that are beyond the view of the geostationary satellites.

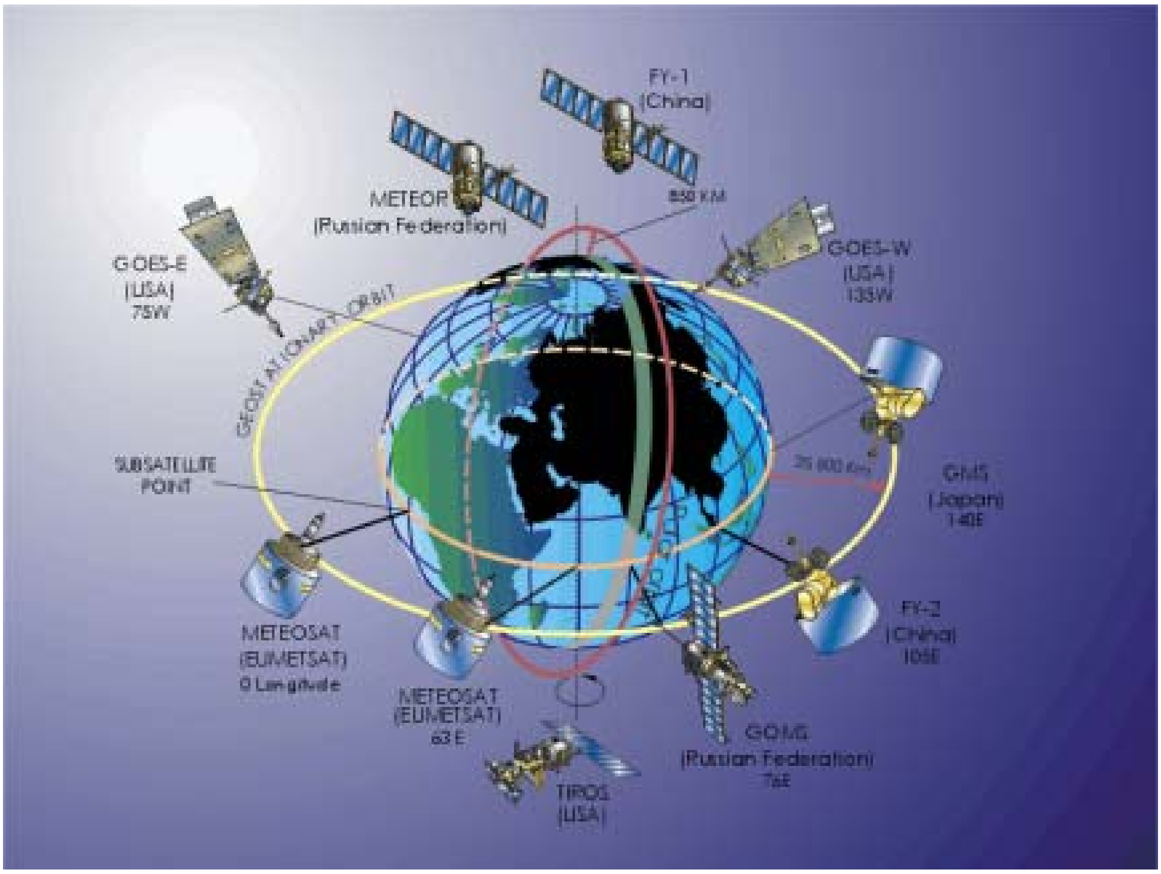


**Figure 6** – The present configuration for the space-based component of the Global Observing System

NOTE: Information on the characteristics, capabilities and uses of the current system of meteorological satellites is contained in the *CGMS Directory of Meteorological Satellite Applications.* Additional up-to-date information can be found via the *WMO Satellite Activities Homepage:* http://www.wmo.ch/hinsman/satsun.html. *Information on Meteorological and Other Environmental Satellites* (WMO-Pub No. 411) contains further relevant information.

**References:**

[1] First Report of the WMO on the Advancement of Atmospheric Sciences and Their Application in the Light of Developments in Outer Space

[2] Fifth Report of the WMO on the Advancement of Atmospheric Sciences and Their Application in the Light of Developments in Outer Space, WWW – Phase II, August 1966

[3] WMO, WWW, The Plan and Implementation Programme, 1972 – 1975, July 1971

[4] WMO, WWW, Third Status Report on Implementation, July 1970

[5] WMO, WWW, Planning Report No. 36, The Role of Satellites in WMO Programmes in the 1980S, 1977 by D.S. Johnson and I.P. Vetlov

[6] Forty Years of Progress and Achievement, A Historical Review of WMO, Edited by Sir Arthur Davies, Secretary-General Emeritus, WMO, 1990

[7] WMO, WWW, Sixth Status Report on Implementation, July 1973

# CHAPTER 2

## CURRENT CAPABILITIES AND WMO OBSERVATIONAL REQUIREMENTS

In the past forty years, remote sensing capabilities on both polar and geostationary platforms have been established. Those capabilities have proven useful in monitoring and predicting severe weather such as tornadic storm outbreaks, tropical cyclones, and flash floods as well as climate trends indicated by sea surface temperatures, biomass burning, and cloud cover (Figures 2.1 through 2.5). This occurred first with the visible and infrared window imagery of the 1970s, was augmented with the temperature and moisture sounding capability in the 1980s, and further enhanced with microwave imaging and sounding capability in the late 1980s and 1990s.

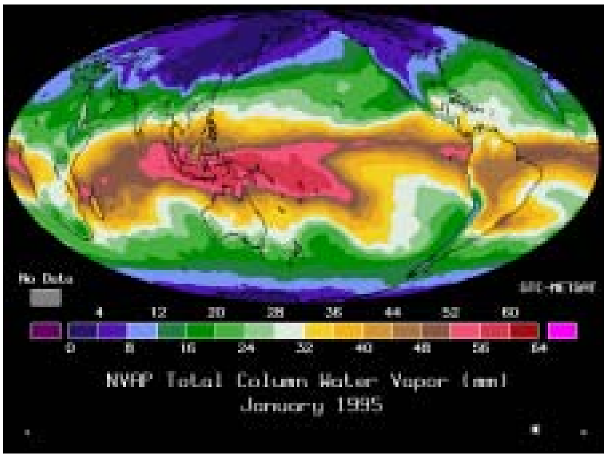


**Figure 2.1** - Total Column precipitable water for January 1995 derived from three different observing systems as part of NASA's Water Vapour Project. (NVAP)

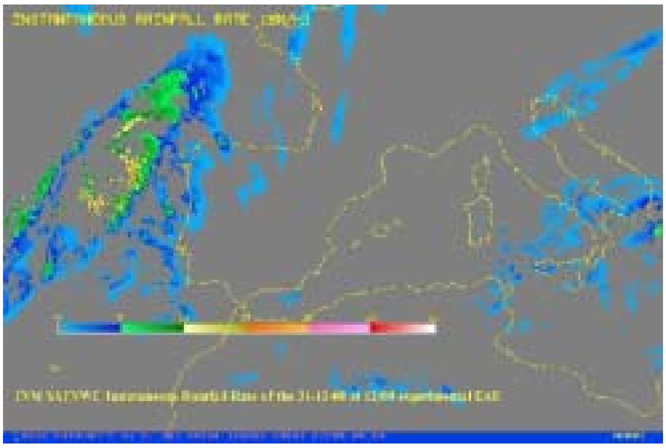


**Figure 2.2** - Instantaneous rainfall rate in a cold-front approach NW Spain, derived from Meteosat imagery. convective rainfall can also be seen over southern Italy. (INM)

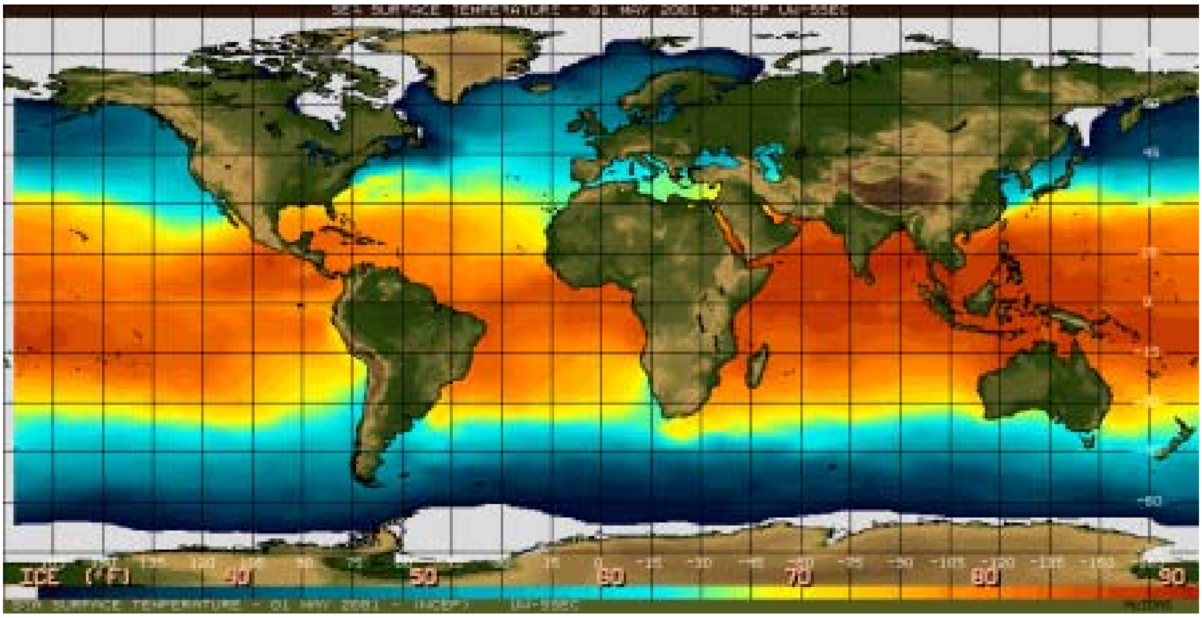
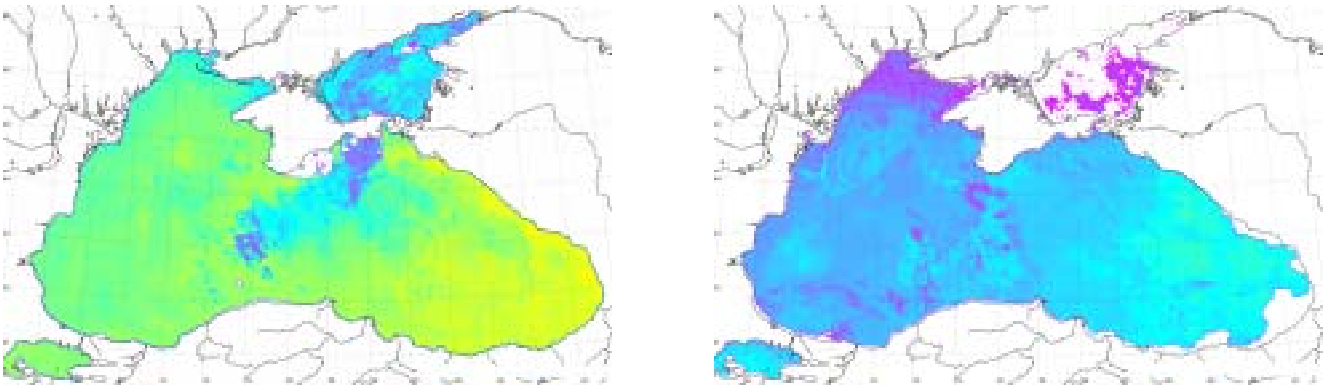


**Figure 2.3** - Map of global Sea Surface Temperatures for 1 May 2001 derived from NOAA Polar Orbiting satellites. (CIMSS)

Satellite imagery, especially the time continuous observations from geostationary instruments, dramatically enhanced our ability to observe and measure atmospheric cloud motions and to monitor hurricanes and severe thunderstorms. Geostationary depiction of temporal and spatial changes in atmospheric moisture and stability are improving severe storm warnings. Atmospheric flow fields (wind field composites from cloud and water vapour drift) are helping to increase the accuracy of hurricane trajectory forecasting.



**Figures 2.4 a and b** - Sea Surface Temperatures in the Black Sea (Planeta). Figure 2.4 a (on left) shows the conditions near the start of winter, 29 October 2000 and Figure 2.4 b (on right) shows the situation near the end of winter, on 6 March 2001

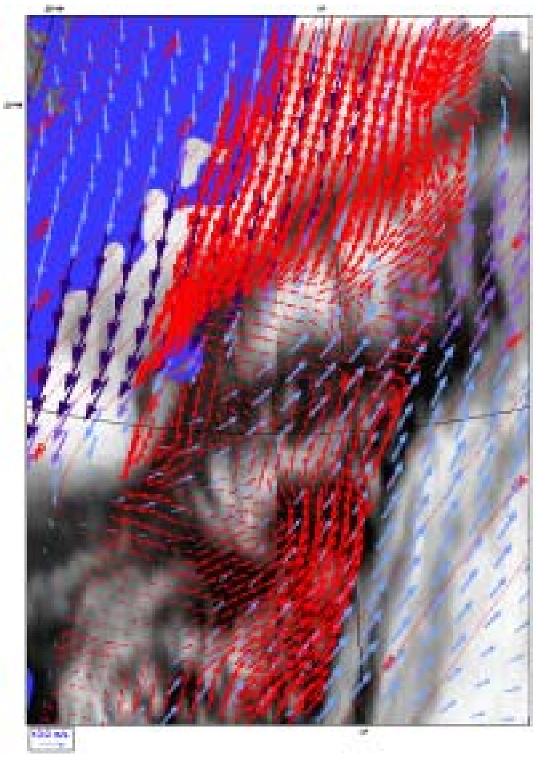


**Figure 2.5** - Composite image showing ERS Scatterometer winds as red vectors together with 10 metre winds (in blue) from the HIRLAM NWP model. It can be seen that in some areas the satellite data confirms the model analysis, in others the satellite winds add new information. The wind fields are superimposed on a Meteosat cloud image (CMS)

Applications of these data also extend to the climate programmes; archives from the last twenty years offer important information about the effects of aerosols and greenhouse gases and possible trends in global temperature. Satellite sounder data fill important data voids at synoptic scales. Applications include use of radiance data by NWP, temperature and moisture analyses for weather prediction, analysis of atmospheric stability, estimation of tropical cyclone intensity and position, and global analyses of clouds. Polar orbiting microwave measurements help to alleviate the influence of clouds for all weather soundings.

WMO has a long history in defining its observational data requirements. WMO follows a process that results in a hierarchical set of requirements. At the highest level, its Long-term Planning Process guides the WMO. The Fifth Long-term Plan [2] is the current plan and spans the time frame 2000 to 2009. The Plan provides a vision for the twenty-first century and contains overall guidance, objectives, opportunities and challenges for the organization including those for economic development, political development, demographic dynamics, urban environment, human health, energy production and consumption, fresh water, land use, food security and combating desertification, protection of climate and atmosphere, and natural and human-caused disasters. Within each major WMO Programme, i.e., World Weather Watch Programme, World Climate Programme, Atmospheric Research and Environment Programme, Applications of Meteorology Programme, Hydrology and Water Resources Programme, Education and Training Programme and the Technical Cooperation Programme, there are similar but focused high-level requirements with guidance, objectives, opportunities and challenges. Within the various Programmes, there are Technical Commissions assigned responsibility for a specific area, for example, the Commission for Hydrology. In the nearer term, the four year Programme and Budget for WMO contains guidance, objectives, opportunities and challenges that are based on the long-term objectives. The work of the Technical Commissions is guided by the WMO Congress approved Long-term Plan and Programme and Budget. The Long-term Plan is reviewed and updated in a four-year cycle. Within the Technical Commissions as well as the various WMO supported programmes, requirements are derived in order to satisfy the long-term goals. These requirements are manifested in a statement of needs for various systems including observations, telecommunications and data processing.

The current procedure for setting, reviewing and updating observational data requirements for the various Technical Commissions is found in a process called the Rolling Review of Requirements (RRR). All WMO Programmes and supported programmes have ascribed to the RRR process, and it has become an effective tool to assess current capabilities of a global observing system and provide guidance for future enhancements. Requirements versus expected observing system performance are periodically reviewed and updated, normally on an annual basis.

The RRR procedure consists of four stages:

(1) a review of user requirements for observations, within areas of applications covered by WMO programmes;

(2) a review of the observing capabilities of existing and planned satellite and *in situ* systems;

(3) a "Critical Review" of the extent to which the capabilities (2) meet the requirements:

   (a) both *in situ* and satellite observing systems are addressed;

   (b) gaps and overlaps in existing and planned observing system capabilities, are identified along with indications of the user requirements satisfied by these systems;

   (c) user requirements are addressed in an application driven way giving little consideration to measurement characteristics, observing platforms, or data processing systems;

   (d) a database compendium of WMO user requirements and observing system capabilities is generated. The resulting database allows a static view of the observational requirements while the process allows dynamic review and update, as appropriate; and

(e) cost benefit considerations may be developed, however, costs are not included in the review process.

(4) Development of a "Statement of Guidance" (SOG) based on (3) above.

The SOG relies on interpretation and analysis by observing system and applications experts. It is guided by the critical review of the database of user requirements compared with satellite and *in situ* system capabilities. It sets out the potential role for satellites, balloons, aircraft reports, ships, etc. without pre-empting judgement on the best or most cost-effective mix of observations.

The user requirements are user oriented, not system dependent; they are intended to be technology free in that no consideration is given to the type of measurement characteristics, observing platforms, or data processing systems that are necessary (or even possible) to meet them. The requirements are aimed at the 2005-2015 time frame. The comparison of requirements to capabilities utilizes the database summarizing both. As the database changes to better reflect the user requirements as well as existing and planned observing capabilities, the RRR must be performed periodically.

It is recognized that guidance provided by the WMO to satellite operators and other agencies will be only one of many inputs affecting their decisions on future systems, which will be required to meet national or regional objectives and will be constrained by available resources. However, it is hoped that guidance at this level will be helpful in promoting an integrated global observing system that provides the maximum benefit to WMO Members.

It is not intended that the process of reviewing requirements and providing guidance in this way should replace the need for detailed activities on the design of instruments and systems, but rather that general guidance should be provided on the users' requirements for these systems. The detailed specification of instruments and systems will remain a task for relevant agencies, with appropriate technical advice from specialists in the user community.

As shown with many examples throughout this technical document, the space segment of the GOS provides global coverage, with its data being used in a variety of application areas. The different capabilities of the two constellations are complementary and are necessary parts of the space-based component of the GOS. Both constellations are capable of accomplishing data collection and data dissemination missions. With respect to current WMO requirements, the polar-orbiting satellites perform the following missions: imagery; data-collection; direct broadcast; and atmospheric soundings; with today’s geostationary satellites being tasked to perform the same missions with the exception of atmospheric sounding.

The ground segment of the space-based component of the GOS allows for the reception of signals and DCP data from operational satellites and/or the processing, formatting and display of environmental observation products that are distributed to local users, or over the GTS, as required. This capability is normally accomplished through receiving and processing stations of varying complexity, sophistication and cost.

In implementing satellite systems in response to WMO requirements, operational environmental satellite operators make the satellite data reliably available to other Members and inform them of the means of obtaining these data. “Reliably available” is a most important concept and one that currently separates experimental satellites from operational environmental satellites. Operational satellites, in a WMO context, are those satellites with a guaranteed replacement policy that ensure continuity of service for WMO Members, either through in-orbit spares or an on-demand launch policy. Today’s operational environmental satellite operators expend great effort to meet the accuracy, timeliness, and the temporal and spatial observational requirements of the

GOS. It is important to note here, that operators of some experimental satellites are providing valuable information to WMO Members in the form of data for determining sea surface winds, sea level topography and direct broadcast of very high resolution multi-spectral imagery. This important paradigm shift is one of the major factors that will shape the future space based portion of the GOS.

In order to meet the observational and service requirements for the space-based component of the GOS, the number of satellites in polar orbit is sufficient to provide global coverage at least four times per day for instruments with horizon-to-horizon scanning. Typically, this requires one satellite in ante-meridian (a.m.) orbit and one in post-meridian (p.m.) orbit. The number of satellites in geostationary orbit is sufficient to obtain observations, typically at 30 or 15 minute intervals, throughout the field of view between $60^0$ S and $60^0$ N. This implies the availability of five satellites, near-equally spaced around the equator. Contingency plans, involving the use of in-orbit spares and rapid launch call up of replacement satellites are either in place or under development to maximize reliability and utilization.

The imagery and sounding capabilities are of the greatest accuracy possible, independently or in conjunction with surface-based observations. The quantitative data and qualitative information allow the determination of vertical profiles of temperature and humidity; land and sea surface temperature; wind fields at the surface and aloft; cloud amount, type and cloud top temperature and height; snow and ice cover; and radiation balance.

Direct broadcast and data-dissemination are provided in two data streams: a low and a high data rate stream. They provide either direct or near-real-time data dissemination of cloud imagery and, to the extent possible, other real-time data of interest to WMO Members. Satellite operators also ensure the greatest possible compatibility between their different systems, and publish details of the technical characteristics of their instrumentation, data processing and transmissions, as well as the dissemination schedules. The frequencies, modulations, formats and orbital de-phasing between the morning and afternoon satellites are arranged to allow a particular user to acquire data from a particular satellite by a single antenna and signal processing hardware. The means for data dissemination are continually evolving to take advantage of new technologies, for example, the use of Internet and commercial telecommunication networks.

Data collection systems are capable of providing for the collection and relay of data from various kinds of observing and Data Collection Platforms (DCP) in support of all WMO programmes. To ensure compatibility, satellite operators have established and maintain the necessary technical and operational coordination. A number of channels are identical on all geostationary satellites to allow movement of mobile platforms between various geostationary satellite footprints. Satellite operators publish details of the technical characteristics and operational procedures of their data-collection systems, including the admission and certification procedures.

The ground segment includes all the necessary facilities for operational control of the satellites by the satellite operators as well as WMO Member user stations. All WMO Members have endeavoured to install in their territory at least one user station for cloud imagery data from the polar satellite constellation and at least one such station for receiving data from a geostationary satellite.

**References:**

[1] Fourth Report of the WMO on the Advancement of Atmospheric Sciences and Their Application in the Light of Developments in Outer Space, WWW - Phase I, August 1965;

[2] Fifth Long-term Plan.

# CHAPTER 3

## CHALLENGES FOR THE OBSERVING SYSTEMS

### Meeting remote sensing requirements

These are exciting times in satellite remote sensing. Monitoring of the Earth's environment has become an international endeavour. No one country has the observational systems necessary to provide the data it needs for its environmental monitoring and prediction operations. In the past decade, and more so in the next decade, satellite remote sensing contributions to the Global Observing System are being made by an increasing number of international partners. The collaboration and coordination among the international satellite community continues to increase.

The demands for environmental data are enormous, ranging across all components of the Earth system - atmosphere, oceans, and land. The data requirements cover a broad range of spatial and time scales - 100s of metres and minutes to global, seasonal and inter-annual to decadal and centennial time frames. Alongside the operational satellites, the research satellites are providing advanced observations of the Earth and its atmosphere and in the future the distinction between research and operational platforms will narrow.

It is important to note that satellites are one component of an integrated Global Observing System. The surface-based component of the GOS is comprised of a variety of instruments on balloons, planes, ships, buoys, and land surfaces. It remains a challenge to identify the best mix of the space-based and surface-based components that will meet environmental monitoring and prediction requirements.

To achieve the above demands will require significant advances in scientific understanding, observing and computational systems, scientific research and modelling, and extended infrastructure to deliver enhanced and new services effectively and efficiently to end users. We are now entering an era rich with new scientific insight and technological innovations that allow us to observe, understand and model the functioning of the entire Earth system.

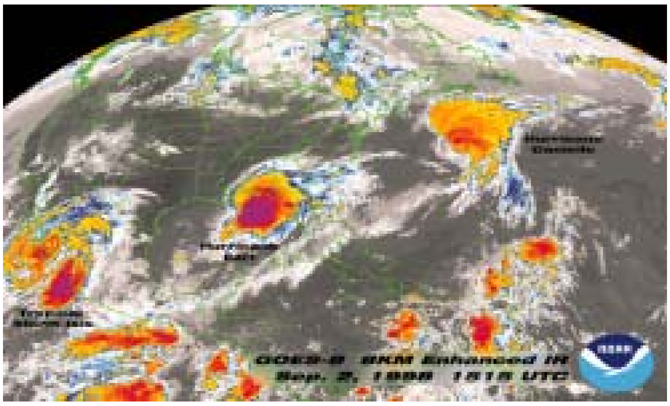


**Figure 3.1** - Hurricanes Danielle and Earl shown on the same colour enhanced GOES-8 image as Tropical Storm Isis, on 2 September 1998. (NOAA/NCEP)

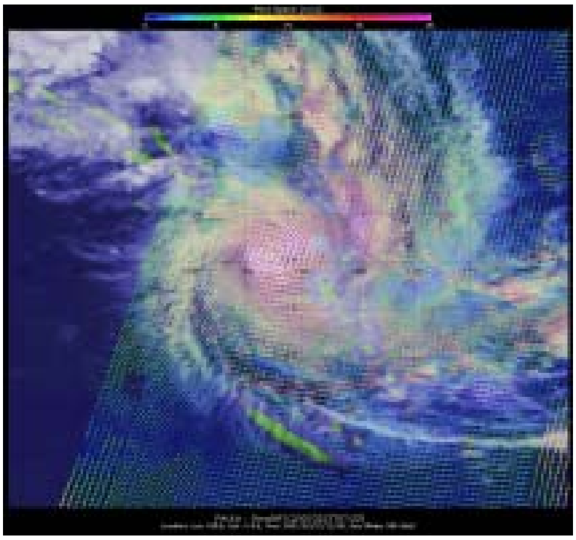


**Figure 3.2** - Tropical Cyclone Paula passing over Vanuatu in late February 2001, shown in a GMS-5 satellite image with superimposed surface winds from QuickScat. (MSNZL)

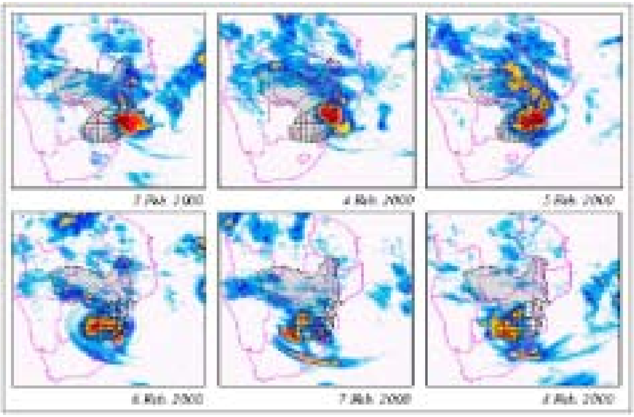


**Figure 3.3** - GMS-5 image of a Typhoon close to Japan with superimposed cloud-track winds. (Blue vectors are low-level clouds, pink vectors are high-level clouds and yellow vectors are winds derived by tracking water vapour). (JMA)

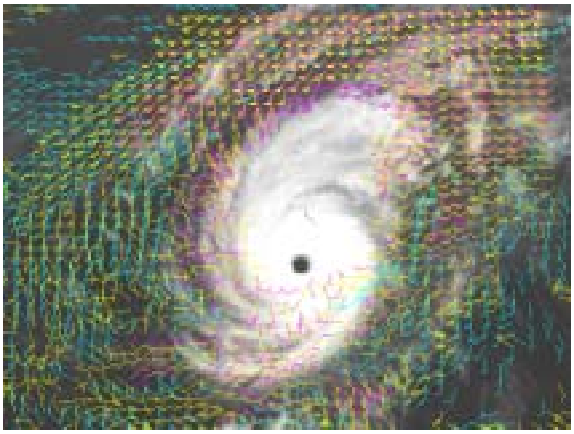


**Figure 3.4** - Tropical Cyclone between Madagascar and Mozambique February 2000. (PUMA)

## Improving Understanding of the Earth System, its Components and their Interactions

### *Comprehensive Models*

The challenge of Earth system modelling is to develop unified comprehensive models of the significant linkages and interactions among the component parts of the system. Such models can be used to test the sensitivity of the Earth's variable environment to various processes or forcings. They can also be replaced by simplified representations (e.g., climatological or similarly specified values) to reduce the computational load. Coupled Earth system models are needed to assess the Earth system variability and change, and the impact on agricultural, economic, and industrial activities of any such changes. Models are also required to provide routine and reliable seasonal-to-interannual and longer-term climate prediction, and will form the basis for data assimilation systems that encompass the entire Earth system.

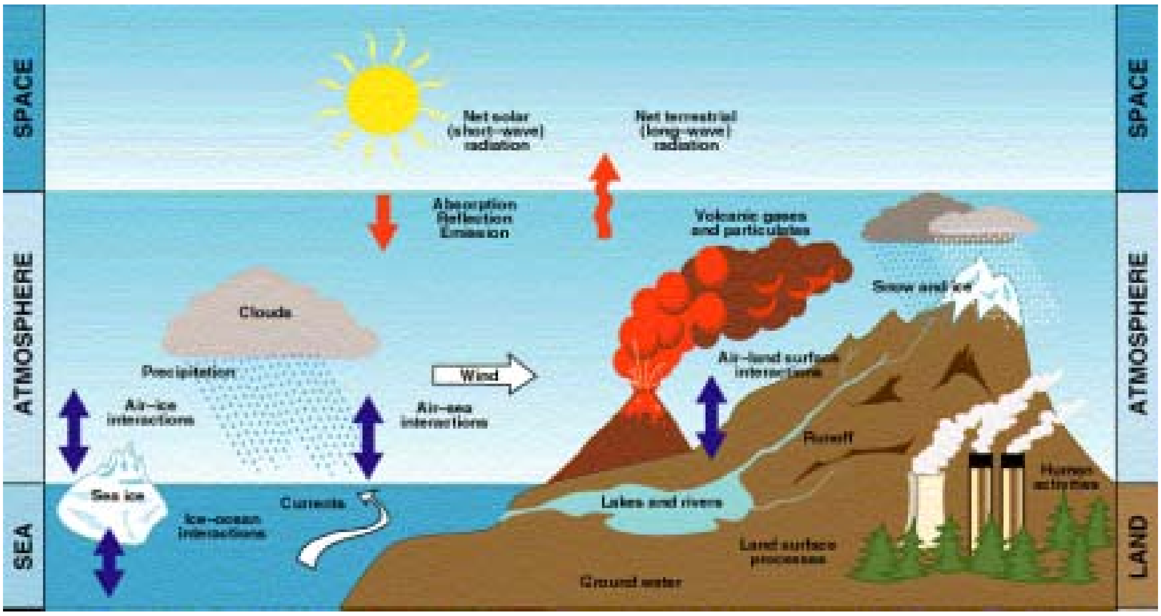


**Figure 3.5 –** Schematic of the Earth system

Advances in computer technology will allow the compilation and running of models that embrace a wide enough range of spatial and temporal scales to explicitly simulate the dynamical connections between different natural categories of phenomena, for instance in the case of the atmospheric circulation by:

- Linking global-scale changes in the atmospheric general circulation to organized weather systems such as tropical cyclones, frontal systems or squall lines;

- Linking organized weather systems to convective-scale phenomena, tornado- and rain-generating storms, and a diversity of terrain and terrestrial ecosystems (e. g., cloud ensemble models; limited-area atmospheric-hydrologic models, etc.);

- Linking cloud-scale dynamics to microphysical and chemical processes.

### *Data Assimilation*

Four-dimensional data assimilation will play an increasingly important role both in facilitating advances and in reaping their ultimate scientific benefit. Data assimilation provides a rigorous framework for integrating information from the models and from the highly heterogeneous observation systems. It is a powerful tool not only for adding information to model-simulated fields through the use of observations, but also for detecting and diagnosing weaknesses in both the models and in the observations. This ability to help detect systematic model errors gives data assimilation a direct role to play in the area of model development. In data assimilation mode, a coupled Earth system model is continually confronted with the actual observational data and is "corrected" by them as the model integration proceeds. Thus four-dimensional data assimilation systems will be used to validate increasingly sophisticated and complete representations of different physical, chemical and biological processes, as well as to measure the linkages among these processes and dynamical processes at different scales.

### *Linkage between observable processes*

Another very significant direction of progress will be the introduction of progressively more realistic representations of linkages between different types of processes, e. g., climate-transport dynamics-chemistry interactions, climate-biosphere-hydrology interactions, ice-sheet and sea-ice dynamics and forcing by atmospheric and oceanic circulations, climatic impacts on the spreading of disease vectors, etc. The emphasis of model development efforts will shift from representing large-scale dynamical transport and plane-parallel approximations of radiative and other fluxes, towards the detailed physical, chemical and biological processes that are actually taking place in the system. More attention will need to be given to the integration of modelling efforts and observational field studies, each supporting the other for optimal scientific advances.

### *Archiving*

There is no possibility of advancing scientific research or improving operational data assimilation systems without the availability of retrospective observed data and products. The long-term stewardship of this information is only possible through planned, carefully constructed systems of data acquisition, processing and archival. Such systems would be rendered worthless without the final piece of the puzzle: a system to allow user access to the data archives. There are many challenges concerning the future processing of satellite observations for the purpose of quality assurance, long-term archiving, dissemination to users and overall stewardship. Perhaps the largest involves the sheer volume of the data, which is becoming available today and will continue in abundance from the proposed high-resolution sensors during the next decade.

### *Communications*

New communications technologies are necessary to move the vast amounts of information from these observing and modelling capabilities among widely diverse users and suppliers. On-board data processing and intelligent communication among satellites in orbit, or between space and the Earth's surface, allow managing large data and information volumes and make a future system more efficient. The ability to mine data archives and fuse data types will also make communication more efficient, enabling the ordering and delivery of tailored information products. The ability to go back and access, search and process historical data records for scientific research and new products and services is essential for Earth system science. As with expanded applications of GPS today, the future will see a broad array of environmental information available to users at their desktops, or even in remote locations via personal information assistants.

Common among any such scenario is the requirement for a flexible and reconfigurable observing architecture that can:

- Accommodate new capabilities without affecting existing ones;
- Receive contributions from all interested nations;
- Integrate observations from a variety of space-based, sub-orbital, and ground-based platforms;
- Tailor observations and information as required for a variety of applications;
- Establish common protocols and standards for sharing readily observations and information among the components of the observing networks and with diverse users.

### *Research to Operations*

Development of capabilities will remain the responsibility of national research and technology agencies, but collaboration between research and operational systems, and among nations, will be essential for the true utility of these capabilities to be realised. A key challenge will be the transition of new technologies into operational observing systems. Collaboration among research and operational agencies throughout the concept definition, design, development, and implementation of such systems is essential. These collaborations may take the form of 'transition missions' that serve both active research and operational demonstration goals, as with the US/European partnership in ocean altimetry. Such steps accelerate the use of new observing data in operational forecasting ahead of the availability of a first truly operational satellite system. The observations of both operational and research satellites will both be used in the analysis. Thus the distinction between them, within the GOS will be seamless. The role of the WMO in bringing research and operational agencies of nations around the world together will be vital in making this vision of the future a reality.

# CHAPTER 4

## NEAR-TERM CONFIGURATION OF THE SPACE-BASED COMPONENT OF THE GLOBAL OBSERVING SYSTEM (GOS)

Geostationary satellites provide a continuous view of weather systems making 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. The warning capability has been the primary justification for the geostationary spacecraft. The polar-orbiting satellite system provides the data needed to compensate the deficiencies in conventional observing networks; it is able to acquire data from all parts of the globe in the course of a series of successive revolutions. The polar-orbiting satellites are principally used to obtain daily global cloud cover and quantitative measurements of surface temperature and temperature and water vapour soundings in the atmosphere; these global data are acquired by a single set of observing sensors. Together, the polar-orbiting and geostationary satellites constitute a truly global meteorological satellite network.

Currently, observations from both polar orbiting and geostationary instruments are close to achieving accuracies, resolutions, and cycle times for key meteorological parameters such as cloud type, temperature and humidity profiles, (from infrared and microwave sensors), and upper level winds (from tracking the movement of cloud and water vapour features). The polar and geostationary platforms for the present and the next ten years are summarized in the following paragraphs; the instruments on board and their capabilities can be found in Annex IV.

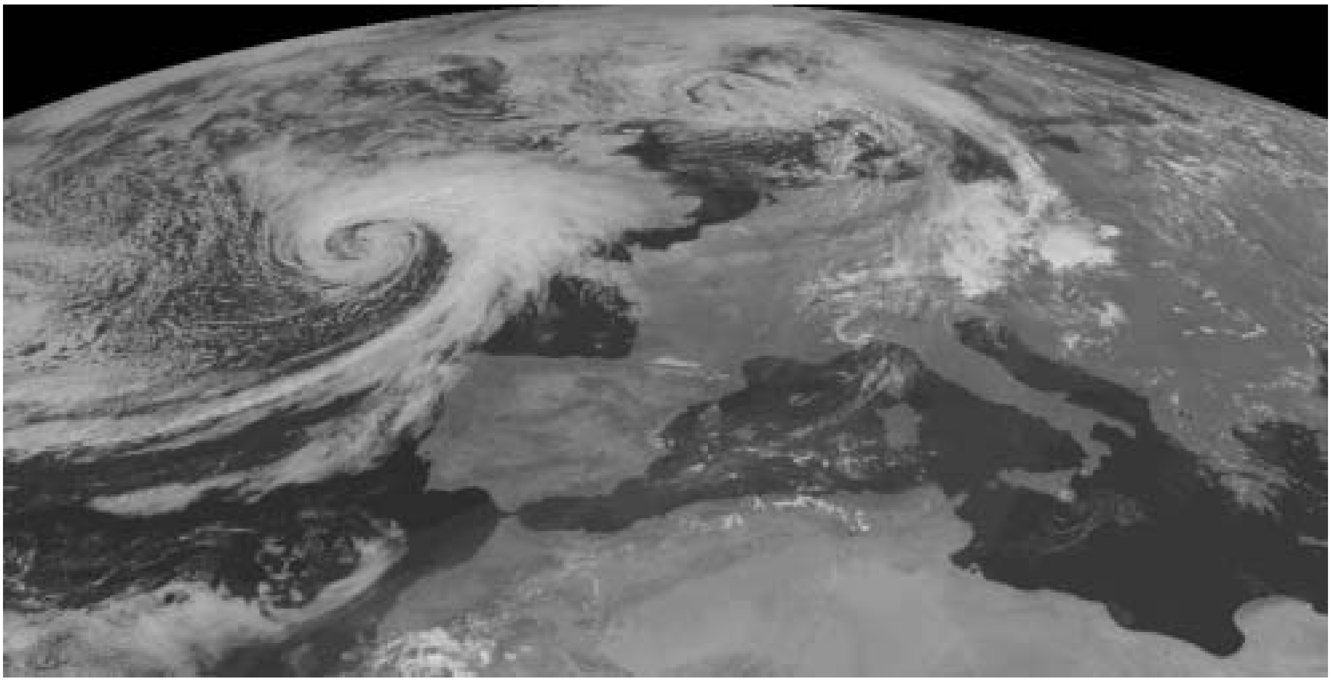


**Figure 4.1** - Meteosat visible image showing an intense depression off the west coasts of Europe together with its associated trailing cold front. A mature depression is shown off the coast of Norway with its occluded front over the Baltic Sea. Widespread showery activity in the cold air over the Atlantic is contrasted with the largely cloud-free conditions over much of France and the Iberian peninsula. (EUMETSAT)

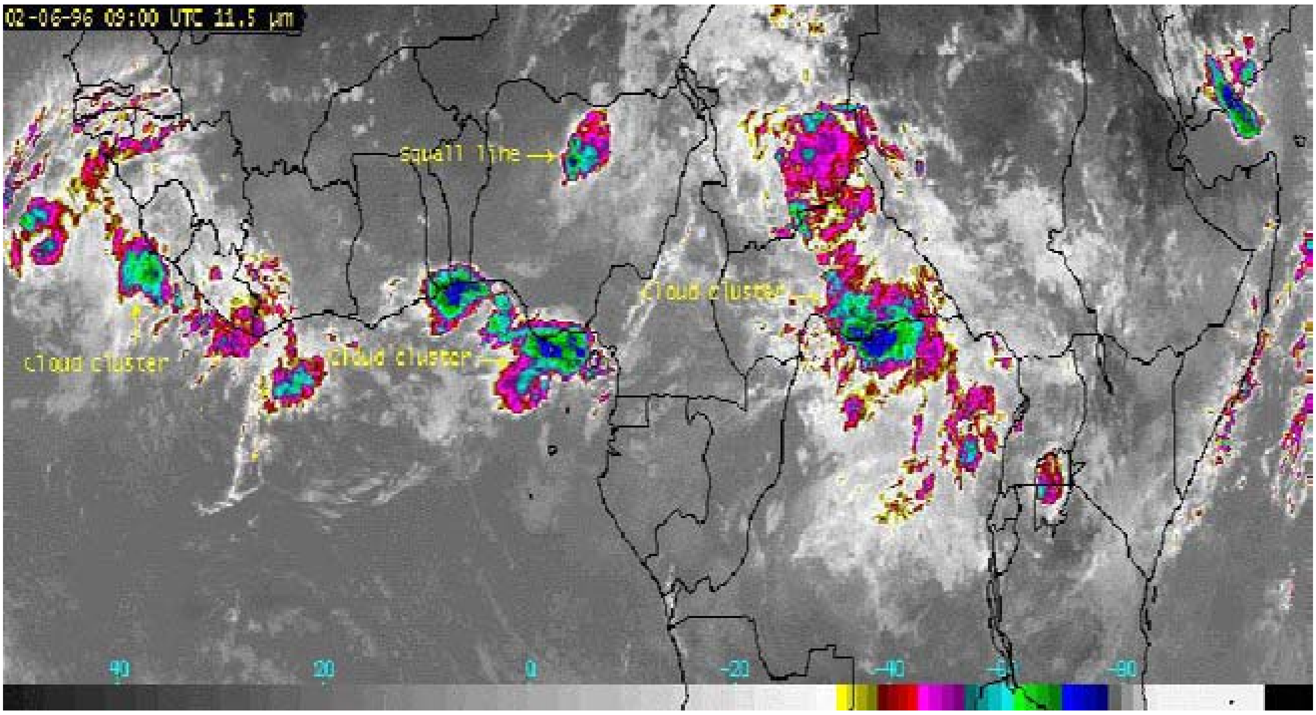


**Figure 4.2** - Cloud clusters indicative of heavy local rainfall and a squall line, seen on a Meteosat infrared image enhanced through colour coding of the cloud-top temperature. (PUMA)

## Current and Future Polar platforms

Polar orbiting satellites provide global coverage twice a day. Their orbital altitude of 850 km makes it technically feasible to make high spatial resolution measurements of the atmosphere/surface. To provide a reasonable temporal sampling for many applications at least two satellites are required, thereby providing 6-hourly coverage. However, observational user requirements already specify more demanding temporal coverage equivalent to at least 3-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. They carry a multi-spectral imager (usually with 1 km resolution visible, near-IR, and IR window bands for observing cloud cover and weather systems, deriving sea surface temperature, detecting urban heat islands and fires, and estimating vegetation indices), a multi-spectral infrared sounder (usually with roughly twenty broad spectral bands of 20 km resolution for deriving global temperature and moisture soundings), and a multi-spectral microwave sounder (most recently with twenty microwave channels of 50 km resolution for deriving temperature soundings even in non-precipitating cloud covered regions).

Current operational polar orbiters include the NOAA series from the USA and the METEOR, RESURS, and OKEAN series from the Russian Federation 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. The Russian Federation METEOR series will evolve into the METEOR 3M series and the Chinese FY-1 series will be replaced by the FY-3 series.

Research and Development missions continue to make many contributions in the area of polar orbiting remote sensing measurements. To maximize the impact of those data and the associated expenditures in resources (manpower and financial) by operational users, space agencies are committing to (a) open and timely access to the data in standard formats, (b) preparation of the community for new data usage, and (c) data continuity.

NASA's Earth Observing System includes multiple platforms. Terra has been in an AM orbit since December 1999 and is providing global data on the state of the atmosphere, land, and oceans, as well as their interactions with solar and Earth radiation. Aqua followed in a PM orbit in May 2002 and will provide climate related data with respect to clouds, precipitation, atmospheric temperature / moisture content, terrestrial snow, sea ice, and SST.

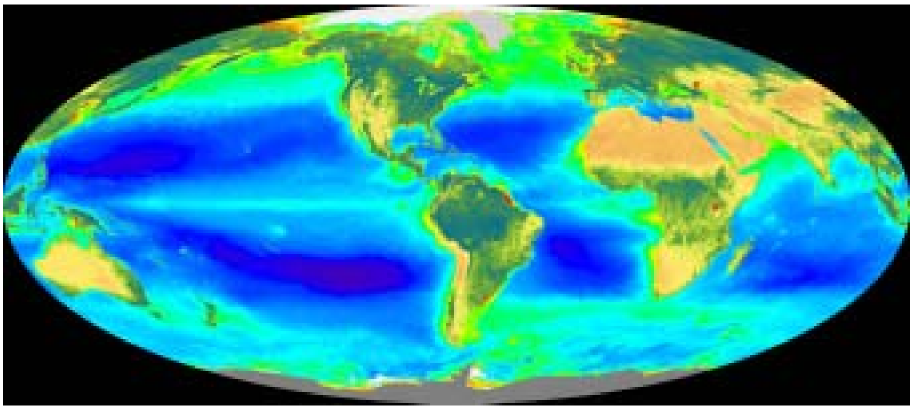


**Figure 4.3** – SeaWiF's map of phytoplankton pigment concentration over the oceans together with a vegetation index over the land areas, showing global biomass in one image. Ocean colours range from dark blue (less than 0.1 mg/m$^3$ up to red in some coastal areas (10 mg/m$^3$). (GSFC)

The NASA/CNES Topex/Poseidon and Jason-1 satellites provide a wealth of observations on the status of the ocean topography, and this is used in both short-term storm analysis and climate studies. In 2004 Aura will provide a suite of chemistry measurements focusing on atmospheric trace gases in the upper troposphere and lower stratosphere. In addition, the Earth Observer series has started providing hyperspectral vis/NIR data.

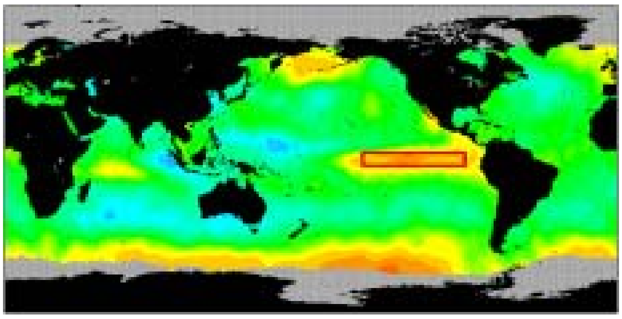


**Figure 4.4** - Global sea levels, showing the region (red box) used to determine the sea level index (Topex/Poseidon)

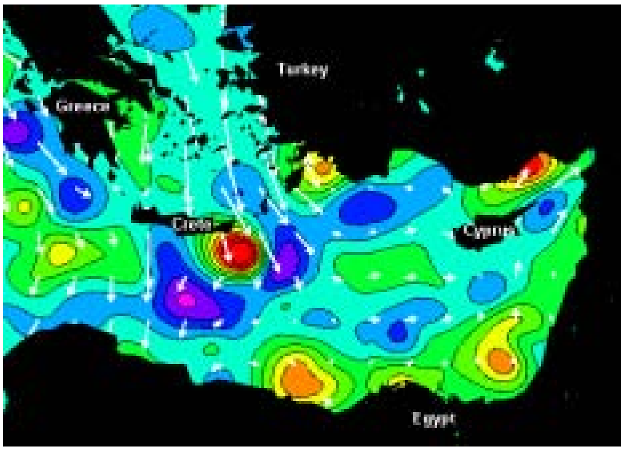


**Figure 4.5** - Map of Sea Level Anomaly in the Eastern Mediterranean from Topex/Poseidon Data. The scale ranges from +/- 30 cm (red to blue). (CLS)

ESA launched the ENVISAT platform in March 2002. It will provide measurements of the atmosphere, ocean, land, and ice over a five year period. ENVISAT has an innovative payload that will ensure the continuity of the data measurements of the ESA Earth Remote Sensing (ERS) satellites, as well as facilitating the development of operational applications. Thereafter, several Earth Explorer missions are planned to study the gravity field (2005), atmospheric dynamics (2007), polar ice (2004), and soil moisture and salinity (2006).

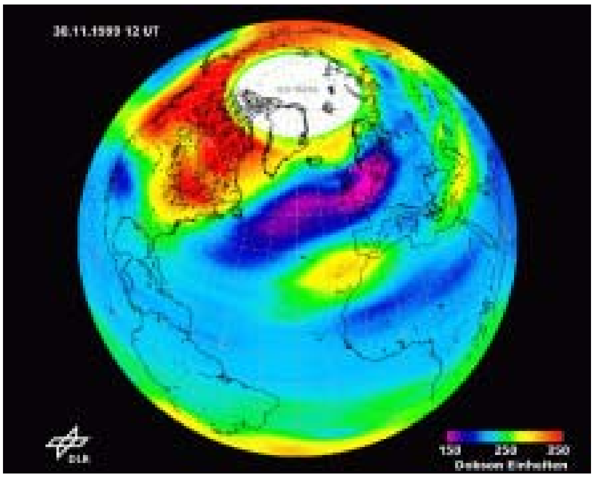


**Figure 4.6** - Distribution of stratospheric ozone over the northern hemisphere on 30 November 1999 from GOME/ERS-2 data (DLR)

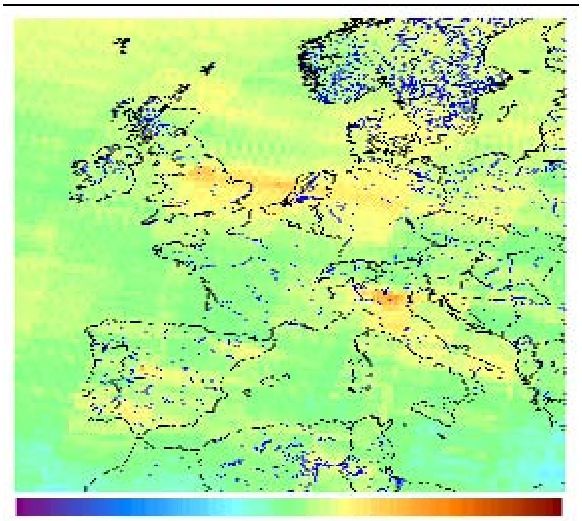


**Figure 4.7** - Distribution of stratospheric $NO_2$ over Europe, derived from GOME data on ERS-2. (DLR)

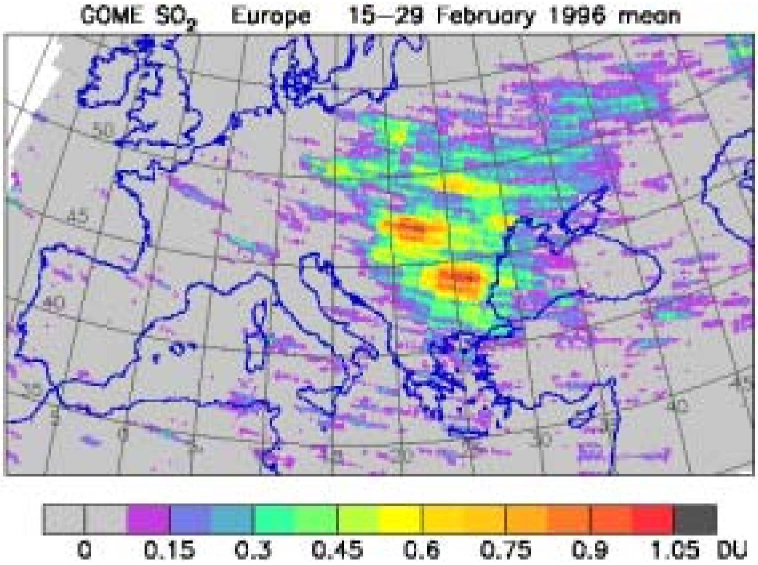


**Figure 4.8** - Distribution of $SO_2$ of anthropogenic origin over Europe, obtained from ERS-2/GOME data. (AWI)

NASA and NASDA launched in 1997 a joint mission, the Tropical Rainfall Measuring Mission (TRMM). TRMM is designed to monitor and study tropical rainfall and the associated release of energy that helps to power the global atmospheric circulation shaping both weather and climate around the globe. It also provides information on soil moisture. By combining TRMM precipitation data with ocean vector winds data from QuikSCAT (launched in 1999), researchers have demonstrated the ability to significantly improve hurricane track and landfall prediction.

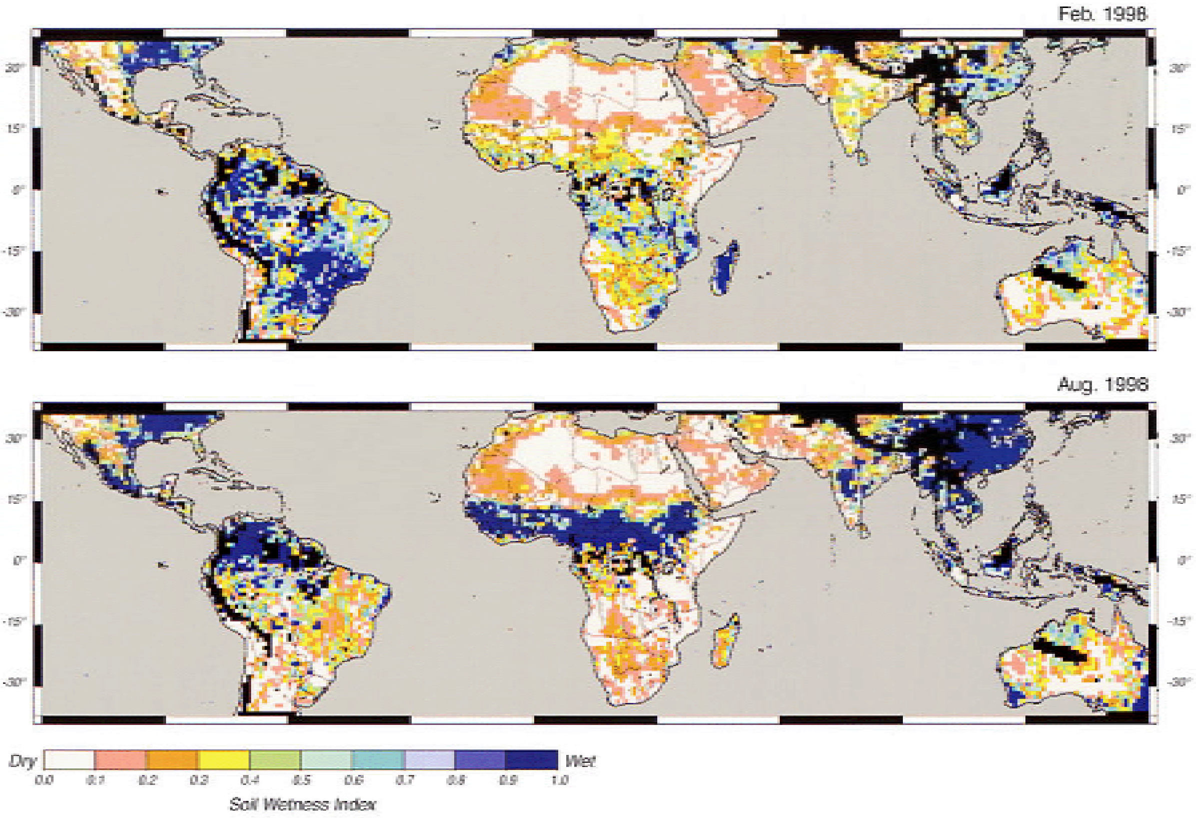


**Figure 4.9** - Global soil-wetness index computed from data from the Precipitation Radar on TRMM (NASDA)

NASDA will be continuing their ADvanced Earth Observing Satellite mission with ADEOS-2 in 2002. The ADEOS-2 mission is designed to monitor and investigate the causes of frequent climate changes occurring in the world, expansion of the ozone holes, and global environmental changes. NASDA will follow this with the Advanced Land Observing Satellite (ALOS) in 2003 that will utilize advanced land observing technology. Later this decade, the Global Change Observation Mission (GCOM) will be aimed at observing parameters over the long term (as long as 15 years), and to understand the mechanism of the global environmental change. GCOM-A1 will observe ozone and greenhouse gases and GCOM-B1 will monitor energy and the general circulation from a sun-synchronous orbit.

Canada launched RADARSAT-1 in 1995; it is equipped with synthetic aperture radar (SAR) and is proving to be useful in a variety of fields, including disaster and environmental monitoring.

Indian Remote Sensing Satellites (IRS) IRS-1C and IRS-1D were launched in 1995 and 1997, by the Indian Space Research Organization (ISRO). The IRS satellites are equipped with an optical sensor – Panchromatic sensor (PAN) that has the highest level of resolution, at 5.8m, of the current Earth observation satellites. It is being utilized for land application studies.

The People's Republic of China is providing the newest series of polar-orbiting satellites, the FY-1 series. The FY-1 series has greatly enhanced imaging capabilities from polar orbit with its 10 channel radiometer that includes the same five channels as found on NOAA's AVHRR and five new channels.

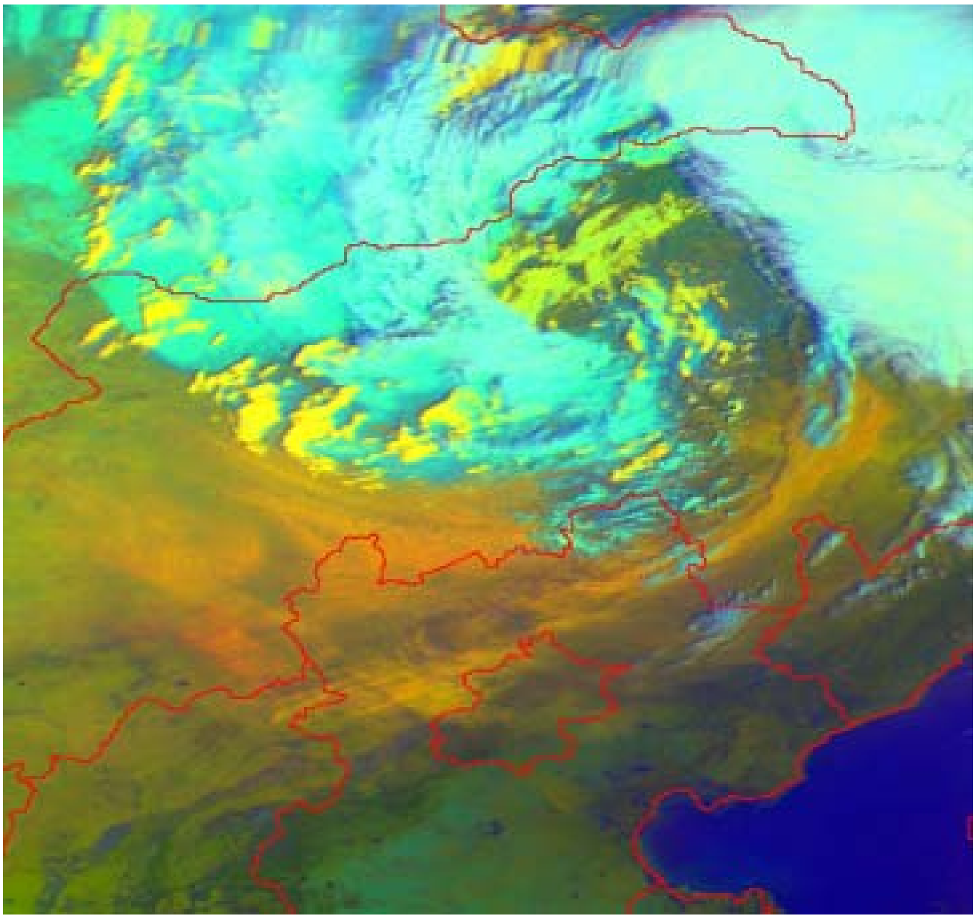


**Figure 4.10** - Duststorm (red-orange tones) over China observed by the PRC's FY-1C polar satellite using an instrument with similar characteristics to AVHRR. (NSMC)

## Current and Future 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, at least five equally spaced satellites around the equator are needed to provide global coverage; polar regions are either very poorly observed, or not observed at all because of the large zenith viewing angles.

Currently, there is global coverage from geostationary orbit (more than 5 operational satellites for image data and products (e.g., cloud motion winds) and 2 satellites are also providing a sounding capability. Reactivating 'retired' platforms provides backup and there have been several examples of this type of activity. The geo-imagers typically have 1 km resolution visible and 5 km IR window bands for observing cloud cover and weather systems in motion and estimating atmospheric motion vectors. The geo-sounders to date have eighteen broad spectral bands of 10 km resolution for deriving atmospheric temperature and moisture trends in time.

Some of the satellites provide a real-time transmission capability to allow immediate access to the imagery for real-time applications. Products are disseminated on the WWW's Global Telecommunications System (GTS) by the satellite operators for near real-time applications.

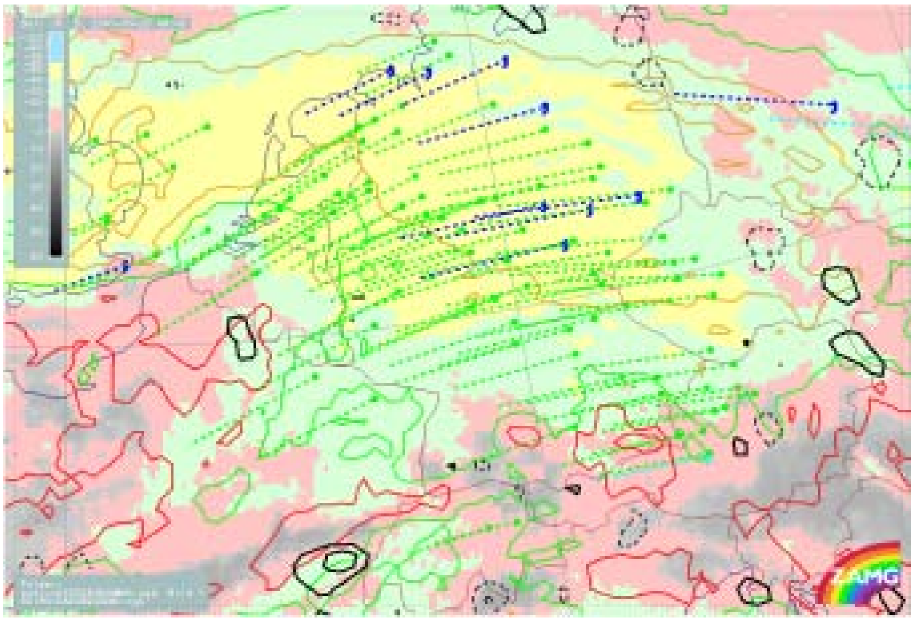


**Figure 4.11** - Meteosat infrared image colour coded with cloud-top temperatures, together with two hour forecast of cloud edge locations (solid lines), forecast tracks of precipitation events (dashed vectors) and areas of current cloud development or dissolution (black lines). (ZAMG)

At present there are satellites at 0° longitude and 63°E (Meteosat 5 and 7 operated EUMETSAT), 76°E (GOMS operated by the Russian Federation), 105°E (FY2B operated by the People's Republic of China), 140°E (GMS-5 operated by Japan), and 135°W and 75°W (GOES 8 and 10 operated by the United States of America (USA).

All geostationary satellite instruments are evolving to more spectral coverage and faster imaging. In 2003, Europe is moving to the SEVIRI. Japan will launch JAMI in 2003. China will launch another in the FY 2 series of imagers in 2004. India is enhancing their geo capabilities with INSAT-3A and Metsat, to be launched by 2002, and INSAT-3D (to be launched in 2004). USA will evolve to an Advanced Baseline Imager and Sounder in 2012.

## Enhanced monitoring of selected Earth system components

New observing capabilities demonstrated in a research mode during the next decade will become part of an operational observing system of the future. These include:

### *Atmospheric Sounding*

Continuous observation of tropospheric temperature/moisture profiles, wind pattern and moisture inflow in the far field around weather systems, where the cloud cover is broken, will be demonstrated in 2006. The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument is being developed to demonstrate a unique ability to peer continuously through many layers of the atmosphere from geosynchronous orbit with the precision and accuracy of atmospheric sounding capabilities being developed for low Earth orbit systems (i.e., 1°K accuracy and 1 km vertical resolution). The test instrument is intended to map the three-dimensional distribution of water vapour, determine atmospheric temperature profiles and detect the presence of trace gases, such as carbon monoxide, ozone, and methane) at different altitudes in the atmosphere

### *Atmospheric Winds*

Global wind field measurements will be directly applicable to numerical weather prediction, and extremely valuable for scientific diagnosis of large-scale atmospheric transport, weather systems, and boundary layer dynamics. A space-based Doppler lidar system is being developed to deliver relatively sparse wind data; progress in space-borne laser technology will continue in order to make this active sounding technique available to operational uses.

*Global Precipitation*

Quantitative measurement of the time and space distribution of global precipitation is the next highest climate research priority beyond atmospheric temperature and moisture, and an essential requirement to understand the coupling among atmospheric climate, terrestrial ecosystems and water resources. Satellite remote sensing is the only means to acquire global rainfall data, considering the paucity of surface observations over the ocean and sparsely populated land areas. Measurement of global precipitation would likely be based on frequent observations from a constellation of passive microwave sensors. Meanwhile, detailed vertical atmospheric distribution of rain data would be provided by a common rain radar satellite for refinement and validation of retrieval algorithms for all satellites in the constellation. An early demonstration of this concept is being conducted using the TRMM, Aqua and ADEOS II research satellites in tandem with operational meteorological satellites. These extend to the TRMM-like precipitation measurements to extra-tropical parts of the world for the first time, and demonstrates the concept of 3-hour global precipitation products with utility to a broad range of WMO Members' objectives.

**Figure 4.12** – Global Precipitation Measurement (GPM) constellation

*Soil Water Content*

At present, near-surface soil water content is the only primary hydrologic variable that is not measured at large spatial scale. Scientific evidence shows that near-surface soil water content is the most significant indicator of the state of the terrestrial hydrologic system, and is the governing parameter for partitioning rainwater among evaporation, infiltration, and runoff. Large antennae will be needed to meet these requirements at low microwave frequencies; these remain a significant technological challenge.

*Ocean Surface Salinity*

Ocean salinity, even more than temperature, controls the dynamics of the deep ocean circulation and long-term climate. Sea surface salinity (SSS) determines the depth to which cold surface water may sink to form intermediate and deep ocean water masses. Despite the scientific significance of SSS, there is almost a total lack of systematic ocean salinity measurements world-wide, except for occasional oceanographic cruises and automated measurements on some merchant vessels. Developing low-frequency microwave radiometry techniques for remote sensing of sea-surface salinity is a recognized objective of technology development by several space agencies.

*Cold Climate Processes*

Passive and active (radar) microwave remote sensing methods are being considered by Europe, the US, and Japan to determine the most effective means to acquire information globally on snow extent and water equivalent, soil freezing and thawing that strongly affect the hydrologic regime of river basins at high latitudes.

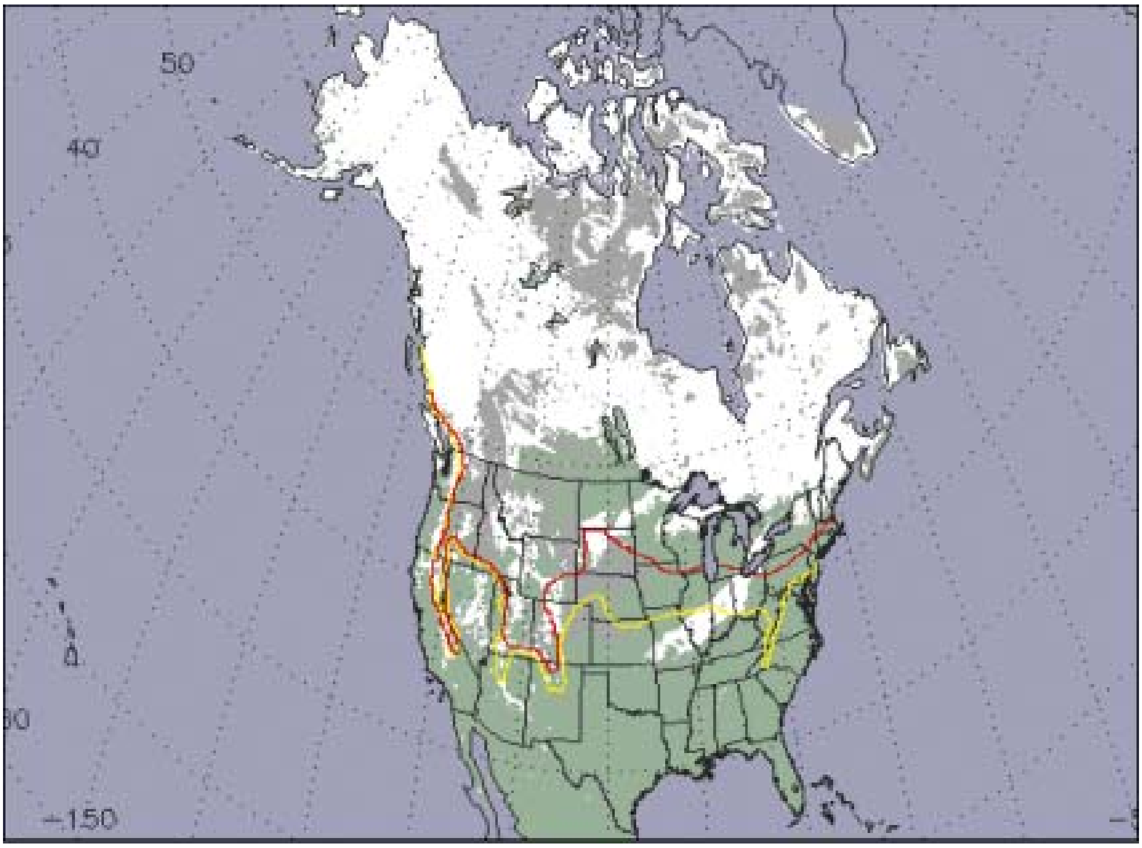


**Figure 4.13 -** Snow cover extent for North America from the Moderate Resolution Imaging Spectroadiometer (MODIS) on Terra. The red and yellow lines represent the average March and February snow lines, indicating below-average snow cover in 2001.

*Carbon Sources and Sinks*

Available *in situ* measurements of near-surface atmospheric carbon dioxide concentrations have been used to constrain inverse models of atmospheric transport and predict hemispherical scale distributions of carbon sources and sinks. The ability to make direct space-based measurements of atmospheric carbon dioxide concentrations, with sufficient accuracy and precision, will provide improved global coverage and overcome problems associated with local effects that complicate surface measurements in the interior of continents. Several research groups are studying a number of passive (spectrometric) or active (lidar) techniques to measure total column and vertical profile abundance of carbon dioxide with an Earth orbiting satellite.

*Vertical profiles of clouds and aerosols*

Atmospheric aerosol content is subject to substantial variation in amount and type, as concentrations are driven by natural and human activities, including agricultural and industrial practices. In the first half of this decade, the first attempt at global observation of the three-dimensional structure of clouds and aerosol distributions will be undertaken. These involve active remote sensing systems (i.e., lasers/lidars and microwave radars) rather than the passive remote sensing systems such as radiometers that are common today. Due to the long term nature of climate change research, such systems are likely candidates to become part of the operational climate observing system in the future.

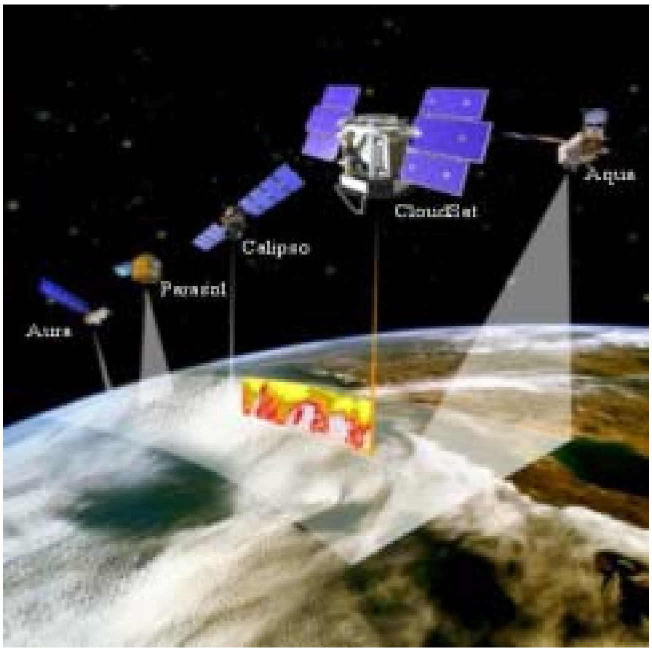


**Figure 4.14 -** The first global, four-dimensional profiles of clouds and aerosols in the atmosphere will be provided by the Cloudsat and Calipso satellites. These will fly in formation with other atmosphere observing satellites to facilitate the combining of data into integrated atmospheric research products.

## Data handling and communications

The scientific understanding and applications benefits enabled by such technologies will rely on efficient data handling and communications. This will include onboard information processing and large bandwidth space-to-space and space-to-ground communications

*On-board information processing*

On-board processing will be crucial in order to reduce to manageable proportions the volume of data which must be transmitted to the ground, to provide useable data products directly to user sites, and/or enable automated spacecraft operation modes minimizing the need for expensive operation control from the ground. A variety of technology breakthroughs are needed, including: adaptive computing "toolkits" for rapid prototyping of new field programmable gate arrays (FPGAs); on-board reconfigurable data path processors for science data processing; advanced holographic memory development; ultra high density fast readout optical storage devices; optimized compression techniques; and on-board data mining tools.

*Large bandwidth space-to-space and space-to-ground communications*.

Constellations of the future may also require substantial spacecraft-to-spacecraft communications, either for coordinating observing tasks among satellites or for transferring observations and information directly from satellites onto the desktop computers of users. To address these challenges, very high speed optical communications transceivers provide the best prospect for high data-rate links compatible with large data volumes, relatively low power use, and available (yet-unallocated) bandwidth. However, optical data links are sensitive to the presence of clouds, so that new mitigation strategies that increase link availability will be needed, based on the use of relay satellites and ground-station diversity. Low Earth and geostationary orbit cross-links is the key system level concept for reliable data return from space. Incorporating data delivery to two-three ground stations, strategically located so as to exhibit anti-correlated cloud cover, increases ground station availability.

# CHAPTER 5

## VISION FOR THE FUTURE: A 2020 PERSPECTIVE

The extension of reliable weather forecasting and assessments of the causes and course of longer term Earth system change are two major accomplishments of WMO and its partner organizations that have a demonstrable value to humanity. But they also open a door towards a greater range of possibilities in the future. Annual losses due to natural disasters, most of which are weather-related, exceed on average 50,000 lives and tens of billions of dollars. Some research activities indicate longer-term climate change will impact the distribution, frequency, and intensity of severe weather events. Annual decisions on food and fibre production, multi-year investments in infrastructure development, and management of fresh water resources to name just a few contemporary socio-economic issues, would see a tremendous benefit from reliable, extended services and products, such as:

- ***30 minute warning of very destructive weather events***; for example, tornado prediction beyond 10 minutes is notoriously difficult but necessary in susceptible areas;
- ***1-12 hour severe weather events***; greatly increased skill for shorter-term severe weather events covered by Nowcasting and Very Short Range forecasting is possible;
- ***5 day hurricane*** track prediction to +/-30 km; to reduce the number of false warnings resulting from the present landfall location uncertainty of 400km at 3 days;
- ***10-14 day weather forecast***; new measurements, especially tropospheric winds, and substantial advances in modelling capability can push short term weather prediction out to the limits;
- ***12 month regional rain rate including Monsoon related forecasts***; recent efforts in global water cycle modelling indicate the potential to deconvolve global-scale water cycle variation into regionally specific projections;
- ***15-20 month El Niño prediction***; “hindcasting” of the two most recent El Niño events indicates that this is possible with an adequate system of space-based and *in situ* observing capability paired with focused modelling efforts;
- ***10 year climate forecasts***; decadal-scale climate prediction is theoretically possible with the extension of the research systems now being deployed to the operational systems of tomorrow.

Meteorological satellites provide essential data for weather forecasting to national weather services around the globe. This has in large part been due to direct broadcast and through global sharing of data and science. Satellites offer high-resolution digital renderings from a range of spectral bands whereby both qualitative and quantitative information about the atmosphere, clouds, the land and the sea surface properties are deduced. The need for a global view requires us to embrace the concept of a composite observing system where the distinctions between geostationary, polar and low Earth orbiting satellites, research and operational satellites, and various sensors are minimized. To prepare for the daunting task of monitoring and understanding the Earth’s system from these new data we must work in a global science collaboration and through operational partnerships.

Mankind’s ability to observe the Earth and its environment from space has always been in transition. Indeed, the operational satellite system in this first decade of the new century is undergoing a metamorphosis, and it will undergo a marked alteration in appearance, character and function.

As the space based remote sensing system of the future develops and evolves, four critical areas (all dealing with resolution) will need to be addressed in order to achieve the desired growth in knowledge and advanced applications. They are:

- spatial resolution – what picture element size is required to identify the feature of interest and to capture its spatial variability;
- spectral coverage and resolution – what part of the continuous electromagnetic spectrum at each spatial element should be measured, and with what spectral resolution, to analyze an atmospheric or surface parameter;
- temporal resolution – how often does the feature of interest need to be observed; and
- radiometric resolution – what signal to noise is required and how accurate does an observation need to be.

Each of these resolution areas should be addressed in the context of the evolving space based observing system wherein the satellite(s) exist, or will exist - this will call for new approaches in all aspects of the operational satellite arena.

## Satellite System Characteristics

Responding to the requirements above, the future satellite systems will be a hybrid of different orbits needed to achieve the desired result. In turn, the satellite systems must be continuously "tuned" with the master system, so that a fully global environmental observing system emerges.

The long-term continuity of well-calibrated and characterized observations from satellites is an essential element in the construction of a climate record, and marks a significant shift from the use of the data sets in the shorter term meteorological forecasting. Having an understanding of the quality of the data and the long-term sensor/system performance becomes a very important issue for climate applications. These factors have significant implications in terms of the quality control of the data sets and will impact both the observational regime and the subsequent data handling and archiving. The need to understand the basic long-term sensor performance for individual sensors and between systems will require a focus of effort on the analysis of the long-term sensor performance and inter calibration. This will enable the data to be used sensibly in product generation, data assimilation and climate modelling.

Creating continuity of the core observations already being made in 2002 will be one priority. This is a complex issue because developments in sensor capability – both spectrally and spatially - will result in the need for formal inter-calibration between systems as new systems are introduced. Furthermore, the long-term sensor performance for a specific system will need to be carefully monitored. Studies with Meteosat archive data have already shown that variations, that at first analysis are significant, are in fact due to variations in the sensor performance. It will, therefore, be necessary to ensure the ancillary data are stored alongside the satellite data observations in an accessible and usable format.

For future systems there will also be a need for better management and knowledge of the orbit for LEO satellites. Orbit drift, as measured by the nominal equatorial crossing time for sun synchronous satellites, has, for certain sensors, a significant impact on the sensor response. Controlling the orbit, or at the very least recording the actual orbit will become a routine requirement for Earth observation satellites. This is already an acknowledged need in certain areas, such as precise ocean surface topography from Topex/Poseidon and Jason-1. The use of GPS class satellites and fixed Earth stations will become routine in this respect.

Data coverage will remain a major issue for LEO satellites. There will remain a drive for higher spatial and temporal resolution, which can only be satisfied by having several satellites making the same or similar observations. However, this in itself will require better harmonization of orbits between agencies in order to optimize the coverage. This will also provide a framework for research satellites to be used in parallel with long-term operational systems. In this way the operational community will be able to take advantage of research data sets, alongside the original conceived research programmes. It will also provide a good mechanism for the introduction of new sensors in a controlled environment that will maximize the cross calibration to support the long-term data record.

### Geostationary Satellites

The geostationary satellite will play a particularly important role in the metamorphosis of the space-based component of the GOS, and in helping frame the context of the system's development and evolution.

Amongst the more important capabilities that will be developed and brought to fruition in a geostationary context are: high spatial resolution hyperspectral imaging and atmospheric sounding capability; routine rapid interval full disk imaging; routine full disk sounding at a variety of temporal resolutions; and, exploration of advanced sensor technology for lightning detection and microwave applications. To maximize the information available from the geostationary and low Earth orbiting satellite system, geostationary satellites will be placed "nominally" at a 60-degree sub-point separation across the equatorial belt. These important capabilities are addressed in more detail below.

#### *High spatial resolution hyperspectral imaging and atmospheric sounding capability*

In 2002, imaging from geostationary orbits has evolved from simple low spatial resolution broadband visible imagers to digital high spatial resolution multi-channel imagers. Products derived from those digital data sets are providing valuable information for a variety of applications ranging from nowcasting to global NWP. In the atmospheric sounding arena multi-channel instruments are being utilized to characterize atmospheric stability features important in the development of severe convective storms.

Issues dealing with clouds and solar zenith angle make the geostationary orbit important for many applications as well as their current meteorological use. They include areas such as smoke and atmospheric optical property monitoring (including water vapour), as well as land, vegetation and selected ocean colour applications. This points towards the development, by 2025, of hyperspectral imaging capability from geostationary altitude in the range between 0.4 and 2.5 microns. For certain of those applications, the spatial resolution available from geostationary orbit will not be adequate to meet the user needs. However, when viewed from a system's context, the information from the geostationary observations will be able to place the lower Earth orbiting observation into a perspective that deals with temporal evolution and variability (such as algae blooms) that cannot be captured by the higher resolution low Earth orbiting sensor.

Furthermore, science and applications that develop during the next twenty years will allow us to merge the hyperspectral data streams into channels, pseudo-channels and spectral combinations that will allow for the development of new applications from a uniformly calibrated spectral suite of observations. The merging of sensor spectral characteristics for use in polar and geostationary orbit is a critical and necessary step forward that will enable the "satellite system's" full exploitation for applications and science studies that range from nowcasting to climate and across applications areas that range from ecology to oceanography and into weather.

#### *Routine rapid interval full disk imaging*

In 2002, 15 minute interval images are becoming routine for the USA and Europe, with operations that provide more frequent views at times of severe weather (but at the expense of larger area views). Plans for future USA GOES and European METEOSAT satellites call for more rapid interval imaging, as do plans for China's and Japan's geostationary satellites. The advantages of frequent interval imaging are ubiquitous, and range from better observations of cloud pattern evolution for nowcasting to more accurate cloud motion vectors to having more opportunities for cloud free views of a scene for derivation of products such as sea surface temperature.

The expectation by 2025 is that imaging frequency will be 5 minutes at the full disc, but with the option for slower scan rates to increase signal to noise for some important hyperspectral applications.

### *Routine full disk sounding at a variety of temporal resolutions*

By 2025, all geostationary satellites should aim to support a high spectral resolution atmospheric sounding capability at a one hour interval, but with the option for slower scan rates for some applications such as trace gas monitoring. This is based on the perceived needs of nowcasting applications, tracking of atmospheric water vapour at different levels, and possibly selected atmospheric gases. This takes into account the capabilities expected by the low Earth-orbiting component of the system

### *Exploration of advanced sensor technology for lightning detection and microwave applications*

By 2025, the geostationary satellites will carry instrumentation that will allow for the detection of lightning from space.. It is also expected that microwave technology will be tested from geostationary satellites by the mid-2020s. The main utilization will focus on rainfall estimation, and science developed from such an endeavour will be evaluated in the context of a low Earth orbiting global precipitation mission to determine the role of geostationary microwave sensing as part of the space-based component of the GOS.

### *60 degree sub-point separation for geostationary satellites*

The aim for 2025 is for geostationary satellites to be placed “nominally” at a 60-degree sub-point separation across the equatorial belt. This separation provides for good viewing to about 70 degrees N/S, as well as an excellent opportunity for stereographic cloud height assignment, which with a 5-minute full disk allows for very good asynchronous stereo. Furthermore, six satellites in equatorial orbit (all with similar imaging and sounding capabilities) provide for a more substantial backup capability. Thus, the failure of a satellite could result in reallocation of the geostationary constellation to 72-degree separation, similar to that in 2002, while awaiting replacement to a fully robust system.

## Low Earth Orbit Satellites

### *Polar and low inclination orbiting satellites*

Current, polar orbiting satellites provide global imaging and sounding coverage twice a day, and remain the only source of higher temporal coverage in the Arctic and Antarctic regions. The two current operational satellite configuration achieves measurements of the atmosphere/surface with high spatial resolution and reasonable temporal sampling. The benefit of hyperspectral visible and near infrared measurements for land usage, ocean colour, and aerosol plus cloud property studies are already being demonstrated from experimental programmes using VIS/IR and microwave frequencies. As the Global Observing System evolves, a balance or compatibility in improvements in the four areas of spectral, spatial, temporal, and radiometric resolution will be essential. User requirements in several applications areas (including numerical weather prediction) indicate the need by 2025 for a four-polar-satellite system. This would provide two sets of observations in both the morning and the afternoon, which with appropriate equator crossing times would provide for adequate temporal sampling and contingency planning.

Microwave, altimetry, scatterometry, radio occultation, and lidar systems will remain unique to the low Earth orbiting satellites. In the 2025 period sounding will be accomplished with combined radiometric (infrared and microwave) and geometric (radio-occultation) systems. Passive and active remote sensing will be combined to offer the best measurement of water vapour at resolutions commensurate with its natural variability. Altimetry will be pursued with a two-orbit fully operational system with real time capability wide swath (non-scanning) altimeters to enhance mesoscale understanding. Atmospheric wind profiles will be accomplished with Doppler lidar systems, ocean surface wind vectors now employing both the current active techniques and new passive capabilities. Sea surface Temperature (SST) will evolve from data combined from LEO and GEO systems of measurements, whilst expanded ocean colour capabilities will include increased horizontal resolution for coastal areas. SAR data from a multi-satellite system will provide “wave mode” and sea ice/wave monitoring service and three dimensional surface topographic information based on interferometric remote sensing techniques.

Major challenges for the next 25 years include

- Coordination of orbits for LEO missions to generate maximum temporal coverage with some necessary orbit redundancy;
- Resolution of communications issues for real time availability of global data and products;
- Cooperation for calibration / validation / harmonization of basic products; and
- Continuation of data collection services that are crucial for collection of *in situ* data;
- Coordination of missions from different agencies to maximise the range of observations.

Expansion of the polar satellite component of the GOS will be an international collaboration. There will be efforts to facilitate contributions of multi- instruments to larger platforms and formation flying of these platforms with single instrument small satellites to maximize accommodation of scientific and operational requirements. Coordination of international contributions to the polar orbiting observing system to achieve optimal spacing for a balance of spectral, spatial and radiometric and temporal coverage will be a major goal. Operational continuation of research capabilities with proven utility to the GOS will need to transition to operations without interruption of the data flow.

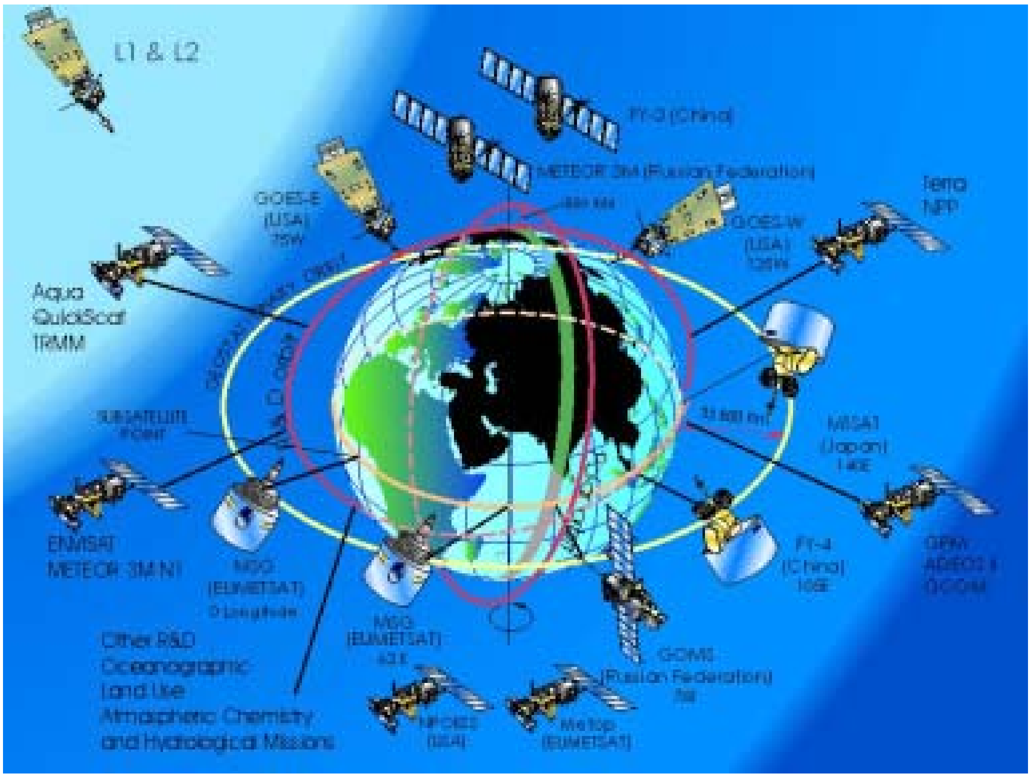
There will need to be a commitment for adequate resources to sustain research developments necessary for improved utilization of these measurements, with parallel funding of exploitation development by the relevant agencies. International algorithm development will assure best talent participation and enhance uniformity in derived products and timely access to these capabilities by all interested nations around the globe without restriction.

## Challenges for the Future

Satellite sentinels at the Lagrangian (neutral gravity) L1 and L2 points would enable around-the-clock monitoring of the entire globe, including the polar regions that are not well-captured from geostationary orbit. A satellite at L1, (on the Earth-Sun line between them) for example, would see diurnal changes in ozone and atmospheric chemistry, which are little understood today. A satellite at L2 (on the Earth-Sun line beyond the Earth) would be an ideal global thermometer, since small global temperature changes would show up most clearly in increasing night-time minimum temperatures.

New observations that are only imaginable today can also be foreseen. These include photon-less remote sensing techniques that could, for example, probe the structure and composition of the Earth below the surface, and new remote sensing devices based on quantum physics principles.

Operational weather and climate forecasting would benefit most from a smart constellation of diverse satellites in various orbits capable of working together with each other and ground-base observations. As an example, when a an emerging event such as a tropical storm, polar low or a volcanic eruption is noted by a ground-based instrument, GEO or sentinel satellite at L1, it could focus the attention of a web of sensors in low Earth orbit. The web would bring to bear active and passive observing technologies across a broad span of the electromagnetic spectrum in order to monitor the event's behaviour and thus better understand the mechanisms that control it. This concept is already in its early stages with today's efforts in formation flying of research and operational satellites. The movement toward autonomous operations would allow many more satellites to be controlled without substantially increasing the level of ground-based support.



***WMO's role***

The potential impacts satellite systems will have on WMO programmes stand as a lighthouse, with a very bright beacon. Satellite data are now continuously alerting to us a new world with quantum leaps in potential for expanded capabilities for observations to support all WMO programmes. The beacon is also a warning and increases in its intensity and repetition as we approach. The future is bright from the perspective of the space agencies. Plans are in place and technology will be providing tremendous possibilities. However, it is also recognized that a single space agency cannot alone provide all the necessary resources to meet all of WMO programmes' requirements. A corollary to that recognition is that WMO, as a unique and focused agency, must prepare for the future by acting as a catalyst for the development of international and integrated satellite data and product dissemination and processing services. There are three specific initiatives that WMO should systematically incorporate into its planning processes.

The first WMO initiative should be the establishment of an adequate data dissemination service for the 2025 era. WMO should initiate the necessary framework to provide a dissemination service whereby all the data from all satellites within the space-based component of the GOS would be available to all WMO Members in a timely fashion. This will require joint participation by all space agencies, and WMO Members. The underlying principle for the service should be availability not delivery. All the data all the time to all Members would unduly constrain any delivery system. Availability of all data based on application areas and associated user's requirements would serve to outline an optimized service capacity.

The second WMO initiative would provide the basis for a global approach to product development. It should be based on emerging technologies such as being demonstrated by the Virtual Laboratory for Education and Training in Satellite Meteorology. WMO should embrace the development of institutionalized programmes dedicated to producing specific and globally accepted products needed by NMHSs, and national and international decision makers for all appropriate application areas. The goal will be universally accepted products that can be prepared at designated processing centres. This development initiative would be the research component of the third initiative, a system of global processing centres for satellite products.

WMO Members would provide the resources for the third initiative at a regional level. International processing centres for the "operational" products globally agreed-upon would minimize duplication of processing power now found throughout many countries. Available resources could remain focused on new product developments. The international and integrated satellite data dissemination service would then make available the final products to WMO user.

By providing a basic suite of observations, international processing and global availability on a timely basis, WMO Members would be able to fully exploit the potential from the satellite systems of the next few decades. The opportunities better, more timely environmental information can bring to society are tremendous. The challenge is before WMO.

# ANNEX I

# PHYSICAL BASIS OF REMOTE METHODS OF DETERMINING HYDRO-METEOROLOGICAL AND GEOPHYSICAL PARAMETERS

## Visible, Infrared and Microwave Spectral Bands for Viewing the Earth Atmosphere

### *Atmospheric Absorption and Emission of Solar Radiation*

The absorption and emission of solar radiation in the atmosphere is accomplished by molecular storing of the electromagnetic radiation energy. Molecules can store energy in various ways. Any moving particle has kinetic energy as a result of its motion in space. This is known as translational energy. A molecule which is composed of atoms can rotate, or revolve, around an axis through its centre of gravity and, therefore, has rotational energy. The atoms of the molecule are bounded by certain forces in which the individual atoms can vibrate about their equilibrium positions relative to one another. The molecule, therefore, will have vibrational energy. These three molecular energy types (translational, rotational, and vibrational) are based on a rather mechanical model of the molecule that ignores the detailed structure of the molecule in terms of nuclei and electrons. It is possible, however, for the energy of a molecule to change due to a change in the energy state of the electrons of which it is composed. Thus, the molecule also has electronic energy. The energy levels are quantized and take discrete values only. As we have pointed out, absorption and emission of radiation takes place when the atoms or molecules undergo transitions from one energy state to another. In general, these transitions are governed by selection rules. Atoms exhibit line spectra associated with electronic energy levels. Molecules, however, also have rotational and vibrational energy levels that lead to complex band systems.

Solar radiation is mainly absorbed in the atmosphere by $O_2$, $O_3$, $N_2$, $CO_2$, $H_2O$, O, and N, although NO, $N_2O$, CO, and $CH_4$, which occur in very small quantities, also exhibit absorption spectra. Absorption spectra due to electronic transitions of molecular and atomic oxygen and nitrogen, and ozone occur chiefly in the ultraviolet (UV) region, while those due to the vibrational and rotational transitions of tri-atomic molecules such as $H_2O$, $O_3$, and $CO_2$ lie in the infrared region. There is very little absorption in the visible region of the solar spectrum. In Figure A1.1 the transmittance of the visible and near infrared reflectance spectrum from 0.4 to 2.5 μm is shown along with the spectral band coverage of current and planned polar orbiting imagers.

### *Atmospheric Absorption and Emission of Thermal Radiation*

Just as the sun emits electromagnetic radiation covering all frequencies, so does the earth. However, the global mean temperature of the earth-atmosphere system is only about 250 K. This temperature is obviously much lower than that of the sun's photosphere. As a consequence of Planck's law and Wien's displacement law discussed earlier, we find that the radiance (intensity) peak of the Planck function is smaller for the earth's radiation field and the wavelength for the radiance (intensity) peak of the earth's radiation field is longer. We call the energy emitted from the earth-atmosphere system thermal infrared (or terrestrial) radiation. In Figure A1.2, the earth radiance to space measured by an airborne interferometer is shown. We plotted the spectral distribution of radiance emitted by a blackbody source at various temperatures in the terrestrial range in terms of wavenumber. We saw that in some spectral regions the envelope of the emission spectrum is very close to the spectrum emitted from a blackbody with a temperature of about 295 K, which is about the temperature of the surface. This occurs in spectral regions where the atmosphere is transparent to that radiation. In other spectral regions the emission spectrum is close to the spectrum emitted from a blackbody with a temperature of about 220 K, which is about the temperature at the tropopause. This occurs in spectral regions where the atmosphere is opaque or absorbing to that radiation. In these spectral regions the atmosphere is said to be trapping the radiation. In Figure A1.3, the radiance from .1 µm to 10 cm emitted by the earth-atmosphere system transmitted to space is shown. Clearly, certain portions of the infrared radiation are trapped by various gases in the atmosphere.

Among these gases, carbon dioxide, water vapour, and ozone are the most important absorbers. Some minor constituents, such as carbon monoxide, nitrous oxide, methane, and nitric oxide, which are not shown, are relatively insignificant absorbers insofar as the heat budget of the earth-atmosphere is concerned. Carbon dioxide absorbs infrared radiation significantly in the 15 µm band from about 600 to 800 cm$^{-1}$. This spectral region also corresponds to the maximum intensity of the Planck function in the wavenumber domain. Water vapour absorbs thermal infrared in the 6.3 µm band from about 1200 to 2000 cm$^{-1}$ and in the rotational band (< 500 cm$^{-1}$). Except for ozone, which has an absorption band in the 9.6 µm region, the atmosphere is relatively transparent from 800 to 1200 cm$^{-1}$. This region is referred to as the atmospheric window. In addition to the 15 µm band, carbon dioxide also has an absorption band in the shorter wavelength of the 4.3 µm region. The distribution of carbon dioxide is fairly uniform over the global space, although there has been observational evidence indicating a continuous global increase over the past century owing to the increase of the combustion of the fossil fuels. This leads to the question of the earth's climate and possible climatic changes due to the increasing carbon dioxide concentration. Unlike carbon dioxide, however, water vapour and ozone are highly variable both with respect to time and the geographical location. These variations are vital to the radiation budget of the earth-atmosphere system and to long-term climatic changes.

In a clear atmosphere without clouds and aerosols, a large portion (about 50%) of solar energy transmits through the atmosphere and is absorbed by the earth's surface. Energy emitted from the earth, on the contrary, is absorbed largely by carbon dioxide, water vapour, and ozone in the atmosphere as evident in Figure A1.2. Trapping of thermal infrared radiation by atmospheric gases is typical of the atmosphere and is, therefore, called the atmospheric effect.

Solar radiation is referred to as short-wave radiation because solar energy is concentrated in shorter wavelengths with its peak at about 0.5 µm. Thermal infrared radiation from the earth's atmosphere is referred to as long-wave radiation because its maximum energy is in the longer wavelength at about 10 µm. The solar and infrared spectra are separated into two spectral ranges above and below about 4 µm, and the overlap between them is relatively insignificant. This distinction makes it possible to treat the two types of radiative transfer and source functions separately and thereby simplify the complexity of the transfer problem.

### *Atmospheric Absorption Bands in the Infrared Spectrum*

Inspection of high resolution spectroscopic data reveals that there are thousands of absorption lines within each absorption band. The fine structure of molecular absorption bands for the 320-380 cm$^{-1}$ is due to water vapour, and for the 680-740 cm$^{-1}$ region it is due to carbon dioxide. The optically active gases of the atmosphere, carbon dioxide, water vapour, and ozone are all tri-atomic molecules.

The water molecule forms an isosceles triangle that is obtuse. The 6.3 µm band has been identified with a fundamental vibrational mode of H2O. Two other fundamental vibrational modes are found close together in a band near 2.7 µm, i.e., on the short-wave side of the infrared spectral region.

The band covering the region from 800 to 400 cm$^{-1}$ shown in Figure A1.2 represents the purely rotational spectrum of water vapour. The water molecule forms an asymmetrical top with respect to rotation, and the line structure of the spectrum does not have the simplicity of a symmetrical rotator such as found in the $CO_2$ molecule. Close inspection shows that the absorption lines have no clear-cut regularity. The fine structure of the 6.3 µm band is essentially similar to that of the pure rotational band.

In the region between the two water vapour bands, i.e., between about 8 and 12 µm, the so-called atmospheric window, absorption is continuous and is primarily due to water vapour. Absorption by carbon dioxide is typically a small part of the total in this region. The overlap of water vapour with ozone in this region is insignificant in the computations of cooling rates since water vapour is important mainly in the lower atmosphere, while cooling due to ozone takes place primarily in the stratosphere and higher.

The ozone molecule is of the tri-atomic non-linear type with a relatively strong rotation spectrum. The three fundamental vibrational bands occur at wavelengths of 9.066, 14.27, and 9.597 µm. The very strong and moderately strong fundamentals combine to make the well-known 9.6 µm band of ozone. The other fundamental is well-masked by the 15 µm band of $CO_2$. The strong band of about 4.7 µm produced by the overtone and combination frequencies of $0_3$ vibrations is in a weak portion of the Planck energy distribution for the atmosphere. Note that the absorption bands of $0_3$ in the UV part of the solar spectrum are due to electronic transitions in the ozone molecule.

### *Atmospheric Absorption Bands in the Microwave Spectrum*

A brief summary of the absorption lines in the microwave spectral region follows. Molecular oxygen and water vapour are the major absorbing constituents here. Figure A1.4 shows the transmittance for frequencies below 300 GHz. Below 40 GHz only the weakly absorbing pressure broadened 22.235 GHz water vapour line is evident; this line is caused by transitions between the rotational states. At about 60 and 118.75 GHz, there are strong oxygen absorption lines due to magnetic dipole transitions. For frequencies greater than 120 GHz, water vapour absorption again becomes dominant due to the strongly absorbing line at 183 GHz.

A special problem in the use of microwave from a satellite platform is the emissivity of the earth surface. In the microwave region of the spectrum, emissivity values of the earth surface range from 0.4 to 1.0. This complicates interpretation of terrestrial and atmospheric radiation with earth surface reflections.

### *Remote Sensing Regions*

Several spectral regions are considered useful for remote sensing from satellites. Figure A1.5 summarizes this. Windows to the atmosphere (regions of minimal atmospheric absorption) exist near 4 µm, 10 µm, 0.3 cm, and 1 cm. Infrared windows are used for sensing the temperature of the earth surface and clouds, while microwave windows help to investigate the surface emissivity and the liquid water content of clouds. The $CO_2$ and $O_2$ absorption bands at 4.3 µm, 15 µm, 0.25 cm, and 0.5 cm are used for temperature profile retrieval; because these gases are uniformly mixed in the atmosphere in known portions they lend themselves to this application. The water vapour absorption bands near 6.3 µm, beyond 18 µm, near 0.2 cm, and near 1.3 cm are sensitive to the water vapour concentration in the atmosphere.

### Sounding the Atmosphere

Meteorological observations from space are made through the electromagnetic radiation leaving the atmosphere. Outgoing radiation from earth to space varies with wavelength for two reasons: (a) Planck function dependence on wavelength, and (b) absorption by atmospheric gases of differing molecular structure ($CO_2$, $H_2O$, $O_3$...). Figure A1.2 shows an observed infrared spectrum of the radiance to space. Around absorbing bands of the constituent gases of the atmosphere, vertical profiles of atmospheric parameters can be derived. Sampling in the spectral region at the centre of the absorption band yields radiation from the upper levels of the atmosphere (e.g., radiation from below has already been absorbed by the atmospheric gas); sampling in spectral regions away from the centre of the absorption band yields radiation from successively lower levels of the atmosphere. Away from the absorption band are the windows to the bottom of the atmosphere. The interferometer on this day observed surface temperatures of 296 K in the 11 µm window region of the spectrum and tropopause emissions of 220 K in the 15 µm absorption band. As the spectral region moves toward the centre of the $CO_2$ absorption band, the radiation temperature decreases due to the decrease of temperature with altitude in the lower atmosphere.

With careful selection of spectral bands in and around an absorbing band, it was suggested that multispectral observations can yield information about the vertical structure of atmospheric temperature and moisture. The concept of profile retrieval is based on the fact that atmospheric absorption and transmittance are highly dependent on the frequency of the radiation and the amount of the absorbing gas. At frequencies close to the centres of absorbing bands, a small amount of gas results in considerable attenuation in the transmission of the radiation; therefore most of the outgoing radiation arises from the upper levels of the atmosphere. At frequencies far from the centres of the band, a relatively large amount of the absorbing gas is required to attenuate transmission; therefore the outgoing radiation arises from the lower levels of the atmosphere. However, the derivation of temperature profiles is complicated by the fact that upwelling radiance sensed at a given wavelength arises from a rather large vertical depth (roughly 10 km) of the atmosphere. In addition, the radiance sensed in the neighbouring spectral regions arises from deep overlapping layers. This causes the radiance observations to be dependent and the inverse solution to the radiative transfer equation for temperature profiles to be non-unique. Differing analytical approaches and types of ancillary data are needed to constrain the solution in order to render temperature profiles.

There is no unique solution for the detailed vertical profile of temperature or an absorbing constituent because (a) the outgoing radiances arise from relatively deep layers of the atmosphere, (b) the radiances observed within various spectral channels come from overlapping layers of the atmosphere and are not vertically independent of each other, and (c) measurements of outgoing radiance possess errors. As a consequence, there are a large number of analytical approaches to the profile retrieval problem. The approaches differ both in the procedure for solving the set of spectrally independent radiative transfer equations (e.g., matrix inversion, numerical iteration) and in the type of ancillary data used to constrain the solution to insure a meteorologically meaningful result (e.g., the use of atmospheric covariance statistics as opposed to the use of an a priori estimate of the profile structure). There are some excellent papers in the literature which review the retrieval theory which has been developed over the past few decades (Fleming and Smith, 1971; Fritz *et al*, 1972; Rodgers, 1976; and Twomey, 1977).

There are several products that come under the category of soundings. They include the clear field of view (FOV) brightness temperatures, profile retrievals of temperature and moisture, as well as their layer mean values, lifted indices, CAPE, and thermal wind profiles. Additionally from the imager, there are derived product images of precipitable water and lifted indices. A brief description follows.

Vertical temperature profiles from sounder radiance measurements are produced at 41 pressure levels from 1000 to 0.1 hPa using a simultaneous, physical algorithm that solves for surface skin temperature, atmospheric temperature and atmospheric moisture. Also, estimates of surface emissivity and cloud pressure and amount are obtained as by products. The retrieval begins with a first guess temperature profile that is obtained from a space/time interpolation of fields provided by the numerical weather prediction models. Hourly surface observations are also used to provide surface boundary information. Soundings are produced from an nxn array of FOVs whenever more than 30% or more FOVs are determined to be either clear or "low cloud". The FOVs are "cloud filtered" and co-registered to achieve an homogeneous set. The location (latitude and longitude) of the retrieval is assigned to the mean position of the filtered sample. A "type" indicator is included in the archive to indicate if the sounding represents "clear" or "low cloud" conditions. A quality indicator is included to indicate if the retrieval has failed any internal quality checks.

Vertical moisture (specific humidity) profiles are obtained in the simultaneous retrieval, and thus are provided at the same levels as temperature. Since the radiance measurements respond to the total integrated moisture above a particular pressure level, the specific humidity is a differentiated quantity rather than an absolute retrieval. Geopotential height profiles are derived from the full resolution temperature and moisture profiles. Layer means of either temperature or moisture can also be derived. Ten or more precipitable water layers will be integrated from retrievals of specific humidity. These and the total precipitable water are provided in the standard archive.

Atmospheric stability indices (such as lifted index, CAPE, …) for each retrieval can also be derived. The lifted index is an estimate of atmospheric stability that represents the buoyancy that an air parcel would experience if mechanically lifted to the 500 hPa level. The lifted index expresses the difference in temperature between the ambient 500 hPa temperature and the temperature of the lifted parcel. A negative value (warmer than the environment) represents positive buoyancy (continued rising); whereas a positive value denotes stability (returning descent). The formulation used to derive LI is a thermodynamical relationship requiring the 500 hPa temperature and a mean pressure, temperature, and moisture for the boundary layer. These quantities are available from the retrieved profile. CAPE, another measure of atmospheric instability, can also be provided.

The geopotential height of the pressure level as derived from a 1000 hPa height analysis (from the NWP forecast supplemented with hourly data), a topography obtained from a library (10 minute latitude/longitude resolution) and the retrieved temperature and moisture profile are contained in the archive of each retrieval. Thickness can be calculated from this profile.

Thermal winds can be provided with each profile. These are derived from objective analyses of the geopotential profiles calculated with each retrieval. The objective analysis is a 3-dimensional, univariate recursive filter that uses as a background the same fields that provide the first guess to the temperature retrieval algorithm (NWP forecasts and surface analyses). The analyses are currently performed on a 1 degree latitude/longitude grid. Gradient winds are calculated using finite difference operators that involve surface-fitting over retrieval gridpoints centred at the gridpoint closest to each retrieval. Wind estimates are provided from 700 to 400 hPa. These winds are most useful in the extra-tropics over water.

Vertical temperature and moisture (specific humidity) profiles are obtained in a simultaneous physical retrieval (Ma *et al*. 1999). The overall quality of these products has been assessed in case studies and comparison of information content with forecast model backgrounds. Satellite sounder moisture contained in broad layers in the troposphere were compared to those inferred from radiosonde measurements. The total column water vapour RMS difference with respect to radiosondes for a one year period in 1996-97 has been reduced from 3.3 mm for the forecast first guess to 2.6 mm for the satellite retrievals, roughly an improvement of 20%. It is found that the satellite is typically drier than the radiosonde in the mean by 0.7 mm in the lowest layer (surface to 900 hPa) and more moist in the mean by 0.3 mm in the middle (900 to 700 hPa) as well as the upper (700 to 300 hPa) layers; the satellite improves upon the model first guess in all layers in the RMS difference by 0.1 to 0.4 mm (Menzel et al. 1998). The inferred atmospheric stability (such as lifted indices) of air parcels elevated to 500 hPa are found to be less stable in the mean by 0.6 C from those inferred from radiosondes with a RMS difference of 2.2 C. In the vicinity of radiosondes, the satellite depiction of atmospheric stability is improving upon numerical model first guess information. More significant is the fact that much larger differences (greater than 100%) between satellite soundings and model forecasts often occur over oceanic regions where radiosondes are unavailable; this indicates a much larger potential for satellite soundings to influence the forecast model in data sparse regions.

### Tracking Atmospheric Motions

Geostationary satellite imagery has been used as a source of wind observations since the launch of the first spin scan camera aboard the Application Technology Satellite (ATS 1) in December 1966. It was recognized immediately that features tracked in a time sequence of images could provide estimates of atmospheric motion. Historically, wind vectors have been produced from images of visible (for low level vectors) and infrared long-wave window radiation (for upper and low level vectors and some mid level vectors). More recently, in order to improve the coverage at mid levels and over cloud free areas, wind tracking has been applied to water vapour imagery (at 6.7 and 7.2 μm).

The basic elements of wind vector production have not changed since their inception. These are: (a) selecting a feature to track or a candidate target; (b) tracking the target in a time sequence of images to obtain a relative motion; (c) assigning a pressure height (altitude) to the vector; and (d) assessing the quality of the vector. Initially, these elements were done manually (even to the point of registering the images into a movie loop), but the goal has always been to automate procedures and reduce the time consuming human interaction.

To use a satellite image, the feature of interest must be located accurately on the earth. Since the earth moves around within the image plane of the satellite because of orbit effects, satellite orbit and attitude (where the satellite is and how it is oriented in space) must be determined and accounted for. This process of navigation is crucial for reliable wind vector determination. With the assistance of landmarks (stars) to determine the attitude (orbit) of the spacecraft over time, earth location accuracies within one visible pixel (one km) have been realized.

Operational winds from GOES are derived from a sequence of three navigated and earth located images taken 30 minutes apart. The winds are calculated by a three-step objective procedure. The initial step selects targets, the second step assigns pressure altitude, and the third step derives motion. Altitude is assigned based on a temperature/pressure derived from radiative transfer calculations in the environment of the target. Motion is derived by a pattern recognition algorithm that matches a feature within the "target area" in one image within a "search area" in the second image. For each target two winds are produced representing the motion from the first to the second, and from the second to the third image. An objective editing scheme is then employed to perform quality control: the first guess motion, the consistency of the two winds, the precision of the cloud height assignment, and the vector fit to an analysis are all used to assign a quality flag to the "vector" (which is actually the average of the two vectors).

WVMVs (imager band at 6.7 μm which sees the upper troposphere and sounder bands at 7.0 and 7.5 μm which see deeper into the troposphere) are derived by the same methods used with CMVs. Heights are assigned from the water vapour brightness temperature in clear sky conditions and from radiative transfer techniques in cloudy regions.

The basic concept behind the cloud drift winds is that some clouds are passive tracers of the atmosphere's motion in the vicinity of the cloud. However, clouds grow and decay with lifetimes which are related to their size. To qualify for tracking, the tracer cloud must have a lifetime that is long with respect to the time interval of the tracking sequence. The cloud must also be large compared with the resolution of the images. This implies a match between the spatial and temporal resolution of the image sequence. In order for a cloud to be an identifiable feature on an image, it generally must occupy an area at least ten to 20 pixels across (where pixel denotes a field of view). Hence for full resolution 1.0 km GOES visible data, the smallest clouds which can be used for tracking are 10 to 20 km across. Experience has shown that a time interval of approximately 3 to 10 min between images is necessary to track clouds of this size, with the shorter time interval being required for disturbed situations. For 4 km infrared images, the cloud tracers are about 100 km across, are tracked at half hour intervals, and represent an average synoptic scale flow. Water vapour images are found to hold features longer and are best tracked at hourly intervals (a longer time interval offers better accuracy of the tracer if the feature is not changing).

Cloud drift winds have been compared to radiosondes and found to be within 5 to 8 m/s rms (the better comparisons occur when the $CO_2$ height algorithm is used for height assignment). This is encouraging. However, it must be recognized that cloud winds are a limited and meteorologically biased data set. The cloud winds generally yield measurements from only one level (the uppermost layer of the cloud) and from regions where the air is going up (and producing clouds). Even with the water vapour motions enhancing the cloud drift winds, the meteorological bias persists. In summary, the satellite derived winds are best used over data sparse regions to fill in some of the data gaps between radiosonde stations and between radiosonde launch times.

## Investigating Clouds

### *Cloud Detection*

Clouds are generally characterized by higher reflectance and lower temperature than the underlying earth surface. As such, simple visible and infrared window threshold approaches offer considerable skill in cloud detection. However there are many surface conditions when this characterization of clouds is inappropriate, most notably over snow and ice. Additionally, some cloud types such as cirrus, low stratus, and roll cumulus are difficult to detect because of insufficient contrast with the surface radiance. Cloud edges cause further difficulty since the field of view is not always completely cloudy or clear. Multispectral approaches offer several opportunities for improved cloud detection so that many of these concerns can be mitigated. Finally, spatial and temporal consistency tests offer confirmation of cloudy or clear sky conditions.

The purpose of a cloud mask is to indicate whether a given view of the earth surface is unobstructed by clouds. The question of obstruction by aerosols is somewhat more difficult and will be addressed only in passing in this section. As many as eight single field of view (FOV) cloud mask tests are indicated for daylight conditions (given that the sensor has the appropriate spectral channels). Many of the single FOV tests rely on radiance (temperature) thresholds in the infrared and reflectance thresholds in the visible. These thresholds vary with surface emissivity, atmospheric moisture, aerosol content, and viewing scan angle.

#### *(a) IR Window Temperature Threshold and Difference Tests*

Several infrared window threshold and temperature difference techniques are practical. Thresholds will vary with moisture content of the atmosphere as the long-wave infrared windows exhibit some water vapour absorption. Threshold cloud detection techniques are most effective at night over water. Over land, the threshold approach is further complicated by the fact that the emissivity in the infrared window varies appreciably with soil and vegetation type. Over open ocean when the brightness temperature in the 11 μm channel ($T_{b11}$) is less than 270 K, we can safely assume a cloud is present. As a result of the relative spectral uniformity of surface emittance in the IR, spectral tests within various atmospheric windows (such as those at 8.6, 11, and 12 μm respectively) can be used to detect the presence of a cloud. Differences between $T_{b11}$ and $T_{b12}$ have been widely used for cloud screening with AVHRR measurements and this technique is often referred to as the split window technique.

The basis of the split window technique for cloud detection lies in the differential water vapour absorption that exists between the window channels (8.6 and 11 μm and 11 and 12 μm). These spectral regions are considered to be part of the atmospheric window, where absorption is relatively weak. Most of the absorption lines are a result of water vapour molecules, with a minimum occurring around 11 μm. Since the absorption is weak, $T_{b11}$ can be corrected for moisture absorption by adding the scaled brightness temperature difference of two spectrally close channels with different water vapour absorption coefficients; the scaling coefficient is a function of the differential water vapour absorption between the two channels. This approach has been used operationally for 6 years using 8.6 and 11 μm bandwidths from the NOAA-10 and NOAA-12 and the 11 and 12 μm bandwidths from the NOAA-11, with a coefficient independent of PW.

A disadvantage of the split window brightness temperature difference approach is that water vapour absorption across the window is not linearly dependent on PW, thus second order relationships are sometimes used. With the measurements at three wavelengths in the window, 8.6, 11 and 12 μm this becomes less problematic. The three spectral regions mentioned are very useful in determination of a cloud free atmosphere. This is because the index of refraction varies quite markedly over this spectral region for water, ice, and minerals common to many naturally occurring aerosols. As a result, the effect on the brightness temperature of each of the spectral regions is different, depending on the absorbing constituent.

A tri-spectral combination of observations at 8.6, 11 and 12 μm bands has been used recently for detecting cloud and cloud properties. The premise of the technique is that ice and water vapour absorption is larger in the window region beyond 10.5 μm; so that positive 8.6 minus 11 μm brightness temperature differences indicate cloud while negative differences, over oceans, indicate clear regions. The relationship between the two brightness temperature differences and clear sky have also been examined using collocated HIRS and AVHRR GAC global ocean data sets. As the atmospheric moisture increases, $T_{b8.6}$ - $T_{b11}$ decreases while $T_{b11}$ - $T_{b12}$ increases.

The short-wave infrared window channel at 3.9 μm also measures radiances in another window region near 3.5 - 4 μm so that the difference between $T_{b11}$ and $T_{b3.9}$ can also be used to detect the presence of clouds. At night the difference between the brightness temperatures measured in the short-wave (3.9 μm) and in the long-wave (11 μm) window regions $T_{b3.9}$-$T_{b11}$ can be used to detect partial cloud or thin cloud within the sensor field of view. Small or negative differences are observed only for the case where an opaque scene (such as thick cloud or the surface) fills the field of view of the sensor. Negative differences occur at night over extended clouds due to the lower cloud emissivity at 3.9 μm. Moderate to large differences result when a non-uniform scene (e.g., broken cloud) is observed. The different spectral response to a scene of non-uniform temperature is a result of Planck's law; the brightness temperature dependence on the warmer portion of the scene increasing with decreasing wavelength (the short-wave window Planck radiance is proportional to temperature to the thirteenth power, while the long-wave dependence is to the fourth power). Differences in the brightness temperatures of the long-wave and short-wave channels are small when viewing mostly clear or mostly cloudy scenes; however for intermediate situations the differences become large. The brightness temperature of the short-wave window channel is relatively insensitive to small amounts of cloud (compared to the long-wave window channel), thus making it the preferred channel for surface temperature determinations.

Cloud masking over land surface from thermal infrared bands is more difficult than ocean due to potentially larger variations in surface emittance. Nonetheless, simple thresholds can be established over certain land features. For example, over desert regions we can expect that $T_{b11}$ < 273 K indicates cloud. Such simple thresholds will vary with the ecosystem, season and time of day and are still under investigation. Brightness temperature difference testing can also be applied over land with careful consideration of variation in spectral emittance. For example, $T_{b11}$ - $T_{b8.6}$ has large negative values over daytime desert and is driven to positive differences in the presence of cirrus. Some land regions have an advantage over the ocean regions because of the larger number of surface observations, which include air temperature, and vertical profiles of moisture and temperature.

Infrared window tests at high latitudes are difficult. Distinguishing clear and cloud regions from satellite IR radiances is a challenging problem due to the cold surface temperatures. One cloud/surface discrimination algorithm is based upon brightness temperature differences between the AVHRR 3.7 and 11 μm channels and between the 11 and 12 μm channels. This cloud/surface discrimination algorithm is more effective over water surfaces than over inland snow-covered surfaces. A number of problems arse over inland snow-covered surfaces. First, the temperature contrast between the cloud and snow surface becomes especially small, leading to a small brightness temperature difference between the two infrared channels. Second, the AVHRR channels are not well-calibrated at extremely cold temperatures (< 200 K). Under clear sky conditions, surface radiative temperature inversions often exists. Thus, IR channels whose weighting function peaks down low in the atmosphere, will often have a larger brightness temperature than a window channel. For example $T_{b8.6}$ > $T_{b11}$ in the presence of an inversion. The surface inversion can also be confused with thick cirrus cloud, but this can be mitigated by other tests (e.g., the magnitude of $T_{b11}$ or $T_{b11}$-$T_{b12}$). Recent analysis of $T_{b11}$-$T_{b6.7}$ (the 6.7 μm water vapour channel peaks around 400 hPa) has shown large negative difference in winter time over the Antarctic Plateau and Greenland, which may be indicative of a strong surface inversion and thus clear skies.

### *(b) Reflectance Tests*

Visible threshold tests are best used in combination with infrared window observations; during daytime they can be combined as follows. Low reflectance measurements will result from thin cirrus cloud or cloud free conditions, the two being easily separable in the infrared window measurements by the large difference in the emitting temperature of the high cold cirrus and the warm underlying surface. High reflectance measurements result from thick clouds at all levels, and the infrared window brightness temperature provides a good indication of the cloud level. Intermediate reflectance data are subject to ambiguous interpretations since they result from a mixture of cloud and surface contributions. Visible data used in the determination of the cloud mask must be uncontaminated by sun glint.

The reflectance ratio takes advantage of the difference in reflection from cloud versus earth surface in wavelengths above and below 0.75 μm. Many earth surfaces are less reflecting below 0.75 μm than above (which is the basis of the vegetation index) , but clouds do not exhibit any great difference in reflectance. One version of the reflectance ratio test can use the 0.87 μm reflectance divided by 0.66 μm reflectance ($r_{.87}/r_{.66}$). With AVHRR data, this ratio has been found to be between 0.9 and 1.1 in cloudy regions. If the ratio falls within this range, cloud is indicated. New analyses suggest that the minimum value may need to be lowered to about 0.8, at least for some cases. For cloud-free ocean, the ratio is expected to be less than 0.75.

Clouds that are low in the atmosphere are often difficult to detect. The thermal contrast between clear sky and low cloud is small and sometimes undetectable by infrared techniques. Reflectance techniques, including the Reflectance Ratio Test can be applied during daylight hours. Use of a channel at 0.936 μm also offers help under daytime viewing conditions; this channel is strongly affected by low level moisture. When low clouds are present they obstruct the low level moisture, hence increasing the reflectance. A reflectance ratio of 0.936 over 0.865 μm, an atmospheric window with similar surface reflectance characteristics, also shows promise.

### *(c) Microwave Tests*

The brightness temperature of a lower tropospheric sounding microwave channel can be regressed against the brightness temperatures of several lower tropospheric infrared sounding channels for clear situations. Therefore, the microwave brightness temperature for a given FOV can be calculated from the observed infrared brightness temperatures. This will be valid in clear sky conditions only. If the observed microwave brightness temperature is greater than the calculated, it is indicative of cloud contamination in the infrared observations and the FOV should be classified accordingly.

### *(d) Resultant Cloud Mask*

All of the single pixel tests mentioned so far rely on thresholds. Thresholds are never global. There are always exceptions and the thresholds must be interpreted carefully. As one approaches the threshold limits, the certainty or confidence in the labelling becomes more and more uncertain. An individual confidence flag must be assigned and used with the single pixel test results to work towards a final determination.

Each threshold determination is “pass”, “conditional pass”, or “fail” along with a confidence assessment. Conditional pass involves those radiances that fall within an uncertainty region of the threshold. The uncertainty is a measure of instrument noise in that channel and the magnitude of the correction due to non-blackbody surface emissivity as well as atmospheric moisture and/or aerosol reflection contributions. The individual confidence flag indicates a one, two, or three sigma confidence level for each single pixel test result. The initial FOV obstruction determination is a sum of the squares of all the confidence flags and single pixel test results.

### *(e) Spatial Uniformity Tests To Find Cloud*

When the single field of view tests do not definitively determine an unobstructed FOV, spatial and temporal consistency tests are often useful. Temporal consistency compares composite previous 30 day clear sky radiances and yesterday's cloud mask to today's clear sky single pixel results. Spatial consistency checks neighbouring clear sky pixel radiances (same ecosystem). If any consistency test fails, the confidence in the final cloud/no cloud determination is reduced by 1 sigma level.

### ***Cloud Properties***

$CO_2$ slicing has been used to distinguish transmissive clouds from opaque clouds and clear sky using High resolution Infrared Radiation Sounder (HIRS) multispectral observations. With radiances around the broad $CO_2$ absorption band at 15 $\mu$m, clouds at various levels of the atmosphere can be detected. Radiances from near the centre of the absorption band are sensitive to only upper levels while radiances from the wings of the band (away from the band centre) see successively lower levels of the atmosphere. The $CO_2$ slicing algorithm determines both cloud level (and hence the associated cloud temperature) and cloud amount from radiative transfer principles. It has been shown to be especially effective for detecting thin cirrus clouds that are often missed by simple infrared window and visible approaches. Difficulties arise when the spectral cloud forcing (clear minus cloudy radiance for a spectral band) is less than the instrument noise.

## **Sensing the Earth Surface**

### ***Temperature***

Sea surface temperatures (SST) are derived using cloud free measurements in the infrared window with varying sensitivity to atmospheric moisture; this is often referred to as the split window technique. SSTs have been measured from satellites for nearly two decades by the Advanced Very High Resolution Radiometer (AVHRR) and, more recently, by the Along Track Scanning Radiometer (ATSR). Both series of satellites operate from sun-synchronous polar orbits about 850 km above ground. Compared with *in situ* measurements by ship and buoy, a great advantage of these satellite SST measurements is their global, nearly uniform coverage (except for clouds) with high spatial resolution (1 km). Significant progress has been made in meteorology, climatology, oceanography, and other branches of geoscience using the AVHRR long term record of high quality SST estimates.

Since 1993, GOES SST estimates have also been possible. Geostationary advantages are frequent sampling which results in a more complete map of SST as clouds move away. Changes in the scene temperature over a short period of time help to detect the presence clouds. The abundance of GOES observations enables stringent screening for cloud free observations while maintaining good spatial coverage of clear sky inferences of SST. Diurnal variations of SST over large areas are observed for the first time and their implications for numerical weather prediction and climate monitoring are being studied.

An integral part of the SST algorithm is the detection of cloud contamination. Correction for atmospheric water vapour absorption and re-emission is done with simple regression of radiance against buoy measurement. Most current SST algorithms do not treat explicitly, among other things, the effects of aerosol, non-blackbody sea surface, and the difference between satellite and buoy measurements (an area estimate of skin SST versus a point estimate of bulk SST). Nevertheless, agreement between satellite and buoy SST reports is within 0.6 C; better results are expected with improved multispectral cloud detection and accounting for reflection from the ocean surface.

Over land, accounting for the surface emissivity is critical. There is good experimental evidence that high spectral resolution infrared measurements (from interferometers and grating spectrometers) will enable determination of surface emissivity as well as temperature. The algorithm utilizes infrared window measurements that resolve on-absorption line and off-absorption line water vapour features to derive a surface temperature that minimizes the on-line and off-line surface emissivity variations.

### *Moisture*

Satellite remote sensing of soil moisture has not been very successful. Visible and infrared remote sensing see only the very surface layer of soil or of the vegetation canopy above the soil. The wetness of the surface may affect the reflected radiation and will certainly affect the soil temperature, but the changes caused by surface wetness are difficult to quantify and distinguish from other physical phenomena that can change soil brightness or temperature. To observe soil moisture over any reasonable soil depth (say 5 to 15 cm) requires remote sensing from microwave radiation. Microwave window bands can retrieve information from below the soil surface at a depth that is comparable to the wavelength of the microwave radiation. As the microwave instruments sample to longer and longer wavelength, which is required to measure soil moisture at significant depth, the antenna on the satellite has to increase in size and the field of view at the surface gets larger. To date, practical limitations on satellite antenna size has restricted microwave observations to 1 cm wavelength or less. This has allowed observation of surface soil moisture or surface wetness only. A further problem of microwave soil moisture is that overlaying vegetation interferes with the soil signal. This limitation restricts observations to less thickly vegetated regions or confines the signal to situations where there is a very large soil moisture signal, such as occurs under flood conditions or with extensive ponding after heavy rains.

### *Vegetation*

AVHRR measures reflected visible radiation in the 0.58 – 0.68 µm band (channel 1) and the 0.7 – 1.1 µm band (channel 2) of the Earth’s reflected radiation. This band pair, when combined in a quantity called Normalized Difference Vegetation Index (NDVI) has the property of being very sensitive to vegetation density and vigour. The NDVI is defined by:

$$\mathrm{NDVI} = (\mathrm{Ch2} - \mathrm{Ch1})/(\mathrm{Ch2} + \mathrm{Ch1})$$

where the Ch1 and Ch2 values can be expressed in terms of albedo or reflectance. The reflectance of green vegetation is generally low in the red part of the spectrum (Channel 1) and high in the near infrared (Channel 2) regions. As observed vegetation becomes senescent, in poor health, or sparse, the near infrared reflectance (Channel 2) declines and the NDVI decreases. So high values of NDVI denote dense green healthy vegetation. Low NDVI usually indicates stressed vegetation or scenes (arid and semiarid or wintertime) where the amount of green vegetation is low.

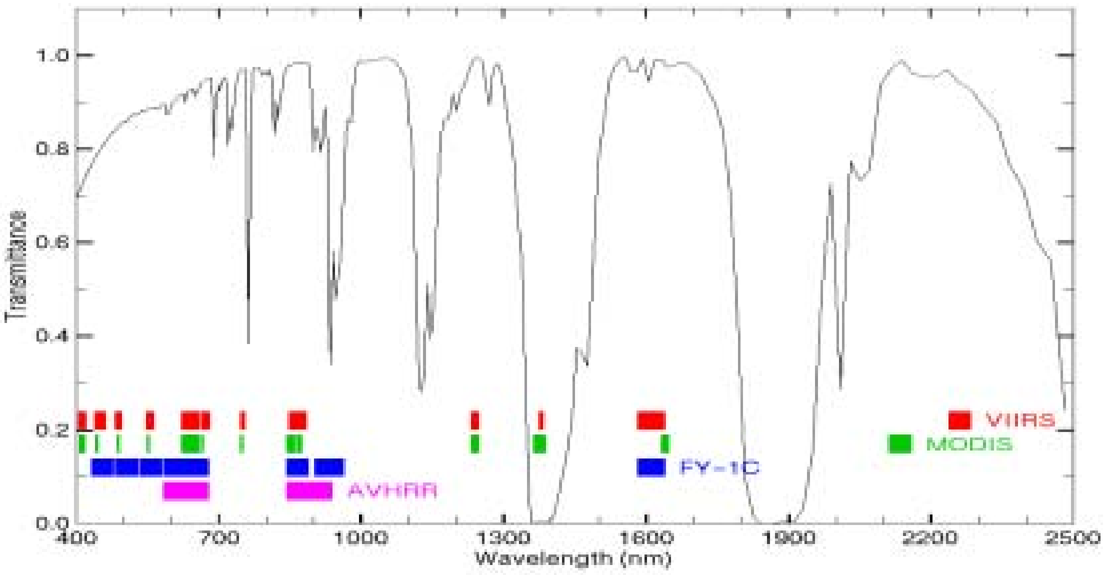
Since 1985 the AVHRR NDVI has been used to make weekly global maps of vegetation index as a means of routinely monitoring world-wide vegetation condition. Vegetation index maps are produced daily, then combined by compositing on the maximum vegetation index observed during the week, to provide a substantially cloud-free vegetation map at the end of the week. The weekly maps are the basis for a variety of other vegetation-related products such as stressed vegetation caused by drought and green vegetation fraction that is used to specify surface conditions in numerical weather prediction models.

## *Fires*

The most practical and economically feasible manner of monitoring the extent of burning associated with tropical deforestation and grassland management is through remote sensing. To date, many remote sensing methods have utilized multispectral data from the Multispectral Scanner (MSS) on Landsat-1, -2,. ., -5, the Thematic Mapper (TM) on Landsat-4 and -5, and the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar orbiters. A number of these techniques calculate vegetative indices (from measurements above and below the vegetation reflectance step function at 0.72 μm) in order to estimate deforestation areas. However, the extent of deforestation is usually underestimated, mostly due to the inability to distinguish between primary and secondary growth

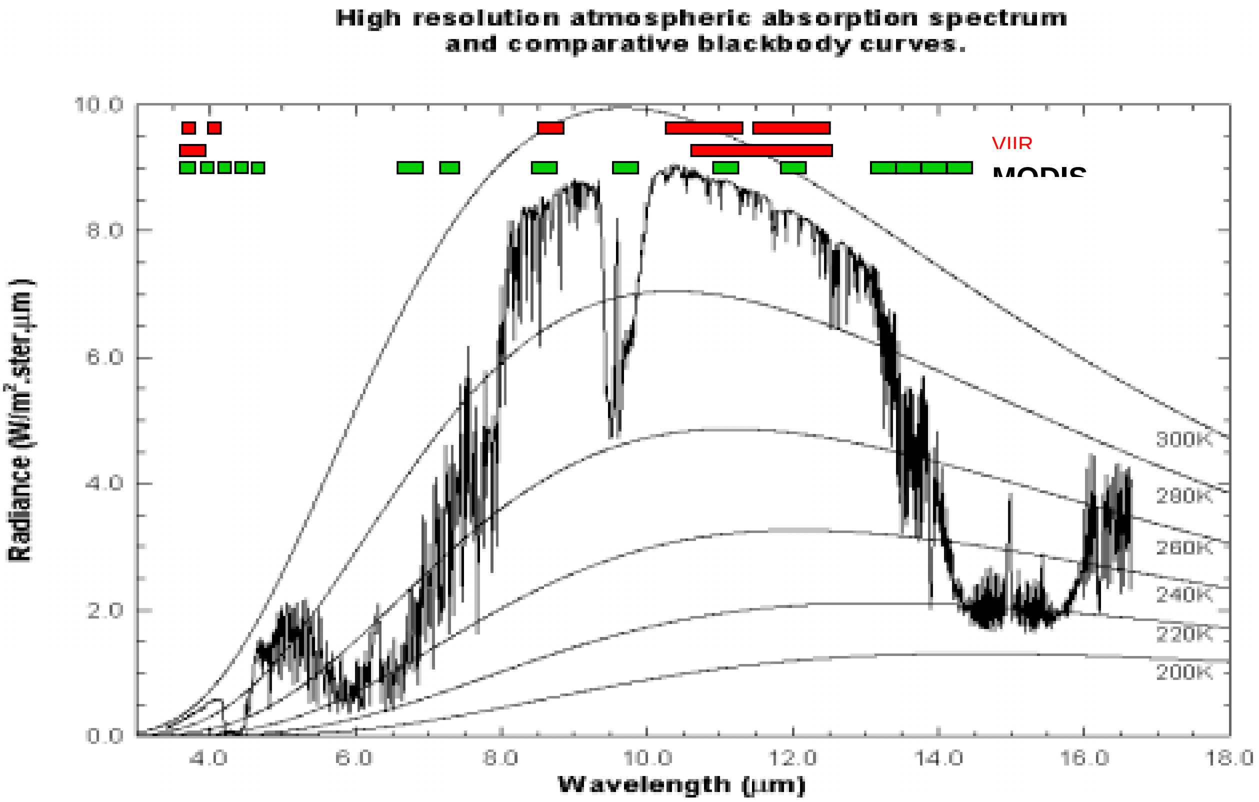
Another estimation of the rate of deforestation can be made by monitoring biomass burning. A technique utilizing the AVHRR 3.7 μm and 10.8 μm channels to detect subpixel resolution forest fires has been used successfully. The technique provides reasonable estimates of temperature and area of fires in 1 km pixels that are not saturated. Unfortunately, many of the pixels are saturated and it is difficult to monitor plume activity associated with these sub-pixel fires, since the NOAA polar orbiting satellite has only one day time pass over a given area. The Geostationary Operational Environmental Satellites offer continuous viewing and less pixel saturation. Furthermore, the fire plumes can be tracked in time to determine their motion and extent. Thus the GOES satellite offers a unique ability to monitor diurnal variations in fire activity and transport of related aerosols.

The different brightness temperature responses in the two infrared window channels can be used to estimate the temperature of the target fire as well as the sub-pixel area it covers. Typically, the difference in brightness temperatures between the two infrared windows at 3.9 and 11.2 μm is due to reflected solar radiation, surface emissivity differences, and water vapour attenuation. This normally results in brightness temperature differences of 2 - 4 K. Larger differences occur when one part of a pixel is substantially warmer than the rest of the pixel. The hotter portion will contribute more radiance in shorter wavelengths than in the longer wavelengths. The fire extent and temperature within a field of view can be determined by considering the upwelling thermal radiance values obtained by both channels. The observed short-wave window radiance also contains contributions due to solar reflection that must be distinguished from the ground emitted radiances; solar reflection is estimated from differences in background temperatures in the 4 and 11 μm channels. Once background temperature is estimated from nearby pixels, atmospheric correction for moisture and smoke is accomplished, and surface emissivity adjustments are made for short-wave and long-wave IR radiation, two equations and two unknowns (fire extent and temperature) result. Burning or smouldering fires are usually covered by clouds and smoke containing organic particles of varying sizes and shapes, necessitating a correction to the transmittance. Most of the smoke is composed of water vapour, but there are other constituents as well. The 11 μm channel is more affected by atmospheric water vapour than the 4 μm channel. With Nimbus-2 data, it was found that the water vapour correction for a moist atmosphere is approximately 4 K at 300 K for the 11 μm window and 2 K at 300 K for the 4 μm window. By calculating a linear regression relationship between the GOES visible brightness counts and GOES infrared window brightness temperature in a variety of haze conditions (approximately 50) and extrapolating to clear sky conditions, the Nimbus corrections were found to be appropriate for the GOES data studied. Emissivity investigations for vegetation similar to that found in the selva and cerrado suggest an emissivity for tropical rainforest of 0.96 in the 4 μm region and 0.97 in the 11 μm region, while the emissivity of dry grassland is .82 and .88 respectively.



O3 O2 H2O H2O H2O H2O CO2 H2O

**Figure A1.1:** The transmittance through the atmosphere of the visible and near infrared reflectance spectrum from 0.4 to 2.5 μm (spectral absorption gases are indicated below) is shown along with the spectral band coverage of current and planned polar orbiting imagers.



CO2 H2O O3 CO2

**Figure A1.2**: Infrared portion of the earth-atmosphere emitted radiation to space observed from an airborne Interferometer. Planck envelopes and line spectra (absorption gases are indicated below) as well as spectral band coverage of polar imagers MODIS and VIIRS are indicated. Sounders cover CO2 and H2O absorption bands and window regions.

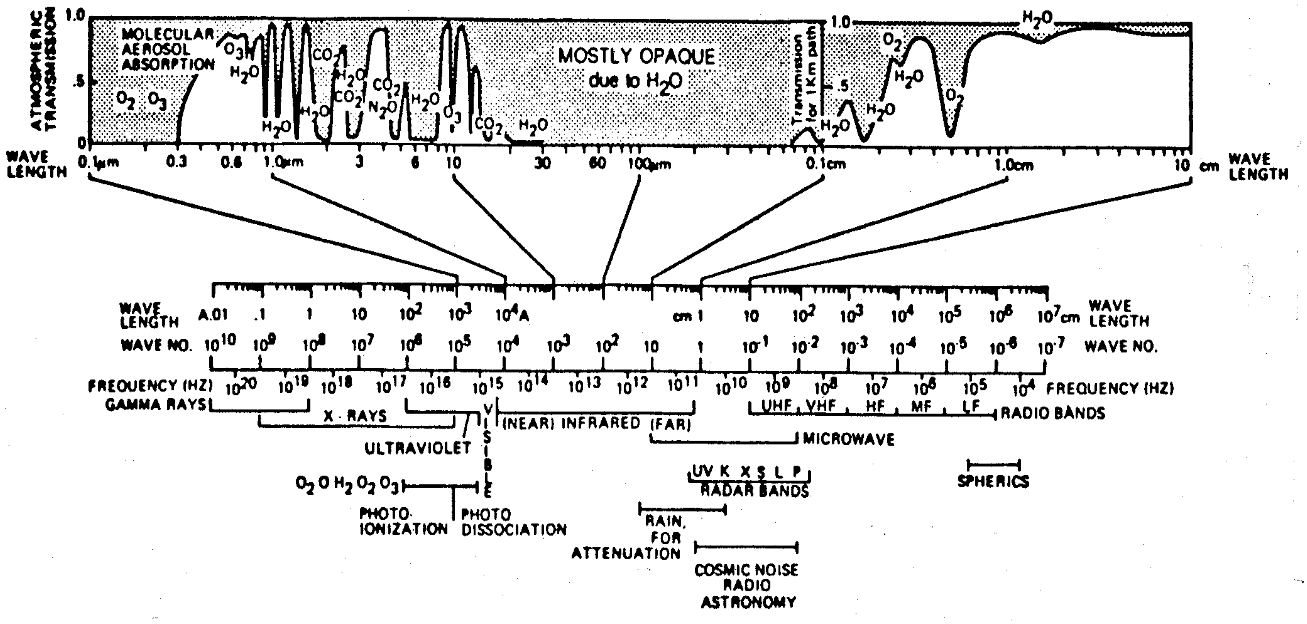


**Figure A1.3:** Atmospheric transmission characteristics from 0.1 µm to 10 cm showing the major absorption bands.

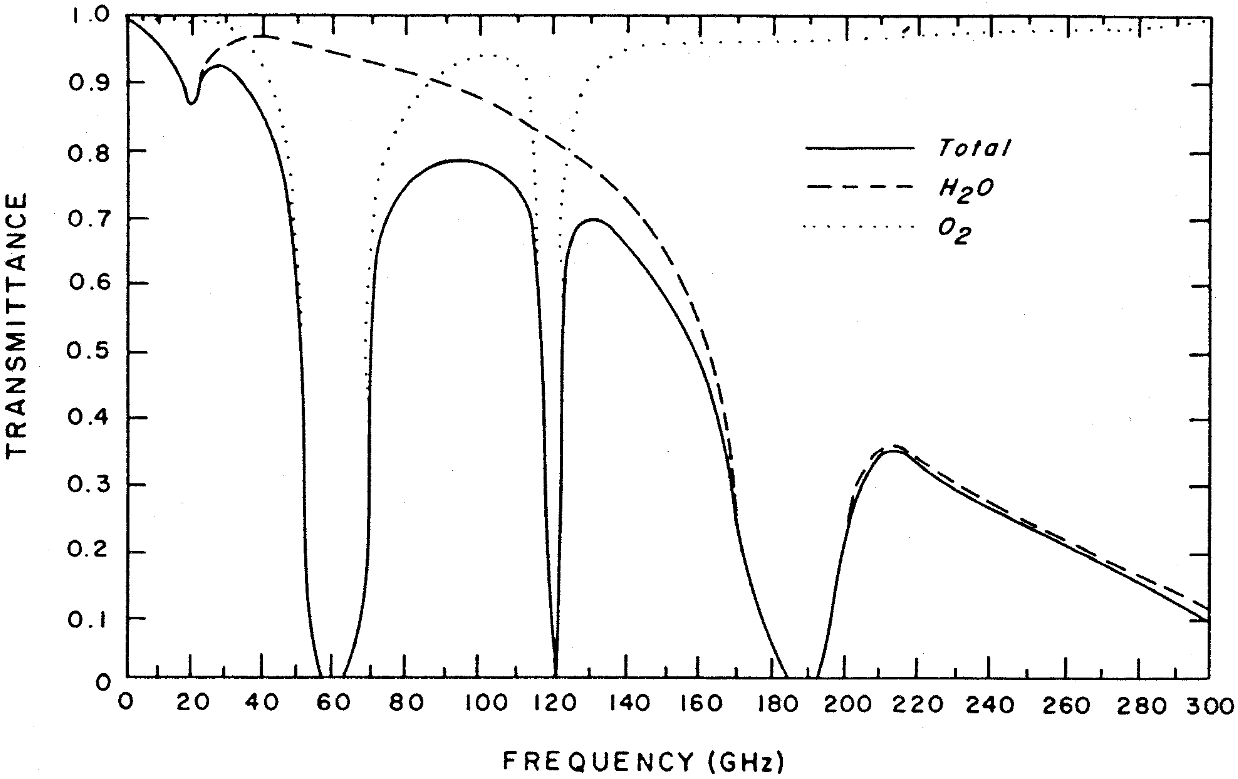


**Figure A1.4:** Atmospheric transmittance in the microwave region of the spectrum as a function of frequency.

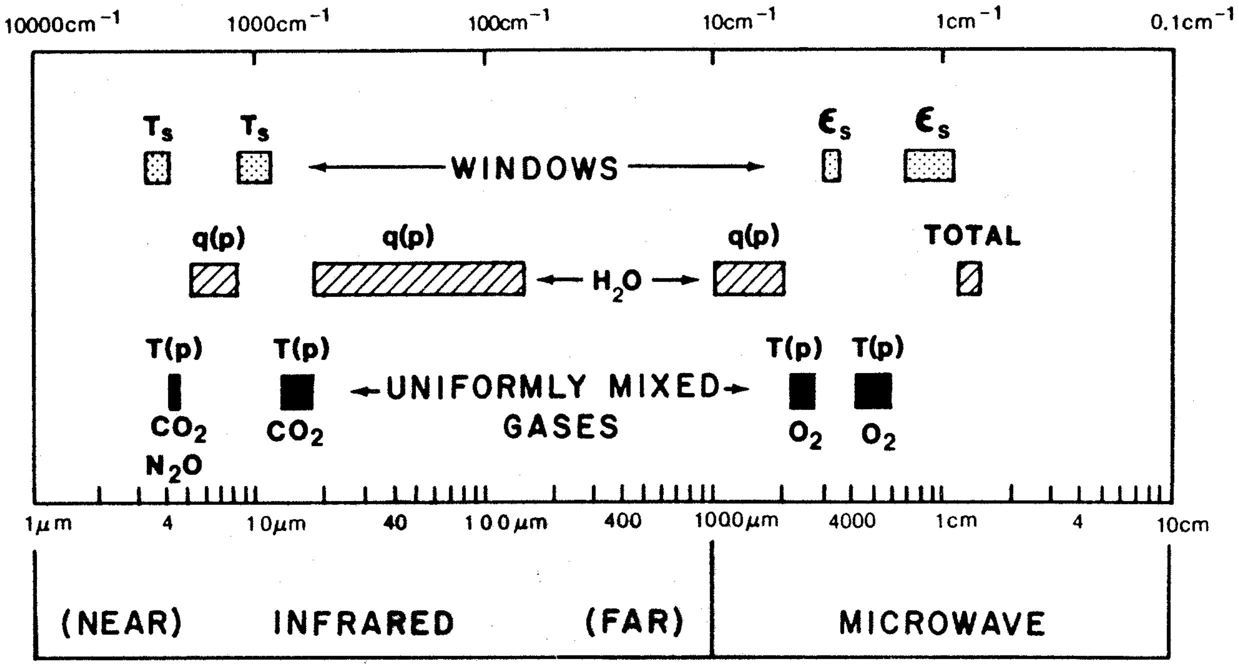


**Figure A1.5:** Spectral regions used for remote sensing of the earth atmosphere and surface from satellites. ε indicates emissivity, q denotes water vapour, and T represents temperature.

# ANNEX II

# OBSERVATIONAL REQUIREMENTS FOR WMO PROGRAMMES

## User rqmts Max/Min

*31-Jan-01*

### Application

### ACSYS

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air specific humidity (at surface) | 100 km | 500 km | | | 12 h | 24 h | 24 h | 48 h | 10 % | 20 % | Tentative | | WCRP |
| Air temperature (at surface) | 100 km | 500 km | | | 12 h | 24 h | 24 h | 48 h | 0.2 K | 0.5 K | Tentative | | WCRP |
| Cloud optical thickness | 100 km | 500 km | | | 12 h | 24 h | 24 h | 48 h | 15 % | 30 % | Reasonable | | WCRP |
| Cloud top height | 100 km | 500 km | | | 12 h | 24 h | 24 h | 48 h | 0.5 km | 1 km | Reasonable | | WCRP |
| Ice thickness 200 km | 500 km | | | 7 d | 30 d | 30 d | 90 d | 1 m | 2 m | Tentative | WCRP | | |
| Ice-sheet topography | 0.1 km | 0.5 km | | | 10 y | 15 y | 30 d | 90 d | 5 cm (vert.) | 10 cm | Tentative | | WCRP |
| Iceberg fractional cover | 1 km | 10 km | | | 365 d | 1500 d | 30 d | 90 d | 10 % (Max) | 20 % | Tentative | | WCRP |
| Iceberg height 1 km | 10 km | | | 365 d | 1500 d | 30 d | 90 d | 1 m | 3 m | Tentative | WCRP | | |
| Sea surface temperature | 25 km | 100 km | | | 24 h | 48 h | 720 h | 1440 h | 0.5 K | 2 K | Reasonable | | WCRP |
| Sea-ice cover 25 km | 100 km | | | 1 d | 7 d | 7 d | 30 d | 5 % (Max) | | 10 % | Reasonable | | WCRP |
| Sea-ice surface temperature | 100 km | 500 km | | | 12 h | 24 h | 24 h | 48 h | 1 K | 2 K | Reasonable | | WCRP |
| Snow cover 1 km | 25 km | | | 1 d | 5 d | 7 d | 30 d | 10 % (Max) | | 20 % | Reasonable | | WCRP |
| Snow water equivalent | 10 km | 25 km | | | 1 d | 5 d | 7 d | 30 d | 5 mm | 20 mm | Tentative | | WCRP |
| Wind vector over sea surface (horizontal) | 25 km | 100 km | | | 12 h | 24 h | 720 h | 1440 h | 1 m/s | 5 m/s | Reasonable | | WCRP |

### Aero Met

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atmospheric temperature profile - Lower troposphere (LT) | 50 km | 100 km | 0.15 | 0.6 km | 1 h | 3 h | 1 h | 2 h | 2 K | 5 K | Firm | | WMO |
| Cloud drop size (at cloud top) | 50 km | 100 km | | | 1 h | 3 h | 1 h | 2 h | 15 µm | 30 µm | Firm | gnd - Fl 260 | WMO |
| Cloud ice profile - Higher troposphere (HT) | 50 km | 100 km | 0.15 | 0.6 km | 1 h | 3 h | 1 h | 2 h | 10 % | 25 % | Firm | | WMO |
| Cloud ice profile - Lower troposphere (LT) | 50 km | 100 km | 0.15 | 0.6 km | 1 h | 3 h | 1 h | 2 h | 10 % | 25 % | Firm | | WMO |
| Cloud water profile (< 100 µm) - Lower troposphere (LT) | 50 km | 100 km | 0.15 | 0.6 km | 1 h | 3 h | 1 h | 2 h | 10 % | 25 % | Firm | | WMO |
| Cloud water profile (> 100 µm) - Lower troposphere (LT) | 50 km | 100 km | 0.15 | 0.6 km | 1 h | 3 h | 1 h | 2 h | 10 % | 25 % | Firm | | WMO |
| Specific humidity profile - Lower troposphere (LT) | 50 km | 100 km | 0.15 | 0.6 km | 1 h | 3 h | 1 h | 2 h | 5 % | 10 % | Firm | | WMO |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind profile (horizontal component) - Higher troposphere | 50 km | 100 km | 0.15 | 0.6 km | 0.0833 | 0.167 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | Near steep topography or jet streams min requirements for vertical gradient information 5m/s1000ft | WMO |
| Wind profile (horizontal component) - Lower stratosphere | 50 km | 100 km | 0.15 | 0.6 km | 0.0833 | 0.167 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | Near steep topography or jet streams min requirements for vertical gradient information 5m/s1000ft | WMO |
| Wind profile (horizontal component) - Lower troposphere | 50 km | 100 km | 0.15 | 0.6 km | 0.0833 | 0.167 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | Near steep topography or jet streams min requirements for vertical gradient information 5m/s1000ft | WMO |
| **Agricultural Meteorology** | | | | | | | | | | | | | |
| Fire area | 0.01 | 10 km | | | 0.25 d | 1 d | 0.0416 | 0.25 d | 10 % | 20 % | Reasonable | Saturation lvl not reached before fire detected | WMO |
| Fire temperature | 0.01 | 10 km | | | 0.25 d | 1 d | 0.0416 | 0.25 d | 50 K | 200 K | Reasonable | Saturation lvl not reached before fire detected | WMO |
| Land cover 100 m | 1000 m | | | 1 y | 2 y | 10 d | 30 d | 10 classes | | 4 classes | Reasonable | Land utilization map composition | WMO |
| Land surface temperature | 0.1 km | 10 km | | | 1 h | 72 h | 3 h | 24 h | 0.3 K | 2 K | Reasonable | Detection of areas affected by frost; drought eval | WMO |
| Leaf Area Index (LAI) | 0.01 | 10 km | | | 5 d | 7 d | 1 d | 5 d | 5 % (Max) | 10 % | Reasonable | Evapotranspiration estimation; crop productivity | WMO |
| Normalized Differential Vegetation Index (NDVI) | 1 km | 10 km | | | 1 d | 7 d | 1 d | 5 d | 5 % (Max) | 10 % | Reasonable | Event detection; crop state estimation | WMO |
| Photosynthetically Active Radiation (PAR) | 5 km | 100 km | | | 0.0416 | 7 d | 1 d | 5 d | 10 W/m2 | 50 W/m2 | Reasonable | Photosynthesis estimation; crop procductivity eval | WMO |
| Precipitation index (daily cumulative) | 10 km | 50 km | | | 24 h | 72 h | 24 h | 48 h | 2 mm/d | 10 mm/d | Reasonable | Evaluation of soil moisture and avail to plants | WMO |
| Snow cover | 1 km | 10 km | | | 5 d | 7 d | 1 d | 5 d | 2 % (Max) | 10 % | Reasonable | Evaluation of crop wintering | WMO |
| Snow water equivalent | 1 km | 10 km | | | 7 d | 30 d | 1 d | 7 d | 5 mm | 500 mm | Reasonable | Evaluation of soil water storage in spring | WMO |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soil moisture | 0.1 km | 1 km | | | 1 d | 7 d | 1 d | 5 d | 10 g/kg | 50 g/kg | Reasonable | Crop state and productivity estimation | WMO |
| Soil type 0.1 km | 10 km | | | 1 y | 2 y | 10 d | 30 d | 15 classes | | 5 classes | Reasonable | Crop state estimation, soil moisture evaluation | WMO |
| Vegetation type 50 m | 500 m | | | 30 d | 60 d | 1 d | 7 d | 30 classes | | 5 classes | Reasonable | Land utilization map composition; crop eval | WMO |

## AOPC

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atmospheric temperature profile - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 2 km | 3 km | 3 h | 6 h | 3 h | 12 h | 1 K | 3 K | Firm | Signal size in B.D. Santer et al., 1999 JGR, 104, 6305-6333, supports this need. | GCOS |
| Atmospheric temperature profile - Higher troposphere (HT) | 100 km | 500 km | 0.1 km | 0.5 km | 3 h | 6 h | 3 h | 12 h | 0.5 K | 2 K | Firm | Signal size in B.D. Santer et al., 1999 JGR, 104, 6305-6333, supports this need. | GCOS |
| Atmospheric temperature profile - Lower stratosphere (LS) | 100 km | 500 km | 0.1 km | 0.5 km | 3 h | 6 h | 3 h | 12 h | 0.5 K | 2 K | Firm | Signal size in B.D. Santer et al., 1999 JGR, 104, 6305-6333, supports this need. | GCOS |
| Atmospheric temperature profile - Lower troposphere (LT) | 100 km | 500 km | 0.1 km | 2 km | 3 h | 6 h | 3 h | 12 h | 0.5 K | 2 K | Firm | Signal size in B.D. Santer et al., 1999 JGR, 104, 6305-6333, supports this need. | GCOS |
| Cloud cover 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 10 % (Max) | | 20 % | Firm | Accuracies should apply to low and high clouds separately. See Hansen et a (1995) in T.R. Karl (Ed.) 1995 Long term climate monitoring by the Global Climate Observing System. Kluwer. Also, Climatic Change 31, Nos. 2-4. | GCOS |
| Cloud ice profile - Total column | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | Missing | Missing | Firm | | GCOS |

| Application Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cloud top height | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 0.5 km | 2 km | Firm | Accuracy should be 5hPa (10hPa - Min). Hansen et al. (1995) in T.R. Karl (Ed.) 1995 Long term climate monitoring by the Global Climate Observing System. Kluwer. Also, Climatic Change 31, Nos. 2-4. | GCOS |
| Cloud top temperature | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 0.3 K | 0.6 K | Firm | Hansen et al. (1995) in T.R. Karl (Ed.) 1995 Long term climate monitoring by the Global Climate Observing System. Kluwer. Also, Climatic Change 31, Nos. 2-4. | GCOS |
| Cloud water profile (< 100 µm) - Total column | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | Missing | Missing | Firm | | GCOS |
| Cloud water profile (> 100 µm) - Total column | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | Missing | Missing | Firm | | GCOS |
| Downwelling solar radiation at TOA | | | | | 0.125 d | 7 d | 0.125 | 1 d | 1 W/m2 | 2 W/m2 | Firm | See Hansen et al. (1995) in T.R. Karl (Ed.) 1995 Long term climate monitoring by GCOS. Kluwer. Also, Climatic Change 31, Nos. 2-4. Climate forcing by strat O3, need low bias & spectrally-resolved (~1nm) solar irradiance. UV monitoring may need higher freq. | GCOS |
| Land surface temperature | 100 km | 500 km | | | 3 h | 6 h | 3 h | 6 h | 1 K | 3 K | Firm | Signal size supports this need. See P.D. Jones et al. 1999. Surface air temperature and its changes over the past 150 years. Rev. Geophys., in press. | GCOS |
| Normalized Differential Vegetation Index (NDVI) | 100 km | 500 km | | | 168 d | 720 d | 10 d | 30 d | 10 % (Max) | 20 % | Firm | | GCOS |

| Application<br>Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outgoing long-wave radiation at TOA | 200 km | 500 km | | | 3 h | 6 h | 3 h | 24 h | 5 W/m2 | 10 W/m2 | Firm | Accuracy is consistent with Hansen et al. (1995) in T.R. Karl (Ed.) 1995 Long term climate monitoring by the Global Climate Observing System. Kluwer. Also, Climatic Change 31, Nos. 2- | GCOS |
| 4. | | | | | | | | | | | | | |
| Outgoing short-wave radiation at TOA | 200 km | 500 km | | | 3 h | 6 h | 3 h | 24 h | 5 W/m2 | 10 W/m2 | Firm | Accuracy is consistent with Hansen et al. (1995) in T.R. Karl (Ed.) 1995 Long term climate monitoring by the Global Climate Observing System. Kluwer. Also, Climatic Change 31, Nos. 2-4. | GCOS |
| Precipitation rate at the ground (liquid) | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 0.6 mm/h | 2 mm/h | Firm | | GCOS |
| Precipitation rate at the ground (solid) | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 0.6 mm/h | 2 mm/h | Firm | | GCOS |
| Sea surface temperature | 100 km | 500 km | | | 24 h | 72 h | 3 h | 12 h | 0.3 K | 1 K | Firm | Signal size supports this need. See P.D. Jones et al. 1999. Surface air temperature and its changes over the past 150 years. Rev. Geophys., in press. | GCOS |
| Sea-ice cover 100 km | 500 km | | | 1 d | 7 d | 0.125 | 1 d | 10 % (Max) | | 20 % | Firm | Decadal changes may be of order 5% (Walsh, 1995 in T.R. Karl (Ed.) 1995 Long term climate monitoring by the Global Climate Observing System. Kluwer. Also, Climatic Change 31, Nos. 2-4.) | GCOS |
| Significant wave height | 100 km | 250 km | | | 3 h | 6 h | 3 h | 12 h | 0.5 m | 2 m | Firm | | GCOS |

| Application Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Snow cover 100 km | 500 km | | | 1 d | 7 d | 0.125 | 1 d | 10 % (Max) | | 20 % | Firm | Decadal changes may be of order 5% (N. Nicholls et al. 1996 Observed Climate Variability and Change. Chapter 2 of Climate Change 1995 (IPCC Second Assessment). | GCOS |
| Snow water equivalent | 100 km | 500 km | | | 1 d | 7 d | 0.125 | 1 d | 5 mm | 10 mm | Firm | | GCOS |
| Specific humidity profile - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 3 h | 6 h | 3 h | 12 h | 5 % | 10 % | Firm | Signal sizes in section 3.3.7 of N. Nicholls et al. 1996 Observed Climate Variability and Change. Chapter 2 of Climate Change 1995 (IPCC Second Assessment). support this need. | GCOS |
| Specific humidity profile - Higher troposphere (HT) | 100 km | 500 km | 0.5 km | 1 km | 3 h | 6 h | 3 h | 12 h | 5 % | 10 % | Firm | Signal sizes in section 3.3.7 of N. Nicholls et al. 1996 Observed Climate Variability and Change. Chapter 2 of Climate Change 1995 (IPCC Second Assessment). support this need. | GCOS |
| Specific humidity profile - Lower stratosphere (LS) | 100 km | 500 km | 0.5 km | 1 km | 3 h | 6 h | 3 h | 12 h | 5 % | 10 % | Firm | Signal sizes in section 3.3.7 of N. Nicholls et al. 1996 Observed Climate Variability and Change. Chapter 2 of Climate Change 1995 (IPCC Second Assessment). support this need. | GCOS |
| Specific humidity profile - Lower troposphere (LT) | 100 km | 500 km | 0.1 km | 2 km | 3 h | 6 h | 3 h | 12 h | 5 % | 10 % | Firm | Signal sizes in section 3.3.7 of N. Nicholls et al. 1996 Observed Climate Variability and Change. Chapter 2 of Climate Change 1995 (IPCC Second Assessment). support this need. | GCOS |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specific humidity profile - Total column | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 1000 kg/m2 | 2500 | Firm | | GCOS |
| Wind profile (horizontal component) - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 2 km | 3 km | 3 h | 6 h | 3 h | 12 h | 3 m/s | 7 m/s | Firm | 1m/s is typically several % of climatological wind strength aloft. | GCOS |
| Wind profile (horizontal component) - Higher troposphere | 100 km | 500 km | 0.5 km | 1 km | 3 h | 6 h | 3 h | 12 h | 2 m/s | 5 m/s | Firm | 1m/s is typically several % of climatological wind strength aloft. | GCOS |
| Wind profile (horizontal component) - Lower stratosphere | 100 km | 500 km | 0.5 km | 1 km | 3 h | 6 h | 3 h | 12 h | 2 m/s | 5 m/s | Firm | 1m/s is typically several % of climatological wind strength aloft. | GCOS |
| Wind profile (horizontal component) - Lower troposphere | 100 km | 500 km | 0.1 km | 2 km | 3 h | 6 h | 3 h | 12 h | 2 m/s | 5 m/s | Firm | 1m/s is typically several % of climatological wind strength aloft. | GCOS |
| Wind vector over sea surface (horizontal) | 100 km | 500 km | | | 3 h | 6 h | 3 h | 12 h | 2 m/s | 5 m/s | Firm | Trend signal shown in Fig. 3.19 of N. Nicholls et al. 1996 Observed Climate Variability and Change. Chapter 2 of Climate Change 1995 (IPCC Second Assessment) supports this need. | GCOS |

## Atmospheric chemistry

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerosol profile - Higher stratosphere & mesosphere (HS & M | 50 km | 500 km | 1 km | 10 km | 6 h | 24 h | 12 h | 168 h | 10 % | 20 % | Firm | Ozone chem, Rad climatology | WMO |
| Aerosol profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 5 km | 6 h | 24 h | 12 h | 168 h | 10 % | 20 % | Firm | Ozone chem, Rad climatology | WMO |
| Aerosol profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 5 km | 6 h | 24 h | 12 h | 168 h | 10 % | 20 % | Firm | Ozone chem, Rad climatology | WMO |
| Aerosol profile - Lower troposphere (LT) | 50 km | 500 km | 1 km | 5 km | 6 h | 24 h | 12 h | 168 h | 5 % | 20 % | Firm | Ozone chem, Rad climatology | WMO |
| Cloud imagery | 100 km | 200 km | | | 3 h | 12 h | 72 h | 72 h | | | Firm | Rad climatology | WMO |
| Ozone profile - Higher stratosphere & mesosphere (HS & | 50 km | 500 km | 1 km | 5 km | 3 h | 48 h | 72 h | 168 h | 5 % | 25 % | Firm | Strat chem/clim, Rad effects/clim, Ozone chem | WMO |
| Ozone profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 5 km | 3 h | 168 h | 72 h | 168 h | 3 % | 20 % | Firm | Trop chem/clim, Rad effects/clim, Ozone chem | WMO |
| Ozone profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 5 km | 3 h | 168 h | 72 h | 168 h | 3 % | 20 % | Firm | Oxid cap, Rad effects/clim, Strat climat, O3 chem | WMO |

| Application Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ozone profile - Lower troposphere (LT) | 50 km | 500 km | 1 km | 5 km | 3 h | 168 h | 72 h | 168 h | 3 % | 20 % | Firm | Trop chem/clim, Rad effects/clim, Oxid cap | WMO |
| Ozone profile - Total column | 25 km | 100 km |  |  | 6 h | 48 h | 3 h | 168 h | 6 DU | 20 DU | Firm | UVB pred/anal, Dynamics | WMO |
| Specific humidity profile - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 1 km | 5 km | 12 h | 72 h | 72 h | 168 h | 5 % | 20 % | Firm | Atmos dynamics, Rad clim, Ozone chem, 5% RH | WMO |
| Specific humidity profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 5 km | 12 h | 72 h | 72 h | 168 h | 5 % | 20 % | Firm | Oxid cap, Atm dyncs, Rad climat, Ozone chem, 5% RH | WMO |
| Specific humidity profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 5 km | 12 h | 72 h | 72 h | 168 h | 5 % | 20 % | Firm | Oxid cap, Atm dyncs, Rad climat, Ozone chem, 5% RH | WMO |
| Specific humidity profile - Lower troposphere (LT) | 50 km | 500 km | 1 km | 5 km | 6 h | 72 h | 72 h | 168 h | 5 % | 20 % | Firm | Oxid cap, Atm dyncs, Rad clim, Ozone chem, 10% RH | WMO |
| Trace gas profile BrO - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile BrO - Higher troposphere (HT) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile BrO - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile CFC 11 - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Rad climatology, Atmos dynamics | WMO |
| Trace gas profile CFC 11 - Higher troposphere (HT) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Rad climatology | WMO |
| Trace gas profile CFC 11 - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Atmos dynamics | WMO |
| Trace gas profile CFC 12 - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Rad climatology, Atmos dynamics | WMO |
| Trace gas profile CFC 12 - Higher troposphere (HT) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Rad climatology | WMO |
| Trace gas profile CFC 12 - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Atmos dynamics | WMO |
| Trace gas profile CH4 - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 2 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile CH4 - Higher troposphere (HT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 2 % | 10 % | Firm | Oxidizing cap, Atm dyncs, 03 chem, Rad clim | WMO |
| Trace gas profile CH4 - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 2 % | 10 % | Firm | Oxidizing cap, Atm dyncs, O3 chem, Rad clim | WMO |
| Trace gas profile CH4 - Lower troposphere (LT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 2 % | 10 % | Firm | C budget, bdry | WMO |
| Trace gas profile ClO - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |

| **Application** Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trace gas profile ClO - Higher troposphere (HT) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile ClO - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile ClONO2 - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile ClONO2 - Higher troposphere (HT) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile ClONO2 - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile CO - Higher troposphere (HT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap | WMO |
| Trace gas profile CO - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap | WMO |
| Trace gas profile CO - Lower troposphere (LT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap | WMO |
| Trace gas profile CO2 - Lower troposphere (LT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 2 % | 5 % | Firm | C budget, bdry | WMO |
| Trace gas profile HCl - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 2 % | 5 % | Firm | Ozone chem | WMO |
| Trace gas profile HCl - Higher troposphere (HT) | 100 km | 500 km | 1 km | 1.5 km | 6 h | 24 h | 72 h | 168 h | 2 % | 5 % | Firm | Ozone chem | WMO |
| Trace gas profile HCl - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 2 % | 5 % | Firm | Ozone chem | WMO |
| Trace gas profile HNO3 - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Atmos dynamics, Ozone chem | WMO |
| Trace gas profile HNO3 - Higher troposphere (HT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem, Atm dyncs | WMO |
| Trace gas profile HNO3 - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem, Atm dyncs | WMO |
| Trace gas profile HNO3 - Lower troposphere (LT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem, Atm dyncs | WMO |
| Trace gas profile N2O - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 2 % | 20 % | Firm | Atmos dynamics, Rad clim, Ozone chem | WMO |
| Trace gas profile N2O - Higher troposphere (HT) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 2 % | 20 % | Firm | Rad climatology, Atm dyncs, Ozone chem | WMO |
| Trace gas profile N2O - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 2 % | 20 % | Firm | Rad climatology, Atm dyncs, Ozone chem | WMO |
| Trace gas profile NO - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile NO - Higher troposphere (HT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem | WMO |
| Trace gas profile NO - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem | WMO |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trace gas profile NO - Lower troposphere (LT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem | WMO |
| Trace gas profile NO2 - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Ozone chem | WMO |
| Trace gas profile NO2 - Higher troposphere (HT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem | WMO |
| Trace gas profile NO2 - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem | WMO |
| Trace gas profile NO2 - Lower troposphere (LT) | 50 km | 500 km | 1 km | 4 km | 6 h | 24 h | 72 h | 168 h | 5 % | 10 % | Firm | Oxidizing cap, Ozone chem | WMO |
| Trace gas profile NO2 - Total column | 50 km | 500 km | | | 24 h | 48 h | 72 h | 168 h | 5 % | 15 % | Firm | Atmospheric chemistry | WMO |
| Trace gas profile OH - Higher stratosphere & mesosphere (HS & M) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 30 % | Firm | Ozone chem | WMO |
| Trace gas profile OH - Higher troposphere (HT) | 100 km | 500 km | 1 km | 1.5 km | 6 h | 24 h | 72 h | 168 h | 5 % | 30 % | Firm | Ozone chem | WMO |
| Trace gas profile OH - Lower stratosphere (LS) | 100 km | 500 km | 1 km | 3 km | 6 h | 24 h | 72 h | 168 h | 5 % | 30 % | Firm | Ozone chem | WMO |
| Trace gas profile OH - Lower troposphere (LT) | 100 km | 500 km | 1 km | 1.5 km | 6 h | 24 h | 72 h | 168 h | 5 % | 30 % | Firm | Ozone chem | WMO |

## CLIVAR

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ocean chlorophyll | 100 km | 500 km | | | 1 d | 6 d | 30 d | 90 d | Missing | Missing | Speculative | | WCRP |
| Ocean salinity | 100 km | 250 km | | | 30 d | 60 d | 9 d | 120 d | 0.1 ‰ | 0.3 ‰ | Reasonable | | WCRP |
| Ocean suspended sediment concentration | 100 km | 500 km | | | 1 d | 6 d | 30 d | 90 d | Missing | Missing | Speculative | | WCRP |
| Ocean topography | 100 km | 200 km | | | 5 d | 10 d | 10 d | 30 d | 2 cm | 5 cm | Speculative | Gravity mission needed | WCRP |
| Ocean yellow substance | 100 km | 500 km | | | 1 d | 6 d | 30 d | 90 d | Missing | Missing | Speculative | | WCRP |
| Sea surface temperature | 10 km | 50 km | | | 3 h | 6 h | 24 h | 72 h | 0.1 K | 0.3 K | Reasonable | | WCRP |
| Sea-ice cover | 15 km | 50 km | | | 1 d | 3 d | 3 d | 7 d | 2 % (Max) | 5 % (Max) | Reasonable | | WCRP |
| Wind vector over sea surface (horizontal) | 50 km | 250 km | | | 12 h | 24 h | 72 h | 168 h | 1 m/s | 5 m/s | Reasonable | | WCRP |

## GEWEX

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cloud base height | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 0.5 km | 2 km | Tentative | | WCRP |
| Cloud cover | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 5 % (Max) | 20 % | Reasonable | | WCRP |
| Cloud ice profile - Higher stratosphere & mesosphere (HS & | 50 km | 250 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud ice profile - Higher troposphere (HT) | 50 km | 250 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud ice profile - Lower stratosphere (LS) | 50 km | 250 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud ice profile - Lower troposphere (LT) | 50 km | 250 km | 1 km | 2 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud ice profile - Total column | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 10 g/m2 | 20 g/m2 | Tentative | | WCRP |
| Cloud top temperature | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 0.5 K | 2 K | Reasonable | | WCRP |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cloud water profile (< 100 µm) - Higher troposphere (HT) | 50 km | 250 km | 1 km | 10 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud water profile (< 100 µm) - Lower troposphere (LT) | 50 km | 250 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud water profile (< 100 µm) - Total column | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 10 g/m2 | 50 g/m2 | Tentative | | WCRP |
| Cloud water profile (> 100 µm) - Higher troposphere (HT) | 50 km | 250 km | 1 km | 10 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud water profile (> 100 µm) - Lower troposphere (LT) | 50 km | 250 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Tentative | | WCRP |
| Cloud water profile (> 100 µm) - Total column | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 10 g/m2 | 50 g/m2 | Tentative | | WCRP |
| Land surface temperature | 50 km | 250 km | | | 3 h | 12 h | 720 h | 1440 h | 1 K | 4 K | Reasonable | | WCRP |
| Precipitation index (daily cumulative) | 50 km | 250 km | | | 1 h | 12 h | 720 h | 1440 h | 0.5 mm/d | 5 mm/d | Reasonable | | WCRP |
| Snow cover15 km | 250 km | | | 1 d | 7 d | 30 d | 90 d | 10 % (Max) | | 50 % | Reasonable | | WCRP |
| Snow water equivalent | 15 km | 250 km | | | 0.5 d | 7 d | 30 d | 90 d | 5 mm | 20 mm | Tentative | | WCRP |
| Soil moisture | 15 km | 250 km | | | 1 d | 10 d | 10 d | 30 d | 10 g/kg | 50 g/kg | Tentative | | WCRP |
| **Global modelling** | | | | | | | | | | | | | |
| Aerosol profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 5 km | 6 h | 168 h | 720 h | 1440 h | 10 % | 20 % | Tentative | | WCRP |
| Aerosol profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 10 km | 6 h | 168 h | 720 h | 1440 h | 10 % | 20 % | Tentative | | WCRP |
| Aerosol profile - Lower troposphere (LT) | 50 km | 500 km | 0.1 km | 1 km | 6 h | 168 h | 720 h | 1440 h | 10 % | 20 % | Tentative | | WCRP |
| Atmospheric temperature profile - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 5 km | 10 km | 3 h | 12 h | 720 h | 1440 h | 1 K | 3 K | Reasonable | | WCRP |
| Atmospheric temperature profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 3 km | 3 h | 12 h | 720 h | 1440 h | 0.5 K | 3 K | Reasonable | | WCRP |
| Atmospheric temperature profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 3 km | 3 h | 12 h | 720 h | 1440 h | 0.5 K | 3 K | Reasonable | | WCRP |
| Atmospheric temperature profile - Lower troposphere (LT) | 50 km | 500 km | 0.3 km | 3 km | 3 h | 12 h | 720 h | 1440 h | 0.5 K | 3 K | Reasonable | | WCRP |
| Downwelling solar radiation at TOA | | | | | 1 d | 6 d | 30 d | 90 d | 0.1 W/m2 | 1 W/m2 | Reasonable | | WCRP |
| Sea surface temperature | 50 km | 250 km | | | 1 h | 12 h | 720 h | 1440 h | 0.5 K | 2 K | Reasonable | | WCRP |
| Sea-ice cover | 15 km | 250 km | | | 1 d | 15 d | 30 d | 90 d | 5 % (Max) | 50 % | Reasonable | | WCRP |
| Significant wave height | 100 km | 250 km | | | 12 h | 24 h | 720 h | 1440 h | 0.5 m | 1 m | Reasonable | | WCRP |
| Specific humidity profile - Higher stratosphere & mesosphere (HS & M) | 50 km | 250 km | 1 km | 3 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Reasonable | Accuracy: Goal 5%, Threshold 10% in RH | WCRP |
| Specific humidity profile - Higher troposphere (HT) | 50 km | 100 km | 0.5 km | 2 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Reasonable | Accuracy: Goal 5%, Threshold 10% in RH | WCRP |
| Specific humidity profile - Lower stratosphere (LS) | 50 km | 250 km | 0.5 km | 2 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Reasonable | Accuracy: Goal 5%, Threshold 10% in RH | WCRP |

**Application**

| Requirement | Hor | | Vert | | Obs | | Delay | | Accuracy | | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Res | Min | Res | Min | Cycle | Min | avail | Min | | Min | | | |
| Specific humidity profile - Lower troposphere (LT) | 50 km | 100 km | 0.5 km | 2 km | 3 h | 12 h | 720 h | 1440 h | 5 % | 20 % | Reasonable | Accuracy: Goal 5%, Threshold 10% in RH | WCRP |
| Wind profile (horizontal component) - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 2 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 3 m/s | 5 m/s | Reasonable | | WCRP |
| Wind profile (horizontal component) - Higher troposphere | 50 km | 500 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 2 m/s | 5 m/s | Reasonable | | WCRP |
| Wind profile (horizontal component) - Lower stratosphere | 50 km | 500 km | 1 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 2 m/s | 5 m/s | Reasonable | | WCRP |
| Wind profile (horizontal component) - Lower troposphere | 50 km | 500 km | 0.3 km | 5 km | 3 h | 12 h | 720 h | 1440 h | 2 m/s | 5 m/s | Reasonable | | WCRP |
| Wind vector over sea surface (horizontal) | 50 km | 250 km | | | 12 h | 24 h | 720 h | 1440 h | 1 m/s | 5 m/s | Reasonable | | WCRP |
| **Global NWP** | | | | | | | | | | | | | |
| Aerosol profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 5 km | 6 h | 168 h | 12 h | 168 h | 10 % | 20 % | Tentative | | WMO |
| Aerosol profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 10 km | 6 h | 168 h | 12 h | 168 h | 10 % | 20 % | Tentative | | WMO |
| Aerosol profile - Lower troposphere (LT) | 50 km | 500 km | 0.1 km | 1 km | 1 h | 168 h | 1 h | 168 h | 10 % | 20 % | Tentative | | WMO |
| Aerosol profile - Total column | 50 km | 500 km | | | 1 h | 168 h | 1 h | 168 h | 10 % | 20 % | Tentative | | WMO |
| Air pressure over land surface | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 hPa | 2 hPa | Firm | | WMO |
| Air pressure over sea surface | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 hPa | 2 hPa | Firm | | WMO |
| Air specific humidity (at surface) | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 5 % | 15 % | Reasonable | | WMO |
| Air temperature (at surface) | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 K | 2 K | Reasonable | | WMO |
| Atmospheric temperature profile - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 1 km | 3 km | 1 h | 12 h | 1 h | 4 h | 0.5 K | 5 K | Reasonable | | WMO |
| Atmospheric temperature profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 3 km | 1 h | 12 h | 1 h | 4 h | 0.5 K | 3 K | Firm | | WMO |
| Atmospheric temperature profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 3 km | 1 h | 12 h | 1 h | 4 h | 0.5 K | 3 K | Firm | | WMO |
| Atmospheric temperature profile - Lower troposphere (LT) | 50 km | 500 km | 0.3 km | 3 km | 1 h | 12 h | 1 h | 4 h | 0.5 K | 3 K | Firm | | WMO |
| Cloud base height | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 km | 1 km | Tentative | | WMO |
| Cloud cover | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 5 % (Max) | 20 % | Reasonable | | WMO |
| Cloud drop size (at cloud top) | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 µm | 2 µm | Speculative | | WMO |
| Cloud ice profile - Higher troposphere (HT) | 50 km | 250 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Cloud ice profile - Lower troposphere (LT) | 50 km | 250 km | 0.3 km | 5 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Cloud ice profile - Total column | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 10 g/m2 | 20 g/m2 | Tentative | | WMO |
| Cloud imagery | 1 km | 50 km | | | 0.5 h | 6 h | 1 h | 4 h | | | Firm | | WMO |
| Cloud top height | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 km | 1 km | Firm | | WMO |

**Application**

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cloud water profile (< 100 µm) - Higher troposphere (HT) | 50 km | 250 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (< 100 µm) - Lower troposphere (LT) | 50 km | 250 km | 0.3 km | 5 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (< 100 µm) - Total column | 50 km | 250 km | | | 1 h | 4 h | 1 h | 4 h | 10 g/m2 | 50 g/m2 | Tentative | | WMO |
| Cloud water profile (> 100 µm) - Higher troposphere (HT) | 50 km | 250 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (> 100 µm) - Lower troposphere (LT) | 50 km | 250 km | 0.3 km | 5 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (> 100 µm) - Total column | 50 km | 250 km | | | 1 h | 12 h | 1 h | 2 h | 10 g/m2 | 50 g/m2 | Tentative | | WMO |
| Dominant wave direction | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 10 degrees | 20 degrees | Firm | | WMO |
| Dominant wave period | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 s | 1 s | Firm | | WMO |
| Ice thickness | 15 km | 250 km | | | 1 d | 7 d | 1 d | 7 d | 0.5 m | 1 m | Speculative | | WMO |
| Land surface temperature | 50 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 K | 4 K | Firm | | WMO |
| Leaf Area Index (LAI) | 50 km | 100 km | | | 7 d | 30 d | 1 d | 7 d | 5 % (Max) | 20 % | Tentative | | WMO |
| Long-wave Earth surface emissivity | 15 km | 250 km | | | 24 h | 720 h | 24 h | 720 h | 1 % (Max) | 5 % (Max) | Tentative | | WMO |
| Normalized Differential Vegetation Index (NDVI) | 50 km | 100 km | | | 7 d | 30 d | 1 d | 7 d | 1 % (Max) | 5 % (Max) | Tentative | | WMO |
| Outgoing long-wave radiation at TOA | 50 km | 250 km | | | 1 h | 1 h | 240 h | 720 h | 5 W/m2 | 10 W/m2 | Firm | | WMO |
| Outgoing short-wave radiation at TOA | 50 km | 250 km | | | 1 h | 6 h | 240 h | 360 h | 5 W/m2 | 10 W/m2 | Firm | | WMO |
| Ozone profile - Higher troposphere (HT) | 50 km | 500 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Ozone profile - Lower stratosphere (LS) | 50 km | 500 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Ozone profile - Lower troposphere (LT) | 50 km | 500 km | 1 km | 5 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Tentative | | WMO |
| Ozone profile - Total column | 50 km | 100 km | | | 1 h | 6 h | 1 h | 4 h | 5 DU | 20 DU | Reasonable | | WMO |
| Precipitation index (daily cumulative) | 50 km | 250 km | | | 1 h | 12 h | 24 h | 720 h | 0.5 mm/d | 5 mm/d | Reasonable | | WMO |
| Precipitation rate at the ground (liquid) | 50 km | 100 km | | | 1 h | 12 h | 1 h | 4 h | 0.1 mm/h | 1 mm/h | Tentative | | WMO |
| Precipitation rate at the ground (solid) | 50 km | 100 km | | | 1 h | 12 h | 1 h | 4 h | 0.1 mm/h | 1 mm/h | Tentative | | WMO |
| Sea surface temperature | 50 km | 250 km | | | 3 h | 360 h | 3 h | 180 h | 0.5 K | 2 K | Firm | | WMO |
| Sea-ice cover | 15 km | 250 km | | | 1 d | 15 d | 1 d | 7 d | 5 % (Max) | 50 % | Firm | | WMO |
| Sea-ice surface temperature | 15 km | 200 km | | | 1 h | 7 h | 1 h | 4 h | 0.5 K | 4 K | Reasonable | | WMO |
| Significant wave height | 100 km | 250 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 m | 1 m | Firm | | WMO |
| Snow cover 15 km | 250 km | | | 0.5 d | 7 d | 0.5 d | 1 d | 10 % (Max) | | 50 % | Reasonable | | WMO |
| Snow water equivalent | 15 km | 250 km | | | 0.5 d | 7 d | 0.25 d | 1 d | 5 mm | 20 mm | Tentative | | WMO |
| Soil moisture | 15 km | 250 km | | | 1 d | 7 d | 0.25 d | 1 d | 10 g/kg | 50 g/kg | Reasonable | | WMO |
| Specific humidity profile - Higher troposphere (HT) | 50 km | 250 km | 1 km | 3 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Firm | Accuracy 5% in RH | WMO |

| Application<br>Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specific humidity profile - Lower troposphere (LT) | 50 km | 250 km | 0.4 km | 2 km | 1 h | 12 h | 1 h | 4 h | 5 % | 20 % | Firm | Accuracy 5% in RH | WMO |
| Specific humidity profile - Total column | 50 km | 500 km |  |  | 1 h | 12 h | 1 h | 4 h | 1 kg/m2 | 5 kg/m2 | Firm |  | WMO |
| Wind profile (horizontal component) - Higher troposphere | 50 km | 500 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 1 m/s | 8 m/s | Firm |  | WMO |
| Wind profile (horizontal component) - Lower stratosphere | 50 km | 500 km | 1 km | 10 km | 1 h | 12 h | 1 h | 4 h | 1 m/s | 5 m/s | Firm |  | WMO |
| Wind profile (horizontal component) - Lower troposphere | 50 km | 500 km | 0.4 km | 5 km | 1 h | 12 h | 1 h | 4 h | 1 m/s | 5 m/s | Firm |  | WMO |
| Wind profile (vertical component) - Higher troposphere | 50 km | 500 km | 0.5 km | 10 km | 1 h | 12 h | 1 h | 4 h | 1 cm/s | 5 cm/s | Speculative |  | WMO |
| Wind profile (vertical component) - Lower stratosphere | 50 km | 500 km | 0.5 km | 10 km | 1 h | 12 h | 1 h | 4 h | 1 cm/s | 5 cm/s | Speculative |  | WMO |
| Wind profile (vertical component) - Lower troposphere | 50 km | 500 km | 0.5 km | 5 km | 1 h | 12 h | 1 h | 4 h | 1 cm/s | 5 cm/s | Speculative |  | WMO |
| Wind speed over land surface (horizontal) | 50 km | 250 km |  |  | 1 h | 12 h | 1 h | 4 h | 0.5 m/s | 3 m/s | Reasonable |  | WMO |
| Wind speed over sea surface (horizontal) | 50 km | 250 km |  |  | 1 h | 12 h | 1 h | 4 h | 0.5 m/s | 3 m/s | Firm |  | WMO |
| Wind vector over land surface (horizontal) | 50 km | 250 km |  |  | 1 h | 12 h | 1 h | 4 h | 0.5 m/s | 5 m/s | Reasonable |  | WMO |
| Wind vector over sea surface (horizontal) | 50 km | 250 km |  |  | 1 h | 12 h | 1 h | 4 h | 0.5 m/s | 5 m/s | Firm |  | WMO |
| **GOOS Climate - large scale** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Ocean chlorophyll | 25 km | 100 km |  |  | 1 d | 3 d | 1 d | 3 d | 0.1 mg/m3 | 0.5 mg/m3 | Firm |  | GOOS |
| Ocean salinity | 200 km | 500 km |  |  | 10 d | 30 d | 10 d | 30 d | 0.1 ‰ | 1 ‰ | Firm |  | GOOS |
| Ocean topography | 100 km | 300 km |  |  | 10 d | 30 d | 10 d | 30 d | 2 cm | 5 cm | Firm |  | GOOS |
| Sea surface temperature | 10 km | 300 km |  |  | 6 h | 720 h | 6 h | 720 h | 0.1 K | 1 K | Firm |  | GOOS |
| Sea-ice cover | 10 km | 100 km |  |  | 1 d | 6 d | 0.125 | 1 d | 2 % (Max) | 10 % | Firm |  | GOOS |
| Wind speed over sea surface (horizontal) | 25 km | 100 km |  |  | 24 h | 168 h | 24 h | 168 h | 1 m/s | 2 m/s | Firm |  | GOOS |
| Wind vector over sea surface (horizontal) | 25 km | 100 km |  |  | 24 h | 168 h | 24 h | 168 h | 1 m/s | 2 m/s | Firm |  | GOOS |
| **GOOS Climate - mesoscale** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Ocean topography | 25 km | 100 km |  |  | 7 d | 30 d | 2 d | 15 d | 2 cm | 10 cm | Firm |  | GOOS |
| **Hydrology** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Iceberg fractional cover | 1 km | 50 km |  |  | 1 d | 12 d | 1 d | 4 d | 10 % (Max) | 20 % | Firm |  | WMO |
| Iceberg height | 1 km | 50 km |  |  | 1 d | 12 d | 1 d | 4 d | 1 m | 2 m | Firm |  | WMO |
| Land cover 10 m | 250000 |  |  | 0.02 y | 1 y | 1 d | 7 d | 50 classes |  | 5 classes | Reasonable |  | WMO |
| Land surface imagery | 10 m | 250000 |  |  | 1 d | 365 d | 1 d | 7 d |  |  | Reasonable |  | WMO |
| Land surface temperature | 0.01 | 250 km |  |  | 1 h | 168 h | 24 h | 168 h | 0.3 K | 3 K | Reasonable |  | WMO |
| Land surface topography | 100 m | 1000 m |  |  | 10 y | 50 y | 30 d | 600 d | 1 m (vert.) | 5 m (vert.) | Reasonable |  | WMO |

| **Application**<br>Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Leaf Area Index (LAI) | 0.01 | 10 km | | | 7 d | 24 d | 1 d | 5 d | 5 % (Max) | 20 % | Reasonable | | WMO |
| Long-wave Earth surface emissivity | 0.01 | 250 km | | | 24 h | 288 h | 24 h | 288 h | 5 % (Max) | 20 % | Reasonable | | WMO |
| Normalized Differential Vegetation Index (NDVI) | 0.01 | 250 km | | | 1 d | 30 d | 1 d | 7 d | 1 % (Max) | 20 % | Reasonable | | WMO |
| Outgoing long-wave radiation at TOA | 10 km | 100 km | | | 1 h | 12 h | 24 h | 168 h | 5 W/m2 | 20 W/m2 | Reasonable | | WMO |
| Outgoing short-wave radiation at TOA | 0.1 km | 200 km | | | 1 h | 6 h | 24 h | 168 h | 5 W/m2 | 20 W/m2 | Reasonable | | WMO |
| Permafrost 0.1 km | 100 km | | | 0.25 d | 3 d | 0.25 d | 6 d | 5 % (Max) | | 25 % | Reasonable | | WMO |
| Sea level 0.1 km | 10 km | | | 1 d | 7 d | 1 d | 7 d | 2 cm | 10 cm | Reasonable | WMO | | |
| Snow cover 0.1 km | 100 km | | | 1 d | 7 d | 1 d | 6 d | 5 % (Max) | | 20 % | Reasonable | | WMO |
| Snow melting conditions | 0.1 km | 10 km | | | 0.5 h | 12 h | 1 h | 144 h | 5 classes | 2 classes | Reasonable | | WMO |
| Snow water equivalent | 0.1 km | 10 km | | | 1 d | 7 d | 1 d | 6 d | 5 mm | 20 mm | Reasonable | | WMO |
| Soil moisture | 0.01 | 250 km | | | 1 d | 3 d | 1 d | 144 d | 10 g/kg | 50 g/kg | Reasonable | | WMO |
| Vegetation type | 10 m | 1000 m | | | 7 d | 365 d | 1 d | 30 d | 50 classes | 5 classes | Reasonable | | WMO |
| **Nowcasting** | | | | | | | | | | | | | |
| Aerosol profile - Total column | 5 km | 50 km | | | 0.25 h | 12 h | 0.25 h | 2 h | 10 % | 20 % | Firm | | WMO |
| Air temperature (at surface) | 5 km | 20 km | | | 0.25 h | 1 h | 0.25 h | 0.5 h | 0.5 K | 1 K | Reasonable | | WMO |
| Atmospheric stability index | 5 km | 50 km | | | 0.08 h | 0.5 h | 0.25 h | 1 h | Missing | Missing | Firm | | WMO |
| Atmospheric temperature profile - Higher troposphere (HT) | 5 km | 200 km | 1 km | 3 km | 0.25 h | 1 h | 0.08 h | 0.5 h | 1 K | 2 K | Firm | | WMO |
| Atmospheric temperature profile - Lower troposphere (LT) | 5 km | 200 km | 0.5 km | 1 km | 0.25 h | 1 h | 0.08 h | 0.5 h | 0.5 K | 2 K | Firm | | WMO |
| Cloud cover | 1 km | 20 km | | | 0.0083 | 1 h | 0.016 | 0.5 h | 5 % (Max) | 20 % | Firm | | WMO |
| Cloud imagery | 1 km | 5 km | | | 0.05 h | 0.5 h | 0.25 h | 1 h | | | Firm | | WMO |
| Cloud top height | 1 km | 10 km | | | 0.01 h | 0.5 h | 0.02 h | 0.5 h | 0.1 km | 1 km | Firm | | WMO |
| Cloud top temperature | 1 km | 10 km | | | 0.01 h | 0.5 h | 0.02 h | 0.5 h | 0.5 K | 2 K | Firm | | WMO |
| Cloud type 1 km | 10 km | | | 0.01 h | 0.5 h | 0.02 h | 0.5 h | 10 classes | | 5 classes | Firm | | WMO |
| Fire area 5 km | 250 km | | | 0.25 d | 12 d | 1 d | 4 d | 10 % | 20 % | Firm | WMO | | |
| Fire temperature | 5 km | 250 km | | | 0.25 d | 12 d | 1 d | 4 d | 500 K | 1000 K | Firm | | WMO |
| Height of the top of the Planetary Boundary Layer | 5 km | 50 km | | | 0.25 h | 1 h | 0.08 h | 0.5 h | 50 m | 500 m | Firm | | WMO |
| Height of tropopause | 10 km | 200 km | | | 0.5 h | 6 h | 0.5 h | 2 h | 0.1 km | 1 km | Firm | | WMO |
| Land surface temperature | 1 km | 50 km | | | 0.25 h | 1 h | 0.08 h | 0.5 h | 0.5 K | 3 K | Firm | | WMO |
| Normalized Differential Vegetation Index (NDVI) | 5 km | 10 km | | | 1 d | 12 d | 1 d | 5 d | 5 % (Max) | 10 % | Firm | | WMO |

**Application**

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ocean currents (vector) | 10 km | 50 km | | | 0.25 d | 6 d | 0.25 d | 4 d | 0.5 cm/s | 1 cm/s | Firm | | WMO |
| Precipitation rate at the ground (liquid) | 5 km | 50 km | | | 0.08 h | 1 h | 0.08 h | 0.5 h | 0.1 mm/h | 1 mm/h | Firm | | WMO |
| Precipitation rate at the ground (solid) | 5 km | 50 km | | | 0.25 h | 1 h | 0.5 h | 0.5 h | 0.1 mm/h | 1 mm/h | Firm | | WMO |
| Sea surface temperature | 5 km | 50 km | | | 1 h | 6 h | 1 h | 2 h | 0.5 K | 2 K | Firm | | WMO |
| Sea-ice cover | 5 km | 50 km | | | 1 d | 24 d | 1 d | 6 d | 10 % (Max) | 20 % | Firm | | WMO |
| Snow cover5 km | 50 km | | | 0.04 d | 0.25 d | 0.04 d | 0.25 d | 10 % (Max) | | 20 % | Firm | | WMO |
| Soil moisture | 5 km | 50 km | | | 0.5 d | 2 d | 0.25 d | 1 d | 10 g/kg | 50 g/kg | Reasonable | | WMO |
| Specific humidity profile - Higher troposphere (HT) | 5 km | 200 km | 1 km | 3 km | 0.25 h | 1 h | 0.08 h | 0.5 h | 5 % | 20 % | Firm | Accuracy 10% in RH | WMO |
| Specific humidity profile - Lower troposphere (LT) | 5 km | 200 km | 0.5 km | 1 km | 0.25 h | 1 h | 0.08 h | 0.5 h | 5 % | 20 % | Firm | Accuracy 5% in RH | WMO |
| Specific humidity profile - Total column | 5 km | 50 km | | | 0.25 h | 1 h | 0.08 h | 0.5 h | 1 kg/m2 | 5 kg/m2 | Firm | | WMO |
| Temperature of tropopause | 10 km | 200 km | | | 0.5 h | 6 h | 0.5 h | 2 h | 0.5 K | 2 K | Firm | | WMO |
| Wind profile (horizontal component) - Higher troposphere | 5 km | 200 km | 0.5 km | 1 km | 0.25 h | 4 h | 0.08 h | 0.5 h | 1 m/s | 8 m/s | Firm | | WMO |
| Wind profile (horizontal component) - Lower stratosphere | 5 km | 200 km | 0.5 km | 1 km | 0.25 h | 6 h | 0.25 h | 2 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind profile (horizontal component) - Lower troposphere | 5 km | 200 km | 0.5 km | 1 km | 0.25 h | 6 h | 0.25 h | 2 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind profile (vertical component) - Lower troposphere | 5 km | 200 km | 0.5 km | 2 km | 0.25 h | 1 h | 0.08 h | 0.5 h | 1 cm/s | 5 cm/s | Firm | | WMO |
| Wind speed over land surface (horizontal) | 5 km | 50 km | | | 0.25 h | 3 h | 0.25 h | 1 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind speed over sea surface (horizontal) | 5 km | 50 km | | | 0.25 h | 3 h | 0.25 h | 1 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind vector over land surface (horizontal) | 5 km | 50 km | | | 0.25 h | 3 h | 0.25 h | 1 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind vector over sea surface (horizontal) | 5 km | 50 km | | | 0.25 h | 3 h | 0.25 h | 1 h | 1 m/s | 5 m/s | Firm | | WMO |
| **OOPC** | | | | | | | | | | | | | |
| Ocean topography | 100 km | 250 km | | | 10 d | 30 d | 0.125 | 1 d | 5 cm | 10 cm | Firm | | GCOS |
| Sea surface temperature | 200 km | 500 km | | | 24 h | 72 h | 3 h | 12 h | 0.5 K | 2 K | Firm | | GCOS |
| Sea-ice cover | 30 km | 100 km | | | 1 d | 7 d | 0.125 | 1 d | 2 % (Max) | 5 % (Max) | Firm | | GCOS |
| Wind vector over sea surface (horizontal) | 100 km | 500 km | | | 12 h | 24 h | 3 h | 12 h | 2 m/s | 5 m/s | Firm | | GCOS |
| **Regional NWP** | | | | | | | | | | | | | |
| Air pressure over land surface | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 hPa | 1 hPa | Firm | | WMO |
| Air pressure over sea surface | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 hPa | 1 hPa | Firm | | WMO |
| Air specific humidity (at surface) | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 15 % | Reasonable | | WMO |
| Air temperature (at surface) | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 K | 2 K | Reasonable | | WMO |

**Application**

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atmospheric temperature profile - Higher troposphere (HT) | 10 km | 500 km | 1 km | 3 km | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 K | 3 K | Firm | | WMO |
| Atmospheric temperature profile - Lower stratosphere (LS) | 10 km | 500 km | 1 km | 3 km | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 K | 3 K | Firm | | WMO |
| Atmospheric temperature profile - Lower troposphere (LT) | 10 km | 500 km | 0.3 km | 3 km | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 K | 3 K | Firm | | WMO |
| Cloud base height | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 3 h | 0.5 km | 1 km | Tentative | | WMO |
| Cloud cover | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 5 % (Max) | 20 % | Reasonable | | WMO |
| Cloud drop size (at cloud top) | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 µm | 2 µm | Firm | | WMO |
| Cloud ice profile - Higher troposphere (HT) | 10 km | 250 km | 1 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Cloud ice profile - Lower troposphere (LT) | 10 km | 250 km | 0.3 km | 5 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Cloud ice profile - Total column | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 10 g/m2 | 20 g/m2 | Tentative | | WMO |
| Cloud imagery | 1 km | 50 km | | | 0.25 h | 6 h | 0.5 h | 2 h | | | Firm | | WMO |
| Cloud top height | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 km | 1 km | Firm | | WMO |
| Cloud water profile (< 100 µm) - Higher troposphere (HT) | 10 km | 250 km | 1 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (< 100 µm) - Lower troposphere (LT) | 10 km | 250 km | 0.3 km | 5 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (< 100 µm) - Total column | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 10 g/m2 | 50 g/m2 | Tentative | | WMO |
| Cloud water profile (> 100 µm) - Higher troposphere (HT) | 10 km | 250 km | 1 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (> 100 µm) - Lower troposphere (LT) | 10 km | 250 km | 0.3 km | 5 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Cloud water profile (> 100 µm) - Total column | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 4 h | 10 g/m2 | 50 g/m2 | Tentative | | WMO |
| Dominant wave direction | 10 km | 50 km | | | 1 h | 12 h | 0.5 h | 2 h | 10 degrees | 20 degrees | Firm | | WMO |
| Dominant wave period | 10 km | 50 km | | | 1 h | 12 h | 0.5 h | 2 h | 0.5 s | 1 s | Firm | | WMO |
| Ice thickness | 5 km | 250 km | | | 1 d | 7 d | 1 d | 7 d | 0.5 m | 1 m | Speculative | | WMO |
| Land surface temperature | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 K | 4 K | Firm | | WMO |
| Leaf Area Index (LAI) | 10 km | 50 km | | | 7 d | 30 d | 1 d | 7 d | 5 % (Max) | 20 % | Tentative | | WMO |
| Long-wave Earth surface emissivity | 5 km | 250 km | | | 24 h | 720 h | 24 h | 720 h | 1 % (Max) | 5 % (Max) | Tentative | | WMO |
| Normalized Differential Vegetation Index (NDVI) | 10 km | 50 km | | | 7 d | 30 d | 1 d | 7 d | 1 % (Max) | 5 % (Max) | Tentative | | WMO |
| Outgoing long-wave radiation at TOA | 10 km | 250 km | | | 0.5 h | 1 h | 240 h | 720 h | 5 W/m2 | 10 W/m2 | Firm | | WMO |
| Outgoing short-wave radiation at TOA | 10 km | 250 km | | | 0.5 h | 1 h | 240 h | 360 h | 5 W/m2 | 10 W/m2 | Firm | | WMO |
| Ozone profile - Higher troposphere (HT) | 10 km | 200 km | 1 km | 10 km | 0.5 h | 3 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Ozone profile - Lower stratosphere (LS) | 10 km | 200 km | 1 km | 10 km | 0.5 h | 3 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Ozone profile - Lower troposphere (LT) | 10 km | 200 km | 1 km | 5 km | 0.5 h | 3 h | 0.5 h | 2 h | 5 % | 20 % | Tentative | | WMO |
| Ozone profile - Total column | 10 km | 100 km | | | 0.5 h | 6 h | 0.5 h | 2 h | 5 DU | 20 DU | Reasonable | | WMO |

### Application

| Requirement | Hor | | Vert | | Obs | | Delay | | Accuracy | | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Res | Min | Res | Min | Cycle | Min | avail | Min | | Min | | | |
| Precipitation index (daily cumulative) | 10 km | 250 km | | | 0.5 h | 12 h | 24 h | 720 h | 0.5 mm/d | 5 mm/d | Reasonable | | WMO |
| Precipitation rate at the ground (liquid) | 10 km | 50 km | | | 0.5 h | 6 h | 0.5 h | 2 h | 0.1 mm/h | 1 mm/h | Tentative | | WMO |
| Precipitation rate at the ground (solid) | 10 km | 100 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.1 mm/h | 1 mm/h | Tentative | | WMO |
| Sea surface temperature | 25 km | 50 km | | | 1 h | 12 h | 1 h | 24 h | 0.5 K | 1 K | Firm | | WMO |
| Sea-ice cover | 25 km | 50 km | | | 0.5 d | 7 d | 0.3 d | 3 d | 5 % (Max) | 50 % | Firm | | WMO |
| Sea-ice surface temperature | 5 km | 100 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 K | 4 K | Firm | | WMO |
| Significant wave height | 10 km | 50 km | | | 1 h | 12 h | 1 h | 2 h | 0.1 m | 0.2 m | Firm | | WMO |
| Snow cover5 km | 250 km | | | 0.5 d | 7 d | 0.25 d | 1 d | 10 % (Max) | | 50 % | Reasonable | | WMO |
| Snow water equivalent | 5 km | 250 km | | | 0.25 d | 7 d | 0.25 d | 1 d | 5 mm | 20 mm | Tentative | | WMO |
| Soil moisture | 5 km | 250 km | | | 1 d | 7 d | 7 d | 7 d | 10 g/kg | 50 g/kg | Reasonable | | WMO |
| Specific humidity profile - Higher troposphere (HT) | 10 km | 100 km | 1 km | 3 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Firm | Accuracy 5% in RH | WMO |
| Specific humidity profile - Lower troposphere (LT) | 10 km | 100 km | 0.4 km | 2 km | 0.5 h | 12 h | 0.5 h | 2 h | 5 % | 20 % | Firm | Accuracy 5% in RH | WMO |
| Specific humidity profile - Total column | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 1 kg/m2 | 5 kg/m2 | Firm | | WMO |
| Wind profile (horizontal component) - Higher troposphere | 10 km | 500 km | 1 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 1 m/s | 8 m/s | Firm | | WMO |
| Wind profile (horizontal component) - Lower stratosphere | 10 km | 500 km | 1 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind profile (horizontal component) - Lower troposphere | 10 km | 500 km | 0.4 km | 5 km | 0.5 h | 12 h | 0.5 h | 2 h | 1 m/s | 5 m/s | Firm | | WMO |
| Wind profile (vertical component) - Higher troposphere | 10 km | 500 km | 0.5 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 1 cm/s | 5 cm/s | Speculative | | WMO |
| Wind profile (vertical component) - Lower stratosphere | 10 km | 500 km | 0.5 km | 10 km | 0.5 h | 12 h | 0.5 h | 2 h | 1 cm/s | 5 cm/s | Speculative | | WMO |
| Wind profile (vertical component) - Lower troposphere | 10 km | 500 km | 0.5 km | 5 km | 0.5 h | 12 h | 0.5 h | 2 h | 1 cm/s | 5 cm/s | Speculative | | WMO |
| Wind speed over land surface (horizontal) | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 m/s | 3 m/s | Reasonable | | WMO |
| Wind speed over sea surface (horizontal) | 10 km | 100 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 m/s | 3 m/s | Firm | | WMO |
| Wind vector over land surface (horizontal) | 10 km | 250 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 m/s | 5 m/s | Reasonable | | WMO |
| Wind vector over sea surface (horizontal) | 10 km | 100 km | | | 0.5 h | 12 h | 0.5 h | 2 h | 0.5 m/s | 5 m/s | Firm | | WMO |
| **S & I A** | | | | | | | | | | | | | |
| Fractional Photosynthetically Active Radiation (FPAR) | 50 km | 500 km | | | 7 d | 30 d | 1 d | 30 d | 5 % (Max) | 10 % | Firm | | WMO |
| Geoid 100 km | 500 km | | | 20 y | 30 y | 12 y | 24 y | 1 cm | 5 cm | Firm | WMO | | |
| Ocean chlorophyll | 25 km | 100 km | | | 1 d | 3 d | 1 d | 3 d | 0.1 mg/m3 | 0.5 mg/m3 | Firm | | WMO |
| Ocean salinity | 100 km | 250 km | | | 30 d | 60 d | 9 d | 120 d | 0.1 ‰ | 0.3 ‰ | Reasonable | | WMO |
| Ocean suspended sediment concentration | 100 km | 500 km | | | 1 d | 6 d | 30 d | 90 d | Missing | Missing | Speculative | | WMO |

| **Application**<br>Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ocean topography | 25 km | 100 km | | | 7 d | 30 d | 2 d | 15 d | 1 cm | 4 cm | Firm | | WMO |
| Ocean yellow substance | 100 km | 500 km | | | 1 d | 6 d | 30 d | 90 d | Missing | Missing | Speculative | | WMO |
| Sea surface temperature | 50 km | 250 km | | | 3 h | 12 h | 3 h | 24 h | 0.1 K | 0.5 K | Firm | Tropical ocean most | WMO |
| Snow water equivalent | 50 km | 500 km | | | 1 d | 7 d | 1 d | 7 d | 5 mm | 20 mm | Tentative | | WMO |
| Soil moisture | 50 km | 500 km | | | 1 d | 7 d | 1 d | 7 d | 10 g/kg | 50 g/kg | Reasonable | | WMO |
| Vegetation type | 50000 | 500000 | | | 7 d | 30 d | 1 d | 7 d | 18 classes | 9 classes | Firm | | WMO |
| **SPARC** | | | | | | | | | | | | | |
| Aerosol profile - Higher stratosphere & mesosphere (HS & | 100 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 10 % | 20 % | Tentative | | WCRP |
| Aerosol profile - Higher troposphere (HT) | 100 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 10 % | 20 % | Tentative | | WCRP |
| Aerosol profile - Lower stratosphere (LS) | 100 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 10 % | 20 % | Tentative | | WCRP |
| Aerosol profile - Lower troposphere (LT) | 100 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 10 % | 20 % | Tentative | | WCRP |
| Atmospheric temperature profile - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 0.5 K | 1 K | Reasonable | | WCRP |
| Atmospheric temperature profile - Higher troposphere (HT) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 0.5 K | 1 K | Reasonable | | WCRP |
| Atmospheric temperature profile - Lower stratosphere (LS) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 0.5 K | 1 K | Reasonable | | WCRP |
| Atmospheric temperature profile - Lower troposphere (LT) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 0.5 K | 1 K | Reasonable | | WCRP |
| Outgoing long-wave radiation at TOA | 50 km | 250 km | | | 3 h | 6 h | 720 h | 2160 h | 5 W/m2 | 10 W/m2 | Reasonable | | WCRP |
| Outgoing short-wave radiation at TOA | 50 km | 250 km | | | 3 h | 6 h | 720 h | 2160 h | 5 W/m2 | 10 W/m2 | Reasonable | | WCRP |
| Ozone profile - Higher stratosphere & mesosphere (HS & | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 5 % | 10 % | Reasonable | | WCRP |
| Ozone profile - Higher troposphere (HT) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 5 % | 10 % | Reasonable | | WCRP |
| Ozone profile - Lower stratosphere (LS) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 5 % | 10 % | Reasonable | | WCRP |
| Ozone profile - Lower troposphere (LT) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 5 % | 10 % | Reasonable | | WCRP |
| Specific humidity profile - Higher stratosphere & mesosphere (HS & M) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 2 % | 5 % | Reasonable | Accuracy: Goal 1%, Threshold 5% in RH | WCRP |
| Specific humidity profile - Higher troposphere (HT) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 2 % | 5 % | Reasonable | Accuracy: Goal 1%, Threshold 5% in RH | WCRP |
| Specific humidity profile - Lower stratosphere (LS) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 2 % | 5 % | Reasonable | Accuracy: Goal 1%, Threshold 5% in RH | WCRP |
| Specific humidity profile - Lower troposphere (LT) | 50 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 2 % | 5 % | Reasonable | Accuracy: Goal 1%, Threshold 5% in RH | WCRP |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind profile (horizontal component) - Higher stratosphere & mesosphere (HS & M) | 200 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 3 m/s | 5 m/s | Reasonable | | WCRP |
| Wind profile (horizontal component) - Higher troposphere | 200 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 3 m/s | 5 m/s | Reasonable | | WCRP |
| Wind profile (horizontal component) - Lower stratosphere | 200 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 3 m/s | 5 m/s | Reasonable | | WCRP |
| Wind profile (horizontal component) - Lower troposphere | 200 km | 500 km | 0.5 km | 2 km | 6 h | 72 h | 24 h | 168 h | 3 m/s | 5 m/s | Reasonable | | WCRP |
| **Synoptic Meteorology** | | | | | | | | | | | | | |
| Air temperature (at surface) | 10 km | 100 km | | | 1 h | 12 h | 1 h | 4 h | 0.5 K | 2 K | Firm | | WMO |
| Atmospheric stability index | 20 km | 200 km | | | 1 h | 6 h | 1 h | 3 h | Missing | Missing | Firm | | WMO |
| Atmospheric temperature profile - Higher troposphere (HT) | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 0.5 K | 3 K | Firm | | WMO |
| Atmospheric temperature profile - Lower stratosphere (LS) | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 0.5 K | 3 K | Firm | | WMO |
| Atmospheric temperature profile - Lower troposphere (LT) | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 0.5 K | 3 K | Firm | | WMO |
| Cloud imagery | 1 km | 10 km | | | 0.25 h | 6 h | 0.25 h | 6 h | | | Firm | | WMO |
| Cloud top height | 1 km | 10 km | | | 0.25 h | 6 h | 0.25 h | 6 h | 0.5 km | 2 km | Firm | | WMO |
| Cloud type  20 km | 200 km | | | 0.25 h | 6 h | 0.25 h | 6 h | 10 classes | | 5 classes | Firm | | WMO |
| Dominant wave direction | 50 km | 200 km | | | 3 h | 12 h | 1 h | 3 h | 20 degrees | 30 degrees | Firm | | WMO |
| Dominant wave period | 50 km | 200 km | | | 3 h | 12 h | 1 h | 3 h | 0.5 s | 1 s | Firm | | WMO |
| Ozone profile - Total column | 20 km | 50 km | | | 0.25 h | 12 h | 0.25 h | 6 h | 5 DU | 20 DU | Firm | | WMO |
| Precipitation rate at the ground (liquid) | 20 km | 100 km | | | 1 h | 6 h | 0.25 h | 6 h | 0.1 mm/h | 1 mm/h | Firm | | WMO |
| Precipitation rate at the ground (solid) | 20 km | 100 km | | | 3 h | 6 h | 0.25 h | 6 h | 0.1 mm/h | 1 mm/h | Firm | | WMO |
| Sea surface temperature | 5 km | 50 km | | | 3 h | 24 h | 1 h | 24 h | 0.5 K | 2 K | Firm | | WMO |
| Specific humidity profile - Higher troposphere (HT) | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 5 % | 20 % | Firm | Accuracy 10% in RH | WMO |
| Specific humidity profile - Lower troposphere (LT) | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 5 % | 20 % | Firm | Accuracy 10% in RH | WMO |
| Wind profile (horizontal component) - Higher troposphere | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 2 m/s | 8 m/s | Firm | | WMO |
| Wind profile (horizontal component) - Lower stratosphere | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | | WMO |
| Wind profile (horizontal component) - Lower troposphere | 20 km | 200 km | 0.1 km | 2 km | 3 h | 12 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | | WMO |
| Wind speed over land surface (horizontal) | 20 km | 200 km | | | 1 h | 12 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | | WMO |
| Wind speed over sea surface (horizontal) | 20 km | 200 km | | | 1 h | 12 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | | WMO |
| Wind vector over land surface (horizontal) | 20 km | 200 km | | | 1 h | 12 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | | WMO |
| Wind vector over sea surface (horizontal) | 20 km | 200 km | | | 1 h | 12 h | 1 h | 3 h | 2 m/s | 5 m/s | Firm | | WMO |

| Application<br>Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Terrestrial Climate** | | | | | | | | | | | | | |
| Aerosol profile - Total column | 1 km | 4 km | | | 24 h | 48 h | 24 h | 120 h | Missing | Missing | Speculative | | GTOS |
| Aerosol profile - Total column | 1 km | 4 km | | | 24 h | 48 h | 24 h | 120 h | Missing | Missing | Speculative | | GCOS |
| Air specific humidity (at surface) | 25 km | 100 km | | | 3 h | 6 h | 24 h | 72 h | 1 % | 2 % | Speculative | Atmospheric water content near the surface | GTOS |
| Air specific humidity (at surface) | 25 km | 100 km | | | 3 h | 6 h | 24 h | 72 h | 1 % | 2 % | Speculative | Atmospheric water content near the surface | GCOS |
| Air temperature (at surface) | 25 km | 100 km | | | 3 h | 12 h | 24 h | 48 h | 0.2 K | 0.5 K | Speculative | Temperature - air | GCOS |
| Air temperature (at surface) | 25 km | 100 km | | | 3 h | 12 h | 24 h | 48 h | 0.2 K | 0.5 K | Speculative | Temperature - air | GTOS |
| Cloud imagery | 1 km | 10 km | | | 3 h | 12 h | 12 h | 24 h | | | Speculative | Cloud cover | GTOS |
| Cloud imagery | 1 km | 10 km | | | 3 h | 12 h | 12 h | 24 h | | | Speculative | Cloud cover | GCOS |
| Downwelling long-wave radiation at the Earth surface | 25 km | 100 km | | | 3 h | 6 h | 24 h | 120 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - outgoing long-wave in situ | GTOS |
| Downwelling long-wave radiation at the Earth surface | 25 km | 100 km | | | 3 h | 6 h | 24 h | 120 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - outgoing long-wave in situ | GCOS |
| Downwelling short-wave radiation at the Earth surface | 25 km | 100 km | | | 24 h | 120 h | 24 h | 720 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - reflected short wave in situ | GCOS |
| Downwelling short-wave radiation at the Earth surface | 25 km | 100 km | | | 24 h | 120 h | 24 h | 720 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - reflected short wave in situ | GTOS |
| Fire area 0.1 km | 1 km | | | 10 d | 365 d | 30 d | 90 d | 10 % | 20 % | Tentative | GCOS | | |
| Fire area 0.1 km | 1 km | | | 10 d | 365 d | 30 d | 90 d | 10 % | 20 % | Tentative | GTOS | | |
| Fire temperature | 0.1 km | 1 km | | | 10 d | 365 d | 30 d | 90 d | 50 K | 200 K | Tentative | | GCOS |
| Fire temperature | 0.1 km | 1 km | | | 10 d | 365 d | 30 d | 90 d | 50 K | 200 K | Tentative | | GTOS |
| Fractional Photosynthetically Active Radiation (FPAR) | 0.1 km | 2 km | | | 10 d | 30 d | 10 d | 30 d | 5 % (Max) | 10 % | Tentative | | GTOS |
| Fractional Photosynthetically Active Radiation (FPAR) | 0.1 km | 2 km | | | 10 d | 30 d | 10 d | 30 d | 5 % (Max) | 10 % | Tentative | | GCOS |
| Glacier cover | 10 m | 100 m | | | 30 y | 50 y | 720 d | 1500 d | 10 % (Max) | 20 % | Speculative | Glacier inventory | GCOS |
| Glacier cover | 10 m | 100 m | | | 30 y | 50 y | 720 d | 1500 d | 10 % (Max) | 20 % | Speculative | Glacier inventory | GTOS |
| Ice-sheet topography | 0.01 | 0.05 | | | 5 y | 10 y | 365 d | 720 d | 50 cm (vert.) | 100 cm | Speculative | Ice sheet geometry | GTOS |
| Ice-sheet topography | 0.01 | 0.05 | | | 5 y | 10 y | 365 d | 720 d | 50 cm (vert.) | 100 cm | Speculative | Ice sheet geometry | GCOS |
| Land cover 100 m | 1000 m | | | 1 y | 10 y | 90 d | 365 d | 50 classes | | 20 classes | Tentative | | GCOS |
| Land cover 100 m | 1000 m | | | 1 y | 10 y | 90 d | 365 d | 50 classes | | 20 classes | Tentative | | GTOS |

## Application

| Requirement | Hor Res | Min | Vert Res | Min | Obs Cycle | Min | Delay avail | Min | Accuracy | Min | Confidence | Remarks | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Land surface imagery | 1 m | 10 m | | | 1500 d | 3000 d | 1500 d | 3000 d | | | Speculative | Glacier length | GCOS |
| Land surface imagery | 1 m | 10 m | | | 1500 d | 3000 d | 1500 d | 3000 d | | | Speculative | Glacier length | GTOS |
| Land surface topography | 10 m | 1000 m | | | 10 y | 30 y | 720 d | 1500 d | 30 m (vert.) | 100 m | Firm | Topography | GCOS |
| Land surface topography | 10 m | 1000 m | | | 10 y | 30 y | 720 d | 1500 d | 30 m (vert.) | 100 m | Speculative | Topography | GTOS |
| Leaf Area Index (LAI) | 0.1 km | 1 km | | | 10 d | 30 d | 10 d | 30 d | 20 % (Max) | 100 % | Tentative | | GCOS |
| Leaf Area Index (LAI) | 0.1 km | 1 km | | | 10 d | 30 d | 10 d | 30 d | 20 % (Max) | 100 % | Tentative | | GTOS |
| Outgoing long-wave Earth surface | 25 km | 100 km | | | 3 h | 6 h | 24 h | 120 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - outgoing long-wave in situ | GTOS |
| Outgoing long-wave Earth surface | 25 km | 100 km | | | 3 h | 6 h | 24 h | 120 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - outgoing long-wave in situ | GCOS |
| Outgoing long-wave radiation at TOA | 50 km | 100 km | | | 480 h | 1440 h | 816 h | 2448 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - outgoing long wave satellite | GCOS |
| Outgoing long-wave radiation at TOA | 50 km | 100 km | | | 480 h | 1440 h | 30 h | 90 h | 5 W/m2 | 10 W/m2 | Speculative | Radiation - outgoing long wave satellite | GTOS |
| Ozone profile - Total column | 1 km | 8 km | | | 24 h | 48 h | 240 h | 720 h | Missing | Missing | Speculative | | GCOS |
| Ozone profile - Total column | 1 km | 8 km | | | 24 h | 48 h | 240 h | 720 h | Missing | Missing | Speculative | | GTOS |
| Permafrost 0.01 | 1 km | | | 10 d | 365 d | 90 d | 365 d | Missing | Missing | Speculative | Permafrost extent | | GTOS |
| Permafrost 0.01 | 1 km | | | 10 d | 365 d | 90 d | 365 d | Missing | Missing | Speculative | Permafrost extent | | GCOS |
| Precipitation rate at the ground (liquid) | 1 km | 10 km | | | 3 h | 6 h | 24 h | 120 h | 0.05 mm/h | 0.1 mm/h | Tentative | | GTOS |
| Precipitation rate at the ground (liquid) | 1 km | 10 km | | | 3 h | 6 h | 24 h | 120 h | 0.05 mm/h | 0.1 mm/h | Tentative | | GCOS |
| Precipitation rate at the ground (solid) | 1 km | 10 km | | | 3 h | 6 h | 24 h | 120 h | 0.05 mm/h | 0.1 mm/h | Tentative | | GTOS |
| Precipitation rate at the ground (solid) | 1 km | 10 km | | | 3 h | 6 h | 24 h | 120 h | 0.05 mm/h | 0.1 mm/h | Tentative | | GCOS |
| Snow cover 1 km | 5 km | | | 1 d | 3 d | 2 d | 3 d | 5 % (Max) | | 10 % | Tentative | Snow cover area | GCOS |
| Snow cover 1 km | 5 km | | | 1 d | 3 d | 2 d | 3 d | 5 % (Max) | | 10 % | Tentative | Snow cover area | GTOS |
| Snow melting conditions | 10 km | 25 km | | | 24 h | 72 h | 48 h | 72 h | 6 classes | 2 classes | Tentative | Snow surface state | GCOS |
| Snow melting conditions | 10 km | 25 km | | | 24 h | 72 h | 48 h | 72 h | 6 classes | 2 classes | Tentative | Snow surface state | GTOS |
| Snow water equivalent | 10 km | 25 km | | | 1 d | 3 d | 2 d | 3 d | 5 mm | 10 mm | Speculative | | GTOS |
| Snow water equivalent | 10 km | 25 km | | | 1 d | 3 d | 2 d | 3 d | 5 mm | 10 mm | Speculative | | GCOS |
| Soil moisture | 25 km | 100 km | | | 1 d | 5 d | 3 d | 5 d | Missing | Missing | Speculative | | GCOS |
| Soil moisture | 25 km | 100 km | | | 1 d | 5 d | 3 d | 5 d | Missing | Missing | Speculative | | GTOS |
| Wind vector over land surface (horizontal) | 25 km | 100 km | | | 24 h | 120 h | 24 h | 240 h | 2 m/s | 5 m/s | Speculative | Wind velocity | GTOS |
| Wind vector over land surface (horizontal) | 25 km | 100 km | | | 24 h | 120 h | 24 h | 240 h | 2 m/s | 5 m/s | Speculative | Wind velocity | GCOS |

# ANNEX III

## PROCESSING, INTERPRETATION, DISSEMINATION AND STORAGE OF SATELLITE DATA

Since the first environmental satellite launch, satellite data, information and products have played a steadily increasing role in the successful fulfilment of many WMO programmes, ranging from operational meteorology to climate research. Chapters 5 and 8 describe the continuing role of satellites in the monitoring of the atmosphere and ocean, the cryosphere and land surfaces and the use of the observed data to improve our understanding of the complex interaction of meteorological and climatological processes. There is no possibility of advancing scientific research or improving operational data assimilation systems without the availability of retrospective observed data and products. The long-term stewardship of this information is only possible through planned, carefully constructed systems of data acquisition, processing and archival. Such systems would be rendered worthless without the final piece of the puzzle: a system to allow user access to the data archives.

There are many challenges concerning the future processing of satellite observations for the purpose of quality assurance, long-term archiving, dissemination to users and overall stewardship. Perhaps the largest involves the sheer volume of the data, which is becoming available today and will continue in abundance from the proposed high-resolution sensors during the next decade. The increasing data volumes can be clearly understood by the realization that today an operational polar-orbiting satellite produces approximately 2 Terabytes worth of archival data in **one year**, but within the next 10 years, 1 Terabyte of data **per day** will be common. The movement of such large digital files through the Internet will require great increases in communications band width, accompanied by similar increases in storage capacity for archivists and users and in computer power and algorithms to allow for necessary data processing.

But regardless of size of the data bases, there are certain principles of stewardship of data that must be followed to ensure that the data will be maintained in perpetuity and also available to and usable by current and future users:

- Development and maintenance of an archive architecture and paradigm;
- Efficient and effective operational acquisition and recovery of data and metadata;
- Processing of data to ensure integrity;
- Production and maintenance of inventories, directories, catalogues and other suitable means to describe data and information;
- Development and maintenance of a user access system and explicit documentation;
- Long-term Preservation of data.

These principles will be described in some detail below.

### Development and maintenance of archive architecture and paradigm

An archive architecture and paradigm must be established to allow for long-term stewardship of large volume data sets and products. The overall paradigm is that the archive is in a near-on-line status, with portions of it available on line for direct access by users. Near-line archives will be able to deliver data to customers in a matter of minutes to hours, depending on the volume of the request. The last piece of the long-term archive involves an off-site disaster backup copy. For smaller volume data sets it may be possible to keep an additional copy, however for large data sets this is prohibitively expensive.

Satellite data are recorded to digital archive media in units of data sets. Each dataset carries a unique name, used as the tag for tracking and managing data in the archive. The Data

Set Catalogue contains one record for each data set. Each catalogue record carries the unique data set name plus information about the physical location of a data set (e.g., the physical media volume number and/or pathname). This one-to-one relationship of catalogue records to archive data sets provides the essential link between archive and catalogue for managing the data archive.

Each catalogue record contains other data including digital signature information that is necessary to ensure the integrity of data sets. This information is compared to freshly computed digital signature information each time a data set is read, copied or moved. Any change indicates a corrupted data set, which can be replaced from a back-up copy in the official archive.

Ancillary data sets, such as digital elevation models are also archived along with the sensor data.

Metadata files carry documentation about data sources, the sensors, processing algorithms and other information that are essential for efficient and effective use of the data. A metadata file normally describes one type of data, for example from one sensor, and, therefore, applies to numerous data sets. Metadata standards have been developed (for example by the U.S. Federal Geographic Data Committee (FGDC-STD-001-1998) and should be followed in creating and managing metadata.

### Efficient and Effective Operational Acquisition and Recovery of data and metadata

The increasing volume of satellite data (e.g., IJPS, EOS, NPOESS, Next Generation Geostationary Satellites…) will continually put pressure on the capacities of communications system to move the data from points of receipt (ingest) to points of processing. The integrity of data passing through these systems must be monitored and re-communications requests must be issued as soon as possible, or the system will begin to fall behind and face difficult catch-up scenarios as the data keeps pouring from the sensors. At this stage of processing quality assurance procedures must be in place to ensure that the data received at the archive location is the same as sent by the ingest facility. If there is a problem the data stream must be re-transmitted.

### Processing of data to ensure integrity

Once the data have arrived at an archival or data management centre, the continual practice of checking for data integrity begins. Data and products carry digital signatures that include data integrity parameters. These numbers are compared to freshly computed values at each step of the archive and access process to ensure that data have not been lost or corrupted. When data first arrive for archiving, the content of electronic transfers are validated against the transfer log for completeness and tested for integrity via the digital signature. Reports on the integrity of newly archived data and products are always available, and electronic notification of problem data sets are made immediately. Other processing techniques should be in place after the data have been received and checked for completeness. Periodic checks of the archive should be performed to ensure that the integrity has not been damaged. But even more important is using the data to create products or as supplements to operational activities that will help ensure its integrity. This science-based quality assurance integrates product (operational or research) processing into the quality assurance process.

In order to better address user needs for more efficiently determine what products are useful for a given application, particularly long-term climate studies, archive centres will be providing additional quality control information as well as expertise in the use of satellite data. This additional information will include radiance diagrams (so-called radgrams), similar to those used operationally by the numerical weather prediction centres, to monitor the time evolution of statistics of individual satellite channels. Periodic re-analysis of data sets will occur to ensure the optimal merging of all available data and to allow the production of retrieved geophysical variables with the latest algorithms. The periodic re-analysis will also provide an opportunity to work with user groups to access to entire data sets for new product development as the data sets are rotated from near-line archives to on-line archives for some limited period of time.

## Production and maintenance of inventories, directories, catalogues and other suitable means to describe data and information

Metadata, or information about the data, products and storage system and facilities are vital components in the successful stewardship of data This information should be created, kept up-to-date and stored in appropriate metadata catalogues, according to established principles. The catalogues will be available to customers for online searches via the World Wide Web. Metadata also serve the function of documenting the types of measurements made, sensor characteristics, processing methodologies and other information that is important for users of the data.

Data set naming conventions should be established to allow for clear, secure access to appropriate data and products from multiple satellites and sensors. The digital signature information and alternate data set name for each element should be stored as fields in the inventory database for subsequent retrieval and distribution. Inventories will contain information about the dates and geographic locations of each retrievable archive element, as well as its unique identifier, and pointers to the physical media on which it is recorded. Inventories should be made easily searchable via the Internet or other telecommunications mechanism. A browse facility provides thumbnail images for user browsing and making decisions on which data sets to select.

## Development and maintenance of a user access system and documentation

Customers for satellite data should be able to query an online metadata system to retrieve information about the measurements available, the sensor characteristics, the data processing status, data format, and other historical information about the data. Customers should also be able to order data for delivery via FTP for smaller volumes of data. In the case of very large data volumes, delivery via other media such as magnetic tape is preferred.

> On-line data orders interface with customer service systems developed by the data archivists. The access interface performs authorized searches, identifies data sampling and delivery methods, and initiates data retrieval. Typically a customer may be able to search by selecting:

(1) Satellite ID

(2) Data Type

(3) Channel

(4) Latitude / Longitude range

(5) Date / Time

(6) Correlation with other data, etc.

In some cases the customer may wish to establish a subscription service through which a pre-determined class of data are “pushed” from the archive centre without customer interaction.

Elements from archive near-line mass storage are retrieved using a data base management system. The integrity of the elements retrieved is validated via digital signature information from the inventory database. To service requests for custom data sets (e.g., subsets), the retrieval system processes data and creates new data set names and digital signatures.

Acquired data, associated metadata, and digital signature files are packaged for delivery in a predefined order and format. If the data requested is not on-line and electronic transfer (FTP) is selected as the delivery method in the Web-Internet access system, the requestor receives a "data ready" notification via email. The notification will describe the procedures and cost for retrieving the requested data.

For a robust analysis of long time series of data, for example when studying climate variability and change, there will be a need for the periodic re-processing of data and analyses. The reprocessing involves the use of standardized data assimilation algorithms for product development and also corrects biases which may have crept into data over time due to the use of different satellite sensors, orbital decay, etc. The complete archive of data and metadata must be available at the re-processing site. Plans for the long-term archival of large volumes of satellite data must take into account the requirements for data availability levied by reprocessing.

## Long-term Preservation of data

Long-term preservation of satellite data is an on-going process which should involve users, scientists, data managers, and data collectors. Knowledge of the data being preserved and how it will be used are essential underpinnings for successful preservation. Procedures must be developed to determine what data should be added or removed from the archive and when that should be done. Detailed documentation of the data and derived products is essential to minimize user access and processing problems and maximize the value of the archive.

For years there was only one mechanism for storing satellite data retrospectively: on computer-compatible magnetic tapes. But with the recent reduction in the price of computer disk storage, data can be stored on random access disks. But, because of the high volume of satellite data and associated products, keeping much of the data on-line, that is, directly accessible by the users, is not possible. A short time period of data might be kept on-line, with the remainder of the retrospective data stored off-line or near-on-line as a working archive. To preclude the archive becoming inaccessible in case of storage management system failure, data readability will be independent of any storage management system.

Validated data sets and associated metadata (to include quality measures, electronic signatures and checksums) are archived individually as discrete elements or data sets. Information about each data element is entered into inventory catalogue databases and controlled by archive management system software. The physical location and media types used are transparent to the users.

Preservation of data in the archive is an active process that includes these activities:

(1) Copy data to archive media

(2) Create and maintain an archive backup copy off-site

(3) Migrate archive to new media and systems (hardware, operating system, software) to maintain technology compatibility and as a data refreshment process

(4) Monitor data integrity at all above steps as well as during retrievals from the archive.

In addition, random samples of data in the archive are routinely checked for completeness and integrity. Data sets which have integrity problems are replaced by copies made from backup archive sources.

A data migration plan should be developed and implemented that entails the use of automated robotic storage technology. Migration is automatically performed by storage management software according to established parameters.  Migration is performed when new, cost effective media are available to avoid being forced by media or systems obsolescence.  All migrated copies should be capable of being read by other established IT technology.

Copies of all data preserved in the official archive should be stored at an off-site backup facility with a minimum of 50km distance separation from the archive facility.  Such data will maintain the form and structure of the permanently stored archive data and are subject to retrieval (from the off-site storage) only at times of emergency.  Transmission of data to the backup facility will occur on a routine, scheduled basis.

The offsite archive facility may simply maintain copies of the media only or have varying degrees of sophistication ranging to a fully operational off-site facility that mirrors the working archive facility.

> Archive facilities should determine, in consultation with users, how long to store data in an archive, should maintain a data disposition schedule, and dispose of data sets on scheduled dates.  However, it would not be unusual for the highest resolution data, metadata and product processing algorithms to be kept in perpetuity.

## ANNEX IV

# NEAR TERM CONFIGURATION OF THE SPACE BASED COMPONENT OF THE GLOBAL OBSERVING SYSTEM

## POLAR ORBITING SATELLITES

### 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 versus 1 km at nadir), and have 22 spectral bands (between 0.4 and 12.5 µm) with additional capability for sea surface temperature, aerosols, snow cover, cloud cover, surface albedo, vegetation index, sea ice, and ocean colour.

The Visible Infrared Scanner (VIRS) on TRMM is measuring radiances in 5 spectral bands (0.63, 1.6, 3.75, 10.8, 12 µm) at 2 km nadir resolution. These data are being used in combination with TRMM Microwave Imager (TMI) data to estimate precipitation locations and amounts.

NASA's Moderate-Resolution Imaging Spectro-radiometers (MODIS); one on Terra and another on Aqua, is designed to measure biological and physical processes on a global basis every 1-to-2 days. This multidisciplinary instrument is yielding simultaneous, congruent observations of atmospheric (aerosol and cloud properties, water vapour and temperature profiles), oceanic (sea-surface temperature and chlorophyll), and land-surface features (land-cover changes, land-surface temperature, snow cover, and vegetation properties). The MODIS instrument provides imagery in 36 discrete bands between 0.4 and 14.5 µm at 1 km resolution at nadir (selected bands have 250 or 500 meter resolution); signal-to-noise ratios are greater than 500 at 1-km resolution and absolute irradiance accuracies are < ±5% from 0.4 to 3 µm (2% relative to the sun) and 1 percent or better in the thermal infrared (3.7 to 14.5 µm). Any point on the Earth is covered at least once every 2 days.

On the Terra platform, the Advanced Thermal Emission and Reflection Radiometer (ASTER), provided by the Japanese, is imaging the earth at very high-spatial-resolution (15- to 90-m) in order to better understand the physical processes that affect climate change. ASTER measures in three visible and near-infrared (VNIR) channels between 0.5 and 0.9 µm, with 15-m resolution; six short-wave infrared (SWIR) channels between 1.6 and 2.43 µm, with 30-m resolution; and five thermal infrared (TIR) channels between 8 and 12 µm, with 90-m resolution. Combinations of VNIR, SWIR, and TIR are exploited for cloud studies, surface feature mapping, soil and geologic studies, volcano monitoring, and surface temperature, emissivity, and reflectivity determination.

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 very 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 ENVISAT in 2002, will expand upon these capabilities thereby ensuring the production of a unique 10 year near-continuous data set at the levels of accuracy required (0.3 K or better) by both the operational and climate communities.

The Ocean Color and Temperature Scanner (OCTS), onboard ADEOS launched in 1996, achieved measurements in 8 visible and 4 infrared bands at 700 m nadir resolution applicable to observation of the coastal zone and land. OCTS will be succeeded by the Global Imager (GLI) on

ADEOS-2 in 2002. This optical sensor observes reflected solar light as well as emitted infrared radiation from the Earth's surface including land, ocean and cloud. GLI data will be used to provide global information such as surface temperature, vegetation distribution, and ice distribution. These data may be used to determine the global circulation of carbon, to monitor cloud, snow, ice and sea surface temperature, and to determine primary marine production. GLI has 23 channels in visible and near-infrared region (VNIR), 6 channels in short wavelength infrared region (SWIR), and 7 channels in middle and thermal infrared region (MTIR) for its multi spectral observation. It has six atmospheric windows at 1.6, 2.2, 3.7, 8.6, 10.8, 12.0 micron and 3 water vapour sensitive bands at 6.7, 7.3 and 7.5 micron. The ground resolution is 1km at nadir, but some channels in VNIR and SWIR have a resolution of 250m.

China is evolving to FY-3 in 2004, their second series of polar orbiting meteorological satellites. FY-3 will include Visible and Infrared Radiometer (VIRR) with ten visible and infrared channels and the Moderate Resolution Visible and Infrared Imager (MODI) with 20 channels located mainly at VIS and NIR region that are complementary to the VIRR.

**Atmospheric Temperature and Humidity Sounders**

In 1969 and 1970, two important instruments that paved the way for atmospheric thermodynamic profiling were demonstrated in NASA's NIMBUS program. The Satellite Infrared Spectrometer (SIRS) and Infrared Interferometer Spectrometer (IRIS) paved the way for multi-channel infrared radiometers and interferometers that could be used to sound the atmosphere. An important operational milestone occurred in the remote sounding of vertical temperature and humidity profiles in the atmosphere on a worldwide basis with the TIROS Operational Vertical Sounder (TOVS). TOVS evolved to an advanced version in 1998 that consists of the High resolution Infrared Radiation Sounder (HIRS) and the Advanced Microwave Sounding Unit (AMSU). These 18 channel IR (3.7 to 14.7 μm) and 20 channel microwave (23.8 to 89 GHz) sounders produce temperature and moisture profiles in clear and cloudy (non-precipitating) skies every fifty kilometres. NOAA will be transitioning to more capable sounders in the NPOESS era, 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 measuring radiances from 4 to 15.4 μm at 2.5 to 0.6 wavenumber spectral resolution respectively. CrIS 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. The microwave sounder that will compliment CrIS in the NPP/NPOESS era is the 22 channel (23.8 to 183.3 GHz) Advanced Technology Microwave Sounder (ATMS), the next generation cross track microwave sounder.

The EUMETSAT METOP series will realize comparable sounding capability with the Infrared Atmospheric Sounding Interferometer (IASI) in conjunction with the advanced microwave temperature sounding units (AMSU-A) and microwave humidity sounders (MHS / HSB). IASI is a Michelson interferometer measuring radiances from 3.5 to 16.6 μm at 0.25 wavenumber spectral resolution. CrIS/ATMS will fly in the afternoon (1330 ascending) and IASI/AMSU/MHS will fly in the morning (0930 descending) orbit.

The Russian Federation is expanding their Meteor-3M with the launch of N1 in late 2001 and N2 in 2004. N1 carries the sounding microwave radiometer MTVZA (20 channels in the range of 18 to 183 GHz). This will be complemented with an infrared sounding interferometer on N2.

China is adding to their FY-3 series the Infrared Atmospheric Sounder (IRAS). IRAS will have 26 channels where the first 20 channels are almost the same as HIRS/3 and remaining six channels designed to measure aerosols, stratosphere temperature, carbon dioxide content and cirrus. IRAS will be complemented by an 8 channel Microwave Atmospheric Sounder (MWAS) for temperature sounding in cloudy areas.

India has also realized microwave observations for meteorology and oceanographic studies with OCENSAT-1 launched in May 1999 with Multichannel Scanning Microwave radiometer (MSMR) along with Ocean Colour Monitor (OCM).

## Microwave All-Weather Radiometers

Since June 1987, a series of DMSP satellites in polar orbit have carried a scanning microwave radiometer called the Special Sensor Microwave Imager (SSM/I). Because of the ability of microwave radiation to penetrate clouds, SSMI provides night-day, all-weather imaging of the land and ocean surface. NOAA has used the DMSP SSM/I data extensively. A conical scanning microwave imager/sounder will be flown on NPOESS. The Conically Scanning Microwave Image / 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.

Since 1997, NASA has been flying the TRMM Microwave Imager. This multi-channel (10.7, 19.4, 21.3, 37, and 85.5 GHz) dual polarized radiometer is providing measurements useful for estimating rainfall rates over oceans. When used in combination with on-board Precipitation Radar (PR) and VIRS data, precipitation profiles can be estimated.

NASDA has developed the AMSR for high precision monitoring of the global circulation of water and energy cycles regardless of cloud cover. AMSR has 8 frequency bands from 6.9GHz to 89GHz with spatial resolution of about 5km in the 89GHz band and about 60km in the 6.9GHz band. AMSR is able to observe water vapour, precipitation and cloud liquid water and ice like previous microwave radiometers but with much higher spatial resolution. It will fly on Aqua and ADEOS-2 in 2002.

ESA has been flying microwave radiometers (MWR) that measure the integrated atmospheric water vapour column and cloud liquid water content, as correction terms for the radar altimeter signal. In addition, MWR measurement data are useful for the determination of surface emissivity and soil moisture over land, for surface energy budget investigations to support atmospheric studies, and for ice characterization. The next MWR, to be flown on ENVISAT, has evolved from the instruments previously flown on ERS-1 and ERS-2.

China is adding to their FY-3 series the conically scanning Microwave Radiation Imager (MWRI) with 12 channels. This sensor measures thermal microwave radiation from land and ocean surfaces, as well as being sensitive to various forms of water and moisture in the atmosphere, clouds and surfaces. These channels can penetrate clouds and provide forecasters with an all weather measurement capability. At higher frequency channels, the scattering signatures from the cloud and precipitation are also good for detecting rainfall.

## Multi-angle Imagers

France developed the Polarization and Directionality of Earth Reflectance (POLDER) instrument to measure the polarization, and directionality and spectral characteristics of the solar light reflected by aerosols, clouds, oceans, and land surfaces. It flew on ADEOS (1996) and will again be on ADEOS-2 (2002). POLDER is a 2 dimensional CCD array, with wide field of view, multi band imaging radiometer and polarimeter developed by CNES. Multi-angle viewing is achieved at quasi constant 7km × 6km resolution; a filter and polarizer wheel that rotates and scans eight narrow spectral bands in the visible and near infrared (443, 490, 564, 670, 763, 765, 865, 910 nm), and three polarization angles at 443, 670 and 865 nm. POLDER is intended to determine the influence of aerosols and clouds on the Earth's Radiation Budget and to quantify the role of photosynthesis from the continental and oceanic biosphere in the global carbon cycle.

The Multi-angle Imaging Spectro-Radiometer (MISR) flying on Terra is providing multiple-angle, continuous sunlight coverage of the Earth with high spatial resolution. MISR captures multidirectional observations of each scene within a time scale of a few minutes, thereby under virtually the same atmospheric conditions. MISR uses nine individual charge-coupled device (CCD) based pushbroom cameras to observe the Earth at nine discrete view angles: one at nadir, plus eight other symmetrical views at 26.1, 45.6, 60.0, and 70.5° forward and aftward of nadir. Images at each angle are obtained in four spectral bands centred at 446, 558, 672, and 866 nm sampling at 275 m, 550 m, or 1.1 km. Global multi-angle coverage of the entire Earth is accomplished in 9 days at the equator, and 2 days at the poles. MISR measures the heterogeneity and altitude of clouds, aerosols, and the earth surface.

## Ozone Monitors

One approach used to derive vertical profiles of ozone utilizes the ultraviolet portion of the electromagnetic spectrum. 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 confirmed the existence of the Antarctic ozone hole. 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.

The first European ozone monitoring instrument, ESA's Global Ozone Measurement Experiment, GOME, flew onboard the ERS-1 satellite in the 1990s. The primary objective of GOME was the measurement of total column amounts and profiles of ozone and of other gases involved in ozone photo chemistry. The Global Ozone Monitoring by Occultation of Stars (GOMOS) on board ENVISAT (to be launched in 2002) is the newest ESA instrument aiming at ozone monitoring. GOMOS measurements are based on star occultations and offer significant advantages in terms of good/uniform global coverage, day- and night-side operation, and high vertical resolution. It is intended to provide altitude-resolved global ozone mapping and trend monitoring with very high accuracy, as needed for the understanding of ozone chemistry and for model validation. The primary GOMOS mission objectives are: (a) measurement of profiles of ozone, NO2, NO3, OClO, temperature, and water vapour; (b) day- and night-side measurement capability; (c) global coverage with typically over 600 profile measurements per day; (d) altitude measurement capability between the tropopause and 100 km; and (e) altitude resolution of better than 1.7 km.

Japan is launching an Improved Limb Atmospheric Sounder (ILAS-II) on ADEOS-2 in 2002. That sensor is intended to monitor and study changes in the stratosphere that are triggered by emissions of chlorofluorocarbon (CFC), and to evaluate the effectiveness of world wide emission controls of CFC. ILAS-II is a spectrometer that observes the atmospheric limb absorption spectrum from the upper troposphere to the stratosphere using sunlight as a light source (solar occultation technique). The spectrum is analyzed to provide information of height distribution of atmospheric component density, temperature and pressure. The spectrometer covers the infrared region (3-13 micrometer) and the near visible region (753 to 784nm). From these spectral observations, ILAS-II can measure the vertical profiles of species related to ozone depletion phenomena: ozone (O3), nitrogen dioxide (NO2), nitric acid(HNO3), aerosols, water vapour (H2O), CFC-11, CFC-12, methane (CH), nitrous oxide (N2O), chlorine nitrate (ClONO2), and temperature and pressure as well. ILAS-II improves upon the initial measurements made by ILAS (aboard ADEOS in 1996).

China is also including on FY-3 a Total Ozone Mapper and Ozone Profiler (TOM/OP), consisting of two instruments to measure ozone in the earth’s atmosphere. TOM is a 6-channel spectrometer with 50km resolution at the nadir and OP is a 12-channel spectrograph with 200 km resolution at nadir.

**Atmospheric Chemistry Instruments**

NASA with the Canadian Space Agency launched the Measurements Of Pollution In The Troposphere (MOPITT) in Terra in 1999. MOPITT is measuring emitted and reflected infrared radiance in the atmospheric column that permits retrieval of global and temporal distributions of tropospheric CO profiles and total column CH4. Both CO and CH4 are produced by biomass systems, oceans, and human activities. MOPITT operates on the principle of correlation spectroscopy, i.e., spectral selection of radiation emission or absorption by a gas, using a sample of the same gas as a filter. Atmospheric CO sounding and column CO and CH4 are mapped at 22 km by using thermal and reflected solar channels in the regions of 4.7 and 2.3 µm, respectively. Scientific studies are employing these data to derive three-dimensional global maps as part of an effort to model global tropospheric chemistry.

ESA will be flying the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on ENVISAT (in 2002). It is a Fourier transform spectrometer for the measurement of high-resolution gaseous emission spectra at the Earth's limb. It operates in the near to mid infrared where many of the atmospheric trace-gases playing a major role in atmospheric chemistry have important emission features. The objectives of MIPAS are: (a) simultaneous and global measurements of geophysical parameters in the middle atmosphere; (b) stratospheric chemistry of O3, H2O, CH4, N2O, and HNO3; (c) climatology of temperature, CH4, N2O, and O3; (d) study of chemical composition, dynamics, and radiation budget of the middle atmosphere; and (e) monitoring of stratospheric O3 and CFC's.

The SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) on ENVISAT will also be performing global measurements of trace gases in the troposphere and in the stratosphere. It is a is a passive remote sensing spectrometer observing backscattered, reflected, transmitted or emitted radiation from the atmosphere and Earth's surface, in the wavelength range between 240 and 2380 nm.

**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. 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 2002.

SeaWinds provides high accuracy sea surface wind speed and direction measurements by observing microwave reflection from the sea surface. Its wind speed accuracy is 2m/s, wind direction accuracy is 20 degrees, and spatial resolution is 50km; it covers the globe every 2 days. Analyzing SeaWinds' data, combined with those of AMSR or GLI will contribute to the analyses of water circulations and other ocean phenomena.

No additional U.S. scatterometer missions are planned before NPOESS, which plans to use a passive microwave approach with CMIS (Conically Scanning Microwave Image/Sounder) to determine 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 late 2005 include an Advanced Scatterometer (ASCAT) sensor, will enable continuous measurements from a polar orbit through 2020. Tandem missions of broad swath instruments are being discussed to enhance sampling of surface wind fields for oceanographic use; one possibility is for NASDA to fly a NASA scatterometer on GCOM-B1 and the missions of QuikScat and SeaWinds on NASDA’s ADEOS-2 to be extended as long as possible.

## Ocean Colour Instruments

Ocean colour measurements are important in four broad domains of applications; they are the ocean carbon cycle, the thermal regime of the upper ocean, the management of fisheries, and the management of coastal zones. The first observations of ocean colour from space were carried out by the experimental Coastal Zone Colour Scanner (CZCS) from 1978 to 1986 aboard NASA's Nimbus-7 satellite. This instrument provided global and regional data sets which yielded a wealth of new information about the distribution and seasonal variability of primary productivity. During the period 1986 to 1996, the orderly development of ocean-colour science was hindered by the lack of an operational satellite producing ocean-colour data. Although considerable energy was devoted to analysing the results of the then-defunct Coastal Zone Colour Scanner, there was no opportunity to conduct new studies in which observations from space could be matched with in situ data observations in near real time.

The picture began to improve in March 1996, when India launched the German sensor MOS. Although this device does not give global coverage, it is important as the first source of new ocean-colour data in ten years. In August 1996, Japan launched the Japanese sensor OCTS and the French sensor POLDER on the ADEOS mission. This was a very powerful combination, which operated until June 1997. In August 1997, the USA launched the SeaWiFS sensor, which has been in routine operation since September 1997. This instrument is now providing complete global coverage of the oceans every two days.

A number of ocean colour instruments are planned for the very near future (GLI, MISR, MODIS, MERIS, OCI, OCM, OSMI, POLDER-2 scheduled to be launched in 1999-2002). Recent experience has emphasized that a certain controlled redundancy is essential to ensure an unbroken stream of ocean-colour data into the indefinite future.

The MEdium Resolution Imaging Spectrometer (MERIS) instrument will be on ENVISAT and will be the latest imaging spectrometer that measures the solar radiation reflected by the Earth, at a ground spatial resolution of 300m, in 15 spectral bands, it’s visible and near infra-red measurements provide global coverage of the Earth in 3 days. The MERIS mission is the measurement of sea colour in the oceans and in coastal areas. Knowledge of the sea colour can be converted into a measurement of chlorophyll pigment concentration, suspended sediment concentration and of aerosol loads over the marine domain.

## Radiation Budget Monitors

The Earth's radiation budget and atmospheric radiation from the top of the atmosphere to the surface was first measured by the Earth Radiation Budget (ERB) sensors. They flew on Nimbus in 1978, as well as on a free flyer and on NOAA-9 and -10 in the mid 1980s. The Clouds and Earth Radiant Energy System (CERES) is continuing these broad band visible and infrared measurements on the Tropical Rainfall Measuring Mission (TRMM) which was launched in November 1997. CERES is also planned for the NPOESS orbit (1330 local time ascending orbit). 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 February 2002.

CERES data are providing accurate cloud and radiation flux measurements that are fundamental inputs to models of oceanic and atmospheric energetics, and also contributes to extended-range weather forecasting. CERES measures the radiative flows (0.3 – 5 µm, 8 – 12 µm, 0.3 – 50 µm) at the top of the atmosphere at 10 km nadir resolution, and combines these data with that from higher resolution imagers (VIRS on TRMM, MODIS on Terra/Aqua) to produce cloud properties and radiative fluxes through the atmosphere as well as the radiative energy budget at the Earth's surface. The imagers allow determination of cloud top height, fractional cloud cover, cloud liquid water path, droplet size, and other cloud properties that are consistent with the radiative fluxes. CERES provides, for the first time, a critical tie between the measurements of the radiation budget and synchronous measurements of cloud properties. CERES also is providing improved measurements of clear-sky radiative fluxes, that near-simultaneous measurements of both well-calibrated cloud-imager and broadband radiation measurements.

## Altimeters

Altimeters measure the oceans' 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. Altimeters flew on the European ERS-1 and –2 satellites in the 1990's and provided a major quasi-operational contribution. JASON-1, a joint mission between France and the USA scheduled for 2002, will monitor the global ocean with a solid state radar altimeter (POSEIDON-2), a Doppler tracking system receiver (DORIS), a Microwave radiometer, a GPS tracking receiver, and a laser retro-reflector array. A JASON-2 mission will follow-on to the JASON-1 mission with a launch in 2005. NOAA is planning to manifest a dual frequency microwave radar altimeter for its morning (0530 descending) NPOESS platforms.

## *Positioning Sensors*

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 2002. NOAA is planning to manifest a GPSOS on all NPOESS platforms.

The EUMETSAT Polar-orbiting Satellite (METOP), due to be launched in late 2005, 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 WATS (Water Vapour and Temperature in the Troposphere and Stratosphere) where ESA plans to provide accurate dense, stable mapping of atmospheric humidity by means of a constellation of six micro-satellites (proposed as an ESA Earth Explorer Core Mission) that exploit GNSS occultation signals and occultation of signals in X- and Ka band between the micro-satellites. Intended for 2008 launch, WATS will provide about 6000 daily profiles of key ionospheric and atmospheric properties from the tracked GPS radio-signals as they are occulted behind the Earth limb. ESA is also maintaining ACE (Atmospheric Climate Experiment), consisting of a constellation of micro-satellites with GNSS atmospheric sounding receivers, as a hot stand-by mission.

### Wind Lidars

ESA is preparing the Atmospheric Dynamics Mission (ADM-Aeolus) for launch in 2007 on their Earth Explorer series. ADM-Aeolus will provide improved analyses of the global wind field in three-dimensions. This will correct the major deficiency in current wind-profiling techniques and also advance the techniques of atmospheric modelling and analysis. ADM-Aeolus will utilise active Doppler Wind Lidars (DWL) to provide the wind profiles globally, from direct wind observations, as well as cloud top heights, vertical distribution of clouds, aerosol properties, and wind variability. It is expected that ADM-Aeolus, will have a great effect upon operational weather forecasting and enable a more detailed study of the balance and circulation of wind energy on Earth. ADM is a single angle viewing lidar and the derivation of winds will require use of NWP.

### Hyperspectral Imagers

Although not designed for atmospheric purposes, NASA’s Earth Observing (EO-1) mission launched in November 2000 carries two instruments of great interest to the atmospheric science community. They are the Hyperion, a narrow swath (7.5 km) hyperspectral instrument with 30 meter horizontal resolution that samples the spectrum between 0.4 and 2.4 μm at 10 nanometer resolution, and the Local Atmospheric Corrector (LAC), a wide swath (185 km) hyperspectral instrument with 250 meter horizontal resolution that samples the spectrum between 0.9 μm and 1.6 μm at 2-6 nanometer spectral resolution. Both Hyperion and LAC scan across important water vapour absorption bands, and should be able to provide information on the atmosphere’s horizontal water vapour distribution at resolutions here-to-fore unattainable. This important information will help define the requirements for design of future satellite and *in situ* water vapour measuring systems.

## GEOSTATIONARY SATELLITES

### 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, FY-2 and GMS. VISSR enables 5 to 7 km resolution images of the full earth disk every 30 minutes in 2 or 3 visible and infrared windows and one water vapour sensitive band. The USA changed to a staring imager with 5 channels of visible and infrared measurements (0.6, 3.9, 6.7, 11, 12 µm) at 5 km resolution with full disk coverage in 30 minutes in 1993. More changes are underway.

Europe is moving to the Spinning Environmental Visible and Infrared Instrument (SEVIRI) with 12 channels of visible and infrared measurements (broad band visible, 0.6, 0.8, 1.6, 3.9, 6.3, 7.4, 8.7, 9.7, 10.8, 12, 13.4 µm) at 3 km resolution full disk every 15 minutes. For meteorological applications, the following channels are of particular interest: (a) 13.4 µm (CO2) plus 6.3 and 7.4 µm (H2O) channels will improve the height assignment of clouds and provide information on the vertical moisture distribution in the atmosphere; (b) 3.9 µm allows for low cloud and fog detection; (c) split window (10.8 µm and 12.0 µm) together with 3.9 µm have a good potential for land and sea surface temperature determination; and (e) 1.6 µm and 8.7 µm enable discrimination between ice and water clouds. A particular advantage of SEVIRI data for land applications is better monitoring of diurnal variations of cloudiness, earth surface temperature or solar irradiation at the Earth's surface.

Japan will embark on the MTSAT with 5 channels of visible and infrared measurements (0.6, 4, 6.7, 11, 12 µm) 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 to an Advanced Baseline Imager (ABI) that makes full disk images in 8 to 12 spectral bands (similar to those on SEVIRI) 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).

India has been supporting their INSAT series of satellites (with VIS, IR channels) since 1984 for operational short, medium range and synoptic forecasts. INSAT-2E with water vapour channel imaging has been useful for monitoring and forecasting monsoon and cyclone development; INSAT-2E also has a CCD camera providing 1km spatial resolution with around 600km swath. INSAT-3A and Metsat, to be launched by 2002, will have similar capabilities to image in 3 bands. INSAT-3D (to be launched in 2004) will include a split window thermal channel enabling continuous SST monitoring.

China plans to continue evolving their five planned FY-2 geosynchronous satellites. FY-2C, to be launched in 2004, will improve on the first two experimental satellites FY-2A and 2B. The number of spectral channels of Visible and Infrared Spin Scan Radiometer (VISSR) will be increased from 3 to 5.

## Infrared Sounding

With the three axis stablized platform on GOES-8, NOAA was able to introduce geostationary infrared sounders. Measuring the infrared radiation in 18 spectral bands (between 3.7 and 14.7 µm), 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 2011, using an interferometer, focal plane detector arrays, and on board data processing to cover 4.4 to 15.4 µm with 2000 plus channels measuring radiation from 5 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 2005. 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 vapour, 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. 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.

India will be adding a sounding capability to INSAT-3D in 2004; the planned 19 channel sounder will be able to estimate the temperature and humidity profiles of the atmosphere in order to study the mesoscale phenomena in tropical latitudes.

## Radiation Budget

EUMETSAT will be flying the Geostationary Earth Radiation Budget (GERB) starting on Meteosat Second Generation in 2002. This will enable hourly measurements of the Earth’s radiation budget and atmospheric radiation from the top of the atmosphere to the surface. The GERB payload will be a scanning radiometer with two broadband channels, one covering the solar spectrum, the other covering the entire electromagnetic spectrum. Data will be calibrated on board in order to support the retrieval of radiative fluxes of reflected solar radiation and emitted thermal radiation at the top of the atmosphere with an accuracy of 1%.