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Toward the Definition of Climate Observing Requirements in the Era of MSG and EPS

by

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Executive Summary

The definition and design of a climate measuring system is a topic of critical importance to furthering our understanding and prediction of climate change. It is also a topic under study by operational satellite agencies which now consider climate either as part of their mandate or are in the process of considering climate requirements in the planning for future observing systems. EUMETSAT in particular has taken a lead role in this topic by mandating that the agency will contribute to the operational monitoring of the climate and the detection of global climate changes.

1.0 Goals of a climate observing system

This report suggests that a climate observing system should aim to:

- *Identify how the Earth system is changing over the coming decades*
- *Explain why these changes occur*
- *Separate natural from anthropogenic cause and effects*
- *Contribute to ongoing assessment of our predictions of this change.*

A strategy for assigning priorities to fill observational gaps that should be considered in the design of future observing systems is suggested. The strategy is based on identifying key integrating themes which require both advances in observing systems and are a match to satellite observing system capabilities. The hydrological cycle is one such theme and improving observations of the components of the hydrological cycle should be a priority of future observing systems.

2.0 Composition of a Climate Observing System - measurement versus monitoring

The report provides a critical examination of what constitutes a climate observing system and considers the two underpinning requirements as represented schematically as follows:

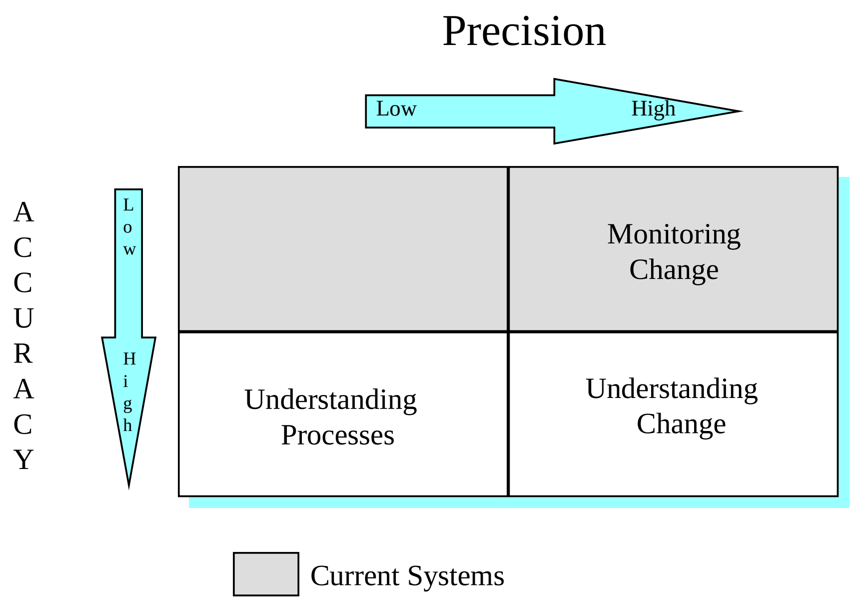

Fig. 1 The climate measurement problem - understanding climate processes requires accuracy (a measurement system) , monitoring climate change requires high precision (a monitoring system), detection and understanding climate change requires both high precision and high accuracy (a climate observing system).

This view of the climate system emphasizes two important requirements of space-based climate measuring systems: a requirement for accuracy and a requirement for precision. Monitoring climate change requires high precision (the requirement of a monitoring system) , studying climate processes requires accuracy (requirement of a measuring system) and understanding climate change requires both high precision and high accuracy (combined requirement of a climate observing system). The time and space scale capabilities of these systems do not have to be the same processes observations typically require time and space resolution high enough to discern fast processes, monitoring change on the other hand might be possible on a much coarser space-time resolution.

The accuracy and precision requirements of climate parameters are not known (most of what has been reported to date reflect more current capabilities than known requirements) and any requirements that do exist have not been converted to measurement requirements (i.e. of the directly measurement quantities). Current models suggest that requirements on precision and accuracy exceed the capabilities of existing systems although in some cases, and with careful and routine practices of calibration and verification, it appears that selected observations approach what is thought to be required to detect climate change in the coming decade or more. However, if the examples of present long-term satellite observations are an indication, true precision of observations is not known *a priori* and requires assessment after a large body of observations have been collected.

3.0 System Uncertainties

Three broad system-level uncertainties are discussed:

1. Instrument error - these largely revolve around the accuracy of calibration and instrument characterization (i.e. monitoring instrument changes after launch). In general, it can be concluded that present calibration strategies are not adequate for detecting (small) global changes and that multiple calibration approaches are required if the accuracy suggested by models of climate change is to be met. Degradation of sensor optics in orbit requires that it is necessary to calibrate routinely in orbit but that this is not sufficient. It is necessary to monitor the instrument for change if high accuracy is to be attained. Experience also points to the importance of vicarious calibration which is used to establish measurement precision. More effort is needed to establish the accuracy of vicarious calibration. This effort should be directed as follows (i) Work towards establishing reference standards. Since model simulations are often an integral component of vicarious calibration, basic model references are needed. The movement towards standard models has begun. (ii) Maintain routine calibrations based on matching with other observations. GEO observations are well suited to this routine approach since they offer many possibilities for time coincident observations than is usually possible with LEO observations. (iii) Continue to develop new and improved methods of calibration.
2. The calibrated radiance data are an important climate data product from current systems. As a minimum operational systems should strive to produce these data for climate purposes. These data have greater intrinsic accuracy and precision than any parameter retrieved from them. Requirements on radiance precision and accuracy are not known since the nature of the climate variability of radiance has yet to be assessed. Changes in radiance are likely to be the most accurate indicator of climate change but unfortunately these indicators alone provide little insight into the nature of the processes that govern this change. Interpretation through retrieval or assimilation is ultimately required. Assimilation of climate-relevant data (such as data relating to hydrological processes) are crude and do not replace the need for improving physically-based retrieval methods.
3. Retrieval uncertainties - radiance products are a necessary output from climate observing systems but are far from sufficient to achieve the climate goals as stated. Retrieval of geophysical information is also necessary to forge understanding. In this context, most of the real uncertainty of observing systems have not been properly evaluated. Uncertainty includes both instrument error as well as error in retrievals and often improved calibration accuracy does not necessarily reduce the overall retrieval error. There are two forms of retrieval error; (i) model errors - these are often the dominant source of error of a retrieval, and (ii) reliance on *a priori* information - this is a critical issue for climate

monitoring and one generally ignored. Retrievals of most sounding products are heavily constrained by climatology. For monitoring purposes it is critical that the extent of reliance of any retrieval on the *a priori* be firmly established since any properties that are too constrained to such information will not provide proper measures of evolving climate change.

4. Sampling errors and biases are also a major component of the uncertainty of satellite observing systems: asynoptic sampling of polar orbiting satellites introduces error in time-mean fields that are significant. These arise chiefly from inadequate sampling of diurnal cycles resulting in an aliasing in the time-mean fields. This error can be mitigated through coordination of polar satellites that provide adequate sample of the diurnal cycle. The synoptic-like sampling from GEOs favours studying fast processes and their evolution. Again, coordination of GEO satellites will greatly improve sampling limitations. This coordination, wherever possible needs to include same instruments (or close copies) and the same QA procedures.

4.0 Relevance to EUMETSAT operations in the new millennium

Developing a climate observing system that both measures and monitors climate is a difficult and complex task. Whereas the goal of any climate observing system might be viewed as one of progressing towards the lower left-hand corner of Fig. 1, this is not likely to be achieved with current operationally-based meteorological observing systems. New systems will be needed to meet both the precision and accuracy requirements, as they become known. However, current and planned systems can contribute towards the problem of climate observations in the following ways:

1. Operational systems are the best chance we have of addressing the significant problem of global sampling. This requires that the Earth be observed from multiple platforms in a coordinated way with (i) coordination of sensors and orbits (adequate diurnal coverage of polar satellites), (ii) maintain orbit stability and avoid large drifts in time, (iii) minimize gaps in time records by having a replacement satellite ready for launch when one fails. EUMETSAT could provide leadership in this area.
2. Strive for on-board calibration and maintain routine vicarious calibration activities. To date this has been limited to selected channels on Meteosat. Calibration and characterization necessarily involves trade-offs between increased costs of sensors. GEO observations are ideally suited for studying climate processes and the single biggest obstacle for doing so is lack of calibration. If trade-offs are necessary, then a minimum calibration activity should include routine vicarious calibration of ALL channels. If the issue of LEO sampling is properly addressed, then one suggestion is to strive for rigorous calibration and characterization of all EPS sensors and consider these data as a primary source of climate data.
3. Include calibrated radiances as part of the climate data stream. The goals of a climate-based SAF should focus on QC of radiances and contribute to the development of vicarious calibration. Such a contribution will be very valuable in the long-term especially since radiance products can also be reprocessed to provided improved information using better algorithms as they become available over the course of time.
4. Continue participation in ongoing World Climate Research Program activities like the ISCCP, GPCP and GVaP.
5. GEOs have a unique capability in the way they sample Earth. However, the capabilities of the sensors on GEOs generally lags behind those of polar orbiting satellites. There has been virtually no opportunity to fly research-quality sensors on GEOs. The Geostationary Earth Radiation Budget (GERB) instrument proposed for MSG is a rare exception and more opportunities to fly climate-type sensors on GEOs must be encouraged. EUMETSAT can play a leadership role in advancing GEO observations into climate change arena.

1.0 Introduction

The worldwide demise of conventional meteorological observing networks places a growing importance on use of satellite measurements to fulfill operational observing needs. While the regular-in-time and global-in-space nature of these observations makes them particularly attractive for climate research and monitoring purposes, current operational satellite observing systems are, on the whole, not optimized for this purpose.

The definition and design of a climate observing system is a topic of critical importance to the climate sciences. It is also a topic of study by operational satellite agencies which now consider climate either as part of their mandate or are in the process of considering climate requirements in the planning for future observing systems. As an example of the growing awareness of the climate agenda in the setting of operational satellites, EUMETSAT is considering as its second goal:

> *to contribute to the operational monitoring of the climate and the detection of global climate change.*

This report attempts to provide a critical examination of what constitutes the goals of a space-based observing system and whether measuring versus monitoring systems are one and the same. The report attempts to provide thoughtful consideration of what is needed of a climate observing system(s) and some assessment of the intrinsic capabilities of different satellites platforms and the types of observations and sensors flown on satellites to address these needs. This report attempts to provide a framework for ongoing dialogue on this important problem. While of general concern, the issues will be focused as much as possible on Meteosat Second Generation (MSG) and the EUMETSAT Polar System (EPS) and the report attempts to address the problem of a balance between what is needed for climate analyses and what can be delivered realistically by operational systems in the era of MSG and EPS. The philosophy of the report is to consider the broader issues relating to climate observations from space. The report does not attempt to reproduce measurement requirements of a long list of parameters such as addressed in the recent NPOESS report (Jacobowitz, 1997).

2.0 Satellites in the era of climate change

Satellite observing systems in current use orbit the Earth in one of two principal orbits - the Low Earth Orbits of polar orbiting satellites (LEOs) and the Geostationary orbit (GEOs). There are two classes of LEO missions - experimental missions that carry payloads of essentially one-of-a-kind sensor or prototype operational sensors and operational missions that carry payloads that are designed for operational purposes with versions of the same instrument flown over many years on multiple satellites. Examples of such programs are the Nimbus series of experimental satellite and more recently ADEOS, EOS and ERS programs.[1] Further discussion of experimental satellites including a historical perspective can be found in Kidder and VonderHaar (1995) among other references.

Operational satellite programs of the USA include both LEOs and GEOs whereas those of Europe and Japan, at present, are based on GEOs. With the imminent arrival of the EUMETSAT Polar System (EPS), and the convergence of the US military and civil polar satellite programs, we anticipate an internationally coordinated system of polar satellites (Fig. 2.1a) with some limited overlap of sensors (Fig. 2.1b).

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[1] More information about NASAs EOS, ESAs Earth observations and NASDAs ADEOS programs can be found under the respective home pages of each program.

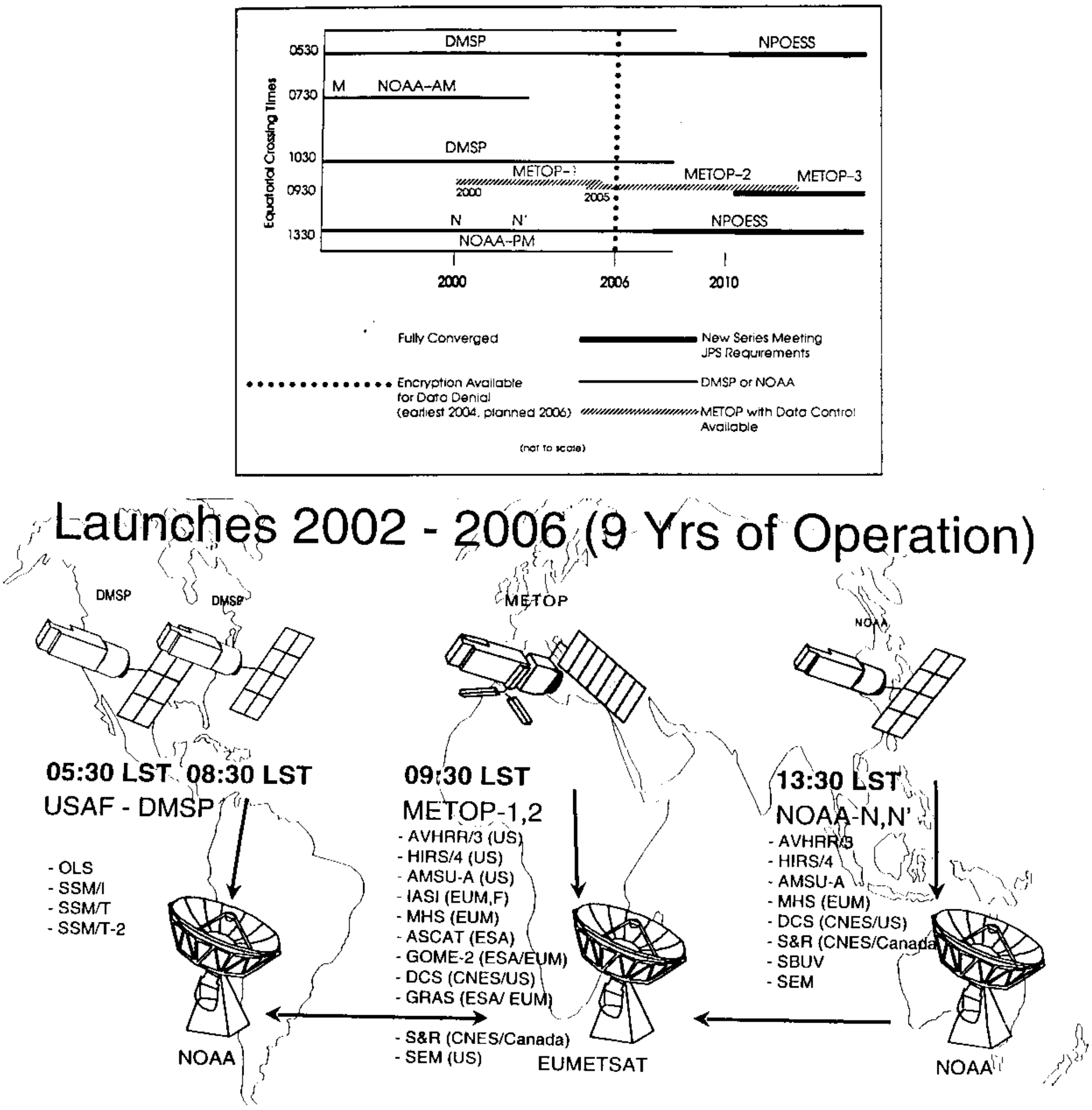


Fig. 2.1 *(a) The scenario for synchronization of polar satellites into the new millennium (from Winokur, 1997) (b) The sensors proposed under this convergence as part of the Joint Polar Systems. The overlap between sensors is less than ideal for climate purposes.*

The first GEO operational weather satellite was the United States GOES-1, launched in 1975. This was followed by Europe's Meteosat launched by the European Space Agency (ESA) and the Japanese GMS or ''Himawari" in 1977, and later by the Indian geostationary series, INSAT, in 1988. Currently a constellation of geostationary satellites exists that more or less acts as a coordinated international system (Fig. 2.2), stationed around the equator, giving almost complete coverage to about 60 degrees latitude. This coverage of the Earth by GEO satellites is an important ingredient in developing a global climate observing system strategy. At this time, GEOs have not flown experimental payloads or even individual sensors that might be considered to provide climate-based observations. The capabilities of the sensors on GEOs generally lags behind those of polar orbiting satellites and there has been virtually no opportunity to fly research-quality sensors on GEOs. The Geostationary Earth Radiation Budget (GERB) instrument proposed for MSG is a rare exception and more opportunities of this type must be encouraged for reasons described below.

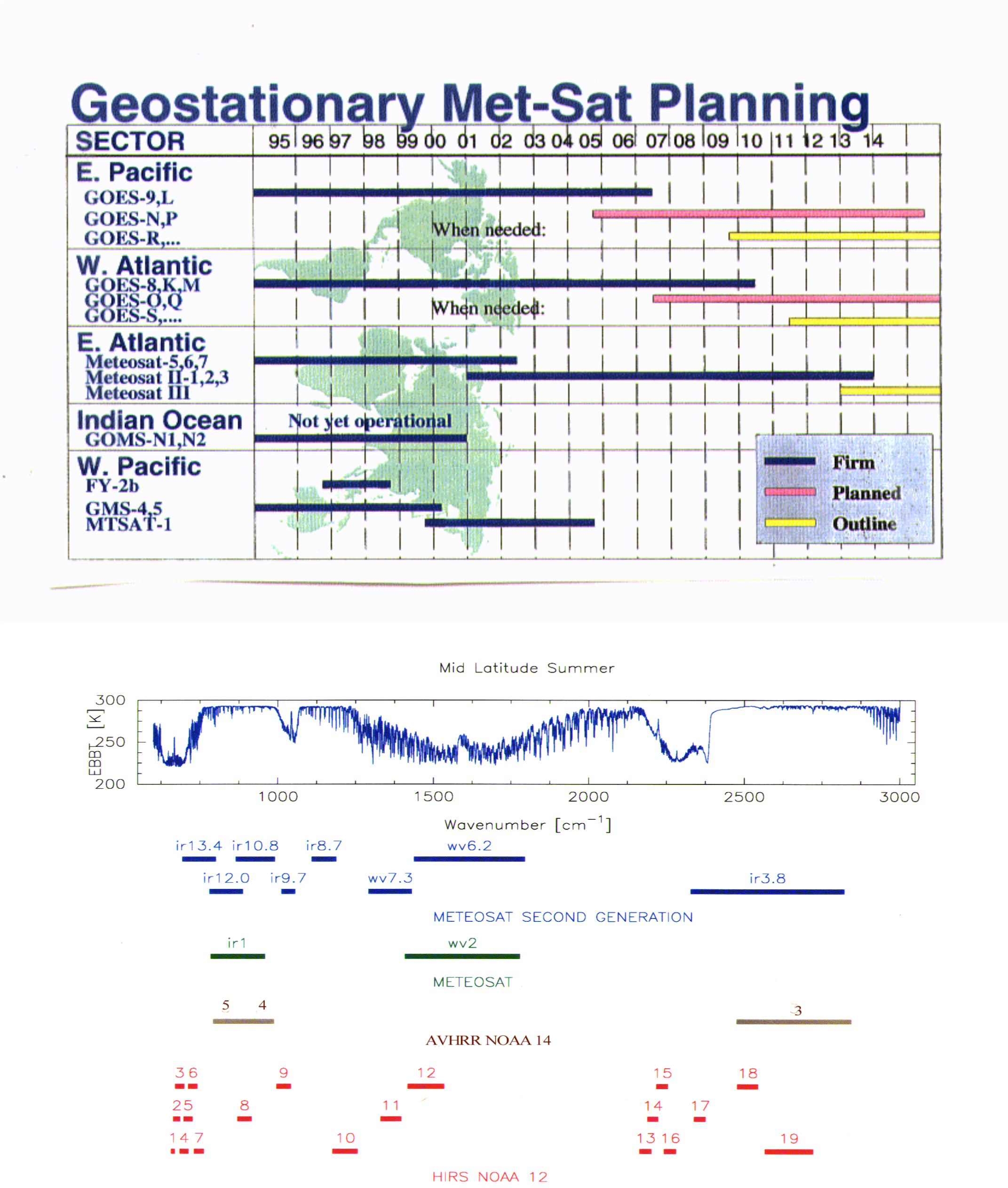


Fig 2.2 *Upper panel - The approximate 20 year plan for the international GEO network beginning at 1995. This plan was current as of September 1997. Lower panel- indication of the spectral overlap of planned sensors on the major GEO platforms*

3.0 The nature of the climate observing problem

3.1 The Climate system

Climate is expressed in terms of statistics such as averages, variances, correlations, and other quantities that characterize the physical structure of the climate system. The climate system may be thought of as composed of a number of subsystems– namely the atmosphere, hydrosphere, lithosphere, cryosphere and biosphere as portrayed in Fig.3.1. The physical properties, structure and composition of these subsystems differ from one to the other. In a thermodynamic sense, these subsystems are *open* with matter and energy being exchanged back and forth thus joining the subsystems to form the integrated global climate system.

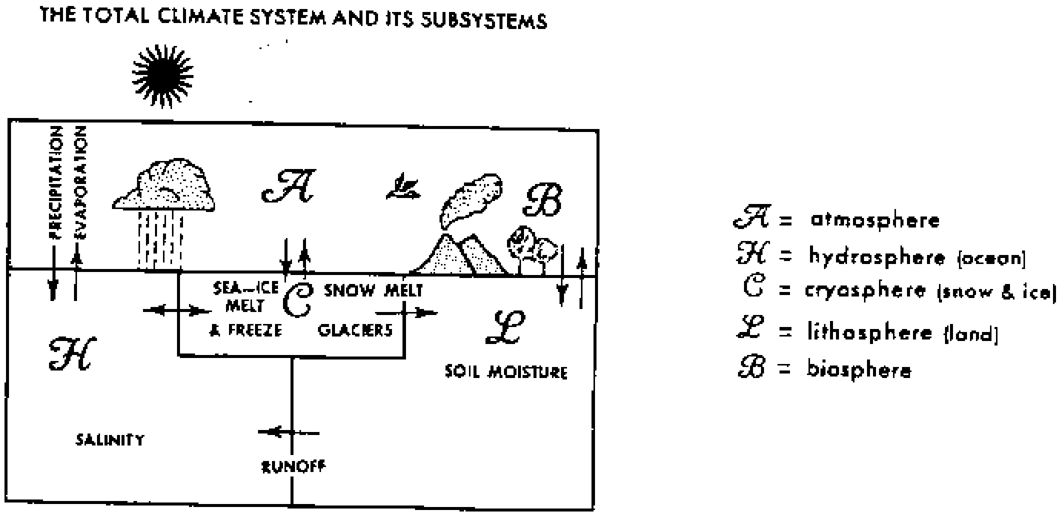


Figure 3.1 *Schematic of the total climate system and its subsystems, highlighting some aspects of the hydrological cycle (from Piexoto and Oort, 1992).*

Research in climate sciences is about developing an understanding of those processes that are responsible for the way climate varies and how climate might respond to inadvertent change of forcing. Climate research may be thought of as falling into the following categories:

- *Quantifying Climate Forcings*: Estimation of the nature and magnitude of the radiative forcings of climate is a topic of continuing research. IPCC 1995 provide a recent update on the estimates of the forcing associated with different radiative processes and provides some measure of the confidence of these estimates. Two basic issues are how strong is the radiative effect and where and how much is the constituent that produces this radiative forcing. Notable in this regard is the estimate of the forcings associated with aerosol, either through direct effects on solar radiation or indirectly through aerosol effects on clouds. Knowledge of where aerosols occur in the atmosphere, how much aerosols exist and their radiative properties are thus important for reducing uncertainties in the forcing.
- *Understanding Critical Processes and Feedbacks*: These studies seek to characterize the behavior of the important processes of each of the subsystems and the exchanges between them. The processes of most relevance are those that govern the response of the climate system to the above mentioned forcings. Understanding the way these processes operate is crucial for testing and developing climate prediction models.

- *Assessing the nature of Climate Variability*: The Earth's climate fluctuates on all time scales, is continually evolving and is far from a static entity. Characterizing natural variability requires an integrated view of the slower evolution of climate with the faster processes projected onto these slower processes associated with seasonal, interannual and multi-decadal change.
- *Detecting and Understanding Climate Change:* Detection of the anthropogenic climate-change signal over and above the noise of natural climate variability is, by and large a statistical problem. Understanding the cause of the climate change requires an integration of the kinds of observations that identify critical processes as noted above and model predictions that may be tested by such observations.

These topics cover a vast range of time and space scales. Figure 3.2 provides a perspective of the sheer breadth of scales of relevance to climate and it is this breadth that imposes real problems in designing climate measuring and monitoring systems. Processes that occur on small scales need to be placed in a global context – for example study of convection in the atmosphere needs to contrast the convection as a function of the characteristic driving force, tropical convection, versus mid-latitude, continental convection versus convection as part of baroclinic systems.

We cannot expect to capture all relevant processes on all time and space scales with a single observing system. This too is implied in Fig. 3.2 by the range of scales resolved by current satellite observations. We should not expect that a satellite observing system is necessarily best suited to address all climate issues. For example, we cannot expect to observe the longer-term variations of climate from platforms that support observations for only a few years or with instruments that either degrade in time or whose characteristics cannot be reproduced easily from one version to another of the same instrument. This is often the intrinsic nature of present satellite sensors. To what extent existing and planned sensors can be used to observe multi-annual to decadal climate variations, even with changed practices in calibration, remains a matter of significant debate.

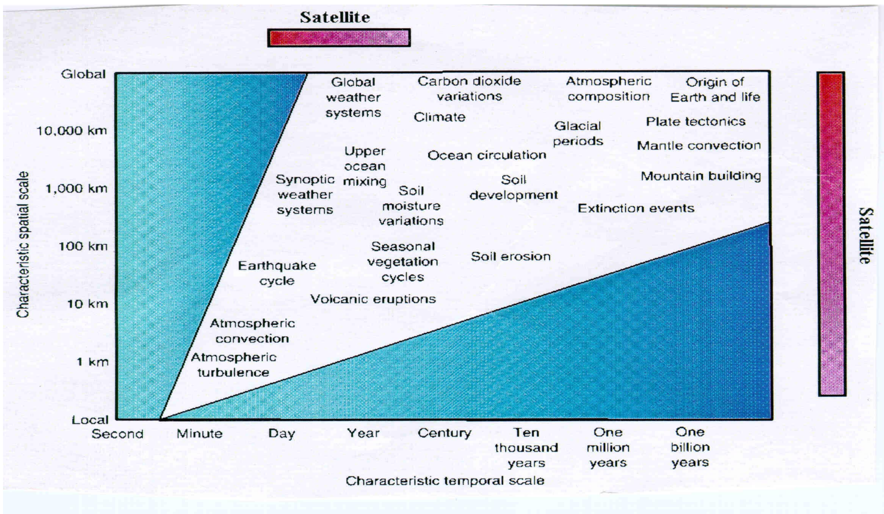


Figure 3.2 *Depiction of the ranges of space scale of various climate components together with the range of time-scale associated with these processes. Space-time characteristics of typical sensors flown on present-day GEOs and LEOs are shown for comparison. The intrinsic space-time properties of these observations is examined later.*

3.2 Integrating themes

The openness of the climate subsystems makes for a science that is diverse in nature. This is not only a challenge for the scientific community but it also represents a real dilemma for science management faced with a broadening science constituency on the one hand and shrinking or limited resources on the other hand. How are priorities set in the era of multi-disciplinary science? How do we determine which of the subsystems are more crucial to understand and over what time scale and how do we establish which subsystem and related processes are best suited to be observed from space? Despite the complexity suggested by the diversity of processes over a large range of scales and despite the difficulty in assigning priorities to science needs, there are a smaller subset of processes that are understood to influence the connections between subsystems more strongly and, by nature, are more germane to much of the climate sciences. It is the suggestion of this study that current (and near future) capabilities of satellites be directed to advance understanding of these processes.

The hydrological cycle, as highlighted in Fig. 3.1, is an important example of a collection of processes that on the one hand integrates the subsystems of climate and on the other hand is poorly observed and thus understood (Fig. 3.3). Clouds are a dominant influence on the energy budget of the climate system and strongly affect the surface energy budget linking the atmosphere to oceans, land surfaces and to ice masses. Clouds also produce precipitation which is essential for the evolution of the hydrosphere and cryosphere and together with temperature, governs the essential properties of the biosphere. Humidity is of basic importance, influencing the formation of clouds and precipitation, affecting the evaporation of water from the Earth's surface and is the principal greenhouse gas that strongly absorbs longwave radiation emitted from the Earth's surface. Observations of temperature, humidity, cloudiness and precipitation are all routinely carried out as part of global weather observing systems, although poorly so for specific hydrological parameters. Taken at face value, there seems to be a match between capabilities of satellite observations and the needs for studying important hydrological and related climate processes.

Figure 3.3, taken from IPCC 1995, reflects the present status of our understanding of changes in important climate variables. The confidence indicators reflect the status of our observing systems which are more advanced in measuring temperature and related parameters than hydrology. New systems as well as improvements to existing systems are required to observe hydrology at a level needed to understand climate change.

3.3 The nature of anthropogenic climate change

Projected estimates of global warming based on predictive models of climate have been available for a number of years. An example of the climate change predicted by one of the present-day coupled ocean-atmosphere climate models is presented in Fig. 3.4. The diagrams show differences between years 150 and years 10 of a model simulation of annually and zonally averaged 300 mb temperature, 850 mb temperature, surface temperature, 300 mb relative humidity and column integrated water vapor. The simulation included increasing CO_2 at a rate of 1% per year (Gordon and O'Farrell, 1997). Scaling these differences by a multiplicative factor of 0.1 corresponds approximately to a climate change for a period of roughly 14 years (which is approximately the period of the EPS) and thus is indicative of a climate change from the present to the year 2010. With this scaling factor applied to the results of Fig. 3.4, the model simulations imply that a change of less than 2% in water vapor, a change in the range 0.1-0.5 K in atmospheric temperature and a change of generally less than 0.3 K in surface temperature might be expected between the present and year 2010.[2] Whether or not predictions such as these are to be accepted ultimately depends on how well the model is tested against observations. The results shown in Fig. 3.4 are presented here only as a guide for illustrating the types of requirements that need to be met by a global monitoring system.

[2] According to the model, surface temperature change may exceed 1K at higher latitudes.

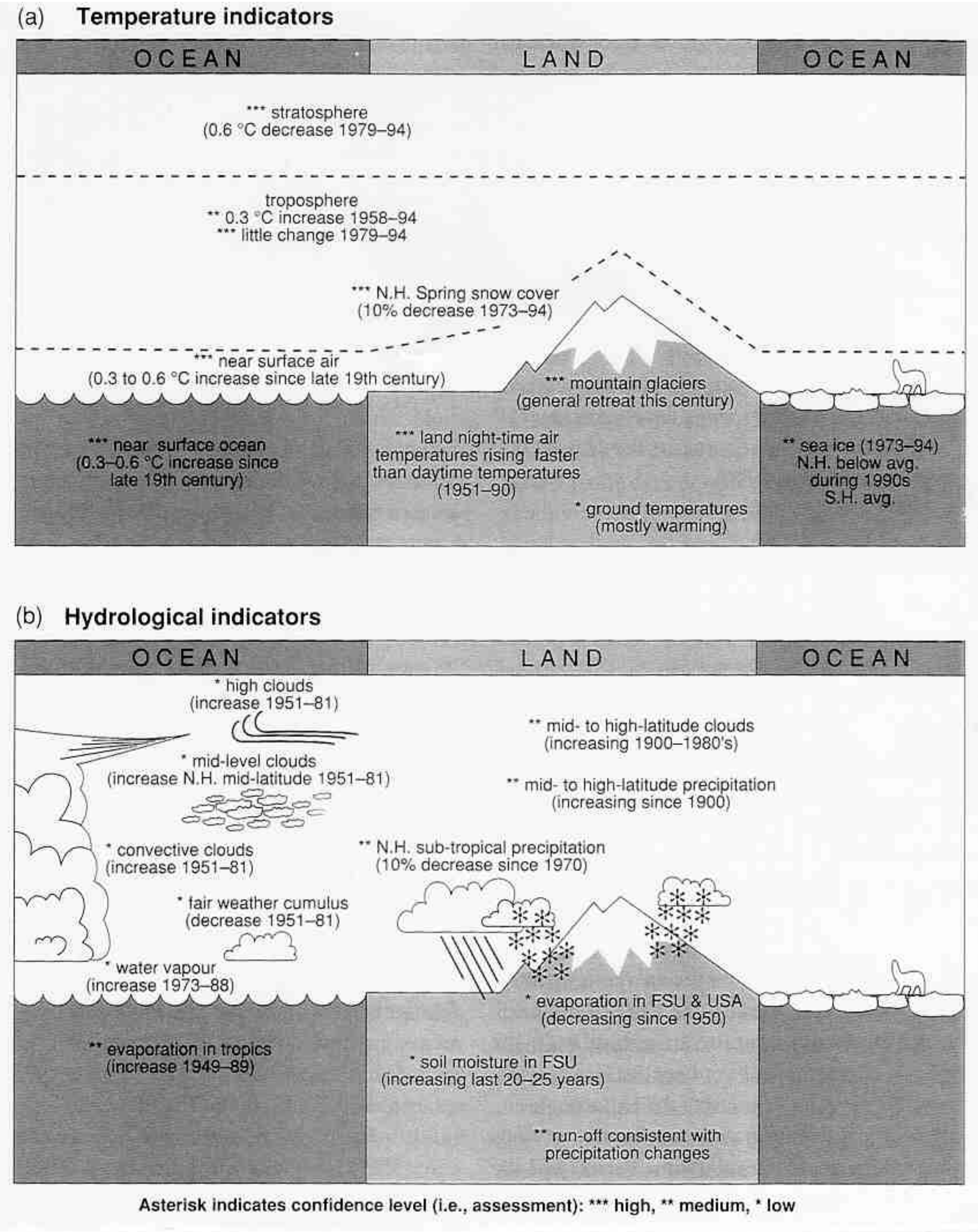
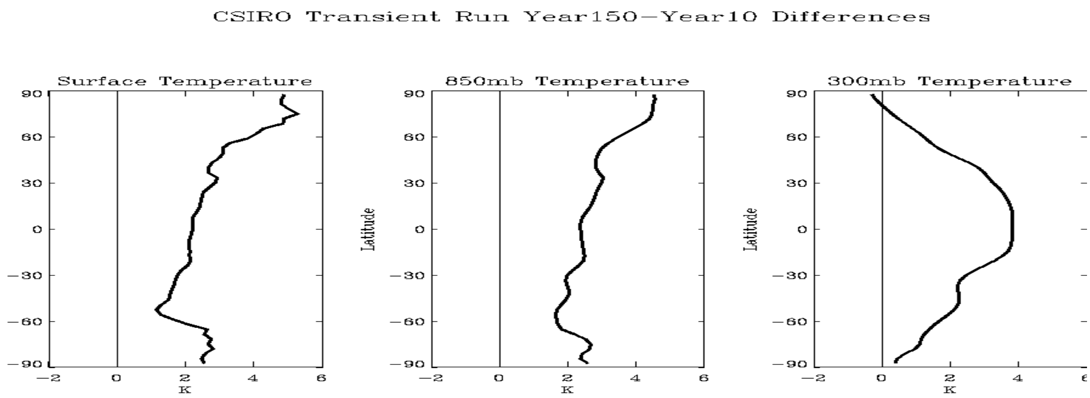


Fig. 3.3 *(a) Schematic of observed variations of temperature and (b) the hydrological cycle (from IPCC, 1995). We have considerably less confidence in predicting changes in hydrology than changes in temperature, to a large extent due to the relatively primitive nature of hydrological observing systems.*



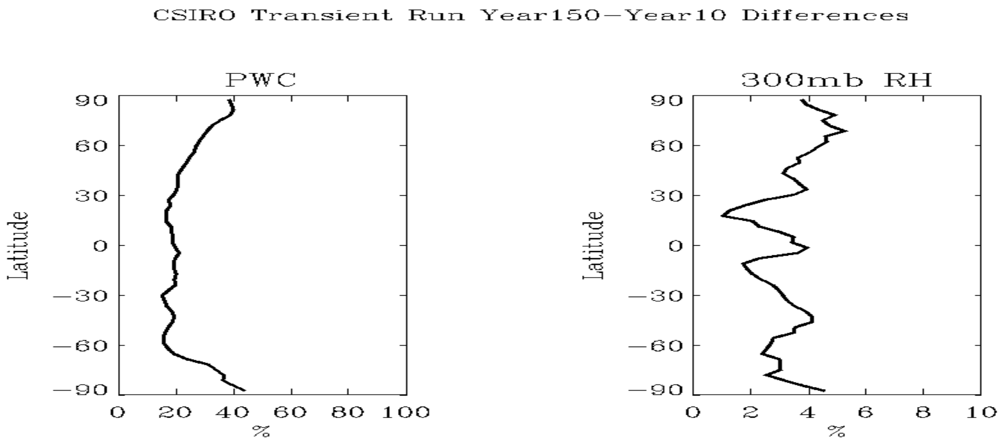


Figure 3.4 *Annual averages of selected quantities expressed as differences between years 150 and years 10 from a model simulation in which CO_2 was increased at a rate of 1% per year. The differences are the zonal averages of 300 mb temperature, 850 mb temperature, surface temperature, 300 mb relative humidity and column integrated water vapor (PWC which is expressed as a percentage change in PWC) .*

3.4 The Nature and Goals of a Climate Observing System

Climate observing systems should collectively support the following goals:

- *Identify how the Earth system is changing over the coming decades*
- *Explain why these changes occur*
- *Separate natural from anthropogenic cause and effects*
- *Contribute to ongoing assessment of our predictions of this change.*

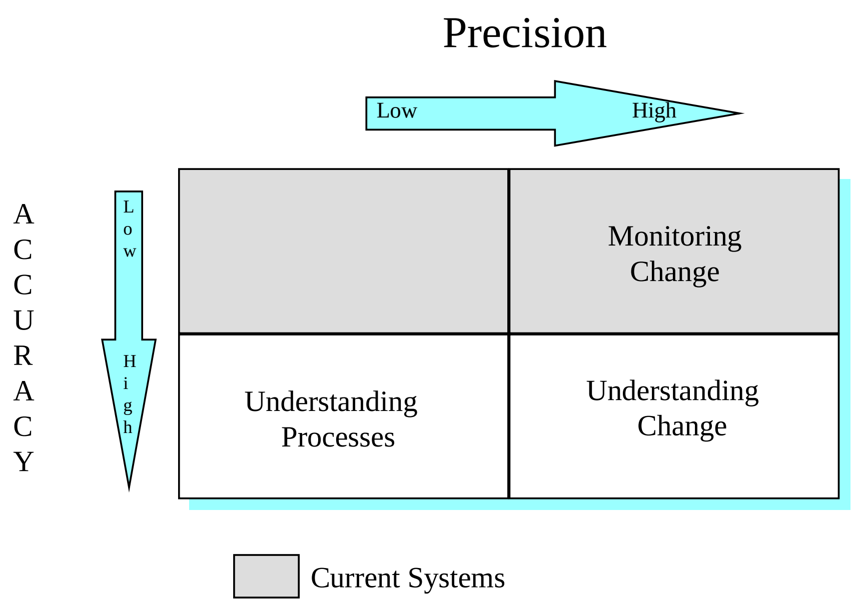


Fig 3.5 *The climate measurement problem - understanding climate processes requires accuracy, monitoring climate change requires high precision, understanding climate change requires both high precision and high accuracy.*

There are two important requirements that need to be considered within the context of these goals; one is a requirement for accuracy and the other is a requirement for precision as broadly expressed in Fig. 3.5. Detecting climate change requires a monitoring system of high precision, understanding natural causes and effects requires accurate observations and understanding climate change requires both high precision and high accuracy. As mentioned above, the climate research community has neither identified the degree of precision required nor the accuracy to meet the objectives described above. We can make educated guesses about the requirements on precision - for example the results of Fig. 3.4 suggest that a precision of better than 1% would be required over a span of 14 years to detect the trends predicted by present-day global climate models. The requirement on accuracy is another matter. Clear guidelines are not given although they are implied in documents like the NPOESS report (Jacobowitz, 1997). It might be argued that understanding the nature of climate change requires an accuracy higher than that of precision (not only do we wish to see change, but we also need to discern the nature of this change). Present-day systems lack accuracy but if care is observed then selected systems may be sufficiently precise to detect change.

It is convenient to consider a climate observing system as one or a combination of two systems:

- *A Climate Measuring System:* This system provides measurements that ultimately lead to understanding climate processes, climate variability and climate change. These measurements must be both relevant and sufficiently accurate to resolve processes and any changes to the processes. Absolute accuracy such as provided by radiance calibration is important since these calibrated data are used to provide information about relevant parameters. The accuracy required of the calibration must be considered within the context of the total system error as highlighted below.
- *A Climate Monitoring System*: the principal goal of this system is to detect climate change. High precision of the data is of paramount importance for application and absolute accuracy is less important if detection of change is the single goal. Understanding the nature of change also requires measurements of sufficient accuracy. Specifying the degree of precision is difficult since we currently lack a clear knowledge of the nature and magnitude of the changes that are required to be detected.

With model uncertainties aside, conversion of the predicted changes of geophysical quantities (like those presented in Fig. 3.4) into spectral radiances are, on the whole, lacking.

Whether or not a single system meets both the goals of monitoring and the goals of measurement is a matter of ongoing debate. Very few of the existing satellite observing systems can claim to be accurate and precise enough to contribute to detection of climate trends and attribution of change. Even those systems that come close to this goal require extensive observations from other sources, including extensive ground truthing of the data, are needed both to confirm and interpret the nature of the trend. Alternative approaches to observing and monitoring climate change from space are needed (e.g. Goody *et al.*, 1997).

4.0 Characterizing satellite measuring systems - retrieval errors

There are a number of elements to a satellite measurement system:

- The platform (e.g. GEO versus LEO)
- Measurement type (active/passive; emissive/scattering; spectral /broad band)
- Instrument type, specifications and characterization (spectrometer/radiometer; calibration, spectral response, sensitivity, signal to noise etc.)
- Retrieval method and geophysical products (including inversion model, uncertainty and quality assessment)
- Relation between the measurement characteristics and science objectives.

Ideally, the design of an observing system begins with the science objectives and converts them to measurement requirements and iterates back and forth between these and instrument capabilities. For example, the quality of the final product must be considered against the needs for and application of the product and changes to the design of the system are required when these needs are not met. Further, the ideal approach should follow standard practice of experimental design wherein observables are defined, a method of retrieval identifies the type of measurement and instrument specifications needed and an instrument is then developed.

In characterizing a space-based observing system of the types now operating, we consider two basic types of uncertainties:

1. Those introduced by the physical retrieval system adopted, including the instrument, its calibration and noise properties, and the assumptions upon which the inversion methods are based. These are hereafter referred to as retrieval errors and are an intrinsic characteristic of the system. Retrieval errors are a limiting factor in climate processes and are discussed immediately below.
2. Those arising from incomplete sampling imposed on the system by the selection of the observing platform. These are the sampling errors that occur in forming space-time means of geophysical quantities and these errors superimpose on the retrieval errors and are discussed in the following section. Sampling errors adversely affect the precision of global-scale observations and thus affect our ability to discern real climate change in these observations

The complete error characteristics of present satellite observing systems are, for the most part, inadequately defined and the true quality of the geophysical product is often not well understood. This is a significant problem since it makes it impossible to link measurements with science requirements properly.

4.1 The nature of retrieval uncertainties

The first set of error characteristics are those associated with the actual retrieval of geophysical parameters within the field of view (FOV) of a given sensor. Retrieval involves a combination of the measuring instrument (imager, sounder, or other sensor) and the retrieval method developed to obtain the required properties. In this context, we represent the retrieval part of the observing system in the following way

$$y = F(x,b) + \varepsilon_y \qquad (1)$$

where x is the vector representing the properties to be retrieved, y is a measurement vector (generally spectral radiances), ε_y is the measurement error (including instrument noise and calibration uncertainties), F is the forward function in most cases representing relevant radiative transfer processes (it is the function of the real atmosphere), and b is a vector of parameters that define F and will be assumed to be known. For example, *b* might represent appropriate spectroscopic information on gaseous absorption, refractive index, etc. In general the function *F* is imperfectly known to us but its broad characteristics might be selected depending on the type of measurement made. For instance, *F* may be defined by scattering processes when visible radiances are measured or *F* might be defined by emission processes in the case of IR radiances. In the most general case, an approximation to *F* is introduced. This approximation is the forward model $f(\underline{x}, \underline{b}, c)$ of the retrieval. As we strive to obtain information about an increasing number of complex parameters, the difference between this model and *F* on the one hand becomes more significant but on the other hand harder to establish. The forward model depends on a set of parameters $\underline{b}$ that generally differs from the real set *b* and other parameters defined by the vector *c*. The latter do not appear in the forward function *F* and are strictly unconnected to the measurements.

Inversion of (1), or its approximate form, requires estimating $\underline{x}$ such that the difference between *y* and $f(\underline{x}, \underline{b}, c)$ is minimised. In practice most problems are ill-posed and some form of constraint is required, usually in the form of constraining $\underline{x}$ via *a priori* information. Practically all inversions, simple or complex, use constraints either explicitly or implicitly. An example of the explicit use of constraints is in sounding retrievals in which profile information is used as an initial guess in retrievals of temperature or moisture. This error source is not a major concern if it is known that a priori data does not propagate into the final retrieval. Unfortunately, it is generally not understood just how much this sort of information is retained in the final retrieval. For climate purposes and especially for monitoring change, it is critical that the extent of reliance of any retrieval on the *a priori* be firmly established since any properties that are too constrained to such information will not provide proper measures of evolving climate change.

We can represent any retrieval problem as one that seeks to estimate *x* by minimising a suitably defined cost function (e.g. Menke, 1989, Rodgers, 1976)

$$\Phi = \Phi(\underline{x} - x_a, y - f(\underline{x}, b), S_a, S_y) \qquad (2)$$

where x_a is the *a priori* estimate of $\underline{x}$, S_a is the error covariance of this a priori and S_y is the error covariance of the forward model which contains both the estimate of the forward model error and the measurement error. These covariance matrices define both the total error of the retrieval and the extent that the retrieval relies on the *a priori*.

4.2 Illustrative example of retrieval uncertainties

The problem of the retrieval of water vapor from NOAA TOVS is chosen to highlight the broader issues of retrieval as they apply to observing climate. The example is chosen on two counts: water vapor is a critical parameter of the climate system and it is informative to assess how well we can observe water vapor from present operational systems. The second reason for choosing this example is that water vapor retrieval from IR radiances is directly relevant to MSG and EPS given the similarity of the channels on the proposed SEVIRI of MSG and the sounding instruments for EPS (discussed further below).

The results now described are taken from Engelen and Stephens (1997). Details of the retrieval approach need not concern us here and the reader is referred to the study of Engelen and Stephens for further details. The method principally uses four channels of TOVS (channels 8,10, 11 and 12) and retrieves water vapor in four layers - the surface to 700 mb, 700-500 mb, 500-300 mb and 300-200 mb. Examples of the distributions of water vapor in these layers derived from a retrieval scheme are shown in the first set of panels of Fig. 4.1. The panels shown on the following page present the total retrieval error and the corresponding contributions by the two components of the error - the contribution by the model, S_y , and the contribution by errors in the a priori, S_a.

A number of noteworthy features follow from study of these error contributions:

- The total error is largest for lower layers and decreases to minimum in the upper most layer
- The magnitudes of the errors significantly exceed the magnitude of the expected changes that have been predicted by models as shown in Fig. 3.4

- The model error contributes most to the upper layer error and least to the lower layer. Conversely, the a priori error has greatest influence on the lower layer and less influence on the upper layer error.

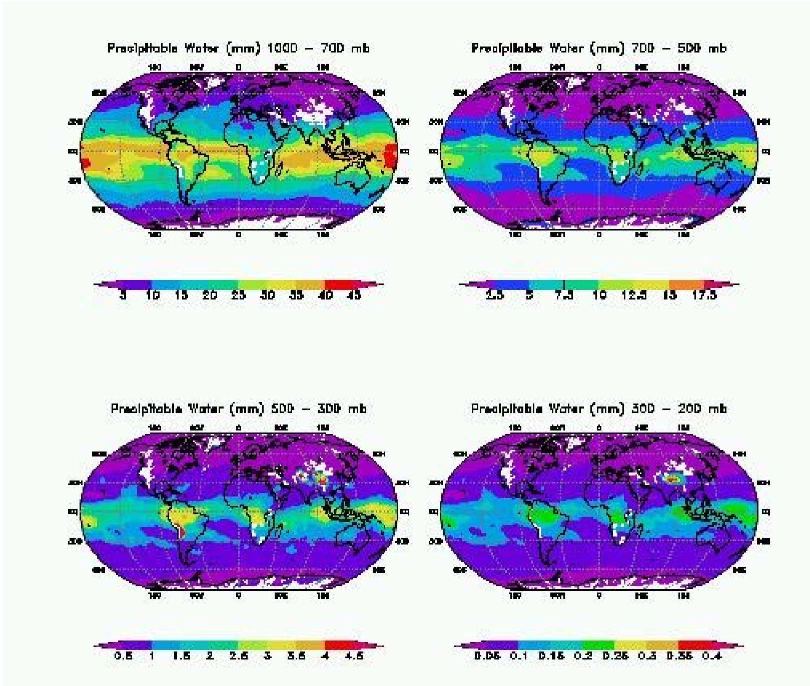


Figure 4.1 *Layer-wise column water vapor and associated errors for TOVS retrieval of water vapor in four layers of the atmosphere: surface-700 mb, 700-500 mb, 500-300 mb and 300-200 mb. The panels shown are the retrieved water vapor. The panels on the following page are panels of total error (upper row), the error due to the mode (middle row) , and the* *__a priori__* *errors (bottom row).*

We now consider the results of Fig. 4.2 which highlights other issues regarding the nature of the TOVS water vapor retrieval problem. The upper panels are a measure of the contribution of the a priori to the retrieval. The magnitude of the quantity plotted represents the percentage contribution of the a priori on the final retrieval. The second row of panels show the percentage change to the total retrieval error introduced by a doubling of the calibration error assigned to the radiances of each channel (changed from 1% used for the results of Fig. 4.1 to 2 % for the results of Fig. 4.2).
When considering the results of Figs. 4.1 and 4.2 together, we infer that:

- There is a substantial reliance on a priori information in the retrieval of water vapor and this reliance is greatest in lower layers (and hence the greater contribution of the a priori error to the total retrieval error of these layers). Even in the upper layers where the observations weigh more heavily in the retrieval, the reliance on the *a priori* remains significant and at about the 30% level.
- In addition to the *a priori* error, the major source of error does not stem from calibration errors for this particular example but from errors of the forward model. For the example given, the rms brightness temperature error of the model used was less than 1.5 degrees (relative to a line-by-line model) which is similar to other state-of-the-art forward models (e.g. RTTOVS, Eyre, 1991).

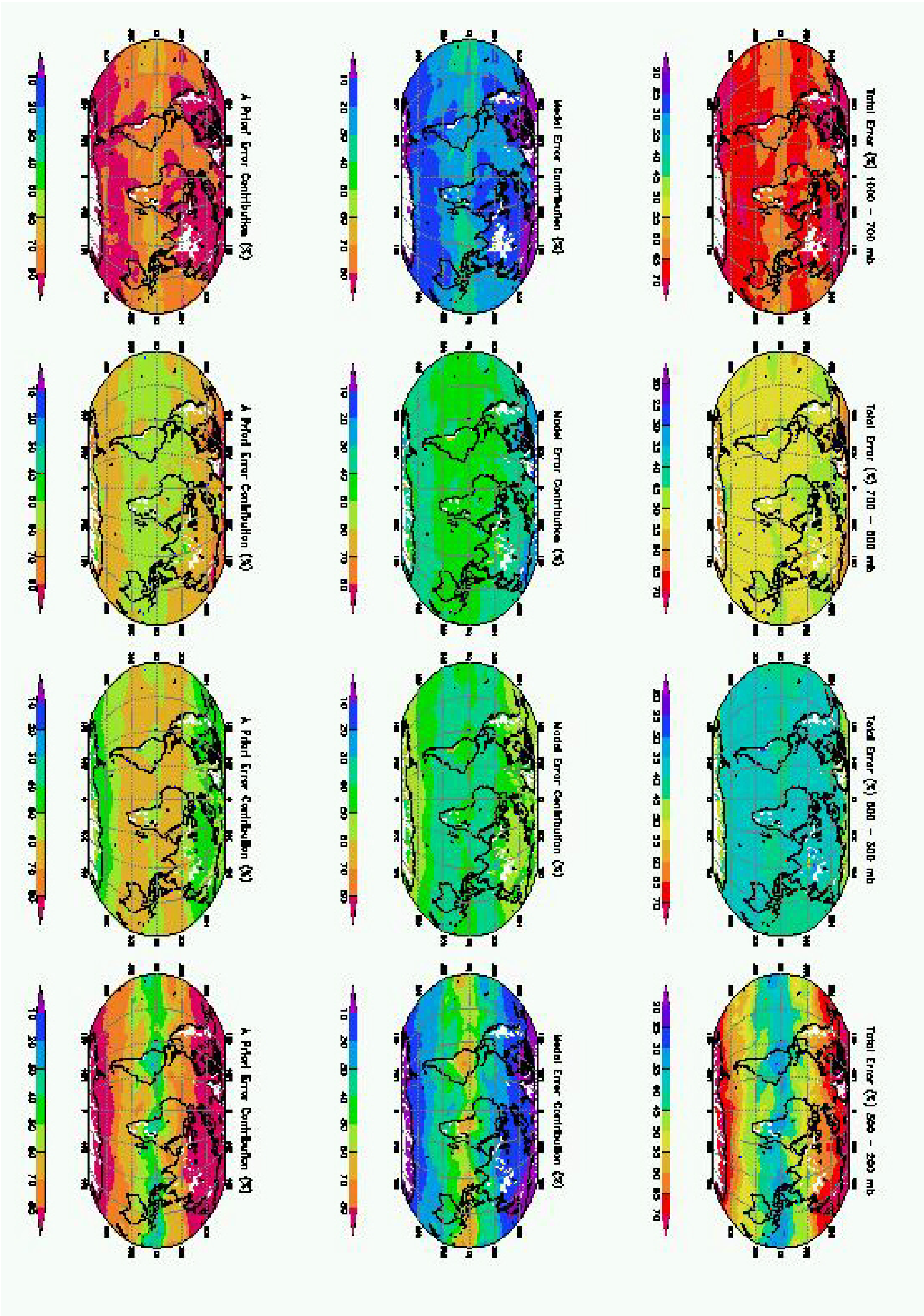


Fig. 4.1 (continued)

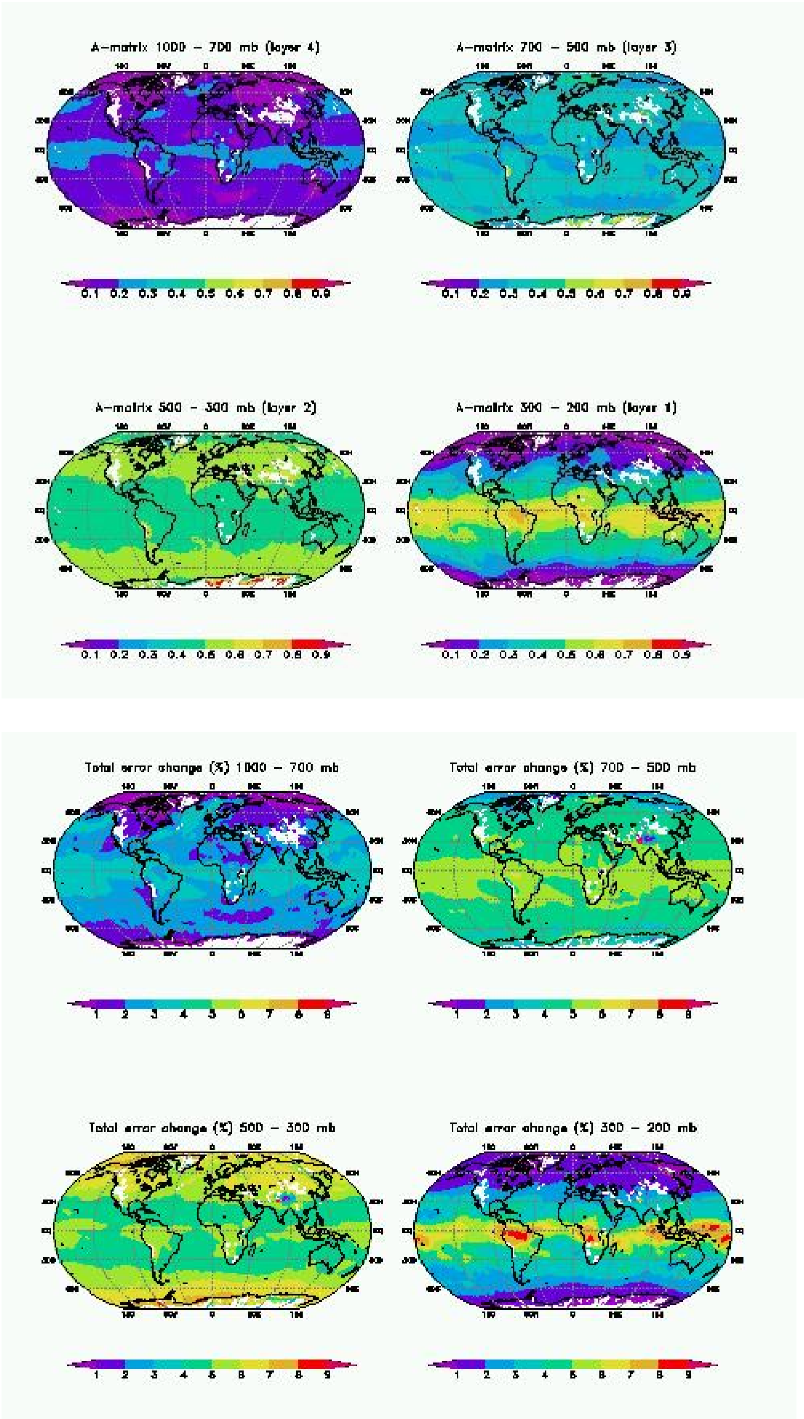


Figure 4.2 *The diagonal elements of the resolution matrix providing a measure of the direct contribution of a priori to the retrieval (upper four panels). The bottom four panels are the percentage change in total error (refer to Fig. 4.1) due to a doubling of the assumed calibration error.*

5.0 Characterizing satellite measuring systems - sampling errors

The sampling characteristics imposed by the two different types of satellite orbits currently in use differ substantially from one another. The unique nature of GEO is that observations from these platforms are synoptic-like wherein all places within the field of view of the satellite are seen at the same time. Time resolved information from GEOs has been used effectively by EUMETSAT in production of cloud and now water vapor winds from analyses of Meteosat data (Holmlund, 1993; Schmetz *et al.*, 1993). A single LEO satellite, on the other hand, views about one-quarter of the globe at different times so the sampling of these processes is more regional and asynoptic in character. A single polar orbiting satellite can observe the entire globe when observations are integrated over sufficiently long periods of time but cannot resolve events that vary on shorter time scales. Coverage of the polar regions is significantly better than for GEOs. An ideal global observing strategy requires a combination of multiple versions of both types of platforms.

5.1 Synoptic Nature of Sampling from Geostationary satellites

Geostationary satellite observations provide a traditional synoptic view of Earth. This rather obvious statement is emphasized in Fig. 5.1 which shows the sample properties of an arbitrary parameter observed along the equator at regular intervals in time. The space-time domain of these observations is represented by the rectangular region of Fig. 5.1 and is contrasted against the space-time properties of a polar orbiting satellite (either in ascending or descending node) which is characterized as diagonal domains of information across (or along) the track of the orbit. The synoptic view is the normal way of studying the atmosphere and the way output from weather prediction and climate models is typically presented.

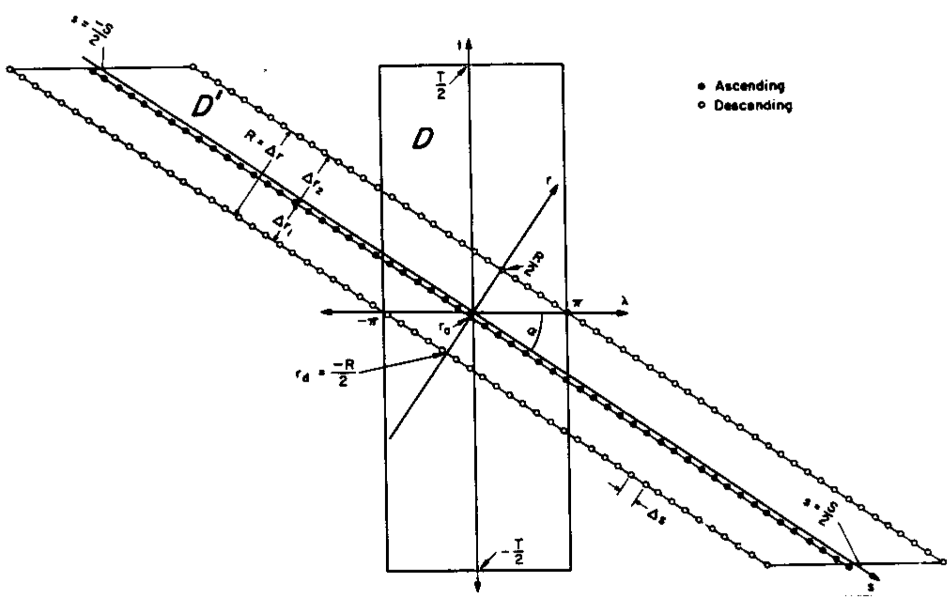


Fig. 5.1 *The sampling geometry in an extended longitude time domain. Geostationary satellites form a regular rectangular array spaced apart by the observing time and the resolution of the observation (a few kilometers). Polar orbiting satellites in ascending and descending mode form a uniformly space array lying along an asynoptic coordinate frame s and r which represent a mixture of space and time (Modified from Salby, 1987).*

5.2 Asynoptic Nature of Sampling from Orbiting Satellites

The intrinsic limitations of polar orbiting satellites is often not appreciated in the context of climate observations yet it is a crucial issue that must be addressed in discussion and ultimate design of any global climate observing system. This limitation follows from the way orbiting satellites asynoptically sample the Earth wherein different locales are observed at different instants of time. This feature of satellite sampling complicates interpretation of any satellite data because space and time behaviors are mixed and a sense of this mixing is shown in Fig. 5.2. This is an important issue since sampling errors appear lead to significant biases in space-time means of certain quantities. We explore the nature of these uncertainties in the following simple way. Suppose we are interested in an evolving field $\Psi(\lambda,t)$ located at a latitude φ over some time domain [-T/2,T/2]. As such, this field can always be represented in terms of a Fourier Series:

$$\Psi(\lambda,t) = \Sigma\,\Sigma\ \Psi(m,\sigma_n)\, e^{i(m\lambda+\sigma_n t)}$$

where $\Psi(m,\sigma_n)$ is the space-time spectrum of the given parameter where m is the zonal wavenumber characterizing structure in longitude λ. The spectra of a field synoptically sampled twice-daily corresponds to the dashed line as shown in Fig. 5.2 and the spectral domain of $\Psi(\lambda,t)$ sampled via a polar orbiter is rotated relative to this synoptic domain in a manner as shown. The angle of rotation of this domain is governed by the angular velocity ω at which the orbital plane precesses about the latitude circle (Salby, 1982). A simple diurnal cycle characterized by m=1 (half the globe in daylight and half in night) and $\sigma_n=2\pi$ projects directly onto the space-time mean m=0, $\sigma_n=0$.

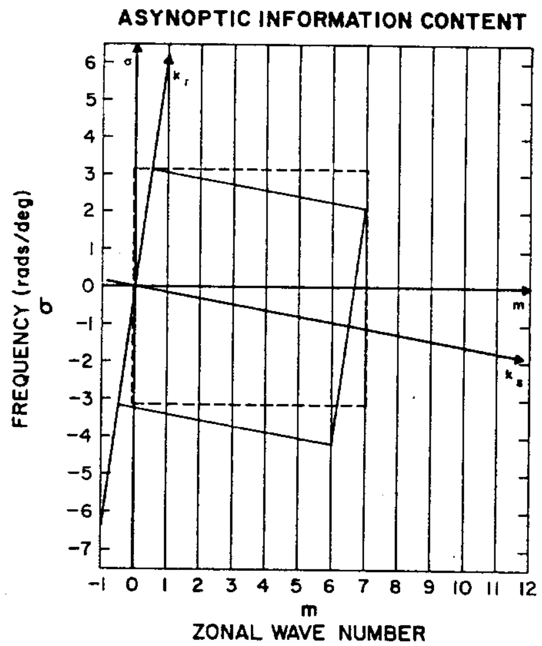


Fig 5.2 *Resolvable wave numbers and frequencies (solid rectangle) in single node asynoptic data. Borders of this rectangle give the Nyquist bounds of asynoptic sampling and as such define the time-space information content of the data. The equivalent content of daily synpoticdata is shown by the dashed rectangle (Salby, 1982).*

Asynoptic sampling biases on time-mean properties are a particular problem when properties undergo a marked diurnal variability, typical of many climate processes, and most particularly those related to hydrological processes (clouds, precipitation and even winds). With a precession of the satellite at a rate closely matched to this cycle (i.e. ω=2π), we see the same wave-form and same phase at each crossing latitude. Thus under-sampling the diurnal cycle introduces significant biases to time-mean fields. Although this systematic error is most serious for polar-orbiting measurements in which diurnal variability is indistinguishable from the time-mean, it surfaces even in precessing measurements because the diurnal cycle is not perfectly repeatable, is spatially coherent which makes it difficult to remove and is sampled too slowly to be truly resolved in such observations. As a result, time-mean behavior is analyzed by under-sampled diurnal variability (as is low-frequency behavior in general), making errors in the two closely related (Salby and Callaghan, 1996).

An example of the magnitude of these errors is given by Salby and Callaghan (1996) who use ISCCP global IR radiance data with a 0.5 deg resolution and a temporal resolution of 3 hrs as the benchmark data set that resolves the dominant large scale cloud features a well as the global diurnal cycle. These data are sampled according to the properties of a sensor on a polar orbiter and compared to the benchmark. Figure 5.3 shows the normalized error:

$$\varepsilon= | \psi - \tilde{\psi} | / <\psi_{true}>$$

where ψ is the true time-mean values of an unsampled quantity, $\tilde{\psi}$ is the asynoptically sampled time-mean of the quantity and the absolute difference is normalized relative to a constant value of the quantity. The fields shown are of a modified IR brightness temperature defined thus:

$$\psi = T-T_o \ ; \ T< T_o$$

$$\psi = T_o \ ; \ T> T_o$$

where T_o is some threshold temperature. ψ is analogous to the Global Precipitation Index (GPI, e.g. Arkin and Ardunuy, 1989). The results provided in Fig. 5.3 show the relative error due to asynoptic sampling of a hypothetical polar orbiting satellite at 850 km orbit inclined at 81^o with a ground scan of 25^o. The data are averaged into 2.5^o bins over 4,8 and 12 weeks. Figure 5.3a (upper three panels) shows the errors when only daylight sampling are used and Fig. 5.3b (lower two panels) is the equivalent example when both day and night sampling is applied in the averaging. In either case, the errors are substantial and reflect the large diurnal cycle in the high clouds that define ψ even when data from day-night sides of the orbit are used. These errors are not significantly reduced by increasing the averaging period since the diurnal cycle remains fixed with respect to the sampling. Neither polar-orbiting nor precessing measurements afford a genuine reduction of the bias by averaging over larger spatial dimension. Systematic error variance is then simply diluted over larger horizontal scale. This compensation follows from the spatial coherence of the diurnal cycle such as in surface temperature over deserts and in cloud cover over convective areas and over marine stratocumulus (Salby *et al.*, 1991; Rozendaal *et al.*, 1995; Bergman and Salby, 1996). The coherence of the diurnal effects prevents any possible cancellation of errors introduced by under-sampling in spatial averages.

5.4 Summary

The ultimate utility of any satellite measurement system for addressing climate-related research goals like those stated above requires careful understanding of the nature of the uncertainties that can be attached to a given system. Major issue that contribute to measurement uncertainty are:

1. Retrieval uncertainties - for the most part, the uncertainty of observing systems are not properly evaluated. This form of uncertainty includes both instrument error and error in retrieval assumptions. Most often, the latter is the dominant source of error and improved calibration accuracy does not necessarily reduce the overall retrieval error.
2. Reliance on *a priori* information - this is a critical issue for climate monitoring and one generally ignored. Retrievals of most sounding products are heavily constrained to climatology. For monitoring purposes it is critical that the extent of reliance of any retrieval on the *a priori* be firmly established since any properties that are too constrained to such information cannot provide proper measures of evolving climate change.

3. Asynoptic sampling of polar orbiting satellites introduces error in time-mean fields that are significant. These arise chiefly from inadequate sampling of diurnal cycles resulting in an aliasing in the time-mean fields. Diurnal biases are prevalent in observing many hydrological parameters (e.g. clouds and precipitation). Sampling errors can be minimised by coordinating polar satellites, sampling throughout the diurnal cycle.
4. The synoptic-like sampling of GEOs favours studying fast processes and their evolution. Again coordination of GEO satellites will greatly improve the sampling limitations of these platforms. This coordination, wherever possible needs to include same instruments (or close copies) and same QA procedures.

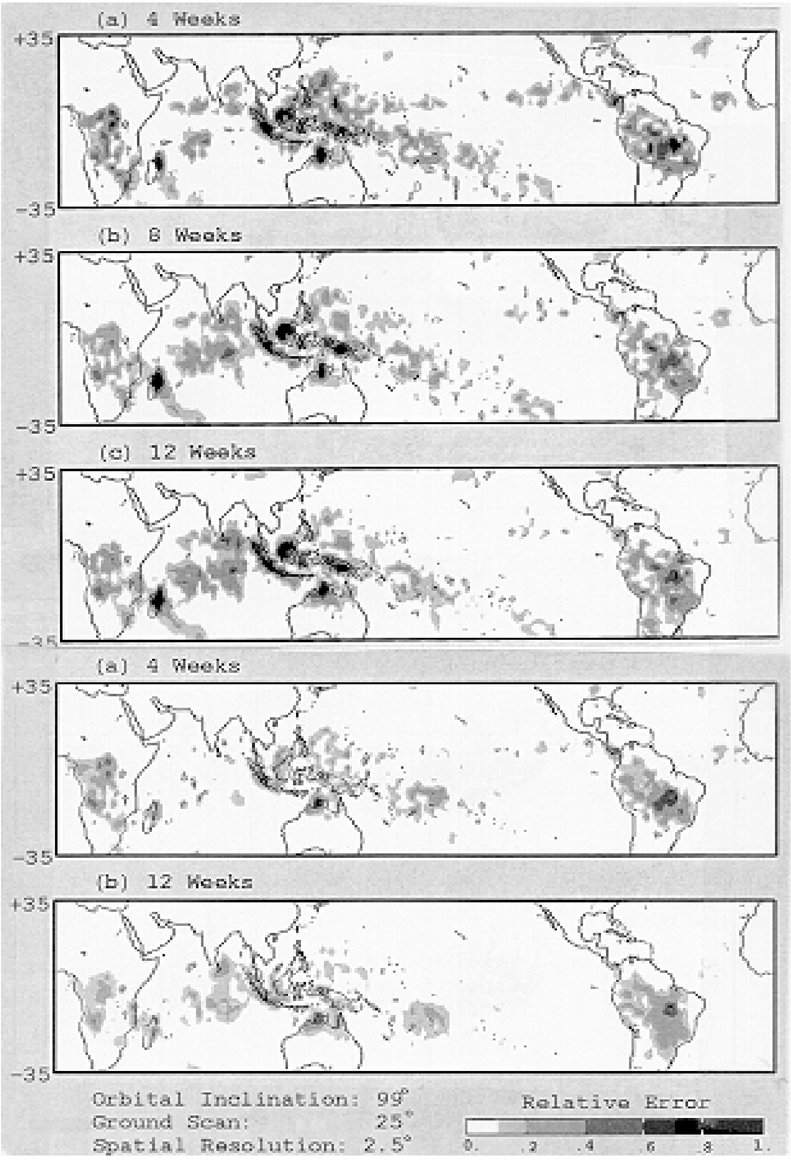


Fig 5.3 *(a) Upper 3 panels (a,b,c) are normalized bias in the time mean distribution of a GPI proxy scaled by a constant factor when day side measurements from a polar orbiting satellite are sampled and compared to full resolution data as provided by a geostationary satellite. (b) Lower two panels (a,b) - as in (a) but with an average of day and night side into true mean.*

6. Lessons Learned

As noted previously, two important requirements of a climate observing system are the requirement for accuracy and the requirement for precision. Observing climate change places stringent requirements that are generally not met by existing systems. However, we have begun to learn what steps are required to address these requirements and maximize the climate-based information content of current satellite observations. These steps are now illustrated with selected examples of satellite observations used in the context of climate research.

6.1 Calibration

The ultimate accuracy and precision of space-based data for studying the climate system hinges on how well the data are calibrated. For many of the operational-like sensors, calibration is of low priority despite the fact that these data are now routinely used in climate data projects (e.g., the International Satellite Cloud Climatology Project, ISCCP, Rossow and Schiffer, 1991). The purpose of calibration is to establish the relationship between measured data and a corresponding known standard reference and therefore establishes the absolute accuracy of the measurement. While some sensors are calibrated prior to launch, in-orbit instrument changes require that this calibration be carried out routinely on the spacecraft in orbit. Since some sensors are only partially calibrated in orbit, and other sensors are either only calibrated prior to launch or not at all, indirect methods of calibration are needed - these are the so-called vicarious calibration methods. Approaches to vicarious calibration vary from application to application and often involve comparison of a measurement to some model simulation of the measurement. On the whole, vicarious calibration is a misnomer since the reference against which the measurement is compared is usually not traceable to a reference standard. As we learn from the examples below, vicarious calibration is generally less accurate than direct calibration and it is sometimes difficult to assign errors to this calibration approach since the approach is generally not tied to an absolute standard. Despite these shortcomings, vicarious calibration when conducted routinely and with care, it critical to assessing instrument precision.

6.2 AVHRR Pathfinder Calibration

Satellite sensors degrade in orbit, initially because of the outgassing from the radiometer components and subsequently because of continuous exposure to the space environment. Thus it is generally insufficient to merely calibrate sensors before launch and assume these calibrations are relevant through the life of the sensor in orbit. The AVHRR visible and near-infrared channels, while uncalibrated, suffer degradation and post launch calibration of these channels has been carried out as part of the AVHRR Pathfinder using the vicarious calibration approach (Ohring and Dodge, 1992). This approach builds on the method developed for ISCCP and is based on (i) the use of terrestrial targets that are radiometrically stable in time, (ii) model simulations and (iii) matching the performance of the AVHRR sensor to a known, calibrated sensor. The terrestrial target use for channel 1 is a portion of the Libyan Desert which is taken to be stable. The absolute calibration scale is based on congruent aircraft/satellite radiance measurements over White Sands, New Mexico that were carried out in 1986. Figure 6.1 show the effects of this vicarious calibration in removing the significant and spurious downward trends of solar radiances. The absolute accuracy of this vicarious calibration procedure is between 5-10%. Measure of precision, on the other hand, might be provided by the rms deviation of the albedo and this deviation is significantly smaller than absolute accuracy. Maintenance of this level of precision requires routine application of the vicarious calibration.

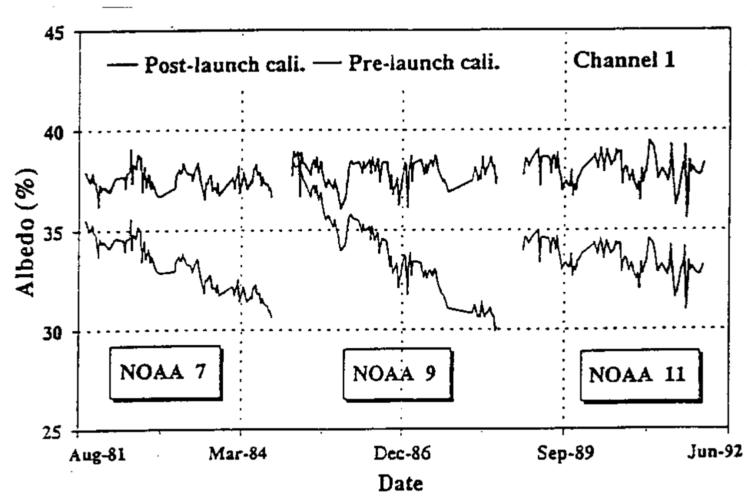


Fig 6.1 *Albedo derived from AVHRR channel 1 over the southeastern portion of the Libyan desert (Rao, 1997)*

6.3 WV channel calibration on Meteosat

Routine on-board calibration of operational-like sensors is carried out more as an exception than as a rule. Furthermore, the inflated size of the optics of imagers on GEOs and the associated costs of doing so usually prevents direct calibration in orbit. Vicarious calibration is the common procedure for calibrating operational GEO sensors[3]. An example of this type of calibration for the Meteosat water vapor channel is described at length by van de Berg *et al.* (1995). The procedure developed is to match in time satellite radiances to radiosonde data at selected locations where the quality of these data are maintained. A radiative transfer model converts these sounding data into synthetic radiances which are then used to convert raw radiance counts to radiance. Figure 6.2 is an example of the calibration factor plotted as a function of time over a five-month period derived by matching the water radiance channel of Meteosat to over 300 soundings. The absolute accuracy of this approach is difficult to estimate and requires some calibration of the model. The precision might be deduced from the variability of the calibration which is claimed to be at the 2% level or even slightly less (Schmetz, 1989; van de Berg *et al.*, 1995).

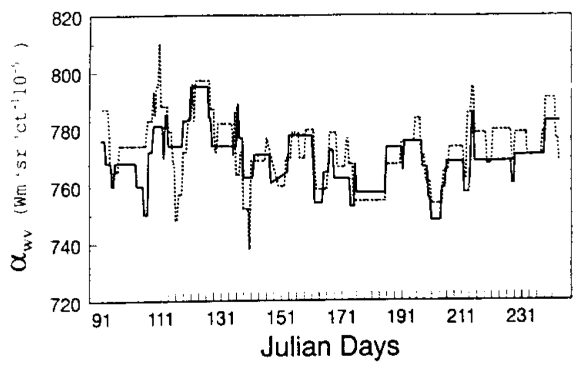


Fig 6.2 *Variation of the calibration coefficient over a five-month period in 1994 derived from about 20-40 co-locations of sondes and satellites radiances per event. The two curves represent different ways of averaging the data (van de Berg et al., 1995)*

[3] Although the IR sensors of the GEOS satellites are operationally calibrated in orbit, vicarious calibration is required to correct for unwanted effects (Weinreb *et al.*, 1997).

6.4 The TOMS experience

The two examples described above refer to calibration of sensors that are either otherwise uncalibrated and include no means of on-board calibration or whose calibration for one reason or another is incomplete. As noted in the above example, the intrinsic accuracy of this vicarious calibration is one issue, but the precision of the calibration is another. Unfortunately, the precision of the AVHRR calibration cannot be addressed when calibration scales are referenced to a single (or even limited number) of matched aircraft flights. High precision thus requires accurate description of an instrument time-dependent characteristics. Characterizing instrument stability must therefore be a major consideration in the design of monitoring systems.

Routine vicarious calibration must be an essential ingredient of any monitoring system. A clear illustration of this point is provided in the example of detection of decadal ozone climate trends using TOMS data. The gradual degradation of optical components (chiefly the solar diffuser, refer to the upper panel of Fig. 6.3) prompted the development of *ad hoc* vicarious calibration to account for instrument drifts. The approach used relied heavily on the surface observing network of Dobson stations which, in turn, are anchored to a known reference standard Dobson spectrometer. The nature of the false trend in ozone introduced by instrument degradation is highlighted in the bottom two panels of Figs 6.3 showing the difference between TOMS derived ozone and the ozone determined from Dobson measurements averaged over all Dobson sites. The version of TOMS used to produce the time series of the upper panel (version 6) does not account for instrument degradation whereas the time series of the lower panel represents a version of TOMS data with degradation effects removed.

6.5 Multiple LEOs: The TOVS experience

There are two notable examples of the combination of data obtained from multiple versions of the TOVS flown on a series of NOAA polar orbiting spacecraft. Combination of data from these multiple platforms produces a data record of approximately 17 years. The issues associated with combining these data are essentially the same, namely what is the accuracy of the given measurement (i.e. how well is it calibrated)? What is the precision of the data over the period of time considered? Finally how do we interpret the data in terms of processes of the physical climate system? Much of the research that reports on analyses of these data records focus on issues of precision while the more controversial topics are those of data interpretation since these ultimately require a retrieval of one sort or another.

The first common issue concerns the removal of sampling biases from the data. The NOAA spacecraft that carry the TOVS are placed in a nominal sun-synchronous orbit which means the time at which any particular location is fixed. Unfortunately these orbits drift at a disturbing rate as indicated in Fig. 6.4. This figure shows the equatorial crossing time of the ascending node of the orbit and shows how dramatic are the drifts of the afternoon crossing times. Orbit drifts create spurious trends in the data. In addition to drifts, there are periods of time since 1981 when data from only one satellite were available which is a further source of bias associated with inadequate sampling of the diurnal cycle.

The second common issue has to do with field-of-view effects that occur as a result of scanning the instrument off nadir. Some correction for this angular effect has to be taken into account if detailed spatial resolution is desired (if not the nadir FOV could be used). A third issue is the different response characteristics of the different versions of TOVS producing different measurements of the same scene with similar but not identical instruments. This is an issue that affects both accuracy and precision and thus our ability to discern trends and providing for periods whereby these different version can be overlapped is required to determine the magnitude of these differences.

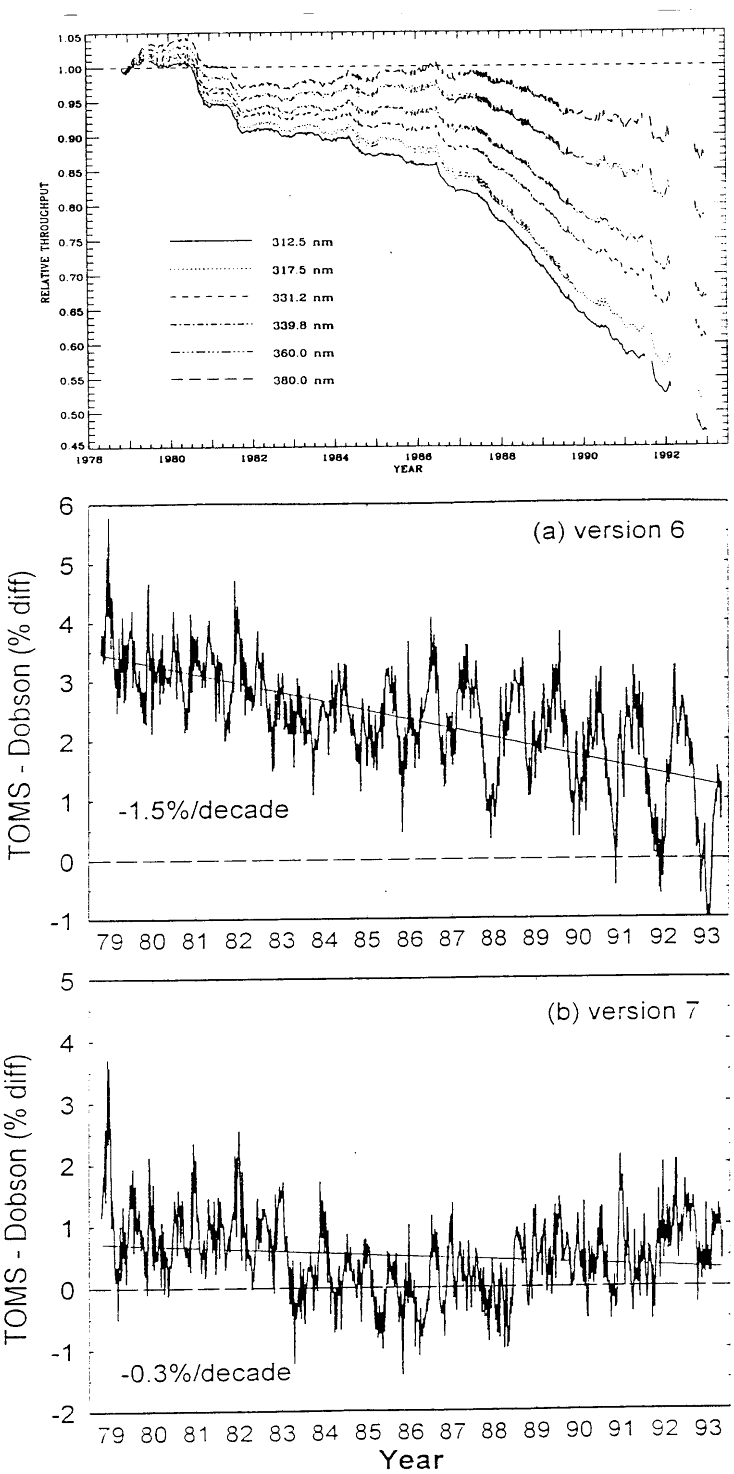


Fig 6.3 *Upper panel shows TOMS total instrument throughput degradation over time relative to day one. Shorter wavelength optics degrade more than longer wavelength optics (Hilstenrath et al., 1997). The lower two panels present the difference between TOMS and Dobson estimated total ozone without account of sensor degradation (middle panel) and correcting for this degradation (lower panel).*

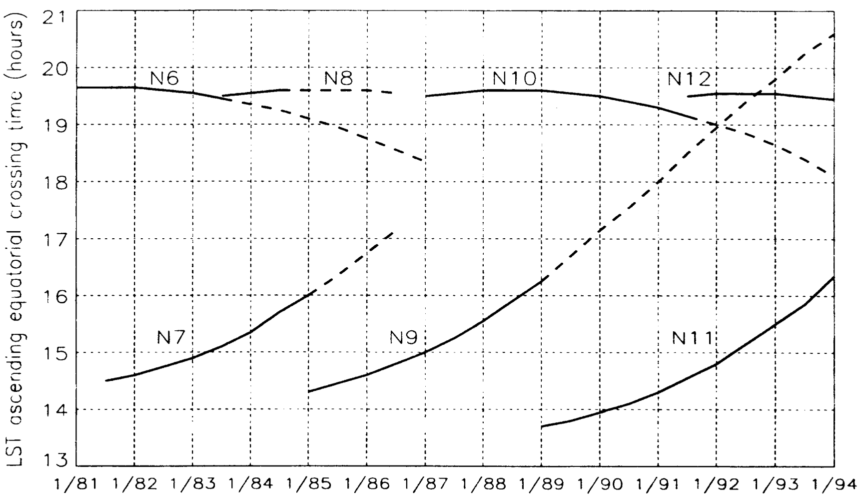


Fig. 6.4 Ascending node equatorial crossing times for the NOAA series satellites. The solid line is the period of operational coverage (Bates *et al.*, 1996).

6.5.1 TOVS Channel 12 water vapor radiances

Bates *et al.*, (1996) describe an empirical method that attempts to correct for sampling biases introduced by both satellite drift and lack of resolution of the diurnal cycle in a 13 year record of the TOVS channel 12 water vapor radiances. They also examine biases that arise through differences between the particular versions of TOVS flown on the different satellites. The satellite-to-satellite differences are summarized in Table 6.1. The inter-satellite monthly mean differences are expressed in terms of channel 12 brightness temperatures for the region from 30N to 30S. In a crude sense this difference can be thought of as an indication of the precision of the data. For monthly mean data, this difference is about 0.25 K except for NOAA-9 which differed from the other satellites by 0.4-0.45 K. Bates *et al.* propose this to be due to an anomalous calibration of that channel of that version of the TOVS.

Determining the accuracy of the data is difficult. One approach would be to rely on pre-launch calibration but this would be unreliable given the usual changes in instrument responsivities in orbit. A second approach would be to use vicarious calibration methods such as those described above in relation to the Meteosat water vapor channel. This is possible although the lack of accuracy of radiosonde upper tropospheric water vapor is a problem that limits our ability measured and simulated radiances.

Table 6.1 *A measure of the precision of 13 years of satellite water vapor radiance data. Given are the inter-satellite differences of the HIRS12 channel on the NOAA spacecraft from 1981 to 1994 from 30 N to 30 S (Bates et al., 1996).*

Mean monthly difference (°C)	Satellite	Year	Pentad (start–finish)	Reference satellite
0.15	TN to N6	81	1–45	N6 to N7
0.25	N6 to N7	81	46–73	N7
		82	1–73	
		83	1–34	
0.10	N8 to N7	83	35–73	N7
		84	1–34	
0.40	N9	84	35–73	ad hoc
		85	1–73	
		86	1–73	
		87	1–3	
0.45	N9 to N10	87	4–73	N10
		88	1–3	
−0.03	N11 to N10	88	4–73	N10
		89	1–73	
		90	1–73	
		91	1–4	
0.26	N12 to N11	91	5–73	N11 to N10
		92	1–73	
		93	1–73	

6.5.2 MSU temperatures

Data from the MSU channels of multiple versions of TOVS have also been combined by Spencer and Christy (1992) to produce a 16-plus year record of global temperatures. Since the characteristic weighting functions of the MSU are broad, these temperatures represent relatively deep layers of the atmosphere. Christy *et al.* (1995) describe the procedures taken to account for the sampling biases and inter-satellite sensor differences.

The authors of this study address the issue of precision of the data in two ways. First they compare independent data of the same type for the same period- in this example this represents averaged data from the MSU flown on different satellites as shown in Fig. 6.5a. These data can be analyzed on different time and space scales to determine the characteristics of their differences. The second step is to compare the data of different characteristics. In this case Spencer and Christy use the vicarious calibration approach described above and compare MSU temperatures variations to simulated temperature variations calculated using the observed radionsondes matched to the MSU observations. An example of such a comparison for 99 stations over the northern hemisphere is presented in Fig. 6.5b. These analyses give confidence in the precision of the satellite observations which is claimed to be at the 0.01 K level for monthly mean temperatures. Both this example and the example of ISCCP illustrate that determining the precision of the data follows a posteriori with the accumulation and analyses of sufficient data.

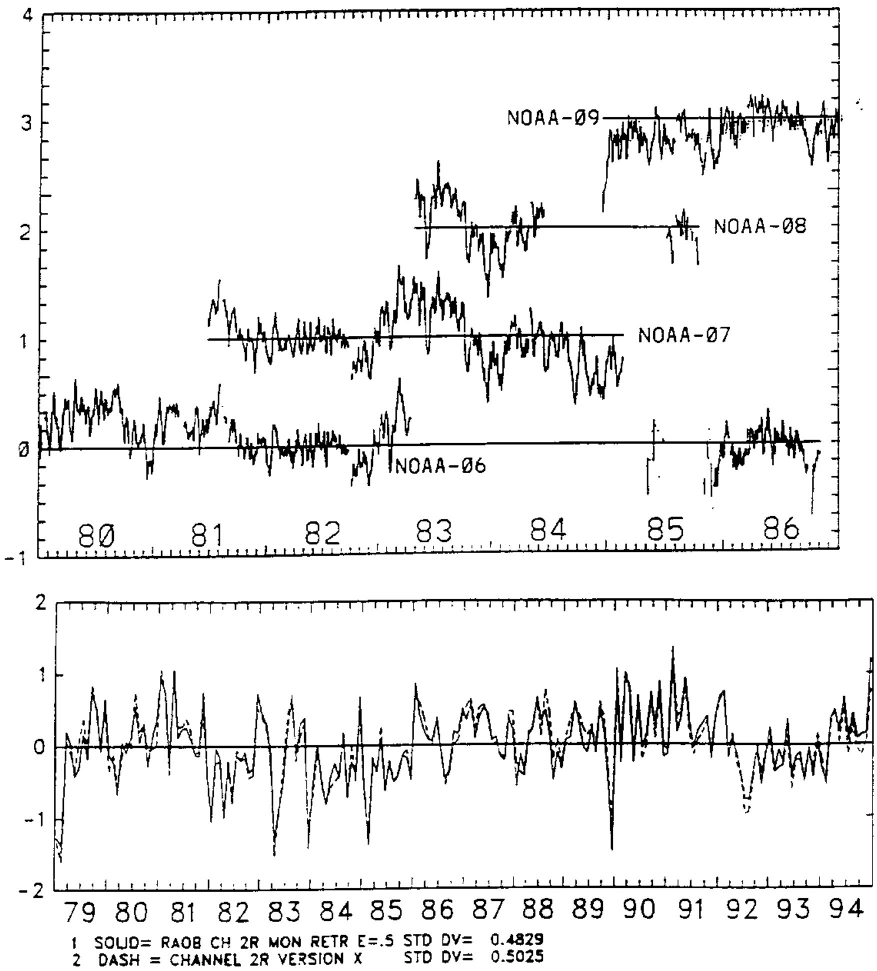


Fig. 6.5 *(a) Time series of global-monthly averaged temperatures anomalies from channel 2 of different versions of MSU on the satellites noted. The time variability is reproduced for those periods when satellites overlap. (b) Comparison of the simulated MSU temperature anomalies using sonde data to actual MSU temperature anomalies. All anomalies are defined with respect to the annual means.*

6.6 Global Water vapor merged from 3 GEOs

Observations of IR radiances in the 6.3 µm band of water vapor (water vapor radiances) have been carried out on operational polar orbiters since 1978 as part of TOVS. Water vapor radiances are now available on the constellation of GEOs as previously described. These radiances provide an ideal opportunity for testing methods of merging data from multiple GEOs thereby creating global distributions of similar data. Schmetz *et al.* (1995) describe one of the first efforts in which data from three operational GEO satellites were combined to produce near global water vapor data for one month, March 1994. The coverage of the three satellites, GOES-7, Meteosat-3 and Meteosat-5 is highlighted in Fig 6.6a.

Figure 6.6b shows the monthly mean UTH for March 1994 from all three satellites. Differences between Meteosat 3 and Meteosat 5 appears as a discontinuity and is a result of differences in the algorithms applied to radiance data from each satellite. This reinforces the earlier point raised that a significant source of uncertainty arises from assumptions contained in algorithms. The more seamless transition from Meteosat 3 to GOES 7 was accomplished in the retrieval by removing inter-satellite biases.

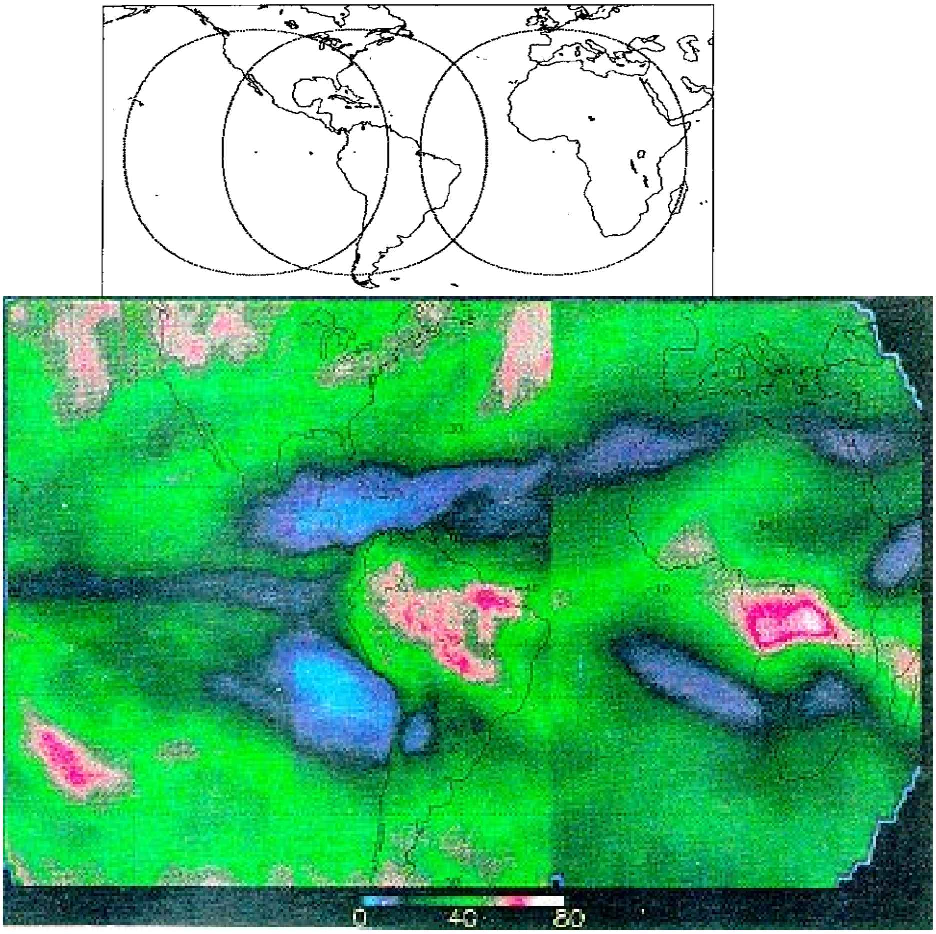


Fig. 6.6 *(a) Upper panel- coverage from three geostationary satellites (GOES-7 at 112W), Meteosat-3 at 75 W and Meteosat-5 out to 50 from nadir (b) Bottom panel- the mean-monthly composite of UTH [percent] binned and averaged to approximately 1 lat-long.*

6.7 The ISCCP experience

ISCCP formerly began in 1983 with the collection of the first internationally coordinated satellite radiance data. The original plan called for this collection for only a five-year period but the ISCCP has since been extended to the year 2000. This program was the first of its kind involving routine collection of operational polar and GEO satellite data merged to produce homogeneous global radiances and climatological products from these radiances. The EUMETSAT commitment continues to be important to the success of this program.

Many key problems that were addressed under ISCCP are broadly relevant to the topic of this report. Most important are:

1. The difficulty associated with the maintenance of an observing network of multiple satellites for an extended period. The ISCCP notionally planned to make use of data from five geostationary satellites as well as data from a single polar orbiter in an effort to fill in the data voids over polar regions. Actual coverage during the first six years of the ISCCP, measured against this hypothetical ideal of six satellites, is presented in Fig. 6.7. Because of the loss of satellites throughout this period, coverage was limited to about 90% for about three of the first six years although with the availability of INSAT data, the data coverage could exceed that originally sought for ISCCP.

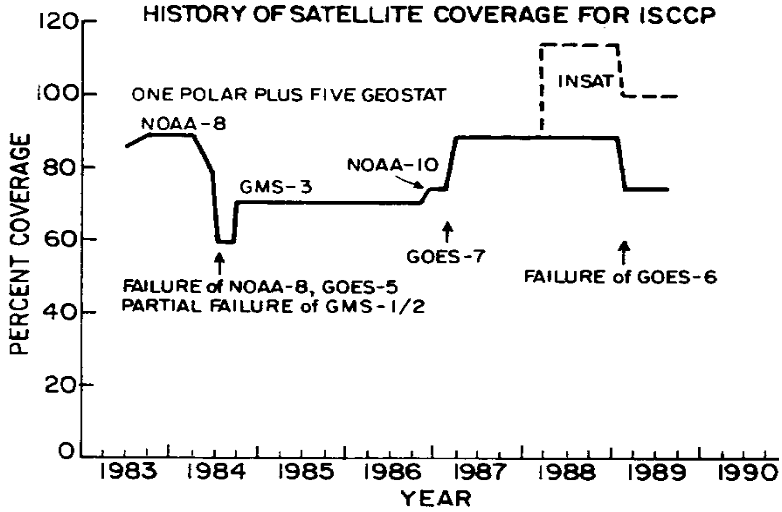


Fig. 6.7 *History of satellite coverage for the ISCCP. The coverage is defined to be at 100% for five geostationary satellites and one polar orbiter satellite, representing eight observations per day (although the actual observation frequency is smaller for polar orbiters). The initial complement of satellites included the NOAA-7, METEOSAT-2, GMS-2, GOES-5, and GOES-6. Failures and replacements of satellites are indicated. Time is given in quarter years (from Rossow and Schiffer, 1991)*.

2. The calibration of the AVHRR visible and IR channels: The principle form of data used by ISSCP is the image data on the GEOs and the AVHRR on the polar orbiting satellite. The procedure adopted by ISCCP is to compare data obtained routinely from each geostationary satellite and the NOAA polar orbiting satellites. A vicarious calibration procedure was developed for the AVHRR which involved aircraft measurements using calibrated sensors over a well-defined reflecting desert surface (Whitlock *et al.*, 1990). Because a number of such campaigns were conducted over the lifetime of the NOAA-9 satellite, Brest *et al.* (1997) suggest the AVHRR on NOAA-9 is the best calibrated and this particular AVHRR was then selected as the calibration reference for both the sensors on GEOS and the other AVHRRs. Periodic, intensive calibration campaigns of this type are a vital component of this strategy but unfortunately these cannot be carried out with sufficient frequency and over a sufficiently diverse range of surfaces to reach the levels of precision necessary to detect climate trends. According to Brest *et al.* (1997), precision of the calibration (they state as relative accuracy) is about 3-5% for the solar channels and 1-2 K for the IR channel. The absolute accuracy of the calibration is of the order of 10% for the solar and 2% for the IR channels. as noted above from discussion of calibration of the AVHRR. Figure 6.8 portrays the history of the IR calibrations over the first five years of the project and the visible calibration over an eight-year period. According to Fig. 6.8a, output from the IR channel varies with time and the operational calibration procedure generally corrects for these changes with only a small adjustment necessary from late 1987 through 1988. The corrections that were required for the NOAA-9 visible radiances are shown in Fig. 6.8b.
3. The geostationary-to-polar orbiter calibration normalization adopted for ISCCP involves two steps. The first is to compare radiances measured at the same time and location with the same viewing geometry

for selected individual targets. The second step examines the time record of the radiances for spurious short-term variations in IR calibrations of the IR channels on the geostationary satellites. The two step procedure is monitored using a number of statistics collected as part of the ISCCP analysis, such as frequency histogram differences in the surface reflection, temperature and cloud reflections (expressed as cloud optical depth) and cloud temperature. Figure 6.9a indicates the magnitude of the corrections used to normalize the geostationary calibration to that of the reference AVHRR and Fig. 6.9b is an 8 year history of the modal differences of these quantities.

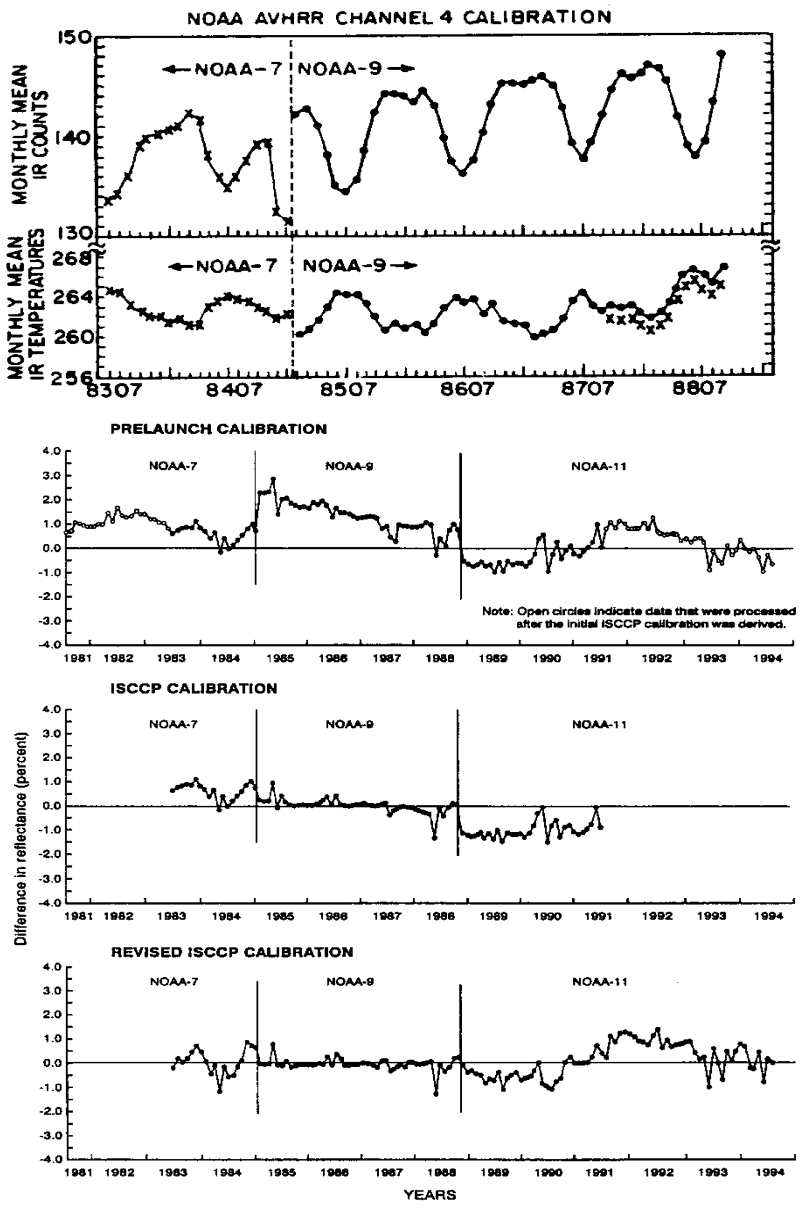


Fig. 6.8 *History of the AVHRR (a) the IR channel 4 for the NOAA-7 and NOAA-9 satellites (from Rossow and Schiffer, 1991) and (b) the visible channels. The nominal calibration is the calibration originally supplied by the satellite operator; the normalized calibration is that used to match NOAA-9 to NOAA-7 and the absolute is the final adjustment. The IR calibration is illustrated by showing the global, monthly mean IR brightness temperatures (Brest et al., 1997) .*

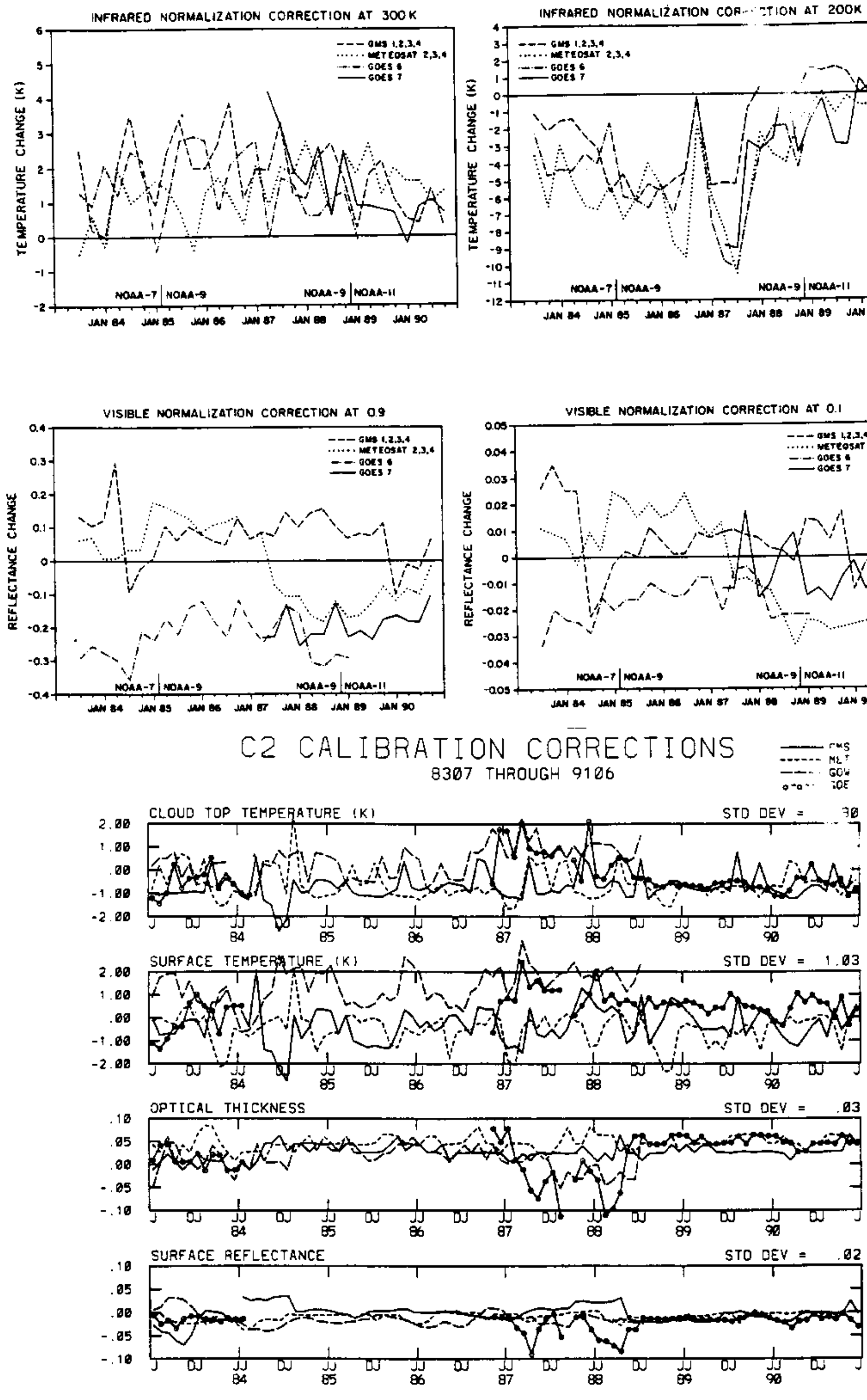


Fig. 6.9 *(a) History of the calibration changes for visible and IR channels on geostationary satellites calculated using results for individual targets from coincident image pairs. Magnitudes are shown for changes in brightness temperature and visible reflectances as noted. (b) An 8 year history of modal differnces between retrieved quantities listed from overlapping GEO and LEO satellite observations. Statistics correspond to 3 hour-280 km resolved data (Brest et al., 1997)*

6.8 Summary

Two important requirements of space-based climate measuring systems are: a requirement for accuracy and the a requirement for precision. Monitoring climate change requires high precision, studying climate processes requires accuracy and understanding climate change requires both high precision and high accuracy. Neither the requirements for accuracy nor precision of measurements (i.e. in terms of the directly measurement quantities) have been spelled out despite the proliferation of a large number of climate requirement documents. In many cases actual requirements are not known and these documents often reflect capabilities rather than real requirements. Present-day systems, on the whole lack accuracy with real decadal-type changes in some instances (e.g. ISCCP) being smaller than the uncertainties of calibration and changes of calibration over a decade of observations. In some instances, however, (e.g. MSU temperatures), measurements seem to possess a precision consistent with what is thought to be required to detect climate trends.

1. It is clear that one single calibration approach (e.g. on-board calibration) will not lead to precision and accuracy requirements that are likely to be consistent with climate change. For space-borne sensors, degradation in orbit requires that calibration be done routinely in orbit and that the instrument be monitored for change. Direct calibration is required to determine levels of accuracy whereas indirect calibration (vicarious calibration) more often establishes the degree of precision of the observations. Vicarious calibration must be viewed as a critical component of both measuring and monitoring systems
2. More effort is needed to establish the accuracy of vicarious calibration. This effort should be directed as follows (i) work towards establishing reference standards. Since model simulations are often an integral component of vicarious calibration, basic model references are needed. The movement towards standard models has begun. (ii) Maintain routine calibrations based on matching with other observations. GEO observations are well suited to this routine approach offer many possibilities for time coindent observations than is usually possible with LEO observations. (iii) developing new and improved methods of calibration.
3. Drifts in satellite orbits makes the task of removing sampling biases from data records more difficult than usual. Stability of the orbits of operational satellites is commitment that operational agencies should strive for as well as preparedness for launching follow-up satellites should one fail so as to minimize gaps in data. Overlapping sensors is important for testing consistency of the data and ultimately determining the precision of the data (e.g. TOVS and MSU examples).
4. An important data product from current systems are the calibrated radiance data. These data have greater intrinsic accuracy and precision than any parameter retrieved from them. Requirements on radiance precision and accuracy are not known since the nature of the climate variability of radiance has yet to be assessed. However, accurate radiance data alone does not necessarily provide insight into the nature of the processes that govern any detected change. Interpretation of change ultimately involves retrieval or assimilation. Assimilation systems unfortunately are far from incorporating of climate-type data (cloudy sky radiances, water vapor radiances and other like data) and therefore should not be viewed as a replacement for retrieval systems.
5. Realistic assessment of the precision of a given measurement requires a long data record that can be analyzed. For example, with a sufficient record of radiances, ISCCP changes its satellite-to-satellite normalization method to remove spurious trends in the ISCCP products.

7. EUMETSAT satellite observing systems: MSG and EPS

EUMETSAT, the European Organization for exploitation of Meteorological Satellites has been responsible since 1987 for the constant provision of half-hourly image data in three spectral bands from its geostationary Meteosat satellites. To ensure continuity into the next millenium, a new satellite system, the Meteosat Second Generation (MSG) is being developed for launch, with MSG-1 expected in 2000.
In 1992, EUMETSAT implemented a preparatory program that established the formal framework for initial activities aimed at developing a EUMETSAT Polar System (EPS) in support of a Joint Polar System (JPS) formed with the convergence of the existing two USA polar satellite programs into the NPOESS.

7.1 Meteosat Second Generation (MSG)

The MSG System has two main components, the Space Segment that comprises three satellites with the first of these, MSG-1, to be launched late in 2000 and the Ground Segment. The latter comprises of a central facility at EUMETSAT headquarters at Darmstadt, Germany, where mission control, spacecraft control, central extraction of meteorological products, and archiving are performed. A schematic overview of the MSG system is provided in Fig. 7.1. In addition to this segment are the satellite application facilities (SAFs) which focus on particular applications of satellite data. At the time of writing this report, three SAFs have been approved, one of which aims to extract and distribute climate related datasets. The role of the SAF for climate applications need to be carefully thought through. There is some advantage in the user being involved in the calibration and whether or not it is desirable for the SAFs to contribute to the vicarious calibration activity warrants careful consideration.

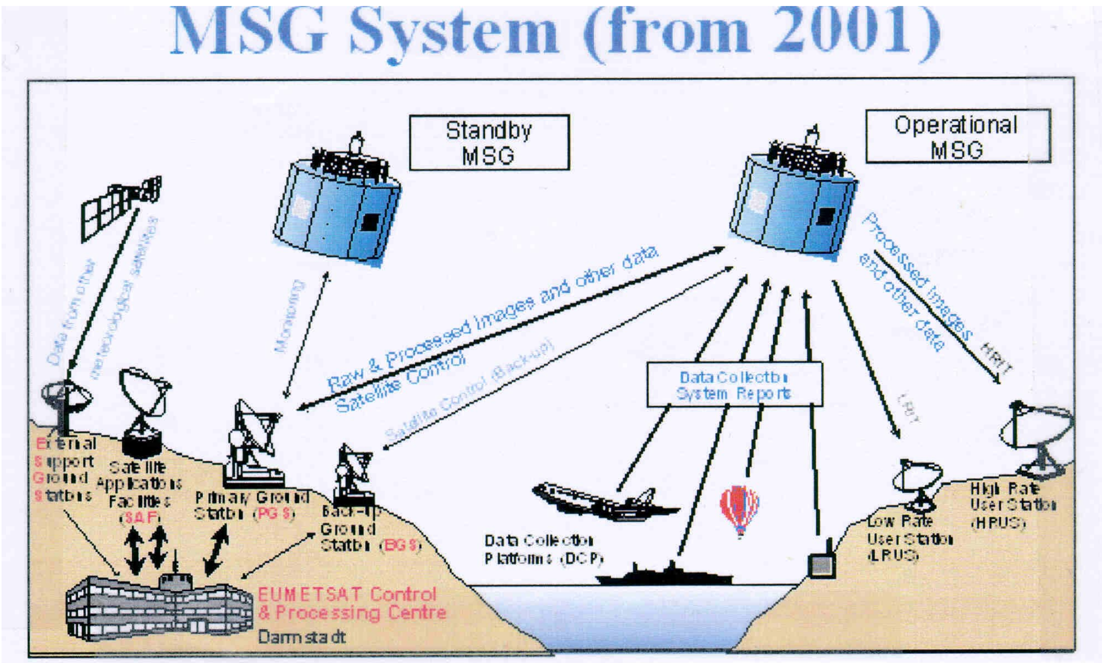


Fig. 7.1 *The MSG system*

The core payload of the MSG comprises the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) which represents a significant enhancement of the capabilities of the current first generation Meteosats. The image data from this instrument is meant to:

- Continue the meteorological applications of earlier Meteosats
- Add selected characteristics of GOES and HIRS sounder instruments
- Add further climate related observational capabilities as demonstrated from AVHRR.

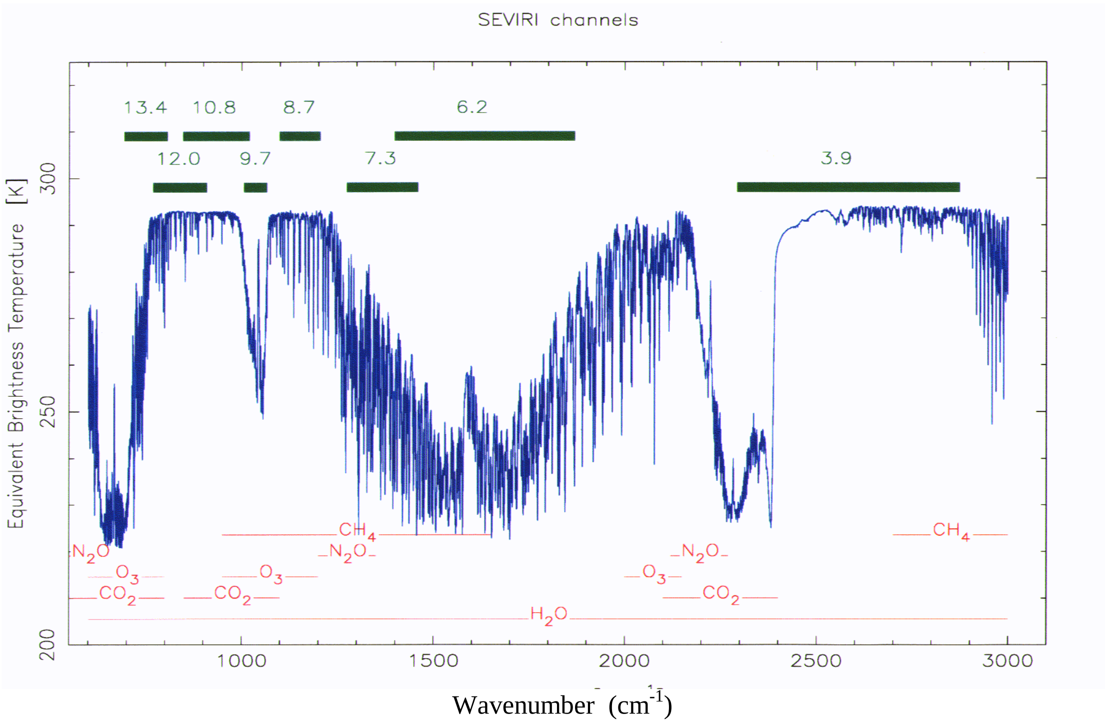


Fig. 7.2 *The SEVIRI spectral channels portrayed relative to an atmospheric absorption*

The post Phase-B specifications of the SEVIRI have 12 spectral channels located in the regions summarized in Fig.7.2 and Table 7.1. The high (spatial) resolution visible channel (HRV) is a carry over from the Metosoat imager providing 1 km observations. Calibration of the IR channels will be carried out on-board using a blackbody operated at two temperatures and this is to be supplemented every revolution by a view to space to establish a zero. No calibration is proposed for the solar channels so the visible and near infrared channels require vicarious calibration similar to that carried out for Meteosat and AVHRR. Current estimates of the accuracy of this approach is at the 5% level.

The climate applications of SEVIRI are potentially widespread with enhanced capabilities for observing clouds, vegetation and water vapor. It is hoped that EUMETSAT through these observations will continue to serve climate programs like the ISCCP and GPCP. The ultimate utility of these data, however, rests with the commitment to calibration which must include a commitment to maintain routine vicarious calibration. Since the number of channels on SEVIRI that overlap channels of operational sensors on polar orbiters (notably HIRS) has increased beyond the current imager, then this vicarious calibration should also include satellite-to-satellite comparisons.

The GEO platform provides a number of advantages over polar platforms. Unfortunately, the sensors on operational GEOs are limited and there has been little opportunity to fly non operational instruments. The flight of the Geostationary Earth Radiation budget (GERB) instrument which was selected through an Announcement of Opportunity process is an important but all to infrequent example of climate specific sensors on a geostationary platform. More opportunities of this nature are needed and it is hoped that ESA in conjunction with EUMETSAT will continue to promote this process.

Table. 7.1 *The SEVIRI spectral characteristics - the values quoted are in* $Wm^{-2}sr^{-1}\mu m^{-1}$ *for the HRV, VIS 0.6, VIS0.8 and NIR1.6 while the other channels are in K.*

	Specification (commitment)	Estimated Performances at 95K	Estimated Performances at 85K
HRV	1.07	0.96	0.96
VIS0.6	0.53	0.51	0.51
VIS0.8	0.49	0.42	0.42
NIR1.6	0.25	0.17	0.17
IR3.9	0.35	0.30	0.28
WV6.2	0.75	0.42	0.35
WV7.3	0.75	0.40	0.33
IR8.7	0.28	0.29	0.26
IR9.7	1.5	0.90	0.79
IR10.8	0.25	0.24	0.21
IR12.0	0.37	0.34	0.23
IR13.4	1.8	1.00	0.51

7.2 EUMETSAT Polar System (EPS)

The EUMETSAT Polar System is the European contribution to the Initial Joint Polar System (IJPS), and later the Joint Polar System (JPS), which will continue the current system of polar orbiting weather satellites, composed of a morning (AM) and an afternoon (PM) satellite. From 2003 on, the European Metop satellites will provide the service in the morning orbit, whereas the U.S. continue to provide the service in the afternoon orbit. Metop-3 will cover within the JPS the mid-morning orbit with NPOESS missions covering the early morning and afternoon orbits.

The EPS is composed of the Space Segment, comprising three Metop satellites, the launcher service, a Ground Segment and is planned to cover 15 years of operations.

The payload on the Metop space craft, which is being developed jointly with the European Space Agency (ESA), comprises:

- the Infrared Atmospheric Sounding Interferometer (IASI)
- the Advanced Very High Resolution Radiometer (AVHRR/3)
- the High Resolution Infrared Radiation Sounder (HIRS/4)
- the Advanced Microwave Sounding Unit -A (AMSU-A)
- the Microwave Humidity Sounder (MHS)
- the GNSS Receiver for Atmospheric Sounding (GRAS)
- the Advanced Scatterometer (ASCAT)
- the Global Ozone Monitoring Experiment (GOME-2), and Imaging Spectrometer (ImS), being considered for Metop-3 (assuming compatibility with the EPS financial envelope).

Data from both satellite systems are to be exchanged via the transatlantic link between the EPS and the NOAA Ground Segments, so that each Ground Segment disposes of the full data set of the Joint System. This includes blind orbit support.

The EPS Ground Segment comprises a central facility, which provides spacecraft control, and data processing, distribution and archiving. Full level 1b data are planned to be distributed to the User Community as well as selected level 2 products. The Satellite Application Facilities (SAF) form the decentralised part of the EUMETSAT Ground Segment and are considered as Centres of Expertise for several meteorological application areas. They provide data and products from level 2 upwards as well as algorithm development.

Data and products are archived in the EUMETSAT Unified Archive (U-MARF), so that the User has one defined off-line interface to EUMETSAT data.

8.0 Acknowledgements

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