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12. Satellite Orbit and Data Sampling Requirements

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Climate forcings and feedbacks vary over a wide range of time and space scales (cf., Peixoto and Oort, 1992). The operation of non-linear feedbacks can couple variations at widely separated time and space scales (e.g., Barnett, 1991) and cause climatological phenomena to be intermittent (Lorenz, 1990). Consequently, monitoring of global, decadal changes in climate requires global observations that cover the whole range of space-time scales and are continuous over several decades. The sampling of smaller space-time scales must have sufficient statistical accuracy to measure the small changes in the forcings and feedbacks anticipated in the next few decades (see Section 3 above), while continuity of measurements is crucial for unambiguous interpretation of climate change. Shorter records of monthly and regional (500-1000 km) measurements with similar accuracies can also provide valuable information about climate processes, when "natural experiments", such as large volcanic eruptions or El Ninos occur. In this section existing satellite datasets and climate model simulations are used to test the satellite orbits and sampling required to achieve accurate measurements of changes in forcings and feedbacks at monthly frequency and 1000 km (regional) scale.

Orbit Selection - Coverage and Sampling Frequency

The geographic coverage and sampling frequency of satellite observations are principally determined by the orbit and are the leading criteria for orbit selection. Other important selection criteria are instrument spatial resolution, the pattern of coverage of Earth's surface, the range of solar illumination geometries encountered, payload mass and mission lifetime. The payload mass that can be orbited by a particular launch vehicle is larger for lower altitude orbits; larger launch vehicles cost more than smaller launch vehicles. The instrument mass and cost required to attain a particular spatial resolution are lower in lower altitude orbits. Satellite mission lifetime is strongly limited by atmospheric drag in low (< 400 km) altitude orbits and by radiation damage rates in high (> 1000 km) altitude orbits.

All of these issues have been studied thoroughly for previous satellite missions and have also been considered in selecting possible orbits for Climsat, but the focus here is on the two most important requirements for monitoring climate changes: complete global coverage and unbiased sampling of diurnal variations. The observing system proposed for Climsat that meets these requirements has the same set of instruments in two orbits: a near-polar sun-synchronous orbit and an inclined and precessing orbit (Fig. 12.1). Orbital altitudes in the range of 500-700 km allow for high enough spatial resolution with a small payload mass and for mission lifetimes ≥ 5 years.

In the atmosphere, diurnal variations are the shortest periodic variation with significant amplitude (cf., Peixoto and Oort, 1992). These variations also interact with the daily variation of solar illumination and the surface to alter several key climate forcings and feedbacks. Emphasis is therefore placed on proper sampling of diurnal

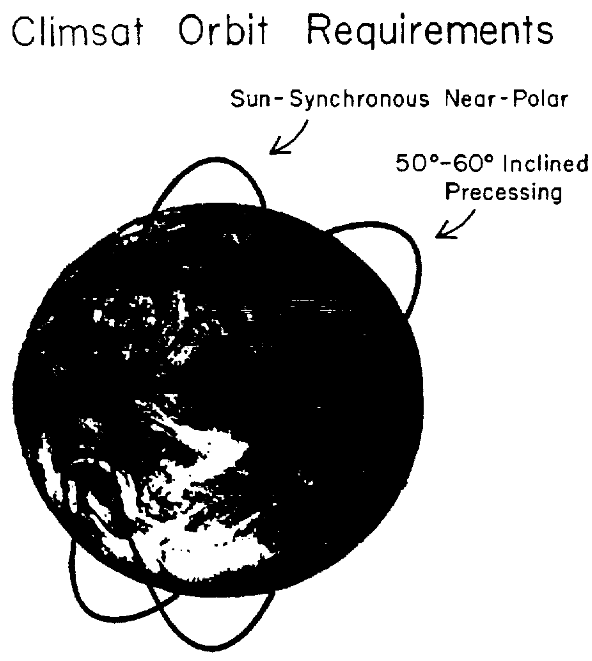


Fig. 12.1. Required satellite orbits for the Climsat observing system.

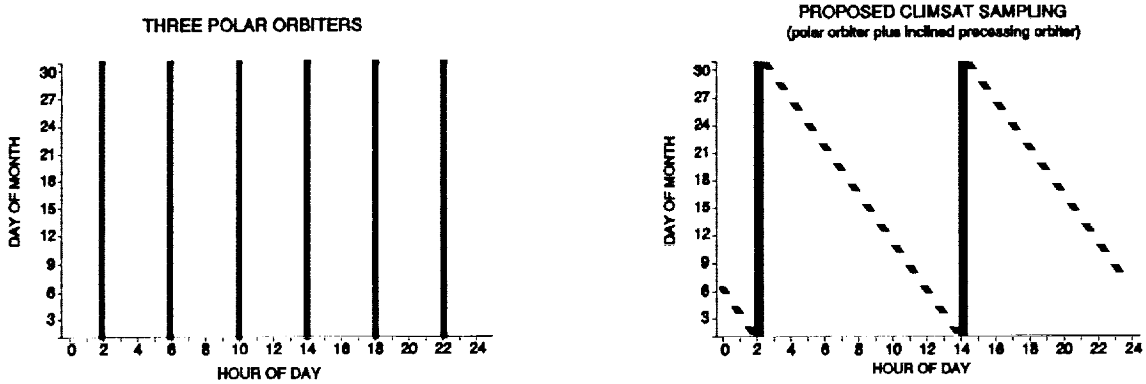


Fig. 12.2. Two alternative sampling strategies for adequate diurnal sampling.

variations, because it produces the strictest requirements. Proper diurnal sampling insures proper sampling of larger synoptic and planetary wave motions as well.

Global coverage and diurnal sampling cannot be satisfied by observations from one satellite (cf., Salby, 1982). A satellite in a polar orbit can view the whole Earth because of Earth's rotation, but the sampling frequency is only twice per day for orbital altitudes between 400-1000 km. The view from a satellite in an equatorial orbit is limited to low latitudes, but the sampling frequency can be more than 10 times per day. Geostationary orbits are special cases, where the view is restricted in both longitude and latitude, but the sampling frequency is limited only by instrument capability.

Figure 12.2 illustrates the sampling from two sets of orbits that provide global observations which adequately resolve diurnal variations. The simplest, direct method requires three sun-synchronous polar orbiting satellites with overflight times about four hours apart (Fig. 2, left panel), each providing two daily samples separated by 12 hours local time (Salby, 1982, 1988b, 1989). The major drawback of this approach for Climsat is that such polar orbits do not provide lower latitude coverage for the SAGE observations. SAGE, unlike most other instruments, must view the sun or moon at Earth's limb (see Section 8); this viewing geometry constrains observations to high latitudes from a polar orbit.

The observing scheme proposed for Climsat (Fig. 12.2, right panel) has only two satellites: one in an inclined orbit which precesses relative to the sun and one in a sun-synchronous polar orbit. The precessing orbit, inclined 50-60° to the equator, provides daily observations at two local times, separated by 12 hours, that vary slowly during the month (slanting lines). Observations from this orbit provide a statistical sample of diurnal variability at all latitudes where it is significant (McConnell and North, 1987; Shin and North, 1988; Bell *et al.*, 1990). The sun-synchronous orbit provides two daily observations over the whole globe at fixed diurnal phases, which allows for separation of diurnal variations from other oscillations with periods near one-half month (Harrison *et al.*, 1983). A similar sampling scheme was successfully used in the ERBE mission (Brooks *et al.*, 1986).

When observations are made in the nadir direction from this pair of orbits over one day, they cover the globe with an effective spacing of about 500-1000 km; Fig. 12.3 shows the orbits projected onto Earth's surface, called the ground tracks. The polar orbiter completes about 14 orbits per day with ground tracks that can be precisely repeated or their longitude can oscillate slightly over several days. The inclined orbiter also completes about 14 orbits per day, but the ground track precesses 5-6° of longitude per day so as to sample diurnal variations. This arrangement of orbits also permits solar occultations at all latitudes for SAGE (Fig. 12.4 shows the distribution of observations). Lunar occultations by SAGE III will increase the density of observations by about 50% over that shown in Fig. 12.4.

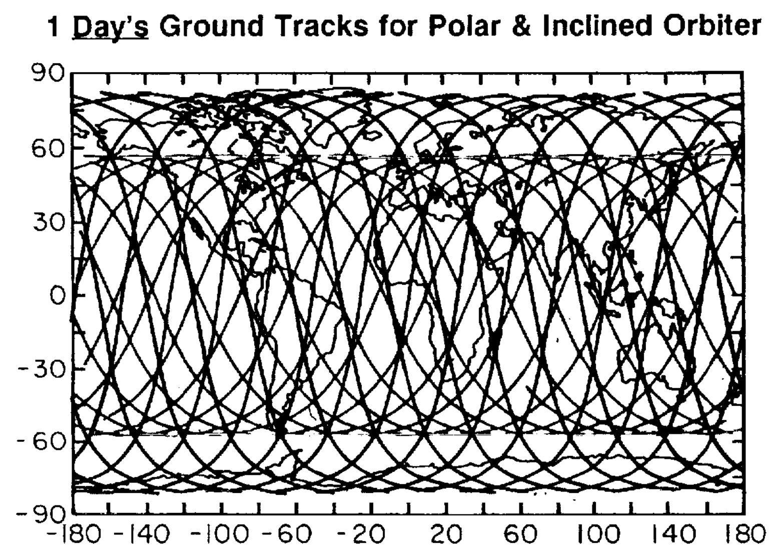
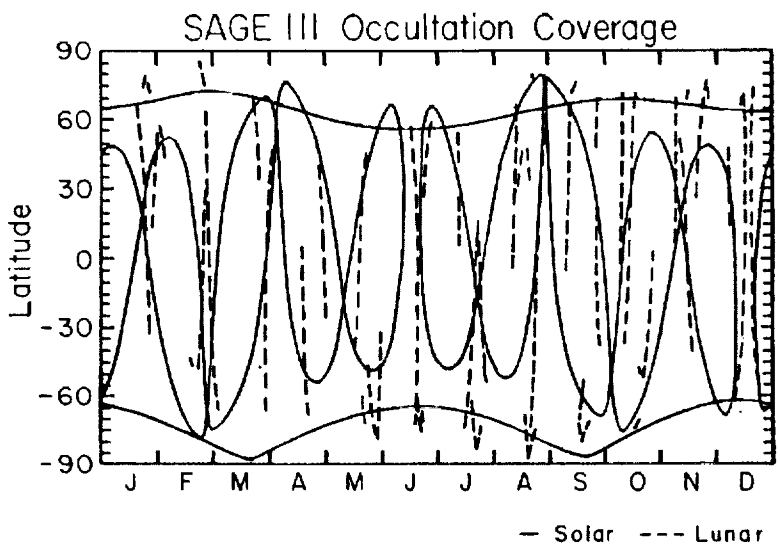


Fig. 12.3. One day's orbit ground tracks for polar (blue) and inclined (red) orbiters.

(a)



(b)

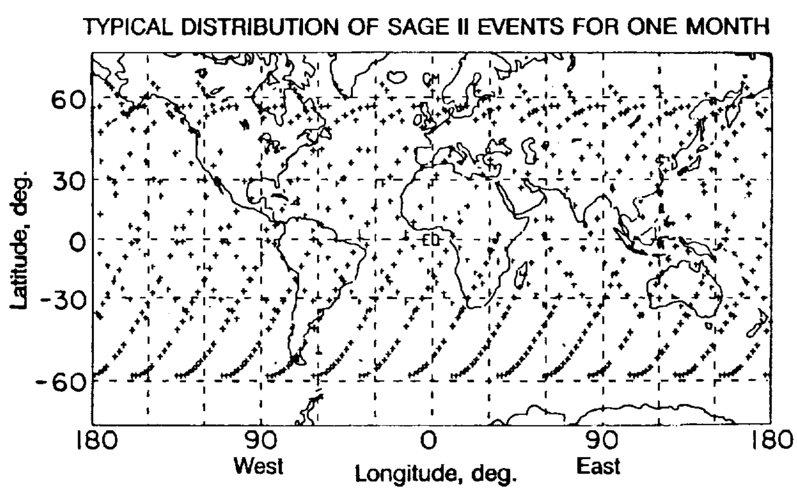


Fig. 12.4. (a) SAGE III solar and lunar occultation coverage over one year. Polar orbiter in blue and inclined in red. (b) typical SAGE sampling for one month from single satellite (inclined orbit, solar occultation). Lunar occultation increases density of observations about 50 percent; polar orbiter adds high latitude observations.

Tests of Climsat Sampling

To test the Climsat observing strategy, real global observations and GCM calculations of several quantities are sampled using actual time records of the satellite ground tracks illustrated above. Samples are collected into global maps and averaged over time and space. Sampling errors are estimated from the differences between the monthly, regional mean values obtained from the sampled and original (taken to be "truth") datasets. The sampling test using real observations directly determines the accuracy of Climsat measurements of monthly, regional averages in the presence of realistic variations in time and space (cf., Section II). The sampling test using a GCM simulation of transient climate change allows a direct test of climate change detection, where the key problem is measuring the change in the presence of large natural variability (e.g., Oort, 1978 and Hansen and Lebedeff, 1987, used GCM simulations to test sampling, cf., Section 1).

Ground tracks are from NOAA-9 (polar orbiter) and ERBS (inclined orbiter), giving positions every five seconds (about 30 km) over one month. The global observations are high resolution (30 km) measurements of cloud and surface properties every three hours for two Januarys and two Julys, obtained by the International Satellite Cloud Climatology Project (ISCCP) from weather satellite data (Rossow and Schiffer, 1991). Another dataset contains daily satellite measurements of humidity profiles at about 250 km spacing over the globe.

The climate change simulation is performed with the GISS GCM (Hansen *et al.*, 1983), which has $8^\circ \times 10^\circ$ horizontal resolution and nine levels in the troposphere. The experiment simulates the transient climate changes produced by a linear increase of greenhouse gases (Scenario B, Hansen *et al.*, 1988); the climate change between 1958 and 2005 is used to test the Climsat sampling, since the global mean temperature change of 0.8°C is similar to the projected change from 1995 to 2015. Samples are collected from three hourly distributions of surface air temperature and vertical profiles of atmospheric temperature and specific humidity in the summers of 1958 and 2005. Sub-grid variations are represented by a bi-linear interpolation among the nearest model grid values to each sample point. In addition, random noise is added to each sample to represent both smaller scale variations and measurement errors: a Gaussian distribution is used, truncated at four standard deviations from the peak, with one standard deviation equal to 2°C for temperatures and equal to 30% of the local mean value for specific humidities at individual locations and altitudes.

Nadir observations are sampled at a spacing of about 30 km along the ground tracks. To simulate the same statistical weight obtained from multiple fields-of-view (FOV), an additional 6-9 samples around the nadir point are collected from the ISCCP dataset, but not from the GCM. Cross-track scanning is also tested on the GCM data by collecting about 200 points equally spaced on a line perpendicular to the satellite track at each nadir point. Since both the ISCCP and GCM datasets are composed of global maps at three-hour intervals, about 2200 nadir point samples are collected from each map.

In the tests using the ISCCP data, samples are taken directly from the population of individual satellite image pixels in the ISCCP dataset, so there is no "measurement error". Essentially, the sampling procedure isolates a subset of the ISCCP pixels (themselves, a sample of the original satellite measurements in FOVs about 5 km is size) that are concentrated at the locations and times defined by the orbit ground track time record. Monthly mean values obtained from the subset are compared to averages over the whole ISCCP population.

Sampling tests were conducted for surface temperature and reflectance, column abundances of ozone and water vapor, vertical profiles of temperature and specific humidity in the troposphere and stratosphere, and cloud properties. For brevity, only the results for cloud amount, surface air temperature and tropospheric humidity are shown. Cloud amount is highlighted because its very large natural variability in both space and time makes it one of the most difficult quantities to monitor accurately. Surface temperature is tested because it has been the primary variable monitored for change and has the best understood sources of error. Water vapor is included both because it is highly variable (though not as variable as cloud cover) and difficult to measure, especially in the upper troposphere, so a large rms measurement error of 30% is included for each sample. The results show that the Climsat sampling is more than adequate to monitor likely changes in these quantities.

Sampling Clouds. Cloud amount is determined by counting the fraction of satellite FOVs (pixels) in a map grid cell that are inferred to contain clouds. In other words, the cloud amount for a single pixel is either 0 or 100%. For ISCCP the original FOVs of about 5 km size have been sampled to a spacing of 30 km; however, this sampling preserves the statistics of the original radiance variations (Sèze and Rossow, 1991a,b). Cloud amount is determined for a map grid with a resolution of about 280 km and has been shown to be accurate to within 5-10%, even for the most difficult cases (Wielicki and Parker, 1992; Rossow and Garder, 1993).

The frequency distribution of cloud amount, as determined from the ISCCP three-hourly data, is bimodal (Rossow and Schiffer, 1991). The bimodal shape (Fig. 12.5, left panel) is nearly constant for data resolutions of 30-280 km, where only about 15-25% of the cases represent cloud cover variations at scales < 280 km (Rossow and Garder, 1993).

The bimodal distribution of cloud amounts means that the natural variability of cloud cover is very large and that sampling error can be very large, since the distribution can be thought of as a probability distribution for a single sample (Warren *et al.*, 1986, 1988). The standard deviation of the distribution in Fig. 12.5 is about 30-35% (Warren *et al.*, 1986, 1988 give values of about 40%), so that more than 1000 samples are required to reduce the sampling uncertainty below 1% (cf. Warren *et al.*, 1986, 1988). Thus, a test of the Climsat sampling on cloud amount is a very strict test.

The accuracy of the monthly mean cloud amount determined from a nadir-viewing, non-scanning instrument in the Climsat orbits is shown on the right side of Fig. 12.5 as the frequency distribution of the sampling errors in individual map grid cells. Reducing the map grid resolution from 2.5° to 10° narrows the range of errors (e.g., the standard deviation of the errors for January 1987 decreases from 7.8% to 3.3%) as does increasing the averaging time period from one month to one season (standard deviations for three month averages decrease to 4.7% for 2.5° map grid and to 2.1% for a 10° map grid). The sampling error for global, seasonal mean cloud amounts from the Climsat orbits is less than 0.5%.

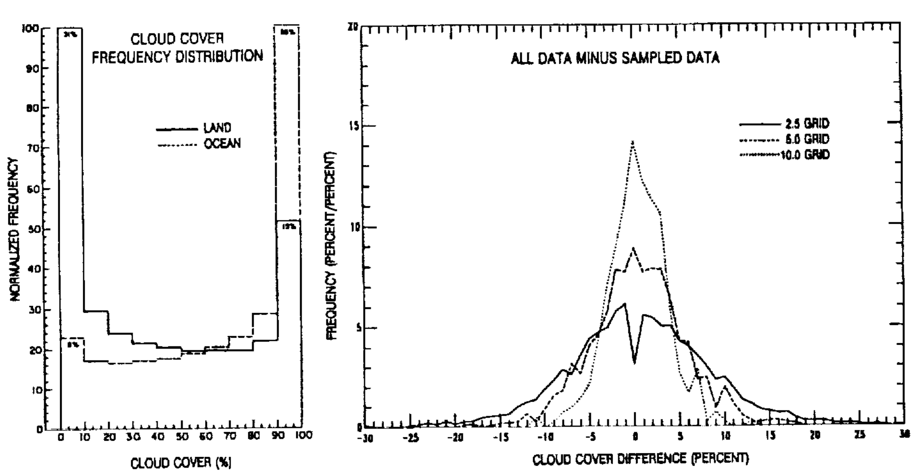


Fig. 12.5. Cloud cover frequency distribution for land and ocean and distribution of differences in monthly regional mean values produced by non-scanning sampling from Climsat orbits.

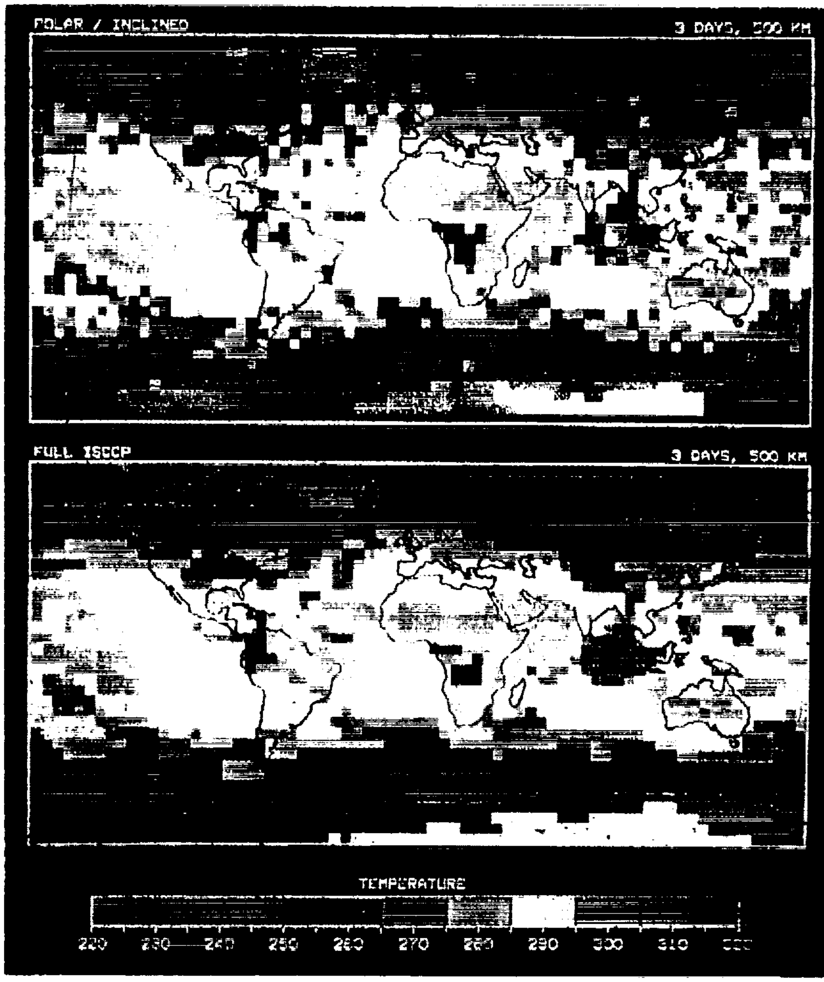


Fig. 12.6. Cloud top temperatures obtained by non-scanning samples from Climsat orbits over three days and by the 30 km sampling from the combination of geostationary and polar orbiting satellites used by ISCCP.

The magnitude of errors associated with diurnally biased sampling is assessed by comparing the cloud amount from the full ISCCP dataset to that determined only from the polar orbiter measurements (cf., Salby, 1988b). Bell *et al.* (1990) have considered the sampling bias from an inclined orbit similar to proposed for Climsat (cf., Section II). Geographic and seasonal variations of both the amplitude and phase of diurnal changes of cloud amount produce a wide range of bias errors, from about -20% to +10%. Cloud variations in midlatitudes are predominately caused by synoptic scale motions, particularly in winter, so that the diurnal-bias error is generally < 5%; however, the predominance of convective scale cloudiness at low latitudes leads to a systematic bias of about 5 - 10% in tropical cloud amounts. Since climate changes may appear both as changes in total cloud amount or in the amplitude or phase of diurnal cloud variations, adequate diurnal sampling is critical for interpreting observed changes.

Cloud top temperatures are, generally, much less variable at smaller scales than cloud cover. Figure 12.6 compares the geographic distribution of cloud top temperatures, accumulated over a three day sampling period and averaged over 500 km, with the corresponding results from the full resolution (3-hour, 30 km) ISCCP dataset. Such a comparison is a more extreme sampling test because the accumulation period period (3 days) is much shorter and the spatial resolution (500 km) higher than required by Climsat objectives. The good agreement between the two datasets is readily apparent. The rms regional (10° resolution) error of seasonal means is < 1.5°C, which is about an order of magnitude smaller than the average geographic variations. The sampling error of the global, seasonal mean is < 0.3°C.

Sampling Surface Temperature and Atmospheric Humidities. A direct test of climate change detection is provided by using the orbital ground tracks to sample the GISS GCM simulations of changes in the summer climate between 1958 and 2005 forced by a linear increase of CO_2 (Hansen *et al.*, 1988). The model global mean temperature increases by 0.8°C, the vertically integrated specific humidity increases by 7% and the upper tropospheric specific humidity increases by 17% over this time interval (Table 12.1). Three-hourly output is sampled using the same orbit ground tracks, the monthly or seasonal mean values are computed, and the difference between 2005 and 1958 are formed. These sampled climate changes are compared to those obtained using the full model outputs.

An estimate of the magnitude of variations at scales smaller than the GCM grid is provided by observed correlation distances and the scatter of surface temperatures and lower troposphere humidities (Fig. 12.7). The rawinsonde data are from the lower 48 contiguous US states and include all monthly means from January 1978 through December 1982 (D. Gaffen, Ph.D. thesis - see Gaffen, 1992; Gaffen *et al.*, 1991, 1992). Correlations of monthly anomalies of 850 mb temperature and dewpoint (a good predictor of surface to 500 mb precipitable water - cf., Gaffen *et al.*, 1991; Liu *et al.*, 1991) as a function of the separation distance indicate that significant variations of these quantities (dashed lines indicate the 95% significance levels) occur at scales $\geq$ 300 km. Thus, the dominant variations of these variables are associated with synoptic scale motions which are almost resolved by the GCM grid. Smaller scale variation has been represented by bi-linear interpolations to each sample point between the GCM values at the grid box centers with added random noise. This approach overestimates the amplitude of smaller scale variations but also underestimates the correlations.

Figure 12.8 shows the effects of sampling on estimation of changes in June mean surface air temperature. Figure 12.8a shows the model predicted changes between 1958 and 2005 and Fig. 12.8b shows differences measured with Climsat sampling. Figure 12.8c shows the differences between Figs. 12.8a and 12.8b (sampling error), while Fig. 12.8d shows the sampling errors with cross-track scanning. Table 12.1 shows that the sampling errors for a non-scanning instrument are about 0.4°C rms, which produces an error in the global mean temperature of only 0.02°C. Both of these are several times smaller than the predicted changes. Figure 12.9 shows the geographic distribution of predicted June humidity changes and sampling errors for the upper troposphere. These results (Table 12.1) show that the Climsat sampling errors for non-scanning instruments are about 12% rms and only -1% for the global mean, significantly smaller than the predicted changes.

Figure 12.10a shows the GCM-predicted changes in summer zonal mean specific humidities as a function of latitude and pressure and Fig. 12.10b shows the changes estimated with Climsat sampling. Figures 12.10c and 12.10d show the absolute sampling errors and the relative sampling

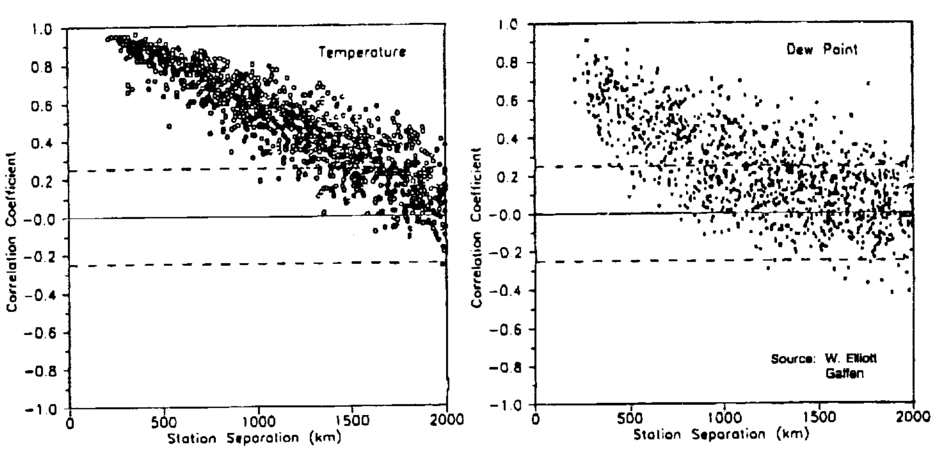


Fig. 12.7. Scatter diagrams of time record correlation coefficients for temperature and moisture against weather station separation distances.

TABLE 12.1. **Changes between summer 1958 and 2005 in globally averaged surface air temperature, vertically integrated and upper tropospheric specific humidities as predicted by the GISS GCM compared with sampling errors using a nadir-viewing instrument in Climsat orbits with and without cross-track scanning.**

	Global Mean Values		Root Mean Square	
Climate Change		(%)		(%)
Surface Air Temperature (°C)	0.80	—	2.06	—
Vertically Integrated Specific Humidity (g/kg)	0.15	7.19	0.25	9.47
Upper Troposphere Specific Humidity (g/kg)	—	17.23	—	47.18
Sampling Error (No Scanning)				
Surface Air Temperature (°C)	0.02	—	0.43	—
Vertically Integrated Specific Humidity (g/kg)	0.003	0.001	0.03	1.33
Upper Troposphere Specific Humidity (g/kg)	—	-0.96	—	11.74
Sampling Error (With Scanning)				
Surface Air Temperature (°C)	0.02	—	0.36	—
Upper Troposphere Specific Humidity (g/kg)	—	-0.05	—	11.33

errors expressed as a percentage of the "true" climate change in Fig. 12.10a. The model predicted changes are largest in the upper troposphere and lower stratosphere and are about an order of magnitude larger than the sampling errors (cf., Table 12.1).

The counter-intuitive result that sampling with scanning instruments does not produce significantly smaller errors than with non-scanning instruments (Figs. 12.8 and 12.9, Table 12.1) focuses attention on the difficulty of detecting climate changes. The main problem is that the natural variability of climate parameters, even on interannual time scales, may be larger than the climate changes predicted to occur over a few decades (Hansen *et al.*, 1988; Manabe *et al.*, 1990; Lorenz, 1990; Karl *et al.*, 1991). Some of the interannual variability in datasets is, in fact, residual error caused by sampling of synoptic variations of the atmosphere and surface. Thus, the limit on measuring climate changes accurately is determined by the magnitude of these natural variations, which can be considered the intrinsic "noise". That this is the case with the sampling errors shown in Figs. 12.8 and 12.9 and Table 12.1 is revealed by three facts.

First, the spatial patterns of the climate changes, shown in Figs. 12.8a and 12.9a, are similar in character to the pattern of differences between any two Junes in the GCM control run (no climate change forcing). In a typical case, the rms regional differences in surface air temperature are about 3.2°C and in upper tropospheric humidity are about 37%, very similar to the rms regional differences in the climate change experiment (Table 12.1). The global mean differences are, however, much smaller in the control run comparison (e.g., 0.2°C for surface air temperature and 1-2% for upper

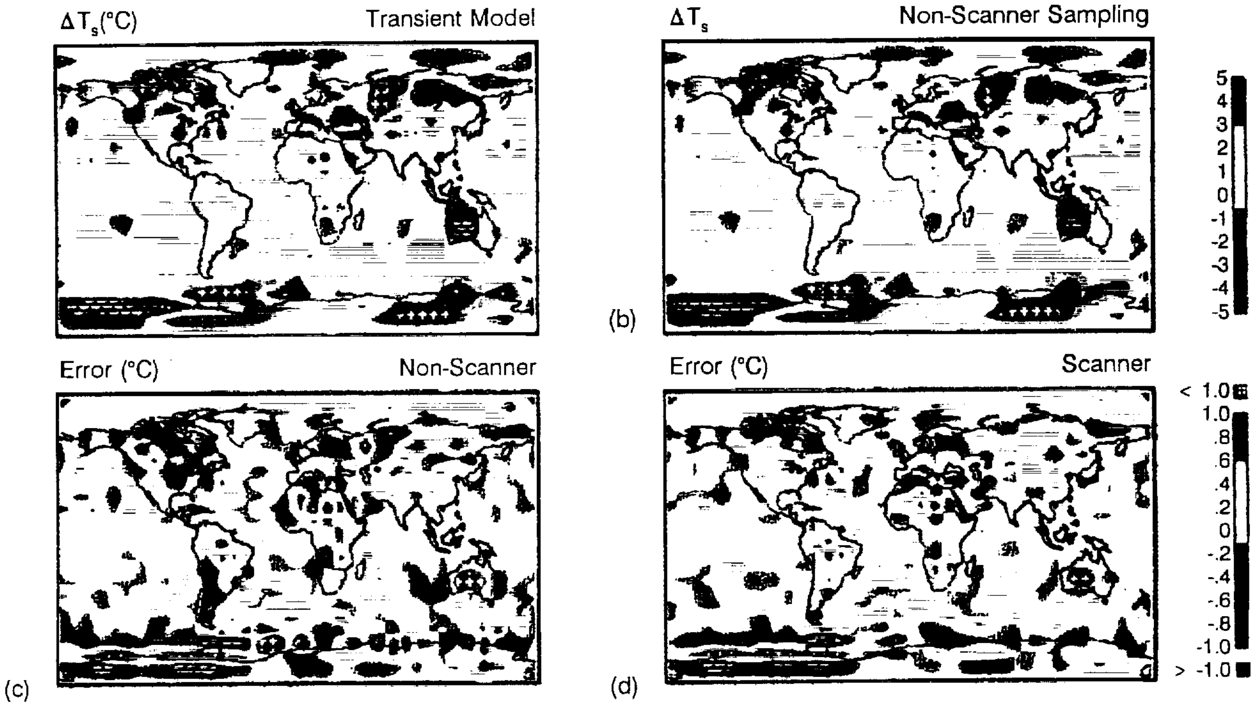


Fig. 12.8. Model-predicted changes (a) in monthly mean surface air temperature [(June 2005) — (June 1958)] and measured changes (b) with Climsat non-scanning sampling. Errors are shown as differences of (a) and (b) in (c). Differences produced by scanning sampling are shown in (d).

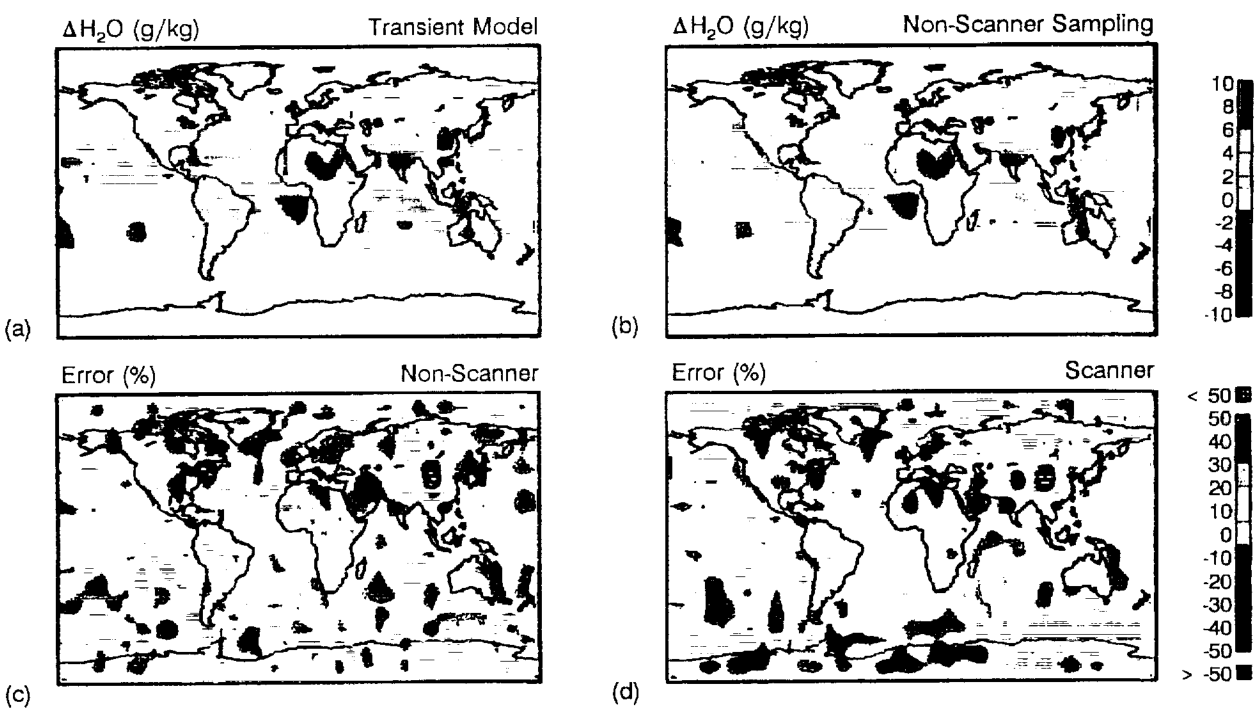


Fig. 12.9. Model-predicted changes (a) in specific humidity (g/kg) in the upper troposphere and measured changes (b) with Climsat non-scanning sampling. Errors are shown (in percent) for non-scanning sampling (c) and scanning sampling (d).

tropospheric humidity) than in the climate change comparison. Thus, the regional variability shown in Figs. 12.8a and 12.9a is predominately the consequence of different realizations of synoptic variations in any two months, rather than climate change. Moreover, changes in this regional variability between two months appear as differences in the global, monthly mean values of any parameter; in other words, this regional "noise" does not completely cancel in the global mean. Consequently, the global mean surface air temperature and upper tropospheric humidity changes are uncertain by at least 0.2°C and 1-2%, respectively, just because of natural variability.

Second, the sampling errors, shown in Figs. 12.8b and 12.9b, are proportional to the changes in Figs. 12.8a and 12.9a. This results from the fact that a one month time record of synoptic variability at one location actually represents only about 10-15 independent samples because the synoptic changes are correlated on time scales of a few days. Thus, for example, a single large storm event in a particular month will both increase the difference between monthly mean values and be more likely to increase the error in a sampled dataset because the storm is a "singular" event with low probability. This effect also explains why the natural variability in surface air temperature is a larger fraction of the climate change (about 25% of the global mean) than for upper tropospheric humidity (about 5% of the global mean), since the larger surface temperature variations occur at midlatitudes with longer correlation times (fewer samples) than the humidity variations which occur in the tropics with shorter correlation times (more samples).

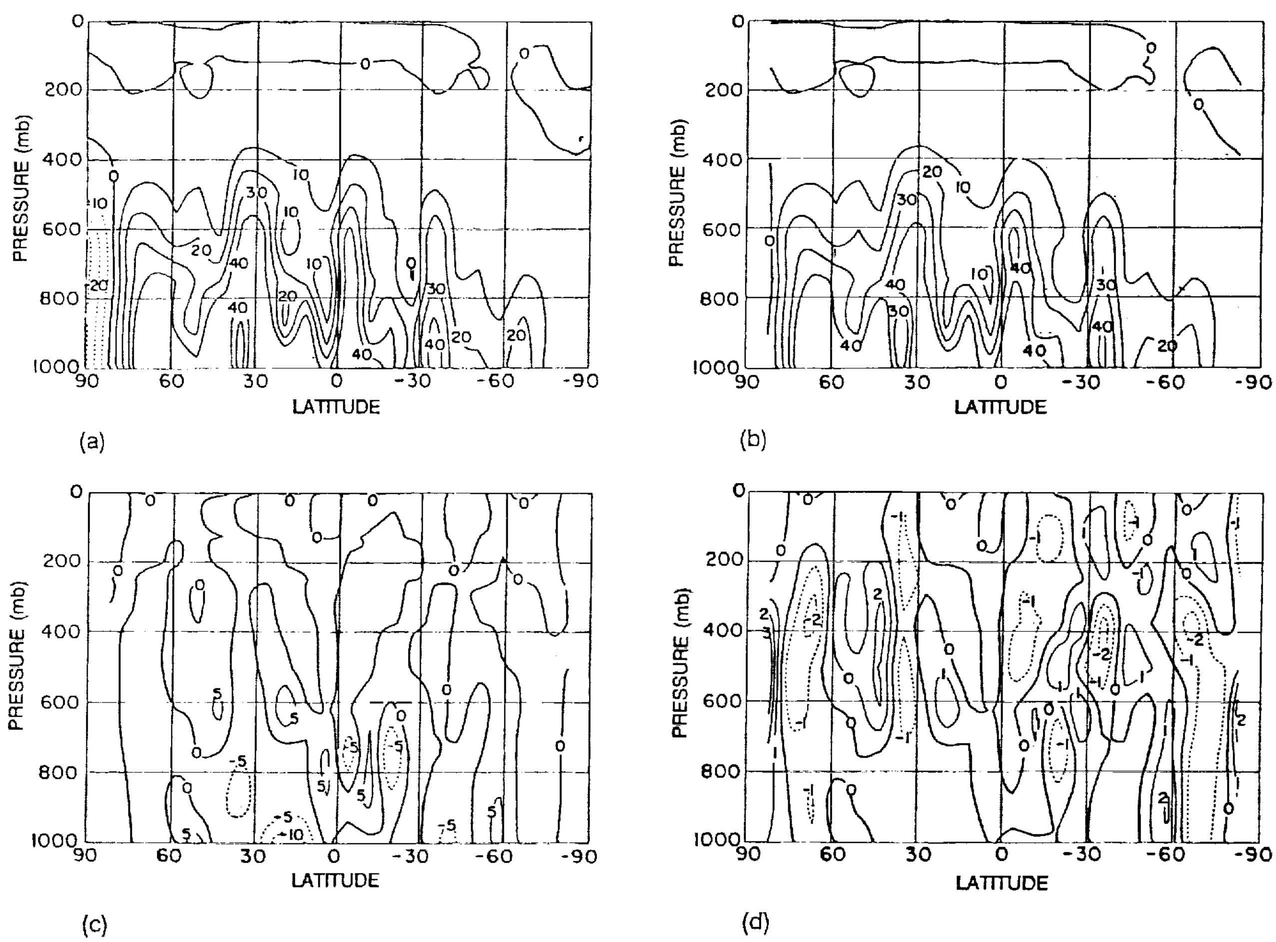


Fig. 12.10. Model-predicted zonal mean changes in specific humidity (a) the changes measured with Climsat non-scanning sampling (b). Absolute (c) and relative (d) differences are displayed in percent.

TABLE 12.2. **Summary of all sampling tests. Regional averages are from a 10° map grid.**

	Global Monthly Average	Global Seasonal Average	Regional Monthly Average (rms)
Surface temperature (°C)	< 0.2	< 0.1	< 0.5
Specific humidity errors (%)			
(vertical integrated)	< 0.1	< 0.1	< 2.0
(upper troposphere)	< 2.0	< 1.0	< 12.0
Ozone column abundance (%)	< 0.03	< 0.02	< 2.0
Cloud top temperature (°C)	< 0.5	< 0.3	< 1.5
Cloud amount (%)	< 0.7	< 0.4	< 3.0

Third, the space-time distribution of the sampling from scanning instruments is different from that of non-scanning instruments, particularly at higher latitudes. The different distributions of the two sampling patterns interact with synoptic variations to produce about the same rms sampling errors but also cause differences in the measured global, monthly mean values of surface air temperature and upper tropospheric humidity that are as large as the differences between two months in the control run. In other words, these two sampling patterns can be considered as two different realizations of the natural variability, producing similar uncertainties in measured quantities. Thus, the much larger number of measurements made with the scanning instrument does not significantly reduce the sampling error which is already dominated by natural variability for the smaller non-scanning dataset.

These sampling studies confirm that the largest source of uncertainty in measuring climate change is limited sampling of natural (synoptic) variability, as long as the observing system provides complete and uniform global coverage and unbiased time sampling. (Even though the GCM tests assumed very large random measurement errors, the sample population for one month of data, even for non-scanning instruments, is so large as to nearly eliminate this source of uncertainty.) Since synoptic variations are correlated on time scales of a few days, the number of independent samples of these variations that can be obtained in one month (during which the forcing can be considered constant) is so small that the uncertainty in mean values remains much larger than predicted climate changes. Likewise, uncertainties in global mean values are not reduced by increasing the spatial resolution of observations because the synoptic variations are also correlated on large spatial scales (cf., Fig. 12.7), which places an intrinsic limit on the number of independent samples that can be obtained. These correlations explain why the non-scanning sampling from the Climsat orbits is as good as the scanning sampling. Moreover, even if an observing system provides uniform space-time sampling, ordinary problems in operating instruments and computer systems cause data losses that produce gaps in spatial and temporal coverage that exaggerate the contribution of the intrinsic noise. Thus, the only way to reduce this source of sampling error enough to measure the predicted decadal climate changes is to make comparisons between observations averaged over at least 3-5 years in each of two decades.

Table 12.2 summarizes the results of the sampling studies using both data and GCM simulations by reporting the largest differences as upper limits on sampling errors. Comparison of these sampling errors with the accuracy requirements in Section 3 shows that Climsat will generally be able to monitor plausible decadal changes of the forcings and feedbacks which it addresses (see also Section 7 and Table 7.4).

13. Panel Discussion

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Dr. Manabe discussed a comprehensive strategy for the validation of a climate model. It includes the monitoring of the factors that force climate, the prediction of climate change by a state-of-the-art model and the validation of the model based upon the comparable assessment of predicted and observed climate changes (Fig. 13.1). He emphasized that the long-term monitoring of climate is an indispensable part of this strategy. In order to distinguish the anthropogenic change from the natural variation of climate, he also stressed the importance of studying the latter by use of a coupled ocean-atmosphere model.

With regard to the monitoring of the energy cycle, he suggested focussing our attention on the monitoring of those variables which we can measure with sufficient accuracy. Dr. Manabe noted specifically that, in the GFDL climate model calculation for doubled CO_2, the CO_2-induced changes of globally averaged, net radiative fluxes at the top of the atmosphere and horizontal transport of heat in the atmosphere and oceans are very small and probably beyond current measurement capabilities. Instead, it may be easier to monitor the long-term change in the thermal structure of the atmosphere and oceans. He suggested that radiation budget measurements are more appropriate as part of process studies, as opposed to continuous monitoring of the detection of long-term change. He noted, however, that it is essential for the validation of a climate model to monitor the long-term changes of key variables such as solar irradiances, cloud, snow cover, sea ice, aerosols and their radiative effect. *[Monitoring the radiation budget is still considered crucial, but since plans are well in hand for spacecraft missions for this purpose, we do not consider this as "missing" - Ed.]*

In conclusion, Dr. Manabe believes that Climsat is a prudent proposal that fills critical gaps in climate monitoring.

Dr. Wigley concurred with Dr. Manabe and emphasized that interpretation of the present climate record requires knowing also about the lag in realized climate warming due to the oceans. Thus complementary programs for frequent and regular monitoring of the 3-D structure of the ocean, such as proposed as part of the Global Climate Observing System (GCOS), can contribute. *[Earlier discussions mentioned also the potential contributions of acoustic tomography, such as proposed by Munk and Forbes (1989), for analysis of the ocean thermal lag problem. Climsat would also represent an important contribution to GCOS plans by providing better calibrated, though less detailed measurements to which the operational weather measurements could be anchored - Ed.]*

Dr. McElroy reviewed scientific questions about tropospheric ozone. He pointed out that in the past decade many of the surprising changes in ozone profiles in the lower stratosphere have been revealed by SAGE measurements. There are two issues concerning ozone profiles: (1) continued monitoring of the 3-D distribution of ozone changes and (2) understanding the mechanisms for the change. He agreed that proposed SAGE measurements on Climsat would be adequate for monitoring ozone changes in the lower stratosphere and upper troposphere. It would be better still if the monitoring could be extended down to 6-8 km in the troposphere. The monitoring must be done with an overview of stratospheric chemistry. Measurements of ozone concentrations need to be good to 3 ppm; CH_4 changes need to be measured as well. A strategy to understand the processes governing the ozone changes needs to be developed; it will most likely involve aircraft measurements in conjunction with the satellite measurements. *[Improvements of SAGE III over its predecessors will increase its depth of penetration into the troposphere (Section 8), but sampling questions remain and require study - Ed.]*

Dr. Charlson endorsed Climsat for monitoring aerosols to quantify their direct effects on the radiative balance of the planet. The science for the indirect effects of aerosols on clouds is relatively

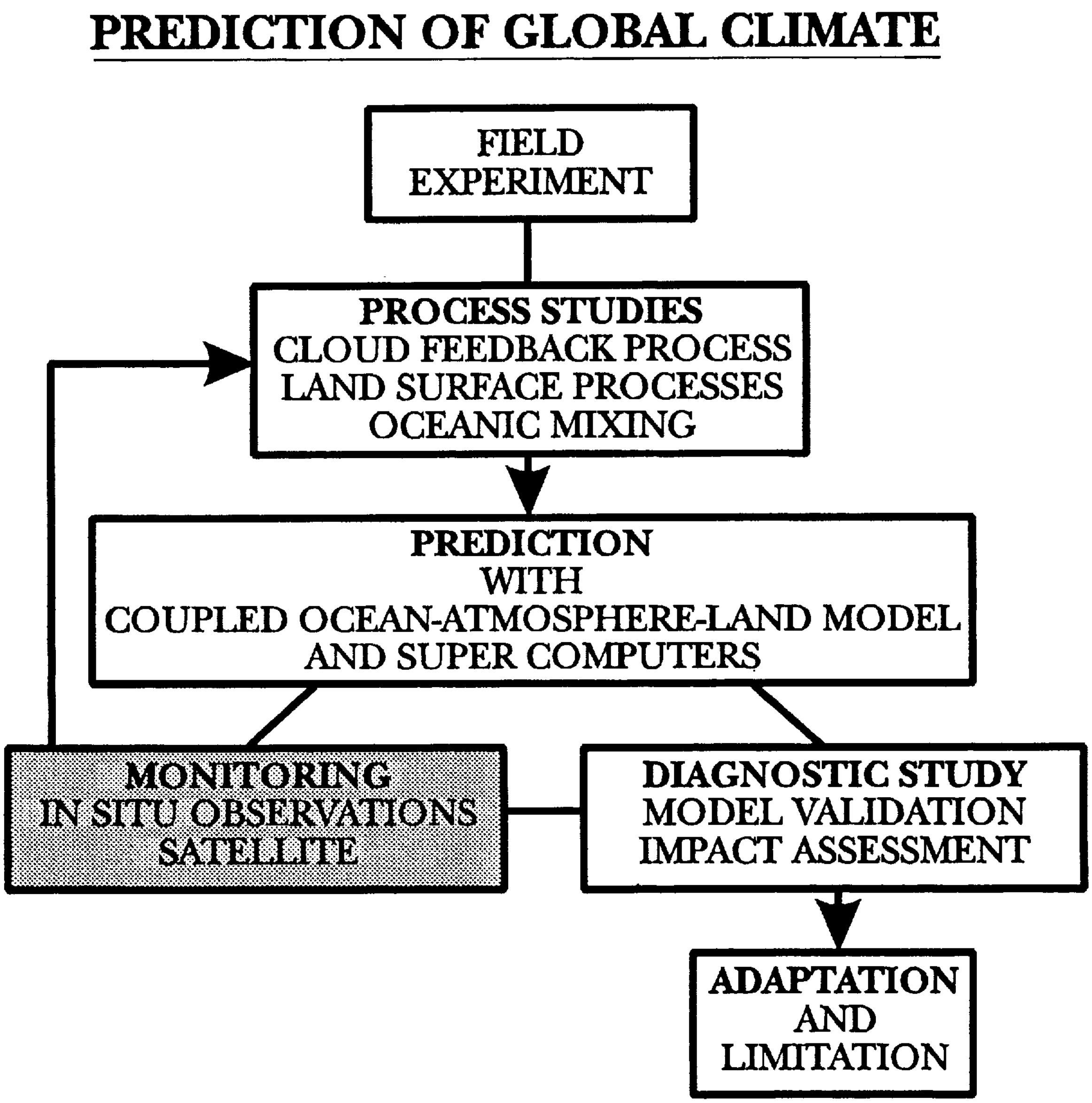

Fig. 13.1 Overall strategy for understanding and predicting climate change, as presented by S. Manabe.

young and it is premature to specify monitoring requirements to address that problem. Dr. Charlson also pointed out that there is a beautiful match between Climsat and ground-based programs, such as those of CMDL and AEROCE, in terms of geographic coverage and the sensitivity in optical thickness measured. However, the ground-based programs are not adequately funded at present. If adequately funded, they could provide the crucial ground-based supplement to Climsat. Echoing Dr. Manabe, he emphasized that understanding the role of aerosols in the changing climate comes only from the integration of ground-based and satellite datasets, process studies, documentation of aerosol composition and source fields in atmospheric chemistry models and climate models.

Dr. Hofmann reviewed the discussion on stratospheric aerosols and stressed the need for continued long-term monitoring of background aerosols in the lower stratosphere/upper troposphere. The monitoring is necessary because changes in background (without volcanic eruption) stratospheric aerosol can result directly from jet aircraft emissions or indirectly via changing stratospheric temperature and circulation. He also pointed out that increases in the mass of aerosols in the lower stratosphere have resulted from an increase in the number of large particles, even though the total number density has remained constant, so measurements of aerosol size are also needed. The relationship between changes in lower stratosphere ozone and large particle density is unclear and needs to be investigated.

Dr. Betts summarized the discussion on water vapor. He argued that the lack of a sufficiently accurate validation dataset of water vapor has been an important limitation on the improvement of climate models. Specifically, ground-based measurements of specific humidity remain poor above 6 km or below -40°C; the quality of humidity measurements from operational satellite instruments such as AMSU and HIRS in this region has not yet been established. Furthermore, products of data assimilation, such as the analyzed fields from ECMWF, are model dependent, and cannot be used as true tests of the performance of any climate model. It was only two years ago that variability in relative humidity at 300 mb in the tropics in the ECMWF GCM was validated by SAGE data, even though the SAGE data are biased towards clear sky.

Dr. Betts suggested that retrievals of humidity profiles need to resolve, at minimum, from the planetary boundary layer to the freezing level, from the freezing level to ~300 mb, and above 300 mb. In other words, vertical resolution of a couple of kilometers is acceptable. *[Such resolution is readily achievable by the MINT instrument on Climsat, especially with cross-comparison to SAGE in the upper troposphere - Ed.]*

Dr. Betts concluded that Climsat can make an important contribution to a <u>coupled</u> dataset on thermodynamics and cloud structure. Because time scales are different at different heights in the atmosphere, this dataset will be crucial for understanding coupling on longer time scales in the tropics.

Dr. Wielicki presented his views on clouds. Monitoring requires instruments that are accurate enough to measure very small changes. He is doubtful that present instruments are capable of the level of accuracy needed for detecting changes in cloud properties. Process studies, on the other hand, will contribute to improving physics in models, which can then be used to extrapolate future changes. Dr. Wielicki believes that EOS has taken a visionary step towards obtaining measurements for understanding cloud processes. Nevertheless, lidar and radar measurements are not included and should be added in the future.

In the discussion opened to all workshop participants, there was a general consensus that decadal monitoring is crucial for understanding climate change and that the monitoring needs to be low cost so that it can be continued for decades. No expensive program will be maintained on decadal time scales. The monitoring should include both ground-based and satellite measurements. Calibration is a central issue. The urgent plea for a reference sonde network highlighted the limitations of uncalibrated data for climate change studies. The discussions further emphasized Dr. Manabe's summary chart (Fig. 13.1) that the monitoring has to be carried out in the broader context of a program that also includes process studies and integrative modeling.

The discussions also generated many comments about EOS and about the relationship of Climsat to EOS.

Dr. Manabe asked whether the scientific objectives of EOS and other satellite programs have undergone the same careful scrutiny as Climsat has. He cautioned that if programs aim for more than what is absolutely needed, then inevitably scientific research will suffer during a budget crunch. He wanted to know: what are the scientific questions EOS is asking? what are the instruments needed to provide answers to the questions? and are those instruments included in EOS?

Dr. Wielicki replied that the evolution of EOS was different from that of Climsat. The Earth system is so intimately linked that it is not effective for each scientific discipline to separately address its measurement needs. The EOS strategy is to "combine and conquer" rather than to "divide and conquer." MODIS was mentioned as an example of an EOS instrument that serves the needs of several scientific disciplines.

Dr. Wielicki reiterated that EOS has recently undergone an engineering review. He also noted that the Payload and other EOS panels, comprising representatives from the science community, have spent innumerable days setting priorities for EOS.

Dr. Charlson emphasized that such reviews do not imply endorsement by the entire community, and he specifically pointed out that aerosol measurements had not been considered a priority by EOS until the recent Arizona meeting *[the EOS Tropospheric Anthropogenic Aerosol Workshop, December 16-17, 1991, chaired by R. Dickinson - Ed.].* Dr. Hofmann commented that while ground-based measurements are acknowledged to be an integral part of EOS, and while members of that community were asked to assist in the justification of the program, there is as yet no follow-through (funding) to integrate ground-based measurements into EOS.

Dr. Manabe's sentiments were echoed several times throughout the discussion. It was suggested that the EOS program is too large for any scientist to fully grasp in its entirety, and that packaging global change observations on such a large scale effectively prohibits careful scrutiny, and thus there may indeed be gaps as well as unnecessary redundancy. Dr. McElroy suggested that there is room for programs intermediate between the regional detailed focus of ARM and the global all-encompassing ambitions of EOS.

It was pointed out that Climsat and EOS are synergistic as well as in competition. It is important to make clear how much duplication there is of Climsat on EOS. Climsat is clearly designed to be a monitoring mission. It was mentioned that the concept of monitoring may be somewhat different in the EOS program. A representative from NASA Headquarters (Dr. Ming-Ying Wei) said that while EOS has never been explicitly labelled as a monitoring program, it attempts to collect long-term datasets as best it can, but acknowledged that there may be data gaps.

Dr. Hansen explained that EOS can provide climate process data but does not fulfill the requirements of climate monitoring, showing a table listing reasons which are contained here in Table 7.5. First, EOS does not include an inclined precessing orbit, so that EOS is not able to monitor change of diurnal cycles. Second, EOS puts "many eggs in a large basket" which cannot be replaced easily, so that the failure of a single instrument or spacecraft will lead to a data gap. Third, monitoring for long-term change requires data continuity and instrument longevity for decades, which is a realistic possibility with Climsat. Fourth, Climsat is comprised of two satellites; the overlap allows cross-calibration of instruments on replacement satellites. EOS, by contrast, has back-to-back missions with no "hot spares" (satellites to launch immediately after a failure). Fifth, small instruments on small satellites are inherently cheaper and easier to replace. Furthermore, EOS does not include all the instruments in the Climsat proposal, in particular, the infrared interferometer, whose single detector gives the needed high wavelength-to-wavelength precision in the thermal region, and which has a proven long life. The conclusion is that Climsat is needed as a complement to EOS.

Dr. Wielicki argued that EOS duplicates much of the capabilities of Climsat, since both SAGE and EOSP are EOS selected instruments, and both AIRS on EOS and MINT proposed for Climsat are spectrometers that cover the thermal region. *[Table 7.5 in Section 7 of this report explains why this apparent duplication of instrumentation does not mean duplication of climate monitoring capability. Neither SAGE nor EOSP is scheduled to fly until the 21st century, and then only on a single spacecraft and orbit. Additionally, the AIRS (infrared spectrometer) has been descoped and now measures only separate portions of the spectrum. If the Climsat mission proceeds, SAGE and EOSP could be excluded from the EOS platforms, thus eliminating the potential duplication and reducing EOS costs - Ed.]* Dr. Rossow noted that instrument design should respond to the scientific questions posed. For example, even though several instruments claim to "do aerosols", most of them do not have the needed sensitivity to detect a change in optical thickness of even 0.1, not to mention the required 0.01.

The costs of EOS and Climsat were also discussed. Dr. Mahlman compared the EOS budget of $750M/yr to that of the US Global Change Research Program (USGCRP) at $1.1B/yr. If we were starting over, the scientific community would "certainly not necessarily" spend the budget in the same way. It was pointed out that the USGCRP must address a large number of questions besides those addressed by EOS. Dr. Mahlman further observed that the wisdom of Climsat is that it is designed specifically for monitoring and that its objectives and budget are consistent with the commitments of the USGCRP, whereas none of the EOS moneys is designated specifically for monitoring in support of the USGCRP.

Dr. Manabe cautioned that with a budget crunch, hardware is delayed while scientific research invariably is decimated. Dr. McElroy reminded the audience that budget crunches reduced the amount of effective science carried out in both the Apollo and Viking programs even though both programs had long-term interests in science.

Further conversation focused on the costs of Climsat. Dr. Hansen stated that Climsat instruments have well-proven predecessors and are not technological challenges, though they incorporate the latest technology where appropriate. With known weight and characteristics (e.g. the number of channels) of the instruments, cost estimates for each instrument should be fairly accurate. It was commented that the number of carbon copies of each instrument needs to be specified at the outset, so that exorbitant restart costs can be avoided, should the manufacturing plant be shut down, as in the case of SSM/I. How many copies are sufficient for two satellites to maintain data continuity should an instrument fail? Dr. Hansen said three for the initial 5-10 year period, but the number is dependent on actual lifetimes. *[Such a scenario presumes a common design target of 5-year instrument/spacecraft lifetime and one hot spare. Previous flight experience suggests that this is a reasonable estimate - Ed.]*

Dr. Hansen proposed that Climsat data would be archived with EOSDIS, which has a protected budget. However, budgets for the essential complementary measurements and for scientific investigations using the data would depend on the scientific scope of and the number of scientists in the Climsat program. Dr. Wielicki said that ERBE's science budget is $5M/yr, which includes costs for data processing and quality checking. If ERBE is used as the model, then, with three instruments, the Climsat science budget would amount to $150M for a decade, comparable to the order of magnitude of the hardware costs. This, it was remarked, would be unprecedentedly heavy weighting towards science. Dr. Hansen cautioned against an expansion of Climsat objectives, quoting Dr. V.

Suomi, who warned that "the worst enemy of a good experiment is a better experiment." The science and supplemental measurements of Climsat should be as tightly focused as possible.

There were comments that it is important to recognize that no satellite program is stand-alone. For example, the Dobson network is crucial to the calibration of TOMS data. Dr. Hofmann stressed that Climsat needs to lock in as much supplemental measurements in advance as possible. Several in-situ monitoring programs, such as those of CMDL and NDSC, all offer opportunities for comparison with and validation of Climsat data. Small programs, such as the balloon soundings of stratospheric water vapor using cross-wind hygrometers, should not be ignored. Sonde data, if calibrated, are crucial for all investigations of the hydrologic cycle, not just for validating water vapor retrievals by Climsat. Dr. Hansen suggested that perhaps some measurements could be funded as part of the Climsat program, while others could be leveraged into ongoing programs, as TRMM has led to increased funding for the Coupled Ocean-Atmosphere Research Experiment (COARE) of the Tropical Ocean/Global Atmosphere (TOGA) Program. Dr. Rind emphasized that satellite measurements should not used as an excuse to "de-select" in-situ measurements.

The discussions adjourned at 3 p.m. Dr. Hansen thanked the participants for their valuable time and candid discussion. He stated that, because of their encouragement, he and his colleagues would continue to push for the Climsat concept.

ACRONYMS

ACRIM:	Active Cavity Radiometer Irradiance Monitor
AEM:	Atmospheric Explorer Mission
AEROCE:	Air/Ocean Chemistry Experiment
AIRS:	Atmospheric Infrared Sounder (EOS instruments)
ARM:	Atmospheric Radiation Measurements (DOE program)
ATMOS:	Atmosphere and Ocean Satellite (German satellite program)
AVHRR:	Advanced Very High Resolution Radiometer (flown on NOAA satellites)
CCD:	Charge Coupled Device
CCN:	Cloud Condensation Nuclei
CFCs:	Chlorofluorocarbons
CERES:	Clouds and the Earth's Radiant Energy System (EOS instrument)
CMDL:	Climate Monitoring and Diagnostics Laboratory (NOAA)
DMS:	Dimethylsulphide
DMSP:	U.S. Defense Meteorolgical Satellite Program (operated by U.S. Air Force)
DOE:	U.S. Department of Energy
ECMWF:	European Center for Medium Range Weather Forecasts
EOS:	Earth Observing System
EOSP:	Earth Observing Scanning Polarimeter (EOS instrument)
ERBE:	Earth Radiation Budget Experiment
ERBS:	Earth Radiation Budget Satellite
GARP:	Global Atmospheric Research Program
GATE:	GARP Atlantic Tropical Experiment
GCM:	Global Climate Model or General Circulation Model
GCOS:	Global Climate Observing System
GFDL:	Geophysical Fluid Dynamics Laboratory (NOAA)
GISS:	Goddard Institute for Space Studies (NASA)
GOES:	Geostationary Operational Environmental Satellite (operated by NOAA)
HMGG:	Homogeneously Mixed Greenhouse Gases
IFOV:	Instantaneous Field of View
IPCC:	Intergovernmental Panel on Climate Change
IRIS:	Infrared Interferometer Spectrometer
ISCCP:	International Satellite Cloud Climatology Project
LIMS:	Limb Infrared Monitor of the Stratosphere
MINT:	Michelson Interferometer
MSE:	Mean Square Error
NASA:	U.S. National Aeronautics and Space Administration
NDSC:	Network for the Detection of Stratospheric Change
NOAA:	U.S. National Oceanic and Atmopheric Administration
OCPP:	Orbiter Cloud Photopolarimeter (flown on Pioneer Venus orbiter)
SAGE:	Stratospheric Aerosol and Gas Experiment (EOS instrument)
SAM:	Stratospheric Aerosol Measurement
SCARAB:	Scanner for Radiation Budget (French, Russian, German satllite series)
SMM:	Solar Maximum Mission
SOLSTICE:	Solar Stellar Irradiance Comparison Experiment
SSM/I:	Special Sensor Microwave/Imager (flown on DMSP satellites)
TES:	Thermal Emission Spectrometer
TOA:	Top of Atmosphere
TOMS:	Total Ozone Mapping Spectrometer
TOVS:	TIROS Operational Vertical Sounder
TRMM:	Tropical Rainfall Measuring Mission (Japan-U.S. satellite mission)
UARS:	Upper Atmospheric Research Satellite
USGCRP:	United States Global Change Program
VAS:	VISSR Atmospheric Sounder (flown on GOES satellites)
VISSR:	Visible and Infrared Spin-Scan Radiometer (flown on many geostationary weather satellites)
WCRP:	World Climate Research Program
WMO:	World Meteorological Organization
WOCE:	World Ocean Circulation Experiment

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13. ABSTRACT *(Maximum 200 words)*

A workshop on Long–Term Monitoring of Global Climate Forcings and Feedbacks was held February 3–4, 1992, at NASA's Goddard Institute for Space Studies to discuss the measurements required to interpret long–term global temperature changes, to critique the proposed contributions of a series of small satellites (Climsat), and to identify needed complementary monitoring. The workshop concluded that long–term (several decades) of continuous monitoring of the major climate forcings and feedbacks is essential for understanding long–term climate change. The existing meteorological and planned ocean observing systems must be maintained, but they will not provide measurements of all the major climate forcings and feedbacks with the required accuracy over the appropriate time scales. Climsat would be able to monitor most of the climate forcings and feedbacks not monitored by current and planned observation systems, but would need to be supplemented by solar monitoring from space, tropospheric aerosol and ozone profile monitoring from selected surface stations, and improved calibration of radiosonde measurements of tropospheric water vapor profiles. The workshop emphasized that Climsat is complementary to the planned global change research program, including the EOS mission, and that strong support of researchers should be an integral part of the implementation of Climsat.

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