FUTURE SATELLITE OBSERVATIONS FOR MODEL DIAGNOSIS AND INITIALIZATION

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Summary: Fundamental environmental information is being obtained globally by satellites in Earth orbit. Such global measurements of the atmosphere, land and ocean surface have already have a major impact on the development of dynamical weather prediction, global ocean circulation research, and climate process diagnostics. New remote sensing techniques and satellite projects planned in the next decade will lead to further advances in understanding the global Earth system and predicting global environmental change. The principal new developments expected in the next decade will be reviewed and assessed from the perspective of data assimilation, numerical weather forecasts, and climate change prediction.

1. INTRODUCTION

Not so long ago, any self-respecting meteorologist would consider that proper meteorological observations were made at suitably located aerological stations, or from a balloon, or even from an aircraft, but certainly not in outer space. For one thing, satellite sensors do not measure any environmental property directly, only the photons that emerge from the Earth atmosphere. It takes "rocket scientists" to infer meaningful Earth properties from such electromagnetic signatures, through convoluted procedures that may involve *a priori* assumptions and/or reliance on empirical knowledge. Thus, the prudent judgment of conventional meteorologists was not without foundation: meteorological quantities inferred from remote sensing measurements are fraught with uncertainties associated with arcane retrieval algorithms or over-simplified empirical relationships supported by inadequate validation data bases. Equally disturbing is the fact that satellites orbiting the Earth do not provide a synoptic picture of the global atmosphere; global coverage from a polar satellite is spread over a 12 hour period (or longer), while any geostationary satellite views only about one third of the surface of the Earth. Nevertheless, satellite observations are key to any future major advance in long-range weather or climate prediction, because of three unique advantages:

- A single polar-orbiting satellite provides uniform coverage of the whole globe; errors may be introduced by a particular sensor or retrieval algorithm but they are, by and large, independent of location (although sensitive to drift in equator-crossing time or sensor deterioration).
- Space-based observations can deliver any required sampling density to capture mesoscale weather systems and provide un-aliased values of area- or volume-averaged quantities (as opposed to discrete *in situ* measurements).
- Satellite remote sensing can observe a broader range of variables.

Global satellite data sets are used for initialization of numerical weather prediction (NWP) or for validation of general circulation model physics. These two applications are often considered separately, especially by climate modelers who are interested mostly in gross validation of model results against observed climatological statistics. ECMWF has led the development of advanced (variational) data assimilation techniques which can be applied indifferently for one or the other purpose, and showed the power of such methods for model improvement as well as model initialization. No difference will henceforth be drawn between these two applications.

2. BASIC ATMOSPHERIC VARIABLES

The first serious attempts to insert satellite observations into NWP systems were made around the time of the GARP Global Weather Experiment (also known as the First GARP Global Experiment) with temperature and water vapor profile data from atmospheric sounding instruments and scattered wind data deduced from the apparent drift of mesoscale cloud systems. The same two basic aerological variables are still at the top of the list of desirable global measurements.

2.1 Atmospheric Temperature and Moisture

The existing atmospheric sounder instruments on operational NOAA satellites are, for the main part, based on the heritage of GARP. The prototype instruments were first tested on NASA's Nimbus-6 spacecraft in 1975 and the resulting TIROS Operational Vertical Sounder (TOVS) system has been in operation since 1978. Significant improvements have recently been introduced to the microwave component of the system, with the introduction of the Advanced Microwave Sounding Unit (AMSU) on the latest NOAA polar-orbiting satellite. An essentially identical but more compact Advanced Technology Microwave Sounder (ATMS) is being developed by NASA for the next generation US National Polar-orbiting Operational Environmental Satellite System (NPOESS).

Another important step will soon be made with the deployment of the experimental Atmospheric Infra-Red Sounder (AIRS) on the NASA EOS-PM mission in late 2000 or early 2001. AIRS is an infrared spectrometer with a resolving power in excess of 1000, corresponding to some 2000 spectral channels instead of the existing 20-channel High-resolution Infra-Red Sounder on NOAA satellites. Like AIRS, successor operational instruments - the NPOESS Cross-track Infrared Sounder (CrIS) and European Infrared Atmospheric Sounder Interferometer (IASI) - will be spectrometers capable of analyzing the full terrestrial radiation spectrum from 3.7 to 15.4μm, rather than radiometers with a limited set of discrete channels. The principal improvement associated with high spectral resolution and elaborate detection systems (cooling to liquid nitrogen temperature in the case of AIRS) is the ability to separate individual lines in the atmosphere's absorption spectrum, and reach the ultimate vertical profile resolution (about 1km) and retrieval accuracy (RMS uncertainty on the order of 1K for tropospheric temperature) that are achievable with this measurement technique (Fig. 1).

It is regrettable that the next generation of infrared sounder instruments on future operational satellite series will use different instrument designs, aiming at performances similar to that of AIRS but more sensitive to the presence of broken clouds in the field of view. Altogether, the expectation is that root-mean square temperature retrieval errors, averaged over the global troposphere, will be reduced to about 1K at a vertical resolution of 1km, as long as the atmosphere is reasonably free of clouds. Retrieval accuracy in the presence of substantial cloud cover is an unresolved issue, and will remain a matter of scientific study and debate for some time. On the basis of existing simulations, AIRS may actually achieve the above level of accuracy with up to 80% cloud cover (Fig. 1) but this performance will not be matched by future operational sounders. Obviously, all infrared systems quit in the presence of a solid cover of opaque clouds. The fall-back solution is reliance on microwave soundings with significantly degraded accuracy: 1.5K (RMS) in the free troposphere and 2.5K (RMS) in the atmospheric boundary layer, according to NPOESS stated requirements. NASA and the NPOESS Program Office are cooperating in the preparation of a flight demonstration mission (NPOESS-preparatory project), scheduled for launch in mid-2005, that will put the new operational instruments (CrIS, ATMS) to the test. Similarly, the first flight of a METOP satellite carrying IASI is planned in 2003 or 2004.

While infrared and microwave sounders provide a wealth of information on atmospheric and surface temperature, total precipitable water, other trace constituents (especially ozone), clouds and precipitation at high spatial and temporal resolution, the inferred data are sensitive to irreducible residual errors in radiance measurement and the mathematical process of profile retrieval. Purely geometric measurements, on the other hand, such as radioelectric propagation delays near the limb of the Earth disc, could in principle be refined to any desired level accuracy. This is the promise of air refractivity observation, based on measurement of the radioelectric propagation delay between any member of the Global Positioning System constellation and a satellite-borne GPS receiver in low Earth orbit. The concept of GPS-based atmospheric sounding has been demonstrated by the GPS-MET experimental satellite launched in 1995. NASA is currently preparing a more complete demonstration with a small constellation of five scientific satellites of opportunity (cooperative missions co-sponsored by NASA) equipped with second generation occultation GPS receivers. The constellation will be complete in 2001 and will permit a significant test of the GPS sounding method with an adequate number of profiles per day, but in a delayed mode only. Excellent vertical resolution, accuracy, and long-term stability can be expected with GPS retrievals of air density, pressure, and temperature as a function of geopotential height, in the stratosphere and upper troposphere. Below 5km or so, however, the presence of water vapor complicates the measurement. Very close to the Earth surface, GPS links are usually lost by automatic phase-lock receivers, but may conceivably be recovered by sophisticated "open-loop" tracking algorithms (yet to be perfected).

Thus, it is the case that several solutions exist to produce global SST data of adequate, if not ideal, accuracy (0.2-0.3°C RMS would be the desired level of accuracy in the tropical Pacific "warm water pool" for ENSO prediction purposes). One can look forward to one or the other method becoming standard operational practice for NWP applications in the future, delivering significantly better than 0.5°C accuracy globally by the middle of the next decade.

3.2 Ocean Winds

Perhaps the most remarkable advance in global observation of the marine environment during recent years has been the success of microwave backscatter measurements to estimate ocean wind direction and speed. The first microwave scatterometer system was flown on the early Seasat mission of NASA in 1978. The European Space Agency (ESA) ERS-1 and ERS-2 satellites provided sufficient wind field coverage and measurement continuity to allow undertaking applications to NWP. The short-lived demonstration of the NASA NSCAT instrument on the ADEOS satellite of Japan's National Space Development Agency (NASDA) provided the first global ocean wind record obtained with a dedicated instrument operating continuously. A similar ASCAT sensor is being developed by ESA for deployment on the operational METOP satellite system commissioned by EUMETSAT.

At the same time, NASA has developed a next-generation wind sensor (Seawinds), launched on the "Quickscat" mission in June 1999 for fast replacement of the lost NSCAT capability. Seawinds will also be embarked on NASDA's ADEOS-2 mission to be launched at the end of year 2000. It is too early to tell whether the new Seawinds system will yield substantially more accurate wind retrievals than the 1-2 m/s uncertainty level achieved with previous instruments. Preliminary comparison of the first wind retrievals (based on pre-launch calibration) with the NCEP analysis shows less than a 2m/s RMS difference in wind speed, and 19-23° RMS difference in direction at mid-latitudes. (Note that differences in wind direction between the NCEP and ECMWF analyses are on the order of 20° RMS). Already demonstrated is the capability to provide daily global coverage of the world's oceans at spatial resolution of 25km, with only minimal gaps (a large gap along the satellite track, which did occur with previous instrument designs, has been effectively eliminated by the new sensor).

The spatial resolution and precision of global ocean wind observation from space are more than adequate to reliably identify and characterize the strength of important weather systems, such as fronts and tropical cyclones in the open ocean. ECMWF and other NWP centers are perfecting data assimilation systems that will extract the full meteorological information content of such single level data. On the other hand, more research and algorithm development work are still needed to achieve the very high degree of accuracy required to define the global wind-stress field for application as an upper boundary condition in ocean circulation models.

3. OCEAN SURFACE VARIABLES

3.1 Sea Surface Temperature

The first infrared images of the Earth surface returned by early meteorological satellites showed fronts and other features in sea surface temperature (SST). Nonetheless, residual uncertainties in SST data derived from imaging infrared radiometer measurements - currently the Advanced Very High Resolution Radiometer (AVHRR) on NOAA polar-orbiting operational environmental satellites - are still on the order of 0.7 to 1°C, due to contamination of the measured radiances by highly variable atmospheric constituents, such as precipitable water or aerosol along the optical path. The best practical solution so far consists in tying the global SST field inferred from satellite observations to accurate but relatively sparse *in situ* measurements transmitted by drifting and moored buoys. A blended global SST data product with significantly reduced (0.5°C RMS) errors is being produced operationally by NOAA, using the above *ad hoc* correction scheme.

Several physics-based methods have been proposed to overcome the problem of atmospheric corrections of infrared radiance data. The European Along-Track Scanning Radiometer (ATSR) takes advantage of the difference in optical path along two lines of sight, one directly at nadir and the other at a 45° slant angle; the down side of the method is a relatively narrow swath that does not allow frequent global coverage. Another method consists in combining surface infrared emission radiometry with atmospheric radiation spectrometry (in essence, simultaneous retrievals of surface temperature and atmospheric temperature and moisture profiles along the line of sight) in order to infer accurate atmospheric corrections. This approach will be exploited by the experimental Moderate-resolution Imaging Spectroradiometer (MODIS) instrument on NASA's EOS Terra and PM satellites, which includes regular atmospheric sounding channels in addition to the usual window channels utilized for cloud and surface radiometry. This approach will be pushed to its ultimate limit with the experimental AIRS sensor on EOS-PM (see section 2.1) which has a small enough footprint (15 km) to resolve significant features of the SST field and accurately determine this parameter for NWP applications.

Another promising development is the improvement of retrieval schemes based on microwave emission radiometry. Microwave radiation emitted by the ocean is largely unaffected by water and aerosol in the atmosphere (except where it rains) and provides an essentially unperturbed view of the ocean surface. The drawback is that microwave emissivity is quite sensitive to changes in sea surface conditions, such as the appearance of whitecaps, that depend upon the force of the wind. Combined retrieval algorithms have been perfected to simultaneously infer ocean wind speed, sea state and sea surface temperature from multiple-frequency microwave radiometry measurements. A residual error on the order of 0.5°C RMS has been achieved with the TRMM Microwave Imager (TMI) sensor on the Japan-US Tropical Rain Measuring Mission (TRMM).

2.2 Tropospheric Winds

There is theoretical evidence that, among the four basic meteorological variables, wind velocity is the most informative observation for NWP. One may take it, then, that there is a strong incentive in acquiring global wind measurements from space. Actually, the goal of determining winds in the tropics was the principal argument for undertaking the METEOSAT geostationary satellite development in Europe. Wind vectors are estimated by tracking small cloud clusters as they drift with the atmospheric circulation. This technique is now applied operationally by geostationary meteorological satellite operators with diverse degrees of success, the main problem being that of finding adequate lagrangian tracers (identifiable cloud systems have dynamics of their own and do not follow exactly the general circulation). and allocating a specific height to those tracers one could identify. Another problem is the difficulty of tracking more than one layer of clouds at a time: SATOB wind data are essentially one-level information. Actually, these weaknesses may be alleviated by the high (spatial and spectral) resolution imaging spectrometers being considered as a possible replacement for "radiometer-sounder" sensors on GOES and other geostationary platforms. The more advanced geostationary sounders will discriminate between several water vapor layers within the troposphere and allow tracking each layer separately. This system could provide a three-dimensional map of the wind field around (but not within) closed weather systems and powerful real-time information on the divergent and rotational components of far-field flow surrounding developing storms.

However, the "holy grail" of meteorological remote sensing would be a capability to observe winds in clear air, at all levels of the troposphere and lower stratosphere, globally. Ten years ago, this goal was thought to be readily achievable by measuring the Doppler shift in a laser pulse backscattered by aerosol particles. Since aerosols are true lagrangian tracers, the Doppler shift would be a direct measurement of line-of-sight (LOS) flow velocity. Then, it would be a simple matter of geometry to deduce horizontal wind from a couple of LOS velocity data. Wind-finding systems based on this concept have been successfully demonstrated from the ground, but the technological difficulties of building a satellite-borne version have not been mastered yet. NASA actually initiated development work for a short-time demonstration of a Doppler wind lidar system on the Space Shuttle, but had to cancel the project due to escalating industrial fabrication problems. One cannot doubt, however, that space agencies (including the US Air Force) will continue to pursue this technological goal and will eventually fly one or several space demonstration missions during the next decade. Thus, prospects are good that the meteorological community will see the deployment of a space-based wind-finding system that will fulfill, at least partially, the need for global wind measurements, but not before the second decade of the next century.

Despite these remarkable achievements, the future of global ocean wind observation from space remains clouded. In Europe, EUMETSAT is proceeding with the deployment of ASCAT on the operational METOP satellite series. On the other hand, no plan exists in the USA for incorporating an active wind-finding sensor on the next-generation NPOESS satellite series. NPOESS will rely instead on a (currently experimental) passive microwave remote sensing method based on polarimetric measurements, such as will be provided by the new Conical Scanning Microwave Imager/Sounder (CMIS) sensor. The US Navy is presently preparing a flight demonstration of this technique (Coriolis satellite project) in year 2002. The passive remote sensing technique is likely to achieve sufficient wind vector accuracy for most weather warning and forecasting applications, but may not meet the more exacting requirements of climate prediction and ocean circulation modeling. For this reason, NASA is considering the possible development of an advanced version (AlphaScat) of the original Seawinds instrument, for deployment on the new Global Change Observation Mission (GCOM) series planned by NASDA. AlphaScat could provide even higher spatial resolution than Seawinds (about 10km), allowing the characterization of near-shore wind shears that drive coastal ocean upwellings and circulation features of considerable practical interest for fisheries, coastal pollution control and other applications. In summary, exciting new developments are underway to develop several competing ocean wind remote sensing systems, and we shall live with this multiplicity of systems for some time in the future.

3.3 Ocean Surface Topography

Ocean surface topography or geopotential height is not, properly speaking, a climate variable but this measurement provides the basic information for deriving the geostrophic component of the ocean circulation. Ocean surface topography also provides an inverted picture of the depth of the oceanic thermocline, and a signature of sub-surface heat content anomalies. The upper-ocean cooling associated with the onset of the most recent 1997-1998 ENSO event, for example, was first detected through its ocean surface topography signature (measured by the US-French TOPEX-Poseidon altimetry satellite), long before any temperature signal appeared on the surface of the tropical Pacific.

Current plans for <u>operational</u> ocean surface height measurement are to embark a radar altimeter on the morning NPOESS spacecraft. This sensor will certainly provide excellent sea-state and significant wave height data. Notwithstanding the quality of the instrument itself, however, ocean topography measurements from a polar-orbiting platform can complement but not replace altimetry data obtained from the optimum TOPEX-Poseidon orbit (66° inclination orbit with a 10 day exact repeat cycle), for the following reasons:

- Ocean surface altimetry measurements from a sunsynchronous platform alias solar tides onto the low frequency spectrum associated with changes in dynamic height. It is true that open-ocean tide models could be developed to correct for this effect but there appears to be an unpredictable component, on the order of 1-2cm, that remains as an irreducible error.

- Orbital parameters of multi-purpose environmental satellite missions are driven principally by Earth viewing applications with broad swath instruments, focused on the observation of relatively large-scale, fast-moving atmospheric circulation disturbances. Nadir altimetry from sun-synchronous orbit provides poor space-time sampling of small-scale, slow-moving ocean circulation eddies or fronts, that are best observed from the optimal "oceanographic orbit" of the TOPEX-Poseidon mission.

In short, the easy solution of adding a radar altimeter to the next-generation operational polar-orbiting meteorological satellite system is not scientifically viable. We are faced with the conundrum that (1) operational environmental satellite operators are understandably reluctant to add yet another satellite system in inclined orbit to the two existing fleets of polar and geostationary satellites, and (2) space research agencies cannot, on their own cognizance, undertake to maintain such an operational environmental monitoring program indefinitely in the future. In the short term, NASA and the French space agency CNES have agreed to continue ocean topography measurements with the experimental Jason-1 satellite mission (to be launched in year 2000) and the two space agencies are seeking cooperative agreements with operational environmental agencies to fund the follow-on missions. There are good prospects for development of many applications of real-time oceanic prediction that will demonstrate the need for continuing global ocean surface topography measurements in the foreseeable future.

3.4 Sea Ice Concentration and Properties

Sea-ice extent, concentration, and thickness are the most significant properties that govern the exchange of momentum and heat between the polar ocean and atmosphere. The first two properties are observable from space but not the third; this is a serious impediment to progress in understanding polar climate dynamics. Nevertheless, valuable information can be derived from the analysis of long time series of sea-ice extent/concentration data for the improvement of sea-ice process models and coupled polar ocean-atmosphere models.

On account of the prevalence of cloudy conditions in the Arctic and Antarctic sea-ice zones, microwave observation techniques are the preferred option for climatological studies, although all observation types (visible and infrared remote sensing and *in situ* observations) are actually exploited for operational applications. The longest systematic record of sea-ice concentration has been assembled from passive microwave imaging observations made by a succession of satellite sensors, most recently the Special Sensor Microwave Imager (SSMI) on US Department of Defense DMSP satellites. NASA's EOS-PM and NASDA's ADEOS-2 spacecraft will carry the Advanced Microwave Scanning Radiometer (AMSR) which will provide a wider range of microwave frequency channels and higher spatial resolution than SSMI. The advances most likely to accrue from these added capabilities are improved discrimination between ice floes of different ages, more reliable estimates of snow accumulation, and better spatial resolution (10km).

Active microwave sensors also have been used with success to determine sea-ice concentration and drift velocity. Existing microwave scatterometer data have been utilized to estimate the global extent, concentration and surface roughness of the ice pack but the usefulness of the data has been limited by relatively poor spatial resolution. The new generation of active instruments (Seawinds and especially AlphaScat) will go a long way toward solving this problem. At the extreme end of the spatial resolution range, informative image data have been obtained over limited areas by various synthetic aperture imaging radar (SAR) systems, such as Canada's RADARSAT. The RADARSAT program was actually undertaken to acquire sea-ice concentration data operationally, in support of the exploitation of oil fields in the Labrador sea and route planning for tanker traffic, but this application has not materialized so far.

The prospects for meaningful scientific uses of space-based SAR have been marred by the perception that such systems have a commercial market and/or strategic applications. This perception has driven civilian SAR systems toward very high (military class) spatial resolution of a few meters or tens of meters, and narrow swaths that are less than ideal for most environmental applications. Nonetheless, in addition to occasional sea-ice data sets, existing European and Canadian SAR satellite have yielded unique information on solid Earth deformation and topography (SAR interferometry), as well as the first high-resolution global map of the Antarctic continent. NASA is now contemplating quantitative scientific applications of space-based SAR systems of moderate (1km) resolution and much larger swath, that could monitor sea-ice over the ocean and snow over land. These potential developments are still at the conceptual stage, however.

4. LAND SURFACE AND HYDROLOGIC VARIABLES

4.1 Land Vegetation Characteristics

Global land vegetation classifications for climate or NWP purposes can be derived from several satellite remote sensing indices, such as the Normalized Differential Vegetation Index (NDVI) based on AVHRR radiance data. Such classifications are still qualitative and can only be interpreted in terms of physical or ecological properties with the help of "tables" describing generic landscapes and vegetation types. One may expect that significant progress will be made with the emergence of a new generation of imaging radiometers, such as the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor on the EOS-AM (Terra) and PM missions, the Medium Resolution Imaging Spectrometer (MERIS) on ESA's ENVISAT mission, and the Global Imager (GLI) instrument on NASDA's ADEOS-2 mission.

Further advances in quantitative characterization of land topography, above-ground biomass, and aerodynamic roughness of the vegetation canopy can be expected from the experimental Vegetation Canopy Lidar (VCL) mission planned by NASA in year 2000. The VCL project will provide multiple lidar altimetry transects across the world's forests and vegetation-covered land and resolve 1m differences in canopy height at 25m along-track intervals.

4.2 Land Topography

Adequate information is provided by standard topographic maps for most climate and weather forecasting applications. With the advent of mesoscale NWP models and physically realistic catchment-scale hydrologic models, such commercially available geographic information may be insufficient. NASA and the US Department of Defense are getting ready to fly the Shuttle Radar Topography Mission (SRTM) later this year. SRTM is a SAR interferometry project, using a pair of similar L-band radar systems held together by a 60m boom that will be deployed from the Space Shuttle. A very precise global map of the Earth continental regions, at a resolution of a few tens of meters, is expected from this dedicated two-week Shuttle mission.

4.3 Soil Moisture

Soil moisture is the key state variable in surface hydrology: it is the switch that controls the partitioning of rainfall among evaporation, river run-off and ground storage. Soil moisture is the life-giving substance that controls the growth of terrestrial vegetation. Soil moisture integrates precipitation and evaporation over periods of days to weeks and introduces a significant element of memory in the atmosphere-land system. There is strong climatological and modeling evidence that the fast recycling of water through evapotranspiration and precipitation is the primary factor in the persistence of dry or wet summer anomalies over large continental regions. Yet, soil moisture cannot currently be quantified over any large area, because *in situ* measurements are sparse and only representative of small areas. Only aircraft-based and, ideally, satellite-based remote sensing may provide meaningful area-averaged estimates of "soil wetness" and inferred volumetric soil moisture over large continental regions.

Remote sensing techniques are only sensitive to changes in wetness and dielectric constant in the uppermost few centimeters of the ground (somewhat deeper in vegetation-free arid regions). Furthermore, a relatively thin vegetal cover can totally absorb the microwave energy emitted by the soil at any frequency currently used by existing imaging radiometers. The only means to penetrate moderate vegetal cover and reach more a few millimeters into the ground is to use the lowest microwave frequencies possible, corresponding to wavelengths of 20cm or more. On the other hand, hydrologic properties show considerable variability at all spatial scales, from meters to kilometers. Broad-beam radiometers that can sense only the integrated radiation from large areas are not very useful for detailed hydrologic modeling nor quantifying physical soil properties (although coarse soil moisture information may be acceptable for weather forecasting purposes). The European Space Agency is currently planning an experimental Soil Moisture - Ocean Salinity measuring mission (SMOS) that would be sensitive to 50x50km^2 area-averaged soil moisture changes. At the same time, NASA is preparing to invest in new microwave technologies that would enable more ambitious soil moisture measurements with spatial resolution on the order of 10km. In both cases, the task requires large antennas, with real or synthetic apertures on the order of 10m or more (using techniques developed by radioastronomers). One may expect that either ESA or NASA (or both) will actively pursue these developments and demonstrate experimental global soil wetness measurements from space in the next few years. The eventual deployment of an operational soil moisture measurement system will take more time (second decade of the 21st century.

4.4 Cold Climate Land Variables (Freeze/thaw & snow water equivalent

Cold climate land parameters, such as the frozen and thawed states of the soil, and snow accumulation, have considerable scientific and practical interest. The freeze-thaw transition determines the onset of photosynthesis and plant growth in cold climate regions. The seasonal snow cover stores large amounts of fresh water and is a critical component of the hydrologic cycle in many regions of the world that are irrigated by meltwater. Seasonal or permanent soil freezing reduces both infiltration and migration of water, and severely restricts the amount of water that can be stored temporarily in soils. Also, by blocking infiltration, frozen soils can dramatically increase the runoff generated by melting snow. Weather forecasting models may account incorrectly for soil freezing or thawing, and thus induce significant errors in predicted surface temperature. Experimental remote sensing algorithms to infer the freeze-thaw state of soils, snow extent and depth, and snow wetness have already been demonstrated but well-considered design trade-offs for an optimal cold climate land observation mission have yet to be defined. Altogether, one may look forward to interesting experimental satellite developments in the next decade, including but not restricted to potential applications of moderate-resolution synthetic aperture radar (SAR) systems.

4.5 River and Lake Stage Height

Monitoring river stage height has been standard hydrologic practice since a century. Nevertheless, the capacity to monitor inland rivers, lakes, reservoirs and wetlands worldwide is stunted by various technical, economic and institutional impediments (including outright denial of hydrologic data), which collectively have resulted in decreasing accessibility to basic hydrologic data. This state of affairs runs against increasing concern for the continued availability of adequate water resources worldwide, and scientific interest in quantitative understanding of the global water cycle. A capacity for consistent global monitoring of inland waters is essential to the future development of Earth system models, water resource prediction and the resolution of water-related contests and other similar societal problems. As it happens, remote sensing techniques developed for other scientific applications, have the potential to monitor effectively the stage of inland rivers and water bodies globally (Fig. 2). The accuracy requirements for hydrologic applications are already met by existing radar altimeters, but the required repeat measurement frequency (once every 1 to 3 days) can only be achieved by a dedicated satellite mission on a specially selected orbit. In the future, this challenge may be alleviated by the introduction of scanning altimetric systems that can cover a substantial area. Doppler lidar techniques could also be applied, in principle, to observation of flow velocity profiles across rivers, a direct method for estimating the volumetric discharge of rivers. Altogether, one may look forward to exciting experimental satellite developments in the next decade, including potential applications of steerable radar and lidar altimeter systems.

5. ICE SHEETS

It is not known definitely whether the Antarctic and Greenland ice sheets are currently decreasing or increasing in volume, nor a fortiori, what would be the impact of further climate change on the mass balance of these ice sheets and the global sea level. NASA will launch the ICEsat (Ice, Cloud and Land Elevation Satellite) mission in July 2001 to establish a baseline for estimating trends in ice sheet volume and its short-term mass balance, based on repeat measurements in the course of a five-year mission and later follow-on polar altimetry missions.

Several kinds of satellite data show promise for quantitative estimation of key ice-sheet parameters. Passive microwave sensors and scatterometers have provided insight into ice accumulation and ablation patterns on polar ice sheets, while the twin European ERS missions and the Canadian RADARSAT Antarctic Mapping Project have produced a wealth of SAR images of the Antarctic ice sheet. The latter mission provided the first high-resolution radar map of the entire Antarctic continent, revealing hitherto unknown features that change our perception of Antarctic ice sheet dynamics, namely the existence of active ice streams that reach far inland and could drain the ice reservoir much faster than previously envisaged. It is anticipated that a second Antarctic mapping program, with full interferometric capability over the whole ice sheet, will be realized sometimes in the next decade.

6. DIABATIC PROCESSES

The true novelty in global satellite observation for model diagnosis and validation is the emergence of active remote sensing techniques, especially radar or lidar systems, that allow probing the atmospheric medium and give insight in diabatic processes that have heretofore been obscured, if not outright hidden, by clouds. Altogether, these new observing capabilities will provide, for the first time, a means to estimate energy atmospheric sources and sinks globally: radiative heating (radiation flux divergence) and the release of latent heat in a vertical air column.

6.1 Global Precipitation

The first major advance has been the success of the joint Japan-US Tropical Rain Measuring Mission (TRMM), launched in November 1997. TRMM carries a fairly complex instrument payload, including, for the first time, a single frequency "precipitation radar" that can probe the three-dimensional distribution of precipitating ice and water within a 200km swath along the satellite track. Even though single frequency radar backscatter is not sufficient to unambiguously determine both drop size and number density, TRMM radar data provide enough insight in the structure of precipitating clouds to "initialize" process-resolving cloud models (actually Cloud Ensemble Models) which allow inferring quantitative estimates of instantaneous precipitation rates. Of course, this is just a beginning and much remains to be done to improve these models and resulting rainfall products. Nevertheless, initial TRMM results have been effective for "tuning" and significantly improving precipitation algorithms based on passive microwave radiometry only.

This advance is quite significant because it opens the prospect for truly global precipitation measurements with not just a single satellite, but a constellation of 6 to 8 spacecraft on appropriately staged polar orbits to ensure frequent sampling (once every 2-3 hours) of the global distribution of rain-producing weather systems.

NASA is currently consulting with international partners to determine how this Global Precipitation Mission could be implemented in the coming 5 to 10 years (and eventually maintained as a systematic measurement for the indefinite future). The Global Precipitation Mission would include one special satellite equipped with both passive and active microwave imaging sensors (hopefully a two-frequency precipitation radar), the Advanced Microwave Scanning Radiometer on Japan's ADEOS-2 and GCOM missions and several ad-hoc microwave imaging sensors and spacecraft (to be defined).

6.2 Cloud Optical Properties

Progress with space-qualified millimeter wave radar transmitters and lidars have made possible the development of a powerful multi-spacecraft project to investigate cloud particle density, physical nature (ice or liquid water) and optical properties, and relate these properties to the weather systems that generated the clouds. The plan is to combine observations by EOS-PM instruments (notably MODIS, AIRS, and the CERES broad-band Earth radiation budget radiometer) with simultaneous measurements obtained by two profiling sensors:

- A two-frequency backscatter lidar and a high-resolution solar radiation (oxygen A-band) spectrometer on the US/French PICASSO-CENA satellite mission to observe aerosols and optically thin clouds, and
- A millimeter-wave Cloud Profiling Radar and A-band spectrometer on the Cloudsat mission, realized by NASA with the support of the US Air Force and the Canadian Space Agency, to investigate the intermediate range of cloud thickness (non-precipitating stratiform clouds and light drizzle).

The PICASSO-CENA and Cloudsat spacecraft will be placed in orbit simultaneously by a single launch vehicle in 2003, and fly in formation with the EOS-PM spacecraft. It is hoped that this three-spacecraft observing system will achieve major progress in understanding atmospheric radiation transfer in cloudy air columns, the three-dimensional structure of aerosol layers and cloud systems (including sub-visible cirrus clouds), and radiative heating of the atmosphere and Earth surface. This breakthrough in global observation of cloud optical properties and distribution should lead, within the next 5 years, to considerable improvement in the ability to understand, quantify and model the radiative impact of clouds on climate and their relationship to weather disturbances.

6.3 Planetary Radiation Budget

NASA has pioneered the measurement of solar irradiance and broad-band radiation fluxes at the top-of-the-atmosphere (TOA). The Earth Radiation Budget Experiment launched by NASA in 1984 (involving three broadband scanning radiometers in different Earth orbits) provided the first quantitative information on the radiative impact of clouds on a planetary scale – since known as "cloud radiation forcing" - and defined a precise upper-boundary constraint for radiation transfer computations in climate models. Several scientific issues remained to be addressed, notably improving our knowledge of the angular distribution of reflected solar radiation (needed in order to estimate total radiant energy fluxes from radiance measurements in one direction only).

Further reduction in uncertainty on the components of the planetary radiation balance (down to 1 Watt/m^2) are expected from the Clouds and Earth's Radiant Energy System (CERES) program involving three broadband CERES radiometers on TRMM and EOS-Terra and PM, two moderate resolution imagers (MODIS) on EOS Terra and EOS-PM (for fractional cloud cover and cloud top optical properties), the Multi-angle Imaging Spectro-Radiometer (MISR) on Terra (for viewing angle diversity), and the Advanced Infrared Sounder (AIRS) on EOS-PM (for resolving the infrared spectrum and correcting the limb-darkening of broad-band radiances). At the same time, France, Germany and Russia have cooperated in the realization of a similar Scanning Radiation Budget (ScaRaB) program on successive experimental Meteor missions. Altogether, it is anticipated that major progress will be made during the next five years in determining the terms of the planetary radiation balance at the top of the atmosphere, thereby providing a definitive reference point for global climate model simulations.

In the long term, the NPOESS program is planning to continue systematic broadband radiation measurements with CERES or a similar instrument on one of the two NPOESS spacecraft indefinitely in the future.

7. CONCLUSION

Space research and satellite observation often retain, in the mind of scientists, a connotation of expensive engineering endeavours, more spectacular than genuinely effective. I would like to dispute this view and argue that no global meteorology, nor climate science, could exist without the support of global satellite observation. Satellite data have given us the capability to quantify global atmospheric, oceanic and land processes, as opposed to making informed guesses on the basis of insufficient *in situ* observations, in the great tradition of the early climatologists, hydrologists and oceanographers. It is true that the refinement of complicated measurement and information retrieval methods is considerably less entertaining than bold guesswork. Fortunately, the "rocket scientists" are not alone in this undertaking and share the same purpose with ECMWF and other NWP centres which are likewise in the business of extracting meaningful information from imperfect measurements. We are particularly indebted to those, in the weather and climate modeling community, who have invested their intellectual efforts in developing and formalizing the sophisticated data assimilation techniques we are now able to use.

		2000	2005	2010
Basic Atmospheric Variables	***Temperature and Moisture***	AIRS(EOS-PM) AMSU, HSB	CrIS(NPP) ATMS IASI, HIRS(METOP) ⟹ AMSU Operational GPS-sounding constellation?	CrIS(NPOESS) ⟹ ATMS ⟹
	Tropo. Winds		Doppler Lidar demonstration(NASA, ESA)?	
Ocean Variables	***Sea surface Temperature***	AVHRR(NOAA, METOP) ⟹ MODIS(EOS-PM) MERIS, AATSR(ENVISAT) TMI (TRMM) ASMR(EOS-PM, ADEOS-2)	VIIRS(NPP) ASMR(GCOM-B) ⟹	VIIRS(NPOESS) ⟹ CMIS(NPOESS) ⟹
	Ocean Winds	Seawinds(Quickscat, ADEOS-2) Coriolis(Expt. Navy)	AlphaScat(GCOM-B)? ASCAT(METOP) ⟹	CMIS(NPOESS) ⟹
	Ocean Topography	Topex-Poseidon Jason-1(NASA/CNES)		Jason-2?

Table 1

		2000	2005	2010
Ice Variables	***Sea-ice Concentration***	SSMI(DMSP) ASMR(EOS-PM, ADEOS-2) Seawinds(Quickscat, ADEOS-2)	ASMR(GCOM-B) ⟹	CMIS(NPOESS) ⟹
	Ice Sheet Topography	ICESat (EOS) ASAR(ENVISAT) RADARSAT-1	RADARSAT-2	ICESat follow-on?
Diabatic Processes	***Precipitation***	TRMM AMSR(EOS-PM, ADEOS-2) AMSU(EOS-PM)	ATMS(NPP) Intl. Global Precipitation Mission?	ATMS(NPOESS) ⟹
	Cloud Radiative Properties	MODIS,CERES, AIRS(EOS-PM) Cloudsat(NASA) PICASSO-CENA(NASA/CNES)		
	Planetary Radiation Budget	ScaRaB(France/Russia) CERES(TRMM, EOS-AM & PM)		CERES(NPOESS) ⟹

Table 2

		2000	2005	2010
Land Surface & Hydrologic Variables	***Vegetation***	MODIS(EOS-AM & PM) MERIS(ENVISAT) GLI(ADEOS-2) Landsat-7 VCL(Expt.)	VIIRS(NPP) GLI(GCOM-B) ⟹ Land Cover Inventory Mission Expt. Vegetation Recovery Mission?	VIIRS(NPOESS) ⟹
	Land Topography	SRTM	Interferometric SAR mission?	
	Soil Moisture		SMOS(ESA Explorer) Expt. Soil Moisture Mission(NASA)?	
	Soil Freeze/Thaw & Snow		Expt. Cold Land Process Mission(NASA)?	
	River & Lake Stage Height		Expt. "HydraSat" Mission(NASA)?	

Table 3

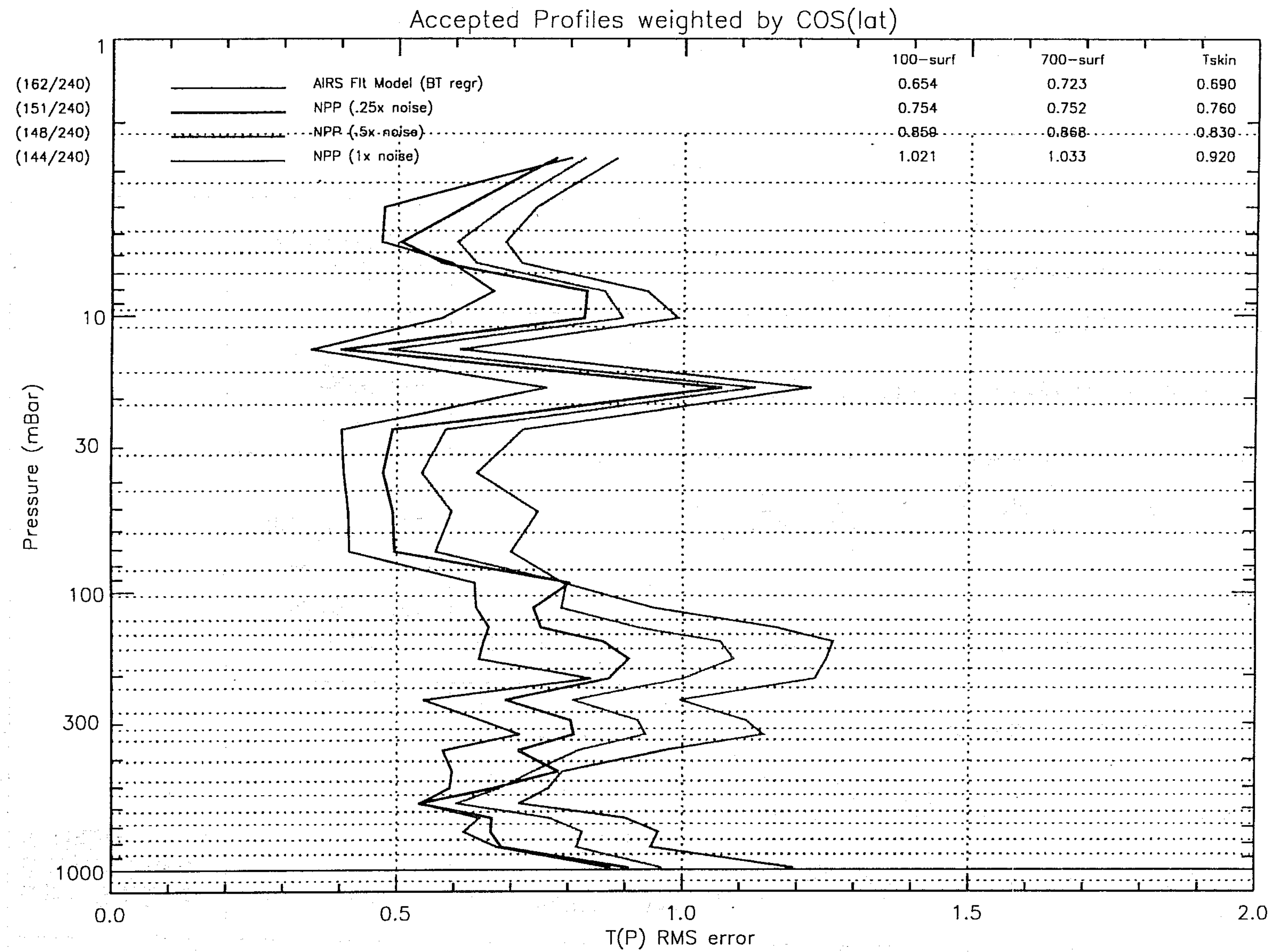

Fig. 1 Simulated global RMS temperature retrieval errors for the NASA Atmospheric Infra-Red Sounder (AIRS) and three possible noise-level options for the future operational Cross-track Infrared Sounder (CrIS) instrument on NPOESS. "Accepted profiles" are those obtained under sufficiently clear air conditions. The rejected fraction of simulated soundings was 33% of the sample in the case of AIRS and about 40% in the case of CrIS. The simulation does not take into account the impact of broken clouds within individual fields of view on retrieval accuracy (significant in the case of an interferometer instrument like CrIS).

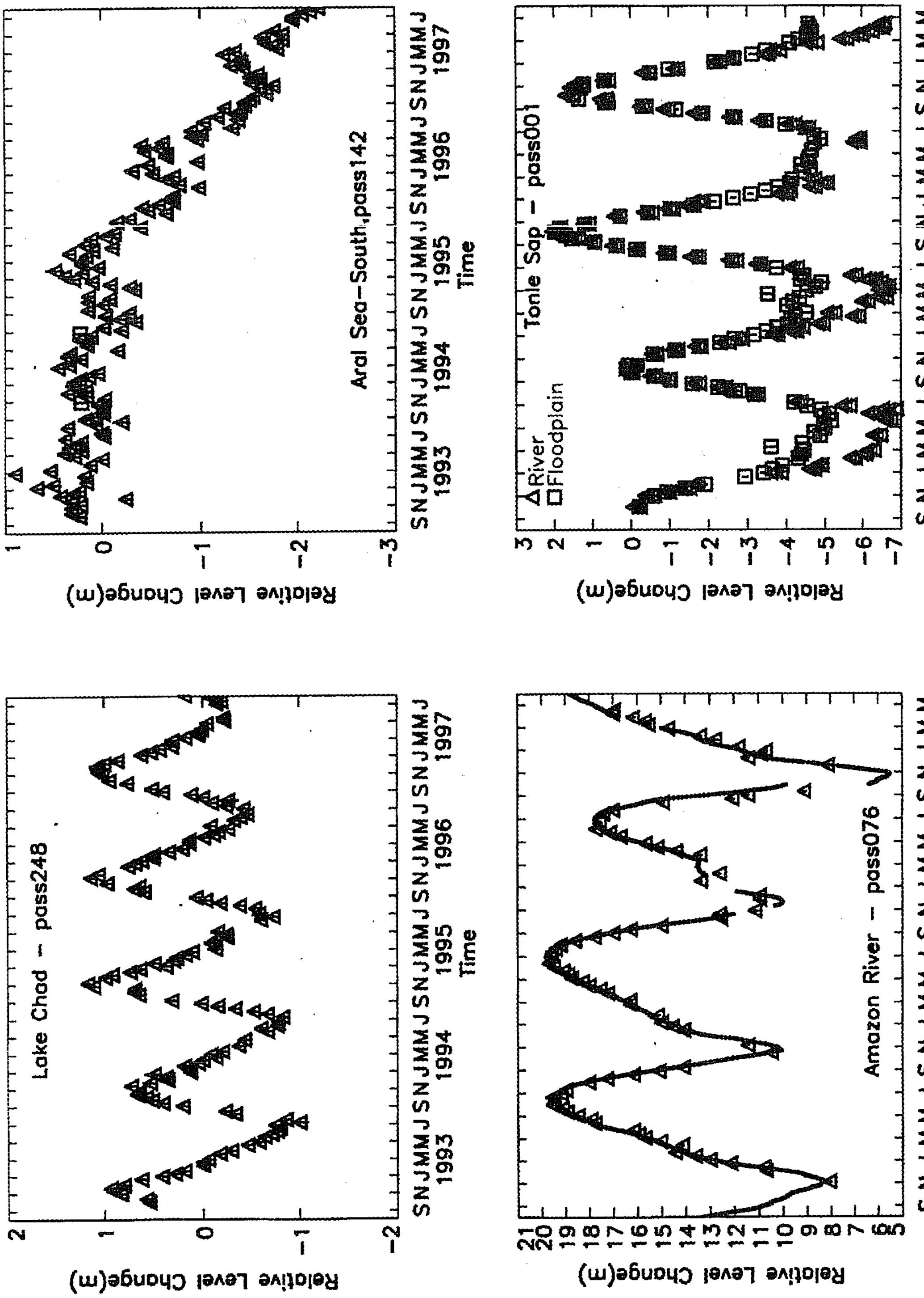

Fig.2 Times series of stage height variations in Lake Chad, the Aral sea, the Amazon river and the Tonle Sap lake in Cambodia. The data are derived from TOPEX/Poseidon radar altimeter measurements. Note the comparison of TOPEX measurements with corresponding river gauge data for the Amazon river (solid line in the third Panel). TOPEX is an oceanic topography mission and was not optimized for the observation of inland water bodies or rivers.