International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R RS.1883

(02/2011)

Use of remote sensing systems in the study of climate change and the effects thereof

RS Series

Remote sensing systems

International Telecommunication Union

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Note*: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R RS.1883

Use of remote sensing systems in the study of climate change and the effects thereof

(2011)

Scope

This Recommendation provides guidelines on the provision of satellite-provided remote sensing data for the purpose of studying climate change.

The ITU Radiocommunication Assembly,

considering

a) that climate change is a global phenomenon affecting all humankind;

b) that climate change is expected to be manifested by serious changes in the Earth's environment in turn giving rise to, or exacerbating, natural disasters;

c) that inherent to the study of climate change are truly consistent, global Earth observing capabilities uniquely met by satellite-borne remote sensing instrumentation or sensors;

d) that such satellite-borne remote sensors exist and are operated in frequency bands allocated to the Earth exploration-satellite service (EESS) today,

recognizing

a) that Resolution 673 (WRC-07) – Radiocommunications use for Earth observation applications, considered that "Earth observation data are also essential for monitoring and predicting climate changes, ... for increasing the understanding, modelling and verification of all aspects of climate change, and for related policy-making, and further noted that more than 90% of natural disasters are climate- or weather-related; ... that, although meteorological and Earth observation satellites are currently only operated by a limited number of countries, the data and/or related analyses resulting from their operation are distributed and used globally ... by climate-change-related organizations";

b) that Resolution 672 (WRC-07) – Extension of the allocation to the meteorological-satellite service in the band 7 750-7 850 MHz, recognized that the data obtained by these meteorological satellites are essential for global weather forecast, climate changes and hazard predictions,

noting

a) that ITU-T Resolution 73 – Information and communications technologies and climate change, recognized that information and communications technologies (ICTs) can make a substantial contribution to mitigating and adapting to the effects of climate change, as presented in Annex 1, and that ICTs play a vital role in monitoring and addressing climate change by supporting basic scientific research, which has helped to bring the issue of climate change into the public domain and to raise awareness of future challenges;

b) that ITU Report – ITU and climate change, speaks to strengthening strategic partnerships with various UN agencies, the World Bank, the European Commission, international and national agencies and organizations (for example, meteorological agencies, the Group on Earth Observations, EUMETSAT, ESA, the Space Frequency Coordination Group, JAXA, NOAA, NASA and Roscosmos), NGOs and the private sector involved in combating climate change and addressed the role that EESS plays in monitoring climate change;

c) that Report ITU-R RS.2178 provides an extensive overview of different radiocommunication applications employed for Earth observation, space research and radio astronomy and describes their societal weight and economic benefits for the global community and, especially, their importance for climate change monitoring and climate change prediction, and for early warning, monitoring and mitigation of man-made and natural disasters,

recommends

1 that administrations should recognize the importance of satellite-borne remote sensors to the study of climate change as explained in Annexes;

2 that operators should continue supplying climate-related environmental data;

3 that the protections given to systems providing crucial climatological observations should be emphasized.

Annex 1

Use of remote sensing systems in the study of climate change and the effects thereof

1 Introduction

Spacecraft in the EESS routinely provide worldwide coverage with the same, or functionally identical, instruments. Thus, they provide datasets that are truly consistent over the entire globe. Frequently such datasets overlap in time and allow the construction of contiguous datasets spanning decades. While such datasets do not span centuries or millennia, they nonetheless provide crucial data to those studying climate change.

Satellites are the best means of providing a snapshot of the present state of our planet from a single, unified perspective. No single instrument spacecraft can provide a complete picture; however, the current fleet of spacecraft, operating in concert and sharing their data, arguably give us the best assessment of global conditions available to us.

These data serve two purposes:

– to provide a baseline for observing and measuring climate change and its effects upon the planet;

– to provide scientifically sound input to climate models.

Climate science has advanced spectacularly through satellite observations. The radiometer flown on Explorer 7 from 1959 to 1961 made possible the direct measurement of the energy entering and leaving Earth. This mission and follow-on missions enabled scientists to measure Earth's energy balance with much greater confidence compared to earlier indirect estimates and resulted in improved climate models. As radiometers improved, these measurements achieved the precision, spatial resolution, and global coverage necessary to observe directly the perturbations in Earth's global energy budget associated with short-term events such as major volcanic eruptions or the El Niño-Southern Oscillation (ENSO). These radiometers directly measure the equator-to-pole heat transport by the climate system, the greenhouse effect of atmosphere trace gases, and the effect of clouds on the energy budget of Earth. These observations have advanced our understanding of the climate system and improved climate models.

Satellites engaged in atmospheric research (e.g. AURA) and supporting operational meteorology (e.g. the European MetOp series and the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting satellites) provide daily three-dimensional worldwide profiles of atmospheric temperature and humidity as well as data regarding minor atmospheric constituents, such as ozone. While these data are fed into weather forecasting models, they also serve to define the current state of the atmosphere and to provide a short-term test of climate models.

Other terrestrial features are monitored by spacecraft not engaged by atmosphere-related endeavours. For example, we can note:

– the Landsat and SPOT series of spacecraft have been monitoring the Earth's surface for decades;
– the QuikSCAT and ADEOS-1 and -2 monitored sea surface winds;
– the TOPEX/Poseidon and the Jason series have been monitoring sea surface heights and temperatures;
– the SMOS satellite and others such as Aquarius and SMAP monitor, or will monitor, soil moisture and ocean salinity.

Other spacecraft and techniques, such as synthetic aperture radar (SAR) and passive microwave observations, are adding to our capabilities for describing our planet, particularly in observing the Polar Regions where winter darkness precludes taking optical images.

2 Ice or the cryosphere

One of the central questions in climate change and cryosphere (ice-region) research is how the warming climate will affect the ice sheets. It is important since the amount of continental ice and melt water entering the ocean strongly contributes to the change in sea level. Prior to the advent of satellites, polar data was restricted to data locally gathered during hospitable seasons. The use of satellite-borne radio instrumentation has proven particularly useful in polar regions as such regions have extended periods of darkness during winter, when observations in the visible spectrum are precluded. The synoptic view from satellites, particularly from satellites equipped with radio sensors, has increased polar data coverage by multiple orders of magnitude, and access is no longer restricted by seasons.

Before satellites, Antarctica's and Greenland's ice sheet mass balance was assumed to be controlled by the difference between ice melting and accumulation rates, and the rate of ice discharge into the ocean was assumed to be constant. Satellite radar images from RADARSAT revealed that:

1. the velocity of ice sheet flow is highly variable;
2. there exist complex networks of ice streams;

3. the velocity of ice stream flow toward the sea has increased measurably in response to climate change.

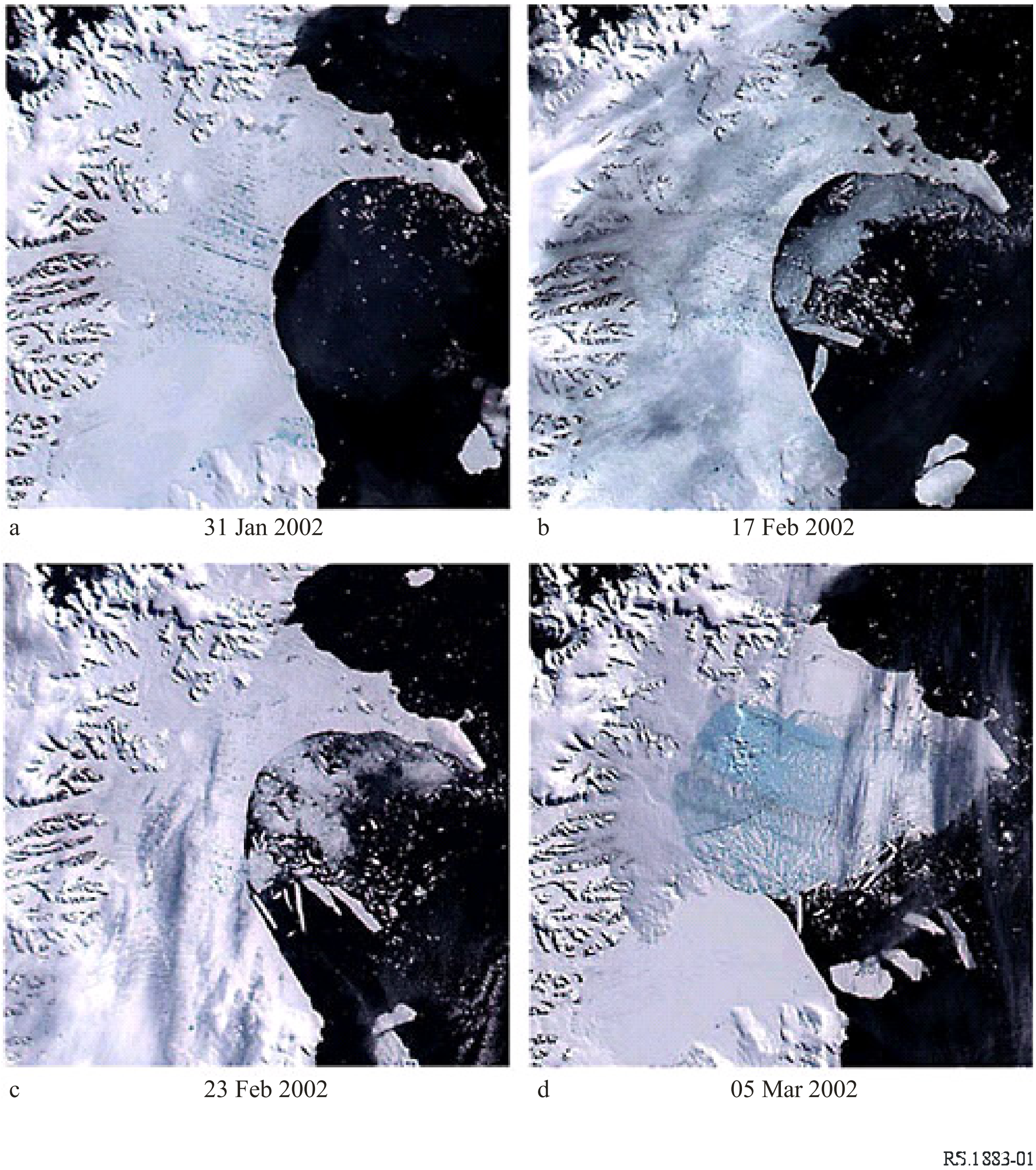
One indication of climate change/global warming is the retreat, rather than advance, of ice sheet flows (both glaciers and sea ice). The study of glacier regimes worldwide reveals widespread wastage since the late 1970s, with a marked acceleration in the late 1980s. Remote sensing is used to document changes in glacier extent (the size of the glacier) and the position of the equilibrium line (the elevation on the glacier where winter accumulation is balanced by summer melt). Since 1972, satellites have provided optical imagery of glacier extent. SAR is now used to study zones of glacial snow accumulation and ice melt to determine climate forcing, and laser altimetry is used as well to measure change in glacier elevation.

Because glaciers respond to past and current climatic changes, a complete global glacier inventory is being developed to track the current extent as well as the rates of change of the world's glaciers. The Global Land Ice Measurements from Space project is using data from the ASTER and the Landsat Enhanced Thematic Mapper to inventory about 160 000 glaciers worldwide. These measurements and the resulting trend analyses are important indicators of climate change and exemplify the value and importance of long-term data sets for understanding the complex climate system.

Ice sheets can be easily monitored by space-borne instrumentation, both active and passive. The breakups of major ice sheets (e.g. the Larsen Ice Shelf B) in the Antarctic have been observed from space. These breakups, if not attributed to global warming, have been accelerated by it. The collapse of the Larsen B Ice Shelf in Antarctica in 2002 – captured only because of frequent coverage by satellite imagery – dramatically illustrated the dynamics of ice sheets on astonishingly short time-scales (Fig. 1). These revelations carry weighty implications: the rapid transfer of ice from the continental ice sheets to the sea could result in a significant rise of sea level.

FIGURE 1

The collapse of the Larsen B Ice Shelf in Western Antarctica. 2 000 km^2, of ice shelf disintegrated in just 2 days

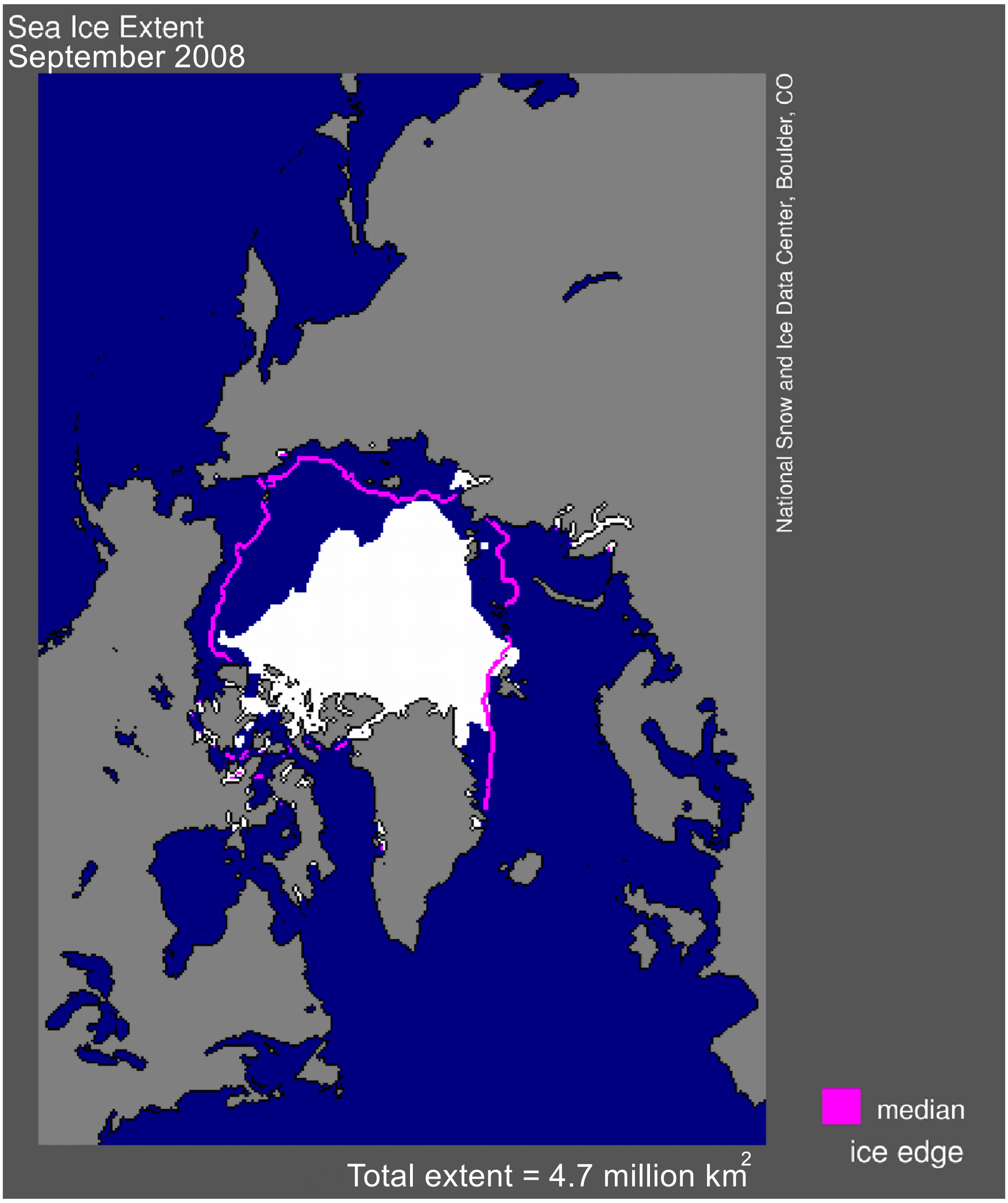


Source: *Earth Observations from Space: the First 50 Years of Scientific Achievements,* p. 3, 2008, downloadable from URL: http://www.nap.edu/catalog/11991.html.

Sea ice has been monitored continuously with passive microwave sensors (electrically scanning microwave radiometer (ESMR), scanning multichannel microwave radiometer (SMMR), special sensor microwave/imager (SSM/I), and advanced microwave scanning radiometer-Earth observing system (AMSR-E)) since 1979. Not limited by weather conditions or light levels, they are well suited for monitoring sea ice because of the strong contrast in microwave emission between open and ice-covered ocean. The long-term 35-year data set from these passive microwave sensors has enabled a trend analysis extending beyond the strong interannual variability of sea ice. Since 2000, record summer ice minima have been observed during 4 out of the past 6 years in the Arctic (Figs 2 and 3). Moreover, most recent indications are that winter ice extent is now also starting to retreat at a faster rate, possibly as a result of the oceanic warming associated with a thinner, less extensive ice cover. These observations of shrinking Arctic sea ice are consistent with climate model predictions of enhanced high-latitude warming, which in turn are driven in significant part by ice-albedo feedback. In contrast to the Arctic, no clear trend in the extent of Antarctic sea ice coverage has been detected.

FIGURE 2

Arctic sea ice extent for September 2008 was 4.67 million km^2 (1.80 million square miles), the second-lowest in the satellite record. The magenta line shows the median ice extent for September from 1979 to 2000



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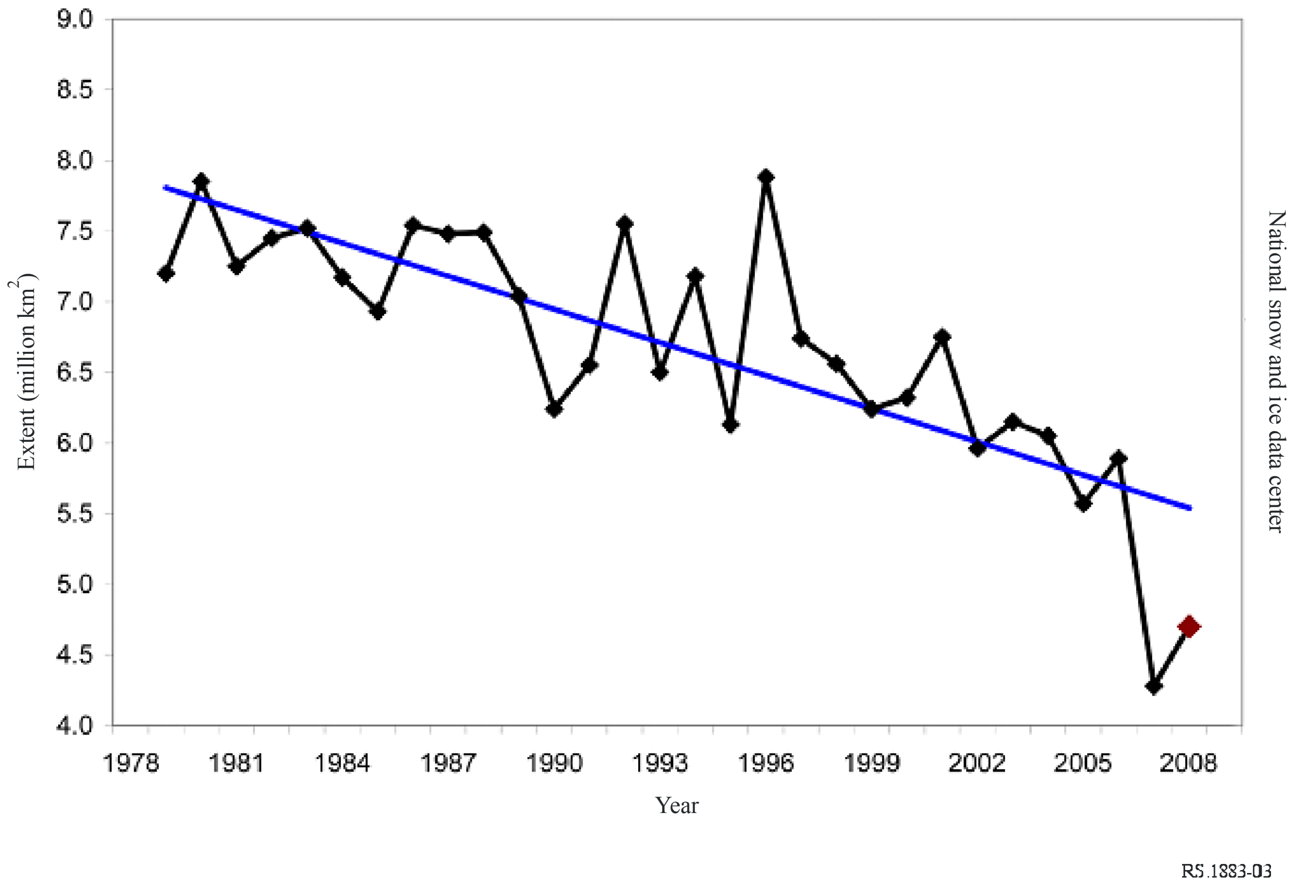
Source URL: http://nsidc.org/news/press/20081002_seaice_pressrelease.html.

FIGURE 3

September ice extent from 1979 to 2008 shows a thirty-year decline. The September rate of sea ice decline since 1979 has now increased to –11.7% per decade



Source: URL: http://nsidc.org/news/press/20081002_seaice_pressrelease.html.

Over the past few years, there have been a growing number of reports forecasting sea ice conditions, and these reports are based entirely or mostly on data from satellites. For example, the Arctic Climate Impact Assessment (ACIA 2005) concluded that continued reductions in Arctic sea ice might soon lead to a seasonally ice-free Arctic and increased maritime traffic because shipping routes through the Arctic Ocean are much shorter than routes through the Panama or Suez canals. However, there is also some evidence that a reduction in the ice cover will be accompanied by greater interannual variability, at least in certain regions.

Understanding changes to ice sheets, sea ice, ice caps, and glaciers is important for understanding global climate change and predicting its effects. In particular, "shrinking ice sheets" and their contribution to sea-level rise were identified as the third most significant "Breakthrough of the Year" for 2006 according to **Science** magazine. Given the projected climate change and associated sea-level rise, having global satellite polar coverage available in the future will serve crucial societal needs unmet by any other observing system.

3 The oceans

The oceans cover about 71% of the globe's surface and play a key role in the climate system in several respects. They are also an excellent indicator of climate change. For example, measuring sea levels reveals vital clues about global warming.

Changes in weather, climate and the environment pose serious challenges to mankind. Meeting these challenges requires further improvements in weather forecasting, especially for mid- to long-term predictions. If there is a clearer picture of what is going to happen in the next 10 days, the next months – or even in the coming season – people and industries can prepare themselves much better for unstable weather patterns. Meeting these challenges also implies a better understanding of global climatic factors that cause such phenomena such as El Niño and La Niña in the Pacific Ocean, dangerous hurricanes and typhoons, and especially rising sea levels.

A key to understanding the forces behind changing weather patterns can only be found by mapping variations in ocean surface conditions worldwide and by using the collected data to develop and run powerful models of ocean behaviour. By combining oceanic and atmospheric models, we can provide the required accurate forecasts on both a short- and long-term basis. The coupling of oceanic and atmospheric models is needed to take the mesoscale (medium-distance) dynamics of the oceans fully into account. This coupling of oceanic and atmospheric models becomes important for weather forecasting beyond two weeks. The oceans are also an important part of the process of climate change, and a rise in sea levels all over the world is widely recognized as potentially one of the most devastating consequences of global warming.

3.1 Sea surface temperature and mean sea level rise

An important contribution to climate science was made by the long-term record of sea surface temperature (SST) from the advanced very high resolution radiometer (AVHRR) flown on the television infrared observation satellite series (TIROS-N) and the NOAA satellite series. SST is now also measured by passive microwave instruments. SST is one of the most important indicators of global climate change and a vital parameter for climate modelling. As the longest oceanographic data record from remote sensing, it has broad impact.

The SST record exposed the role of the ocean in regional and global climate variability and revealed important details about ocean currents. More than 80% of the total heating of the Earth system is stored in the ocean, and ocean currents redistribute this heat across the globe. Trend analysis of the SST record helped improve understanding of the important climate-atmosphere feedbacks in the tropics that are also responsible for El Niño-Southern oscillation (ENSO) events in the Pacific Ocean. Advances in understanding the ENSO, led by satellite observations of sea surface winds, sea surface heights, and sea surface temperatures, have had a profound impact on regional climate and weather predictions. Furthermore, the intensity of hurricanes has been linked to sea surface temperatures. Consequently, both sea surface temperatures and the hurricanes themselves have benefited from studies using data from satellites.

In addition, SST is central in coupling the ocean with the atmosphere and is a controlling factor in the heat and vapour exchange between the two. Trend analysis of SST provided evidence for global warming and the important climate-atmosphere feedback in the tropics that is also responsible for ENSO events. These SST observations, combined with *in situ* vertical temperature measurements of the ocean to a depth of 3 000 m, provided evidence to detect anthropogenic global warming in the ocean.

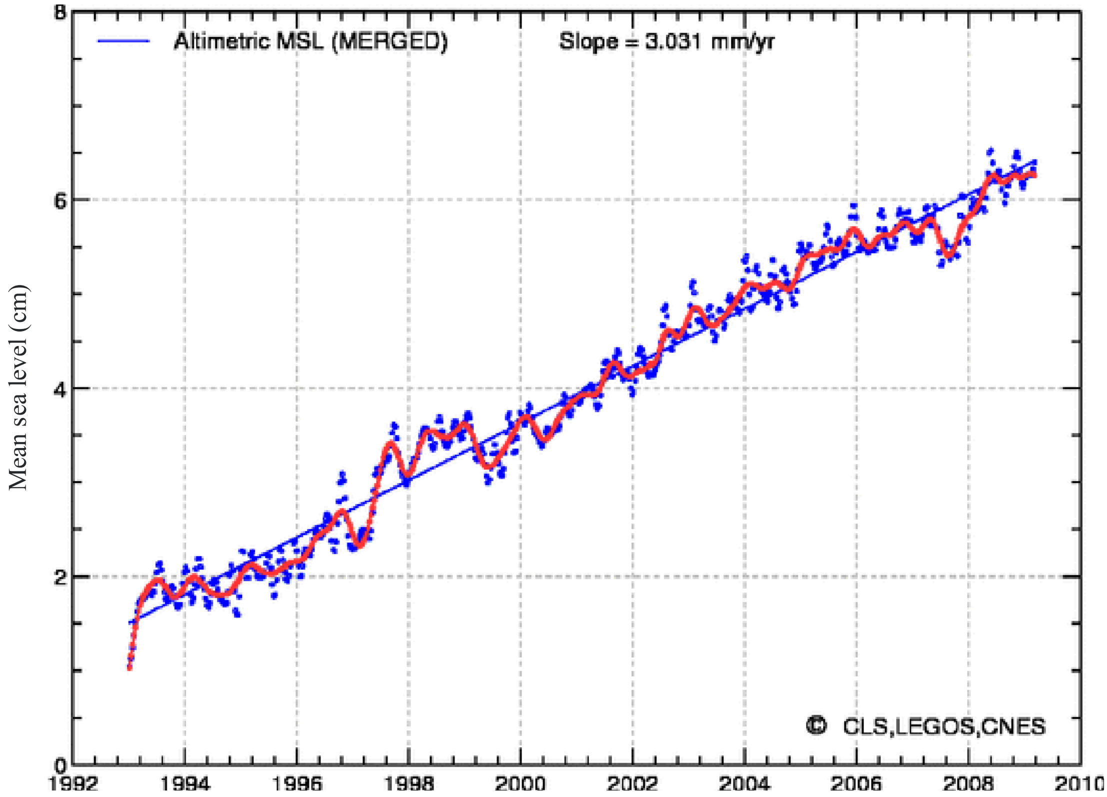
Understanding the increase in SST and anthropogenic heat input to the surface ocean also has important ramifications for quantifying and predicting sea-level rise. Mean sea level rise could be a sign of global warming. Monitoring this level is an application of altimetry, and one of the main issues in Environmental sciences of the 21st century.

It is quite difficult to separate the natural variability of the climate from the effects of global warming. Measurements of the mean sea levels have been derived for 15 years from satellite observations. These observations have been consistent and have produced an accurate time series of satellite observations. However, such a period of time is short. In addition to that, it is necessary to indicate that human induced perturbation is added to the natural climate variability. Therefore, climate change signals can be detected only if they are greater than the background natural variability. Detecting global climate change is much more demanding than monitoring regional impacts.

Part of the observed rise in sea level is due to increased water temperature. The rest could come from melting glaciers and fluctuations in the level of continental waters. Figure 4 shows that the rise is about 3.3 mm/year, roughly 5 cm within 15 years.

FIGURE 4

Mean sea level rise



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However, Mean rise in sea level is only part of the story. The rise in the level of the oceans is far from being uniform. In certain ocean regions the sea level has risen (by up to 20 mm a year in some places), while in other regions it has fallen an equivalent amount. These regional differences, observed by TOPEX/JASON since 1993, mostly reflect sea level fluctuations over several years.

One major concern is that rising sea levels may inundate coastal regions throughout the world, and may completely submerge low islands. While this effect is expected to be significant over a relatively large time-scale (decades to centuries), topography derived from satellite observations (SAR's such as the Shuttle Radar Topology Mission and optically via ASTER) can aid by identifying those areas which are vulnerable.

Sea-surface temperature measurements not only revealed important information about ocean circulations (e.g. the Gulf Stream), but also advanced climate research by providing detailed information on the heat input into the ocean. Ocean colour combined with SST observations led to new discoveries about the physical-biological coupling in the ocean, with important implications for the ocean's role in the carbon cycle.

Satellite observations afford the only means of estimating and monitoring the role of ocean biomass as a sink for carbon. In particular, the fundamental question of whether the biological carbon uptake is changing in response to climate change can only be addressed with satellite measurements. It requires not only ocean colour measurements (phytoplankton biomass and productivity) but also coincident space-based observations of the physical ocean environment (circulation and mixing), land-ocean exchanges (through rivers and tidal wetlands), and other factors such as winds, tides, and solar energy input to the upper ocean. Observing linkages between the physical and chemical environment and the biology of the ocean is a significant achievement of observations from space.

3.2 Soil moisture and ocean salinity

Evaporation, infiltration, and recharge of the groundwater usually occur through the unsaturated vadose zone which extends from the top of the ground surface to the water table. The root zone of the vegetation, wherein vegetation takes-up water, is within the vadose zone and is the interface between the vegetation and the hydrological system. The amount of water available in the vegetation controls plant transpiration and photosynthesis and thus CO_2 sequestration. The amount of water in the vadose zone is also directly linked to the ability of the soil to produce drainage after rainfall. The soil-vegetation-atmosphere transfer (SVAT) schemes used in meteorology and hydrology are designed to describe the basic evaporation processes at the surface and the partitioning of water between vegetation transpiration, drainage, surface runoff, and soil moisture content. A realistic initial value of the amount of water in the vadose zone must be provided to SVAT models.

When dealing with bare soil or sparsely covered vegetation, evaporation rate and runoff can be calculated from the surface soil moisture time series. When dealing with vegetation covered surfaces, the amount of water in the vegetation (vegetation optical depth) has to be accounted for. The vegetation optical depth itself may be a very useful product to monitor the vegetation dynamics.

Knowledge of the distribution of salt (salinity) in the global ocean and its annual and inter-annual variability are crucial in understanding the role of the ocean in the climate system. Salinity is fundamental in determining ocean density and hence the thermohaline circulation. Ocean salinity is also linked to the oceanic carbon cycle, as it plays a part in establishing the chemical equilibrium, which in turn regulates the CO_2 uptake and release. Therefore the assimilation of sea surface salinity measurements into global ocean bio-geo-chemical models should improve estimates of the absorption of CO_2 by the oceans.

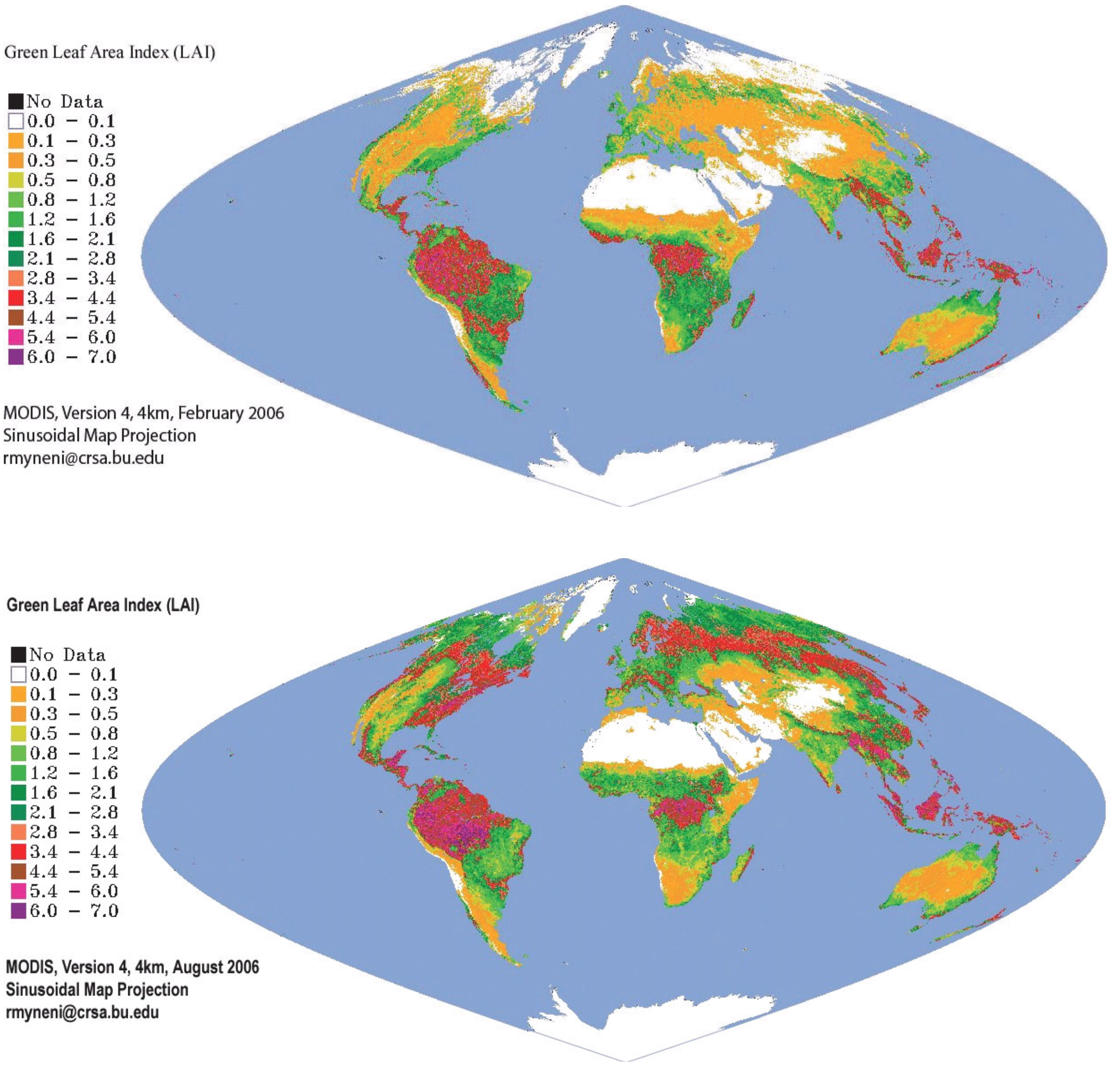
The mission of the SMOS satellite is to monitor the soil moisture along with the SMAP mission and the ocean salinity along with the Aquarius mission.

4 The biosphere

Satellite monitoring of the dynamics of Earth's vegetation is essential to understanding global ecosystem functioning and response to climate variability and climate change. With the MODIS instrument on the TERRA and AQUA satellites, this observation (Fig. 5) has become more precise by its extension to a biophysical measurement.

FIGURE 5

Green Leaf Indices from MODIS showing seasonal changes in vegetation



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Source: *Earth Observations from Space: the First 50 Years of Scientific Achievements,* p. 75, 2008, downloadable from URL: http://www.nap.edu/catalog/11991.html.

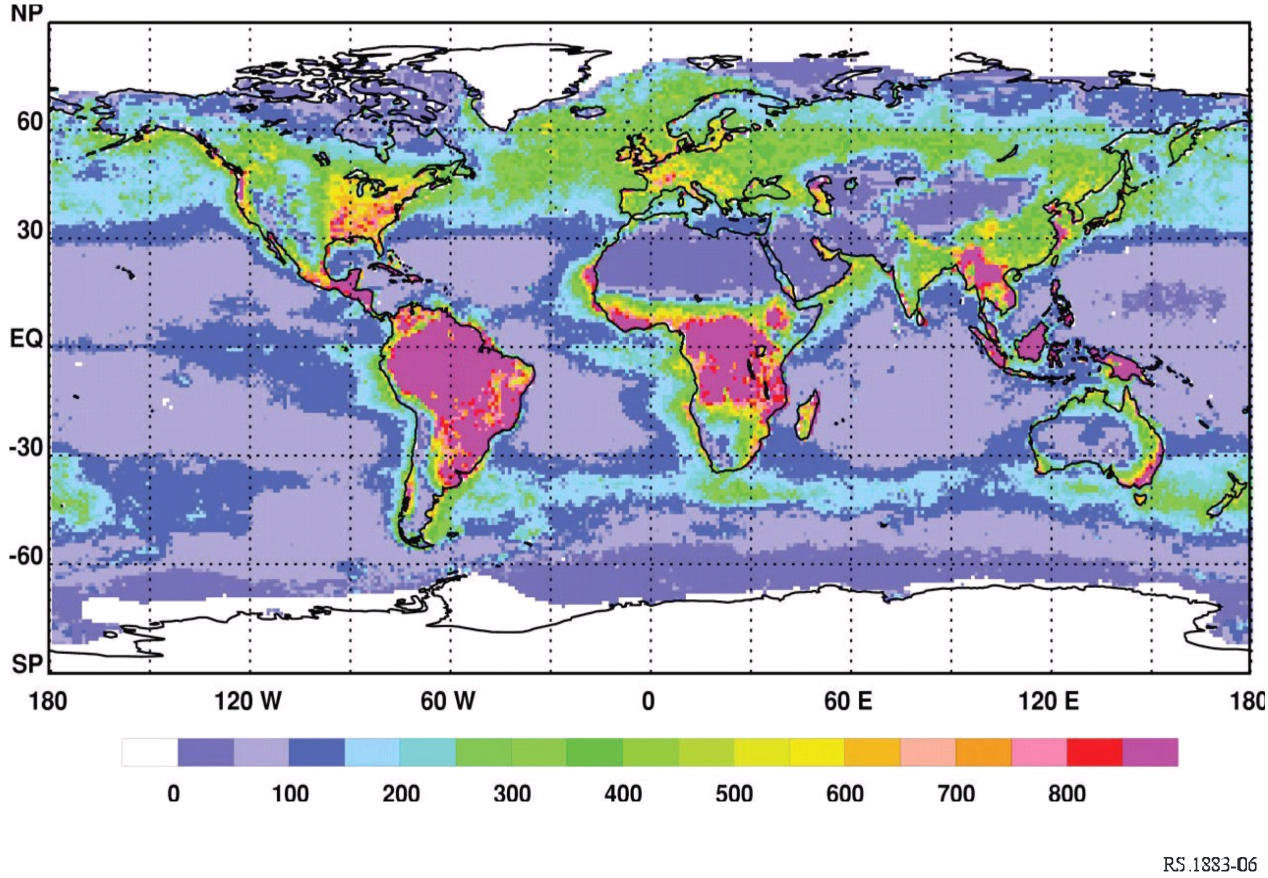
Climate change studies have also been aided by satellite-based research into the Earth's carbon cycle and energy fluctuations.

Net primary productivity (NPP) is defined as the net flux of carbon from the atmosphere into green plants per unit time. Satellite observations of NPP make invaluable contributions to the fundamental understanding of climate change impacts on the biosphere. NPP is influenced by climate and biotic controls that interact with each other. The contribution of land and ocean to NPP is nearly equal (Fig. 6), but there is striking variability in NPP at a local level. Because phytoplankton life cycles are orders of magnitude shorter (days versus years or decades) than those of terrestrial plants, phytoplankton may respond to climate influences on ocean circulation, mixing, and the supply of nutrients and light much more quickly than plants in terrestrial ecosystems. Thus, the oceanic component (roughly half) of the carbon cycle is expected to respond more quickly to climate changes.

FIGURE 6

Global annual NPP (in grams of carbon/m^2/year) for the biosphere, calculated from the integrated CASA-VGPM (vertically generalized production model) model. Input data for ocean colour from CZCS sensor are averages from 1978 to 1983

The land vegetation index from the AVHRR sensors is the average from 1982 to 1990



Source: *Earth Observations from Space: the First 50 Years of Scientific Achievements,* p. 77, 2008, downloadable from URL: http://www.nap.edu/catalog/11991.html.

Launched in 1978, the Coastal Zone Colour Scanner showed that ocean productivity could be observed using visible and near-infrared bands; however, CZCS measurements were saturated over land and thus unusable.

The AVHRR on the National Oceanic and Atmospheric Administration's (NOAA) polar-orbiting weather satellites has obtained a continuous record of daily global observations since 1978, acquiring both red and near-infrared bands. The daily AVHRR data set now spans more than 25 years and is the longest continuous global record available of terrestrial productivity, phenology (the study of periodic plant and animal life cycle events and how these are influenced by seasonal and interannual variations in climate), and ecosystem change for monitoring biospheric responses to climate change and variability.

Although AVHRR was not designed for climate monitoring, continuing improvements in calibration and re-analysis have produced a consistent record for monitoring and assessing past and future biospheric responses resulting from climate change and variability and anthropogenic activities.

A major area of concern is the effect of climate change on agriculture. As the climate warms, the growing season lengthens and northern regions become more productive while southern regions, facing extreme heat, become less productive. Agricultural productivity has been monitored from space for decades. The normalized difference vegetation index (NDVI) has the property of ranging from −1 to +1, and having values around +1 when green vegetation is observed. Technically, the NDVI is the Near-Infrared datum minus the Red datum (visible) divided by the sum of the two.

In the past decade, NDVI data from AVHRR have become a critical component in monitoring climate change, assessing changing length and timing of the growing season, and monitoring the state of the biosphere and other ecosystem phenomena. Long-term records of NDVI have revealed its increase in response to a warming climate during the 1980s and early 1990s, but this trend has levelled off recently. Changes in the planetary NDVI (greenness) were strongly correlated with daily dynamics of terrestrial intercepted photosynthetically active radiation and atmospheric CO_2 concentrations. There is a strong negative correlation between NDVI and atmospheric CO_2 such that NDVI is high when CO_2 concentrations are low and vice-versa. This temporal pattern in ecosystem photosynthesis and respiration demonstrates the dynamic coupling between the biosphere and the atmosphere.

5 Conclusion

Satellite-borne sensors have provided data fundamental to our understanding of the planet and the effects of climate change. Since such instrumentation continues to provide essential data, it should be protected into the future.

Annex 2

Status of observations of major climate variables and forcing factors

The following summary of status of space-based (and in some cases, supporting ground-based) observations of critical climate variables is from the U.S. National Research Council's Report – Earth Science and Applications from Space, National Academies Press, Washington, DC, 2007 (Table 9.A.1, p. 298-303).

This document is available at: http://www.nap.edu/catalog/11820.html.

The Report noted that:

"although the table provides a valuable perspective, its limitations should also be recognized:

1. in some cases, it lists variables that can be obtained through several techniques, but not all techniques are listed;
2. it is limited to satellite observations that are in low-Earth orbit, although a number of the objectives listed can also be achieved through retrievals with multispectral imagery and sounder data from platforms in geostationary and other orbits;
3. few space-based observations can be taken as physical measurements in their own right, and interpretations are often revised as more comparisons are made between inferences based on space-based observations and alternative measures of the physical variables."

Numbers in parentheses refer to the essential climate variables listed in Appendix 1 of GCOS (Global climate observing system), 2003. This document is the second Report on the adequacy of the global observing systems for climate in support of the UNFCCC GCOS-82, WMO Tech. Doc. 1143.

Missions 1, 2, 3, and 4 refer to desired missions, not missions currently planned. The fifth column in the original table was omitted as it tracked internal data sources.

Climate Change and Variability Panel's summary of status of major climate variables and forcing factors

Measurement	Strategy	Current status	Follow-on (2010-2020)
Total solar irradiance (1.2)	Direct measurement	SORCE launched 2003; Glory (TIM only) 2008	NPOESS TSIS-GFE
Earth radiation budget	Multispectral imager combined with broadband radiometers: Scene identification, top of the atmosphere fluxes	MODIS/CERES on Terra (2000), Aqua (2002)	VIIRS/CERES on NPOESS, C1 (2013), Mission 2
Surface radiation budget	Multispectral imager combined with broadband radiometers: Scene identification, top of atmosphere fluxes, radiative transfer modelling	MODIS/CERES on Terra (2000), Aqua (2002)	VIIRS/CERES on NPOESS, C1 (2013) Mission 2
	Surface-based radiometers: ARM, BSRN, CMDL, SURFRAD sites, sparsely located		
Tropospheric aerosols (1.3): geographic and vertical distribution of aerosols, optical depth, size, shape, single scattering albedo	Multispectral imagers: Provide optical depth, some inference of size over oceans and dark surfaces	AVHRR since 1981 (NOAA 7), currently on NOAA 17, 18, 19 VIRS on TRMM (1997) MODIS, MISR on Terra (2000) MODIS on Aqua (2002)	VIIRS on NPP, NPOESS
	UV radiometer-imager: Provide optical depth, some inference of absorption for elevated aerosol layers	OMI on AURA (2004) OMPS on NPP (2010)	OMPS on NPOESS, C3 Mission 1
	Polarimeters: Provide optical depth, size, shape, single-scattering albedo	POLDER on PARASOL (2005) APS on Glory (2008) limited to subsatellite ground track	APS on NPOESS, C3 Mission 1
	Lidar: Provide vertical profile of aerosol concentration, some inference of size and shape	CALIPSO (2006)	Mission 1
	Surface multispectral radiometers	AERONET, ARM	VIIRS on NPOESS, Mission 1
	Surface and Earth broadband flux measurements	CERES on Terra (2000), Aqua (2004) combined with BSRN, ARM, SURFRAD sites	CERES on NPOESS, Mission 2
Stratospheric aerosol properties, optical depth, size, shape, single-scattering albedo (1.3)	Limb and solar occultation measurements: profile of aerosol extinction	HIRDLS on Aura, infrared radiometer; SAGE II on ERBS (1984-2006); SAGE III on Meteor (2002-2006) SciSat (Canadian-U.S.)	None
	Limb-scattered light: profile of aerosol optical depth		OMPS on NPP (2010), NPOESS
	Lidar: Vertical profile of aerosol concentration, some inference of size and shape	CALIPSO (2006)	Mission 1

Measurement	Strategy	Current status	Follow-on (2010-2020)
Cloud properties (1.2): geographic and vertical distribution, water droplet effective radius, ice-cloud crystal habitat and size, mixed-phase cloud water/ice ratio and hydrometeor size and visible optical depth, cloud liquid and ice water amounts	Multispectral imagers: Properties of single effective cloud layer	AVHRR since 1981 (NOAA 7), currently on NOAA 17, 18, 19 inferences of hydrometeor size, but not phase VIRS on TRMM; MODIS on Aqua and Terra provide inference of hydrometeor phase	VIIRS on NPP, NPOESS provides inference of hydrometeor phase
	Multiple-view radiometers, polarimeters	MISR on Terra, cloud altitude from stereo imaging POLDER on PARASOL, hydrometeor size and phase from polarimetry APS on Glory (2008), phase from polarimetry	APS on NPOESS, C3 hydrometeor phase from polarimetry
	15 µm sounders, imagers: Cloud-layer pressure for effective single-layered cloud system, even for optically thin cirrus	HIRS on NOAA 17, 18, 19 MODIS on Terra, Aqua AIRS on Aqua (2002)	CrIS on NPOESS
	Microwave imagers: inference of cloud liquid water over oceans	SSM/I on DMSP TMI on TRMM, AMSR-E on Aqua, CMIS on NPOESS	
	Lidar: Upper boundary, extinction for optically thin clouds with polarization, particle phase	CALIPSO (2006)	Mission 1
	Cloud radar: Cloud boundaries, vertical distribution of liquid water, rates of drizzle when precipitation is light	CloudSat (2006)	Mission 1
Ozone: stratosphere, troposphere (1.3)	UV radiometer-imager: Provides tropospheric column ozone, coarse vertical resolution profiles of stratospheric ozone	OMI on Aura (2004)	OMPS Nadir on NPP (2010), NPOESS, C3
Trace gases controlling ozone (HCI, N_2O, CH_4, H_2O, HNO_3)	Infrared sounders: Provide vertical profiles of tropospheric, stratospheric ozone	HIRDLS on Aura; TES on Aura also provides limb viewing (not being used after 2005); AIRS on Aqua (2002)	None
	Microwave limb sounding: Provides vertical profile of stratospheric ozone	MLS on Aura	None
CO_2 (1.3)	Near-IR spectrometer: High-precision column concentrations of CO_2	OCO (2008); goal is to achieve accuracies sufficient to allow determinations of sources and sinks; Surface-based networks (WMO GAW, NOAA, AGAGE)	None
	Infrared sounders:	AIRS on Aqua (2002)	None

Measurement	Strategy	Current status	Follow-on (2010-2020)
CH_4 (1.3)	Infrared spectrometer: High-precision column concentrations of CH_4	TES on Aura; Surface-based networks (WMO GAW, NOAA, AGAGE)	None
	Infrared sounders:	AIRS on Aqua (2002)	None
Land-surface cover and surface albedo (3) (snow cover, glaciers, ice caps covered later)	Multispectral imagery: Vegetation index, inference of surface albedo	AVHRR on NOAA 17, 18, 19: inferences of atmospherically corrected spectral albedos; MODIS on Terra (2000), Aqua (2002); Landsat series	VIIRS on NPP (2010), NPOESS
	Hyperspectral imagery: Vegetation types, land cover	Hyperion (EO-1)	Mission 1
Temperature (1.2): vertical profiles	Infrared, microwave sounders: Vertical profiles of layer temperatures	HIRS/MSU since 1979 currently on NOAA 17, 18, 19; SSM/I on DMSP (1995, 1997, 1999); AIRS/AMSU on Aqua (2002)	CrIS, ATMS on NPP (2010), NPOESS
	GPS radio occultation: Vertical profiles with resolution of about 0.5-1 km near surface	GPS on CHAMP (2000), COSMIC (2006)	Mission 2
	Surface network: Radiosonde temperature profiles, WMO sonde network (1959)		
Water vapour (1.2): column amounts, vertical profiles	Microwave imaging: Column water-vapour amounts over oceans	SSM/I on DMSP polar satellites (1995, 1997, 1999)	ATMS on NPP (2010), MIS on NPOESS
	Multispectral imagery: Column amounts from near-IR water vapour channels	MODIS on Terra (2000), Aqua (2002)	None
	Infrared sounders: Water-vapour layer amounts at relatively coarse vertical resolution in troposphere	HIRS data from 1979 (TIROS-N), currently on NOAA 17, 18, 19	CrIS on NPP (2010), NPOESS
	High-spectral-resolution infrared radiometers: Water-vapour layer amounts at finer vertical resolution in troposphere	AIRS on Aqua (2002); TES on Aura (2004)	CrIS on NPP (2010), NPOESS
	Infrared, microwave limb-scanning radiometers: Water-vapour layer amounts in upper troposphere, stratosphere	TES, MLS on Aura (2004)	None
	GPS-radio occultation: Profiles of temperature, water vapour with up to about 0.5 km vertical resolution near surface	CHAMP (2000), COSMIC (2007)	Mission 2
	Surface network: Radiosonde water-vapour profiles, WMO sonde network (1959)		

Measurement	Strategy	Current status	Follow-on (2010-2020)
Fire disturbance (3)	Near-IR thermal imagery: High-spatial-resolution detection of fire hotspots	AVHRR data from 1981 (NOAA 7), currently on NOAA 17, 18, 19; MODIS on Terra (2000), Aqua (2002)	VIIRS on NPP (2010), NPOESS
Land biomass, fraction of photosynthetically active radiation	Multispectral imagery: Index of vegetation, inference of FAPAR	AVHRR data from 1979 (NOAA 6), currently on NOAA 17, 18, 19; MODIS on Terra (2000), Aqua(2002); SeaWiFS	VIIRS on NPP (2010), NPOESS Mission 1
(FAPAR) (3)	Radar: Land cover from C-band radar backscatter	RADARSAT 1 (1995), RADARSAT 2 (2007), data commercially available	None
Glaciers, sea ice, ice caps (3)	Multispectral imagery: Area coverage	AVHRR data from 1979 (TIROS-N), currently on NOAA 17, 18, 19; MODIS on Terra (2000), Aqua (2002)	VIIRS on NPP (2010), NPOESS
	Microwave imagers: Area coverage	SSM/I on DMSP (1995, 1997, 1999); AMSR-E on Aqua; TMI on TRMM (1997)MIS on NPOESS	
	Radars: Ice area and flow, sea-ice thickness from topography	RADARSAT 1 (1995), RADARSAT 2 (2007), data commercially available	Mission 3
	Lidar: Ice elevation	GLAS on ICESat (2003)	Mission 1
	Gravity satellite: Ice mass when combined with measure of topography	GRACE (2002)	GRACE follow-on
Permafrost, seasonally frozen ground (3) Snow cover (and snow water equivalent) (3)	Radars combined with microwave radiometers: Combination of area, roughness, topography to provide snow-water equivalent	RADARSAT 1 (1995), RADARSAT 2 (2007), data commercially available	No planned follow-on
Groundwater (3)	Microwave imagers: Soil moisture except for areas covered by ice-snow and heavily forested areas	SSM/I on DMSP (1995, 1997, 1999); AMSR-E on Aqua (2002)MIS on NPOESS	
	Gravity satellite: Large-scale groundwater (requires in situ auxiliary observations)	GRACE (2003)	GRACE follow-on
Lake levels (3)	High-resolution multi-spectral imagery: Lake areas	Landsat 7 (1999)	LDCM
	Radars: Lake area	RADARSAT 1 (1995), RADARSAT 2 (2007), data commercially available	No planned follow-on
	Lidar: Water-surface elevation	GLAS on ICESat (2003)	Mission 1

Measurement	Strategy	Current status	Follow-on (2010-2020)
River discharge (3)	High-resolution imagery: Lake, river areas	Landsat 7 (1999)	LDCM
	Lidar altimeter: River levels	ICESat (2002)	Mission 1
	Radar: Lake, river areas	RADARSAT 1 (1995), RADARSAT 2 (2007), data commercially available	No planned follow-on
Leaf-area index (LAI) (3)	Multispectral imagers: Vegetation index	AVHRR, data since 1981 (NOAA 6), currently on NOAA 16, 17, 18; MODIS on Terra (2000), Aqua (2002); MISR on Terra (2000); SeaWiFS (1997); VIIRS on NPP (2010)	VIIRS on NPOESS
	High-spatial-resolution multispectral imagers: Vegetation index at higher spatial resolution	Landsat 7 (1999); ASTER on Terra (2000); EO-1	LDCM; Mission 1
Sea level	Altimeter: Ocean sea-level height	Jason 1 (2001) GFO	ALT on NPOESS, Mission 4; GRACE follow-on
	SARs: Area of coastal zones	RADARSAT 1 (1995), RADARSAT 2 (2007), data commercially available	None
Sea state (2.1), surface wind (1.1)	Microwave imagers: Surface windspeed	SSM/I on DMSP (1995, 1997, 1999); AMSR-E on Aqua (2002) MIS on NPOESS	
	Scatterometer: Surface wind vector	QuikSCAT (1999); ASCAT on MetOp)	ASCAT on MetOp, Mission 4
Ocean colour (2.1)	Multispectral imagers with UV-blue capabilities: Surface-leaving radiances	SeaWiFS (1997); MODIS on Terra (2000), Aqua (2002)	VIIRS on NPP (2010) and NPOESS
Ocean surface (2.1), sub-surface temperature (2.2)	Multispectral imagery: Sea-surface temperature	AVHRR, data since 1981 (NOAA 7), currently on NOAA 16, 17, 18; VIRS on TRMM (1997); MODIS on Terra (2000), Aqua (2002)	VIIRS on NPP (2010) and NPOESS
	Infrared-microwave sounders: Sea-surface temperature	AVHRR on NOAA 16, 17, 18 AIRS; AMSR-E on Aqua (2002); MODIS on Aqua (2002), Terra (1999)	CrIS/ATMS on NPP (2010);MIS on NPOESS
	Expendable profiling floats: Profiles of temperature, temperature at depth of neutral buoyancy, surface	ARGO floats	

Measurement	Strategy	Current status	Follow-on (2010-2020)
Ocean surface (2.1), subsurface salinity (2.2)	Microwave radiometer and scatterometer: Surface salinity, ocean roughness		AQUARIUS (2010)
	Expendable profiling floats: Profiles of salinity, salinity at depth of neutral buoyancy	ARGO floats	
Ocean surface (2.1), subsurface currents (2.2)	Altimeter: Ocean-surface height from which currents derived	Jason 1 (2001)	ALT on NPOESS, Mission 4
	Gravity satellite: Subsurface or barotropic mass shifts (computed in conjunction with surface altimeter measurements)	GRACE (2002)	GRACE follow-on
	Expendable profiling floats: Position drift at depth of neutral buoyancy (and surface with some caveats)	ARGO floats	
Subsurface phytoplankton (2.2)			
Precipitation (1.1)	Microwave imagers: Rainfall rate over oceans	SSM/I on DMSP (1995, 1997, 1999); TMI on TRMM (1997); AMSR-E on Aqua (2002) MIS on NPOESS, GPM (2012)	
	Precipitation radar: Vertical structure of rain rates	TRMM (1997)	GPM (2012)
	Cloud radar: Rate for light drizzle	CloudSat (2006)	Mission 1