International Telecommunication Union

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Radiocommunication Sector of ITU

Recommendation ITU-R RS.1883-1

(12/2018)

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

RS Series

Remote sensing systems

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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.1883-1

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

(2011-2018)

Scope

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

Keywords

EESS (active), EESS (passive), Earth exploration-satellite service, remote sensing, climate change

Related ITU-R Recommendations and Reports

Recommendation ITU-R RS.1859 – Use of remote sensing systems for data collection to be used in the event of natural disasters and similar emergencies

Report ITU-R RS.2178 – The essential role and global importance of radio spectrum use for Earth observations and for related applications

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 crucial to the study of climate change are truly consistent global Earth observing capabilities which are 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;

e) that over time, the sensing capabilities improve and the sensor sensitivity increases for these satellite-borne remote sensors;

f) that EESS and MetSat systems are essential for monitoring and predicting climate change, monitoring oceans, weather and water resources, weather forecasting and assisting in protecting biodiversity,

recognizing

a) that Resolution **673 (Rev.WRC-12)** resolves: 1) to continue to recognize that the use of spectrum by Earth observation applications has a considerable societal and economic value, as described in Annexes 1 and 2; 2) to urge administrations to take into account Earth observation radio-frequency requirements and in particular protection of the Earth observation systems in the related frequency bands; 3) to encourage administrations to consider the importance of the use and availability of spectrum for Earth observation applications prior to taking decisions that would negatively impact the operation of these applications,

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 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;

d) that the ITU-D Report D-STG-SG02.24-2014, which answers ITU-D Question 24/2 regarding ICT and climate change, noted the serious effects of climate change and the role of remote sensing in monitoring it and understanding the processes involved,

recommends

1 that administrations should become familiar with the applications of satellite-borne remote sensors to the study of climate change and should recognize their importance as explained in Annex 1;

2 that administrations and operators should continue supplying climate-related environmental data as recognized in Annex 2;

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 similar, 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 or 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. A single instrument on a polar orbiting satellite can observe the entire Earth on a daily basis, while instruments on geostationary satellites continuously monitor the diurnal cycle of the disk of Earth below them. Therefore, together the polar and geostationary environmental satellites maintain a constant watch on the entire globe.

These environmental 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.

Improved understanding of the Earth system – its weather, climate, oceans, land, geology, natural resources, ecosystems and natural and human-induced hazards – is essential to better predict, adapt and mitigate the expected global changes and their impacts on human civilisation.

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 following observations:

– The Earth’s surface has been monitored continuously for decades by the Landsat series (since 1973) and the SPOT series (since 1986);

– Sea ice concentrations have been monitored continuously since 1978 by Numbus-7 and then the DMSP series;

– Sea surface winds have been monitored intermittently since 1996 by ADEOS-1 and -2, QUIKSCAT, the RapidSCAT instrument on the ISS-, and lately by OSCAT on OceanSat-2, KU-RFSCAT on HY-2A, and ASCAT on MetOp*;*

– Sea surface heights and temperatures have been monitored continuously since 1992 by TOPEX/Poseidon and the Jason series; and

– Soil moisture and ocean salinity have been monitored since 2009 by the SMOS, Aquarius, and SMAP.

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 and in observing where persistent cloud cover obscures the surface (e.g. the Amazon, central Africa, and island nations).

Sea level rise is expected to produce the earliest serious impact on society due to climate change. Sea level rise has been attributed to rising ocean temperatures and the addition of water from glacial ice. Should all the glacial ice over Greenland melt, the seas would rise by an estimated 7 metres; should all the glacial ice over Antarctica melt, the seas would rise by an estimated 70 metres. Around 40% of the Earth's people live within 100 km of a sea coast and could be at risk of flooding in the long term (centuries to millennia). Eight of the ten largest cities in the world are located on a coast. Those cities and all low-lying coastal areas would be seriously affected by sea levels rising only a few meters. A sea level rise of that magnitude is forecast to occur within the next century or two. Both ocean temperature and glacial mass, contributors to sea level rise, are measured by satellite instruments.

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.

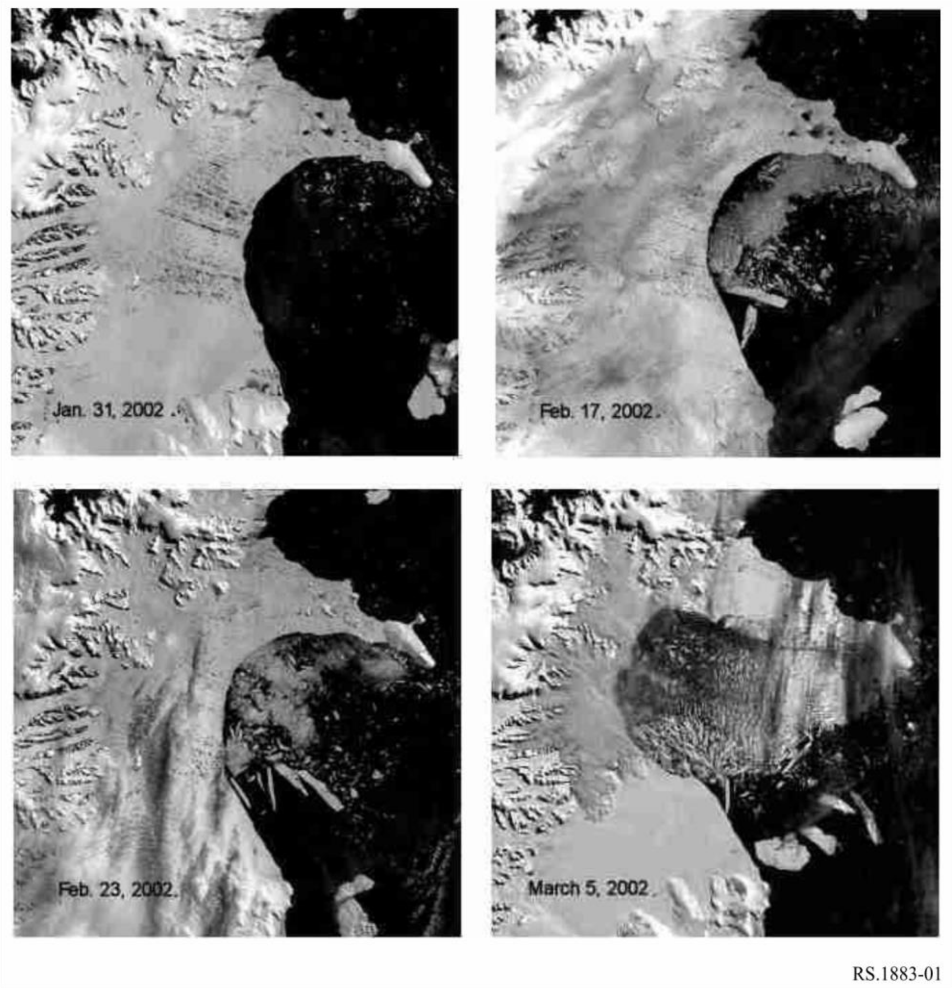
Because glaciers respond to past and current climatic changes, a complete global glacier inventory is being developed to track the current extent as well as the rates of change of the world's glaciers. The Global Land Ice Measurements from Space project is using data from the ASTER and the Landsat Enhanced 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.

Large cracks on ice shelves in the Antarctic can also be monitored from the space. Routine Antarctic summer observations by the combination of Copernicus Sentinel-2 optical images and Sentinel-1 radar products have demonstrated their value for monitoring rapid environmental change and providing information crucial to informed decisions on matters of safety and security in Antarctica.

FIGURE 1

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



Sea ice is formed from ocean water that freezes, whether along coasts or to the sea floor (fast ice) or floating on the surface (drift ice) or packed together (pack ice). The most important areas of pack ice are the polar ice packs. Because of vast amounts of water added to or removed from the oceans and atmosphere, the behaviour of polar ice packs have a significant impact of the global changes in climate. 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 inter-annual variability of sea ice. Since 2000, record summer ice minima have been observed during four out of the past six years in the Arctic (see Fig. 2). 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, as shown in Fig. 3. The linear rate of decline for February is 46 900 square kilometres per year, or 3 percent per decade. Melting and freezing of ice (both sea ice and glacial ice) also influence ocean salinity and link SSS to regional sea level change. 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 1979 and 2017
The magenta line shows the 1981 to 2010 median sea ice extent for the month

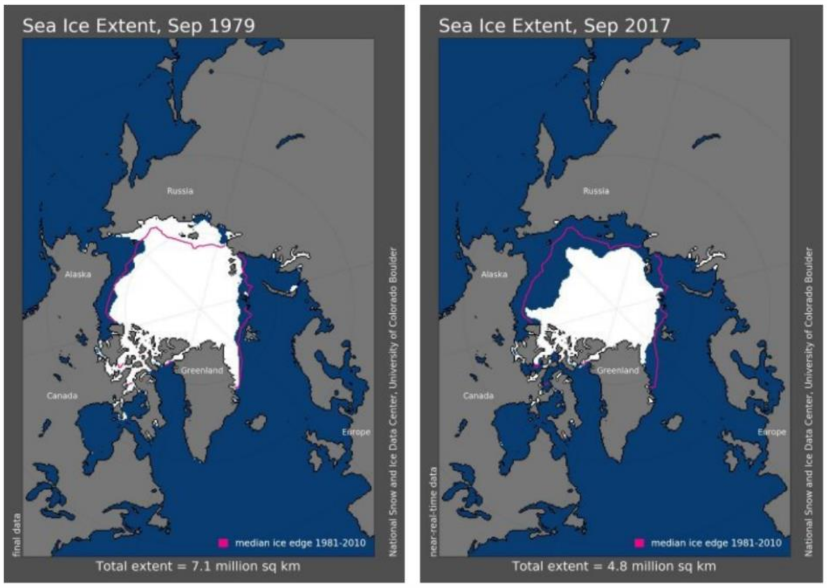


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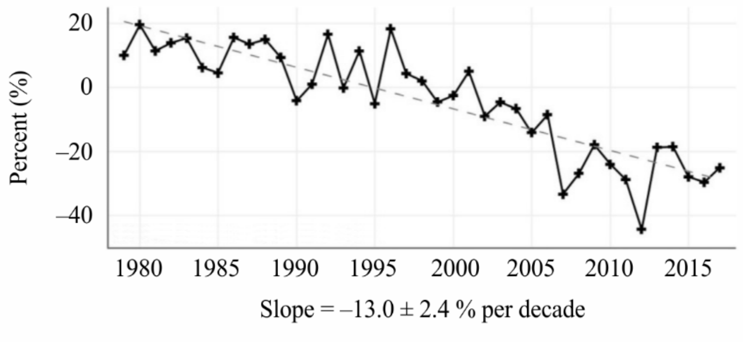
FIGURE 3

September sea ice extent anomaly, from 1979 to 2017



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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.

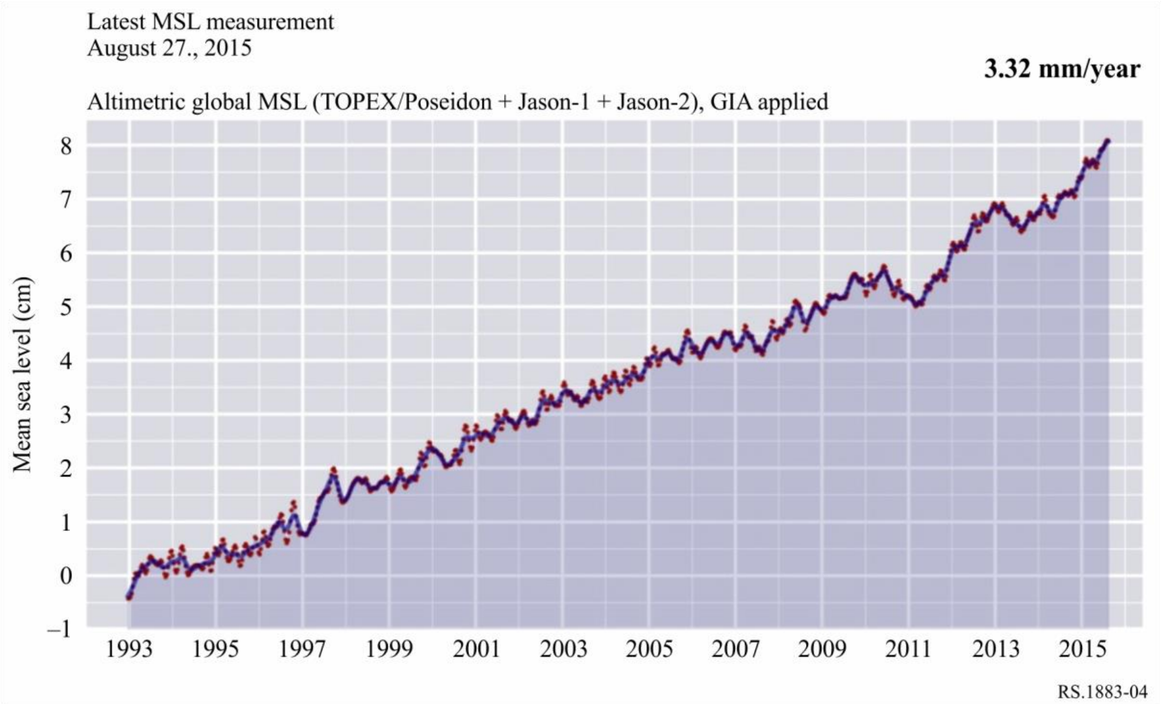
Understanding the increase in SST and anthropogenic heat input to the surface ocean also has important ramifications for quantifying and predicting sea-level rise. Mean sea level rise could be a sign of global warming. Monitoring this level is an application of altimetry, and one of the main issues in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



Source: © CNES, LEGOS, CLS

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 TerraSAR-X, 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.

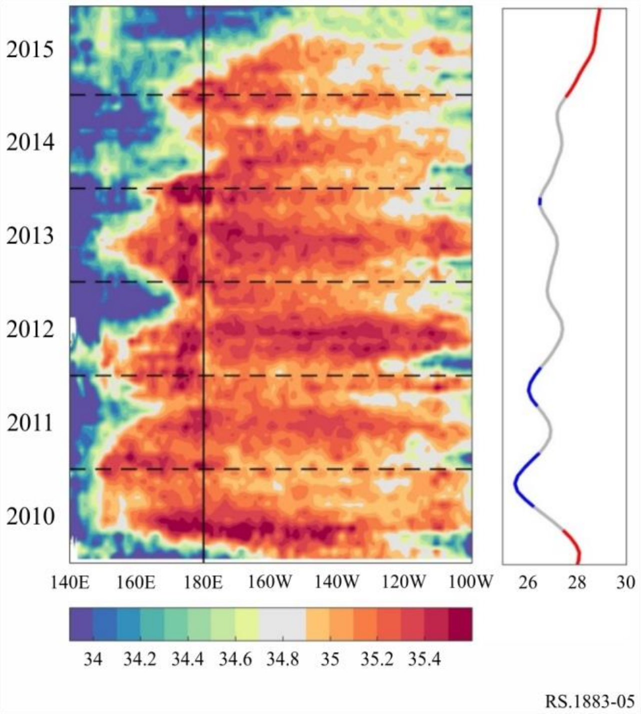
When dealing with bare soil or sparsely covered vegetation, evaporation rate and runoff can be calculated from the surface soil moisture time series. When dealing with vegetation covered surfaces, the amount of water in the vegetation (vegetation optical depth) has to be accounted for. The vegetation 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 salinity of the ocean's surface varies across the world, controlled by the balance between evaporation, precipitation and river runoffs, as well as by ocean dynamics. Launched in 2009, SMOS satellite has provided the longest continuous record of sea-surface salinity measurements from space. The satellite acquired sea-surface salinity observations in early 2010 as a weak El Niño was fading out and reversed into a strong La Niña, which lasted until 2012. Lower than usual salinities were observed in early 2010 in the equatorial Pacific as the Western Pacific Fresh Pool extended east. The pool retracted back westward as La Niña settled in. Recently SMOS satellite found a rise in fresh water in the tropical Pacific Ocean during 2016 El Niño event (see Fig. 5).

FIGURE 5

Salinity at the equator: Average SMOS surface salinity around the Equator (2ºS–2ºN) from 2010 to 2015. The fresh pool (in blue and green) in the western equatorial Pacific Ocean extends east during El Niño events (early 2010 and 2015) and is reduced to the west during La Niña events (end of 2010 and 2011). Right: the ‘Niño 3.4 Index’, based on sea-surface temperature observations, which indicates El Niño events in red and La Niña events in blue



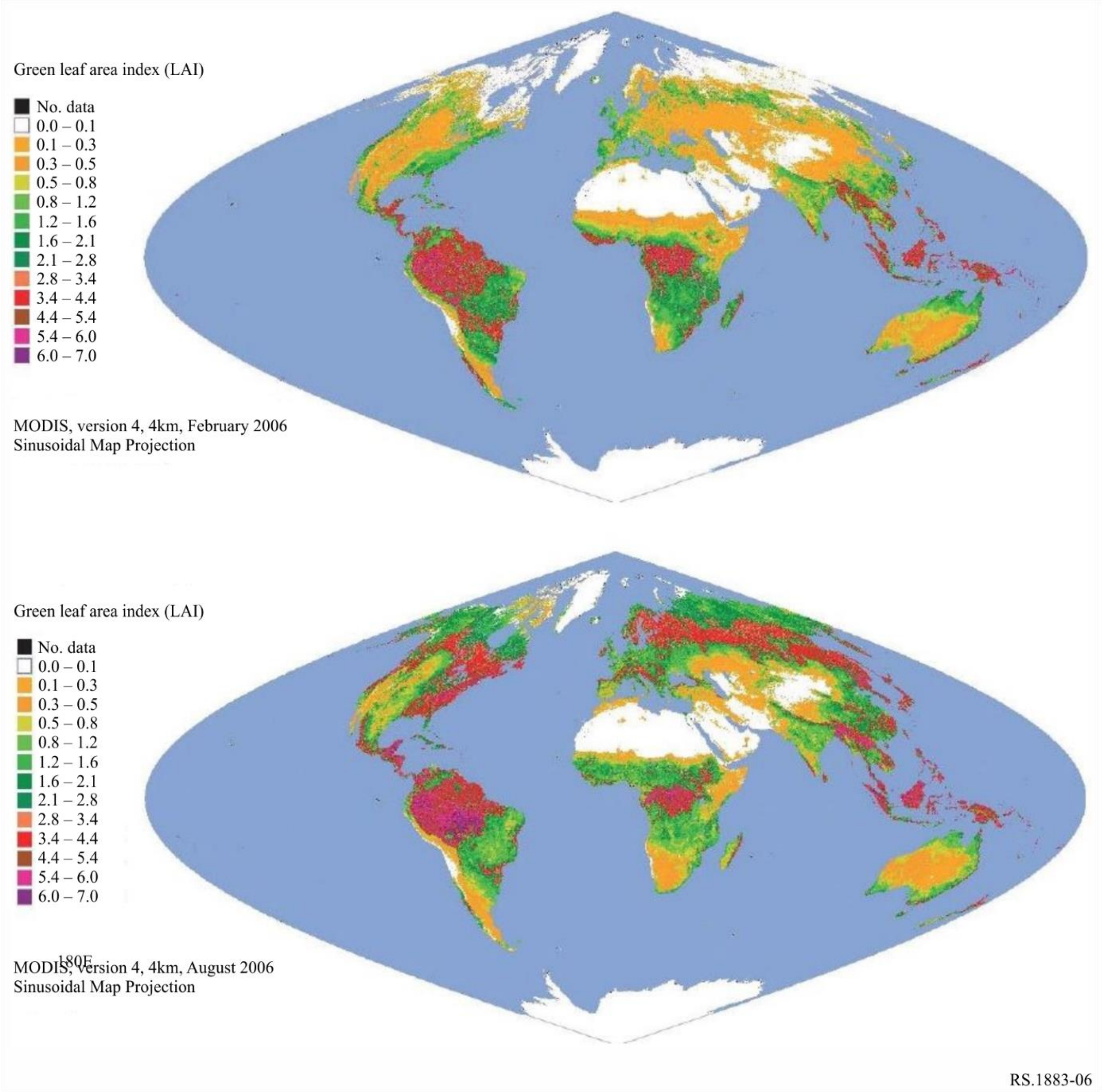
The mission of the SMOS satellite is to monitor the soil moisture along with the SMAP mission and the ocean salinity along with the Aquarius mission.

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 and VIIRS on SUOMI NPP satellite, this observation (Fig. 6) has become more precise by its extension to a biophysical measurement.

FIGURE 6

Green Leaf Indices from MODIS showing seasonal changes in vegetation



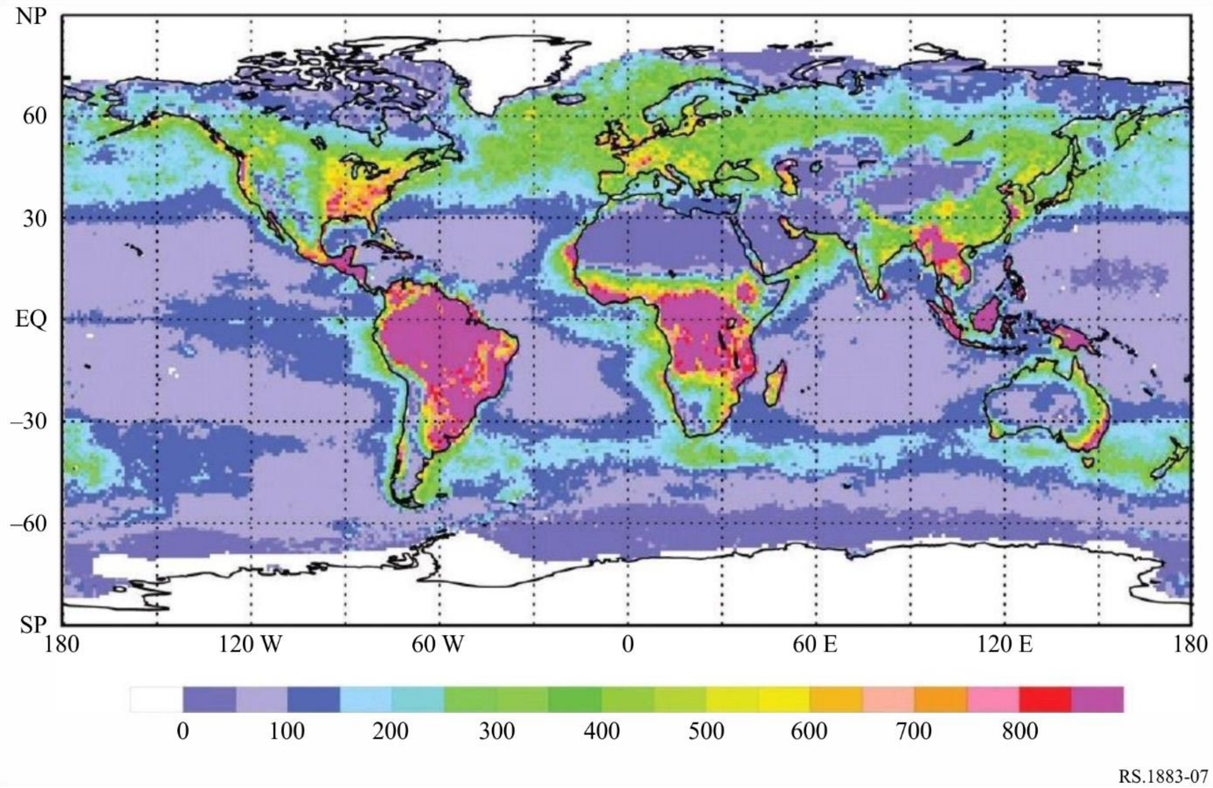
Source: Earth Observations from Space: the First 50 Years of Scientific Achievements, p. 75, 2008, downloadable from URL: http://www.nap.edu/catalog/11991.html.

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. 7), 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 7

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



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 inter-annual variations in climate), and ecosystem change for monitoring biosphere 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 biosphere 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 photo synthetically 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.

The high revisit frequency of the Sentinel-2 satellites is supporting the attempts to mitigate deforestation by providing opportunities to acquire cloud-free image data. This will be of particular benefit in the tropical latitudes, where heavy cloud cover may delay the acquisition of a complete catalogue of data. High-resolution data can support the change detection of flood events for affected countries.

5 Regional climate change and human intervention

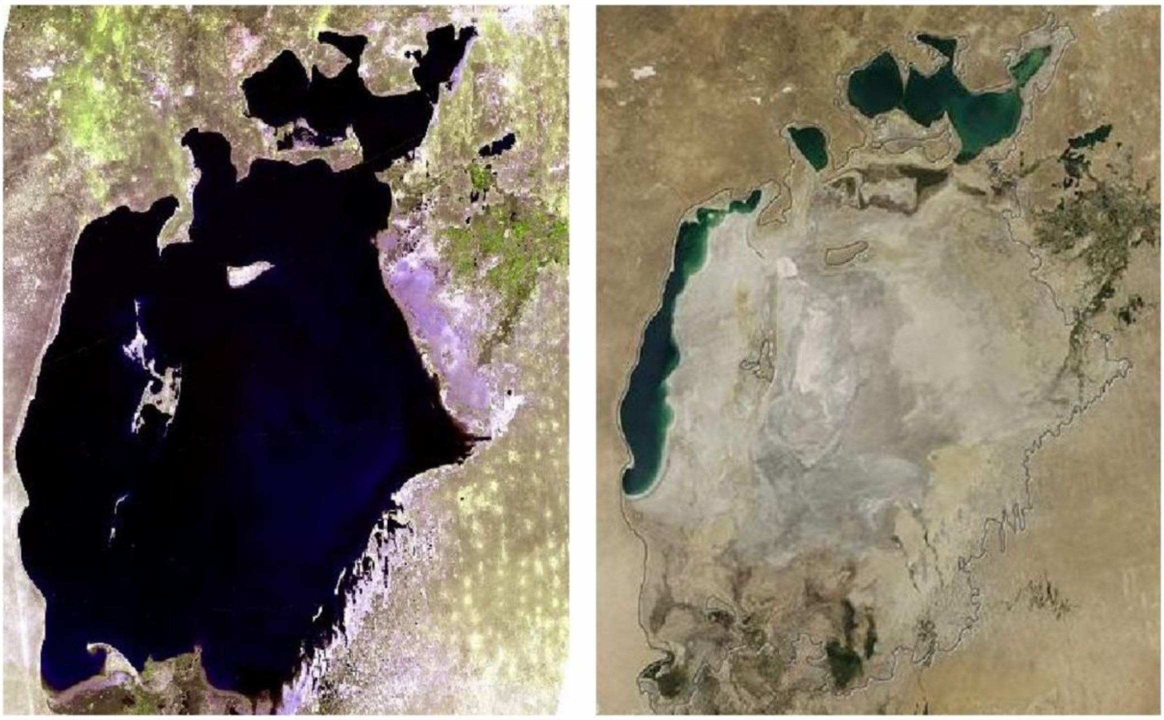
Climate change does not occur homogeneously – that is, the Earth as a whole does not heat up uniformly. Climate change usually occurs regionally with some regions warming up more than others, and some regions may exhibit cooling in the short term.

The environment of the Earth is being stressed by the increase in human population. Many of the actions taken to support that increase affect the climate, both locally and globally and can be observed by satellite instrumentation.

One example occurred when the Amu Darya River was diverted in the 1960’s to irrigate cotton and wheat fields. Decades later, the Aral Sea, once the fourth largest lake in the world with an area of 68 000 square kilometres, almost completely dried up (Fig. 8). The local fishing industry, which had provided one sixth of the fish to the Soviet Union, collapsed. As the coastlines receded kilometres from the towns, the remaining people were plagued by toxic dust storms. The shrinking of the Aral Sea has been called one of the planet’s worst environmental disasters.

FIGURE 8

Historic Area of the Aral Sea



1977 (Landsat-2)

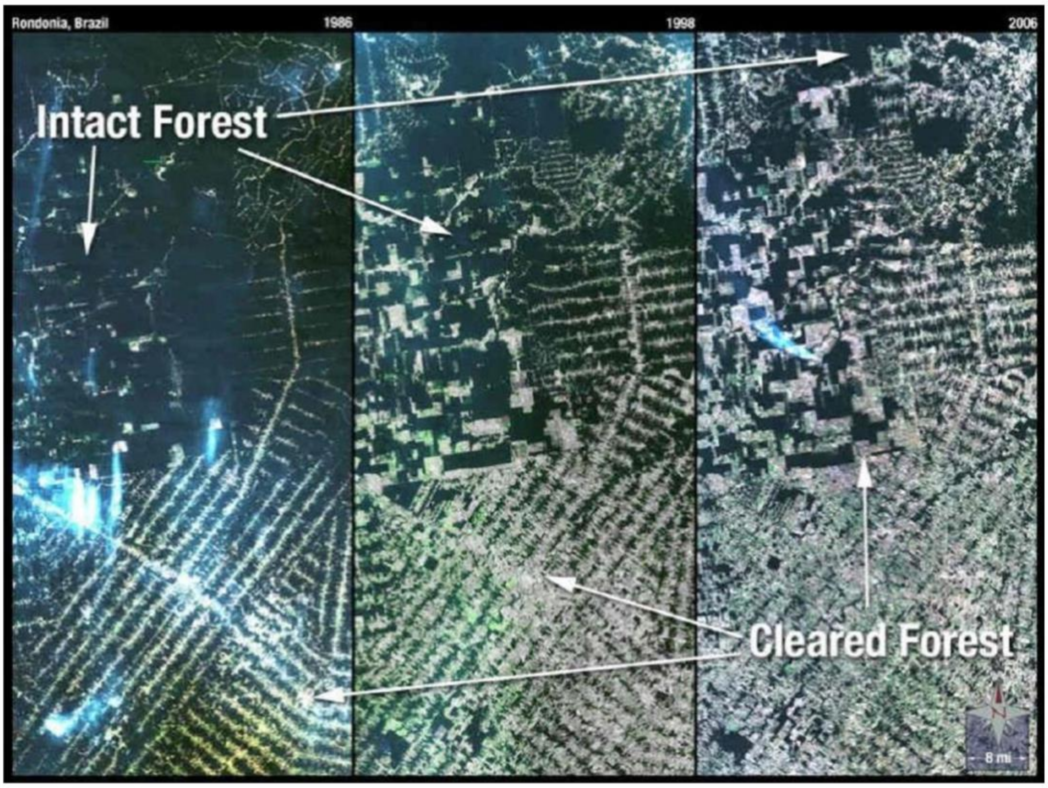
2014 (MODIS on TERRA)

RS.1883-08

Forest trees act as air filters, removing carbon dioxide from the air and providing us with oxygen and water. Satellites can monitor the health and extent of forests. Areas where the forests have been cleared have been mapped (Fig. 9) as well as areas in which the forests have recovered (Fig. 10). In both Figures Landsat data was used. The long-term changes in overall forest cover impact the climate and should be monitored.

FIGURE 9

Deforestation in the Amazon



RS.1883-09

FIGURE 10

Forest deforestation and recovery
Oregon (Northwest USA) Landsat Tree Coverage

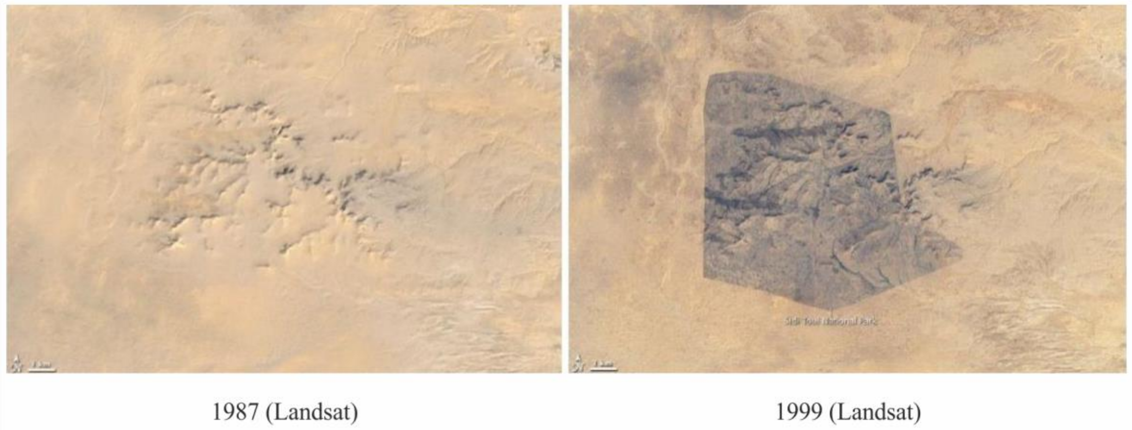
2000 2005 2000-2005

RS.1883-10

The advance of deserts into cropland affects not only the food supply and land available for human habitation, but the change in the Earth’s albedo due to the lack of plant cover affects the Earth’s climate. Grazing by agricultural animals can seriously affect stressed environments, in particular deserts. Goats can eliminate already fragile desert plant life, but the simple addition of fencing to keep such animals away can restore the environment (see Fig. 11)

FIGURE 11

Restoration of Sidi Toui National Park (Tunisia)



1987 (Landsat) 1999 (Landsat)

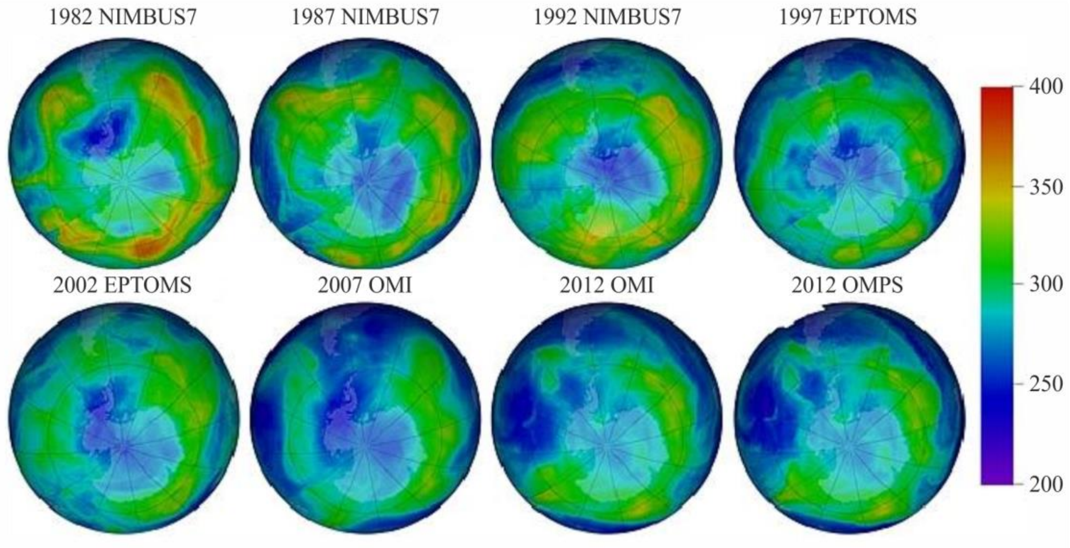
RS.1883-11

By 1987, drought, agriculture and overgrazing had pushed the area towards desertification. In 1993, Tunisia established the Sidi Toui National Park and surrounded it with fences. By 1999, the native grassland had revived (winter image). The conversion of arable land into desert in not necessarily an irreversible process.

Humans have also introduced non-natural chemical compounds into the atmosphere. It was realized in the early 1980's that the ozone layer of the atmosphere which protects us from the sun's ultraviolet radiation, was shrinking. In particular, an ozone "hole" appeared over the South Pole which was increasing in size year by year. This observation was first noticed in satellite data and later confirmed with ground-based observations. The cause was traced to the catalytic destruction of ozone by atomic halogens. The main source of these halogens was the photo dissociation of man-made halocarbon refrigerants, solvents, propellants, and foam-blowing agents.

FIGURE 12

Ozone distribution over the South Pole



RS.1883-12

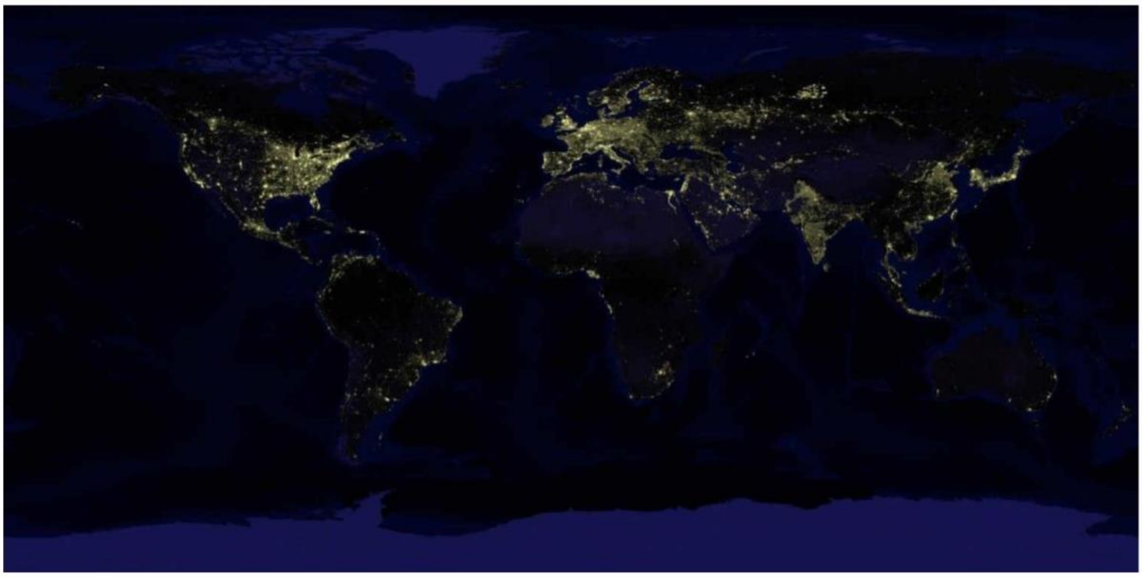
Source: NASA

At the Conference of Plenipotentiaries on the Protocol on Chlorofluorocarbons to the Vienna Convention for the protection of the ozone layer (Montreal, 1987) a protocol was signed to limit the production and use of those chemicals. The result was a slow recovery from the ozone depletion. Satellite instruments have continually monitored this condition of the atmosphere (Fig. 12), and have shown the effect of measures adopted in Montreal and subsequent protocols (London, 1990 and Copenhagen, 1992).

The distribution of the population also influences the climate, as now more than half of the Earth's population resides in urban areas. An initial indication of the distribution of humanity came from night-time observations of the visible light emanating from populated areas (see Fig. 13).

FIGURE 13

Night-time observations of lights from populated areas



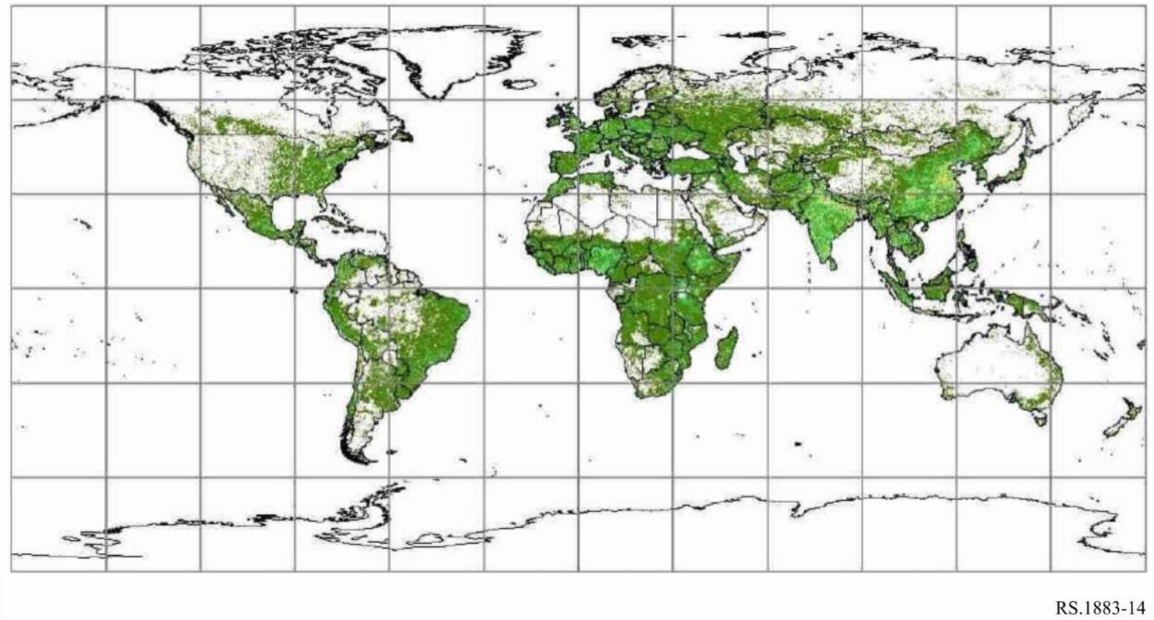
RS.1883-13

(DMSP data)

However, it was realized that these observations led to underestimating the populations of developing nations which lacked the street lights and other night illumination marking the developed nations. A later population model was developed which added proximity to roads, slopes, land cover, and other information to the nighttime light observations. The data for the slopes, land cover, and nighttime lights came from satellite data. This later model is presented in Fig. 14 below and better represents the populations of developing nations.

FIGURE 14

Global population distribution



Urban populations located along coastlines are more vulnerable to sea level rise. Urban populations also require the concentration of more resources, such as water and food, and provide additional stress on the local environment. The heat islands associated with major cities affect the local and regional climate and must also affect the long-term global climate.

6 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

Table A2-1 maps the measurements needed, detailed in Table A2-2, into the technologies used to obtain them. The measurements needed were derived 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.

Table A2-2 lists, by the technology used, the items observed and the missions available to provide those measurements, both circa 2016 (when this annex was written) and in the future. Table A2-2 updates the information given in the U.S. National Research Council's Report mentioned above.

TABLE A2-1

The technologies used to obtain climate-related measurements

Technology **Objective**	**SAR Imagery**	**Radar Altimetry**	**Radar Scatterometry**	**Precipitation/Cloud Radar**	**GPS Rado Occultation**	**Passive MW Imagers**	**Passive MW Sounders**	**LIDAR**	**Optical Imagery (UV-IR)**	**Multispect. Optical**	**IR Sounders/Spectrometers**	**Optical Radiometers**	**Limb Measurements**	**Gravity-Based**
Aerosols, Stratospheric								X					X	
Aerosols, Tropospheric								X		X		X		
Atmos. Temp Profile					X		X							
Atmos. Water Profile					X		X			X	X			
Atmos. Water Total					X		X				X			
Cloud properties				X		X		X		X		X		
Fire Disturbance									X					
Gases, Other											X			
Gases, Ozone									X					
Gases, Trace cntrl Ozone							X				X			
Glaciers/Sea Ice	X					X		X		X				X
Groundwater						X								X
Lake levels	X							X		X				
Land Biomass										X				
Land Cover	X									X				
Leaf Area Index										X				
Ocean Color										X				
Ocean (Sea) Level	X	X												
Ocean Salinity			X			X								
Ocean Surface Height		X	X											X
Ocean Surface Temp.							X			X				
Ocean Wind/State			X			X								
Permafrost, Snow	X					X								
Precipitation				X		X								
Radiation Budget										X				
River Discharge	X							X		X				
Total Solar Irradience												X		

TABLE A2-2

Status of climate change and variability support

Technology	**Objective**	**Measurement**	**Status (circa 2018)**	**Follow-on (2018-2025)**
SAR Imagery	Permafrost, seasonally frozen ground, Snow cover (and snow water equivalent)	Combined with microwave radiometers yields a combination of area & roughness, with topography provides snow-water equivalent	SARs on RADARSATs (1995, +), TSX (2007), TDX (2010), COSMO-SkyMeds (2007, +), C-SAR on Sentinel-1 series (2014,+); HJ-1C (2012); COSI on KOMPSAT-5 (2013); PALSAR-2 on ALOS-2 (2014); RISAT-SAR on RISAT-1 (2012);SAR-C on RISAT-2 (2009); S-M OBRC on METEOR-M2 (2014); SAR-10 on Kondor-E1 (2013); X-SAR on TECSAR (2008)	BRLK on METEOR-MP (2021); S-SAR on NovaSAR-S (2018); SAR-L on SAOCOM-1,2 (2018); SAR-P on BIOMASS (2020); SAR-X on METEOR-MP (2021); SARs on PAZ (2018), CSG (2018, +), RADARSAT constellation (2018, +), RISAT-1A (2019), TSX-NG (2018)
	Lake levels	Lake area		
	River discharge	Lake, river areas		
	Land Cover	Land cover from radar backscatter		
	Sea level	Area of coastal zones		
	Glaciers, sea ice, ice caps	Ice area and flow, sea-ice thickness from topography	SARs on RADARSATs (1995, +), TSX (2007), TDX (2010), COSMO-SkyMeds (2007, +), C-SAR on Sentinel-1 series - 1B (2014,+); SIRAL on CRYOSAT-2 (2010); SRAL on Sentinel-3 series (2016,+)	RADARSAT Constellation (2019); InSAR on NISAR (2021)
Radar Scatterometry	Sea state, surface wind	Surface wind vector	ASCAT on MetOps (2006, +); SCAT on HY-2A (2011); OSCAT on OceanSat-2 (2009); DDMI on CYGNSS (2016); OSCAR on ScaSat-1 (2016)	OSCAT on OceanSat-3 (2018) and SCA on METOP-SG-B (2020); SCAT and SWIM on CFOSAT (2018); SCAT on METEOR-MP, -M (2018); WindRAD on FY-3 (2018)
	Sea salinity	Surface salinity, ocean roughness	KU-RFSCAT on HY-2A (2011); MWRI on HY-2A (2011);	
	Sea ice	Sea ice type, extent		SCA on METOP-SG-A (2022)
Precipitation Radar	Precipitation	Precipitation radar: Rain rate vertical profile	DPR on GPM (2014)	
		Cloud radar: Rate for light drizzle	CloudSat (2006)	
Cloud Radar	Cloud properties (location, drop size, ice- cloud crystal properties)	Cloud radar: Cloud boundaries, vertical distribution of liquid water, rates of drizzle	CloudSat (2006)	

TABLE A2-2 (*continued*)

Technology	**Objective**	**Measurement**	**Status (circa 2018)**	**Follow-on (2018-2025)**
Radar Altimetry	Sea level	Ocean sea-level height	SSALT on JASON series (2001, +); Altika-AMU on SARAL (2013); RA on HY-2A / (2011); SRAL on Sentinel-3 series (2016,+) ; JASON-3 (2016)	KaRIN on SWOT (2020); SRAL on JASON-CS/SENTINEL-6 (2018 +); SHIOSAI on COMPIRA (2019)
	Ocean surface, subsurface currents	Ocean-surface height from which currents derived	POSEIDON on JASON Series (2001, +); RA on HY-2A (2011); SRAL on Sentinel-3 series (2016,+)	SRAL on JASON-CS/SENTINEL-6(2018,+); KaRIN on SWOT (2020)
GPS Radio Occultation	Temperature: vertical profiles	Profiles of atmospheric temperature with up to about 0.5 km vertical resolution near surface	CHAMP (2000), COSMIC/FORMOSAT-2 (2006); KOMPSAT-5 (2013); FY-3 -C (2013); MetOp (2006, 2012); TDX (2010); TSX (2007); Megha-Tropiques (2011); OceanSat-2 (2009); DDMI on CYGNSS (2016)	COSMIC-2/FORMOSAT-7 (2018); FY-3D.-3F(2016-2020); JASON-CS/SENTINEL-6 (2021); GRACE-FO (2018); METEOR-M-N3, METEOR-MP-N1,-N3 (2018); METOP-SG-A,-B (2022)
	Water vapour: column amounts, vertical profiles	Profiles of water vapour with up to about 0.5 km vertical resolution near surface		
LIDAR	Tropospheric aerosols: location and properties	Vertical profile of aerosol concentration, size and shape	CALIPSO (2006)	ATLID on EarthCare (2019)
	Stratospheric aerosols: location and properties	Vertical profile of aerosol concentration, size and shape		
	Cloud properties (location, drop size, ice- cloud crystal properties)	Upper boundary for optically thin clouds with polarization, particle phase		
	Glaciers, sea ice, ice caps	Ice elevation	GLAS on ICESat (2003)	
	Lake levels	Water-surface elevation		
	River discharge	Lidar altimeter: River levels	ICESat (2002)	

TABLE A2-2 (*continued*)

Technology	**Objective**	**Measurement**	**Status (circa 2018)**	**Follow-on (2018-2025)**
Passive Microwave Imagers	Precipitation and cloud properties	Rainfall rate and cloud liquid water	GMI on GPM (2014); SSM/I on DMSP series (1987, +), SSMIS on DMSP series (2003, +); MWRI on FY-3 series (2008, +); MWR on Sentinel-3 series (2016,+)	SSM/IS on DMSP (2020); MWI on METOP-SG-A (2022); MWR on Sentinel-3B (end 2017)
	Glaciers, sea ice, ice caps	Glacier, sea ice extent	SSM/I on DMSP series (1987, +), SSMIS on DMSP series (2003, +); AMSR-2 on GCOM-W1 (2012); MWRI on HY-2A (2011)	
	Snow mass	Snow water equivalent	SSM/I on DMSP (1995, +); AMSR-2 on GCOM-W1 (2012)	
	Groundwater	Soil moisture except for ice-snow covered and heavily forested areas	MIRAS on SMOS (2009); Radiometer on SMAP (2015); SSM/I on DMSP series (1987, +), SSMIS on DMSP series (2003, +); MWRI on FY-3 series (2008, +); VIIRS on SNPP (2011) and NOAA-20 (2018)	
	Sea salinity	Surface salinity	SMAP radiometer on SMAP (2015), MIRAS on SMOS (2009);	
	Sea state, surface wind	Surface wind speed	SSM/I on DMSP series (1987, +), SSMIS on DMSP series (2003, +); Windsat on Coriolus (2003), AMSR-2 on GCOM-W1 (2012); MTVZA-GY on Meteor-M series (2009, +) MWRI on HY-2A (2011)	

TABLE A2-2 (*continued*)

Technology	**Objective**	**Measurement**	**Status (circa 2018)**	**Follow-on (2018-2025)**
Passive Microwave Sounders	Temperature: vertical profiles	Atmospheric temperature profile	MSU since 1979 currently on NOAA series (2002, +); SSM/I on DMSP (1995, +); AMSU on Aqua (2002), MetOp (2006, +); DFMRM on FAST-T; MTVZA-GY on Meteor-M Series (2009, +); MWTS on FY-3 series (2003, +) CrIS, ATMS on SNPP (2011) and NOAA-20 (2018)	MWS, MWI on METOP-SG-A (2022); MTVZA-GY-MP on METEOR-MP (2021)
	Atmospheric Water Properties	Atmospheric water-vapour profiles and total amounts	SSM/I on DMSP series (1995, +); ATMS on SNPP (2011) and NOAA-20 (2018); Altika-RMU on SARAL (2013);AMSU on AQUA(2002), NOAA series (1998, +); AMSU-A on MetOp series (2006 +); SSM/T on DMSP series (1999, +); SAPHIR on Megha-Tropiques (2011); MTVZA-GY on METEOR-M-1 (2009), -M2 (2014); MWRI on FY-3 series (2008 +) and HY-2A (2011); MWR on Sentinel-3 series (2016, +); AMR-2 on JASON-3 (2016)	AMR on SWOT (2020); AMR-C on JASON-CS/SENTINEL-6 (2018);MTVZA-GP-MP on METEOR-MP (2021); MWI and MWS on METOP-SG-A (2022)
	Water vapour: column amounts, vertical profiles	Infrared, microwave limb-scanning radiometers: Water-vapour layer amounts in upper troposphere, stratosphere	TES, MLS on Aura (2004); MWR on Sentinel-3 series (2016,+)	
	Trace gases controlling ozone (HCI, N_2O, CH_4, H_2O, HNO_3)	Microwave limb sounding provides vertical profile of stratospheric ozone	MLS on Aura (2004)	
	Ocean surface, sub-surface temperature	Infrared-microwave sounders: Sea-surface temperature	AVHRR on NOAA series (2000, +); AIRS, MODIS on Aqua (2002); MODIS on Terra (1999); VIIRS, CrIS, ATMS on SNPP (2011) and NOAA-20 (2018); GMI on GPM (2014); AMSR-2 on GCOM-W1 (2012); MWRI on HY-2A (2011); MIRAS on SMOS (2009); WindSat on Coriolus (2003)	

TABLE A2-2 (*continued*)

Technology	**Objective**	**Measurement**	**Status (circa 2018)**	**Follow-on (2018-2025)**
Multispectral Optical Imagery	Earth radiation budget	Combined with broadband radiometers provides scene identification, top of the atmosphere fluxes	MODIS, CERES on Terra (1999), Aqua (2002); VIIRS, CERES on SNPP (2011) and NOAA-20 (2018)	
	Surface radiation budget			
	Tropospheric aerosols: location and properties	Provide optical depth, some inference of size over oceans and dark surfaces	AVHRR since 1981, currently on NOAA series (2002, +); MODIS, MISR on Terra (1999); MODIS on Aqua (2002); VIIRS on SNPP (2011) and NOAA-20 (2018)	TROPOMI on Sentinel-5P (2017); UVNS (Sentinel-5) on Metop-SG-A (2020); UVNS (Sentinel-4) on MTG (2020)
	Cloud properties (location, drop size, ice- cloud crystal properties)	Properties of single effective cloud layer. AVHRR – hydrometeor size VIRS, MODIS, and VIIRS – inference of hydrometeor phase		
	Water vapour column amounts, vertical profiles	Column amounts from near-IR water vapour channels	MODIS on Terra (2000), Aqua (2002)	
	Land-surface cover and surface albedo (snow cover, glaciers, ice caps elsewhere)	Vegetation index, inference of surface albedo	AVHRR on NOAA series (2002, +): inferences of atmospherically corrected spectral albedos; MODIS on Terra (2000), Aqua (2002); Landsat since 1973,-7,-8 (1999, 2013); VIIRS on SNPP (2011) and NOAA-20 (2018); MSI on Sentinel-2A/B (2015/2017)	
	Land-surface cover and surface albedo (not snow cover, glaciers, ice caps)	Hyperspectral imagery: Vegetation types, land cover	Hyperion on EO-1 (2000)	
	Lake, river levels	High-resolution imagery: Lake , river areas	Landsat since 1973, -7, -8 (1999, 2013)	
	Land biomass, fraction of photosynthetically active radiation; Leaf-area index	Vegetation index	AVHRR data since 1979, on NOAA series (2002, +); MODIS on Terra (2000), Aqua (2002); MISR on TERRA (1999); SeaWiFS (1997); VIIRS on SNPP (2012) and NOAA-20 (2018); MSI on Sentinel-2A/B (2015/2017)	FLORIS on Flex (2023)
	Leaf-area index	Vegetation index at higher spatial resolution	Landsat since 1973, -7, -8 (1999, 2013); ASTER on Terra (2000); Hyperion on EO-1; SPOT series (1994, +)	FLORIS on Flex (2023)

TABLE A2-2 (*continued*)

Technology	**Objective**	**Measurement**	**Status (circa 2018)**	**Follow-on (2018-2025)**
	Glaciers, sea ice, ice caps	Area coverage	AVHRR since 1979, on NOAA series (2002, +); MODIS on Terra (2000), Aqua (2002); Landsat since 1973, -7,- 8 (1999, 2013); VIIRS on SNPP(2011) and NOAA-20 (2018)	
	Ocean surface, sub-surface temperature	Sea-surface temperature	AVHRR, data since 1981, on NOAA series (2000, +); MODIS on Terra (2000), Aqua (2002); VIIRS on SNPP(2011) and NOAA-20 (2018)	
Optical (UV – IR) Imagery	Ozone in the stratosphere, troposphere	UV radiometer-imager provides tropospheric column ozone, coarse vertical resolution profiles of stratospheric ozone	OMI on Aura (2004); OMPS on SNPP (2011) and NOAA-20(2018)	UVNS (Sentinel-5) /on Metop-SG-A (2020); UVNS (Sentinel-4) on MTG (2020)
	Fire disturbance	Near-IR thermal imagery provides high-spatial-resolution detection of fire hotspots	AVHRR data from 1981, on NOAA series (2002, +); MODIS on Terra (2000), Aqua (2002); VIIRS on SNPP (2012) and NOAA-20 (2018)	UVNS (Sentinel-5) on Metop-SG-A (2020); UVNS (Sentinel-4) on MTG (2020)
Optical (UV – IR) Radiometers/ Polarimeters	Total solar irradiance	Direct measurement	SORCE (2003); TIM on Glory (2008)	
	Tropospheric aerosols: location and properties	UV radiometer-imagers: optical depth, some inference of absorption for elevated aerosol layers	OMI on Aura (2004); OMPS on SNPP (2011) and NOAA-20 (2018)	
		Polarimeters: optical depth, size, shape, single-scattering albedo		
	Cloud properties (location, drop size, ice- cloud crystal properties)	15 μm sounders, imagers: Cloud-layer pressure for effective single-layered cloud system, even for optically thin cirrus	HIRS on NOAA series (2002, +); MODIS on Terra (1999), Aqua (2002); AIRS on Aqua (2002); CrIS on SNPP (2011) and NOAA-20 (2018)	
		Multiple-view radiometers, polarimeters	MISR on Terra (1999); cloud altitude from stereo imaging	

TABLE A2-2 (*end*)

Technology	Objective	Measurement	Status (circa 2018)	Follow-on (2018-2025)
IR Sounders	Trace gases controlling ozone (HCI, N_2O, CH_4, H_2O, HNO_3)	Provide vertical profiles of tropospheric, stratospheric ozone	AIRS on Aqua (2002)	
	CO_2, CH_4	Infrared sounders:	AIRS on Aqua (2002); CO_2 only with OCO-2 (2014)	
	CH_4	Infrared spectrometer: High-precision column concentrations of CH_4	TES on Aura (2004); AIRS on AQUA (2002)	
	Water vapour: column amounts, vertical profiles	Water-vapour layer amounts at relatively coarse vertical resolution in troposphere	HIRS data since 1979, on NOAA series (2002, +); CrIS on SNPP (2011) and NOAA-20 (2018)	
		High-spectral-resolution IR radiometers provide water-vapour layer amounts at finer vertical resolution in troposphere	AIRS on Aqua (2002); TES on Aura (2004); CrIS on SNPP (2011) and NOAA-20 (2018)	
Limb Measurements	Stratospheric aerosols: location and properties	Limb and solar occultation measurements: profile of aerosol extinction	infrared radiometer; SAGE II on ERBS (1984-2006); SAGE III on Meteor (2002-2006) SciSat (Canadian-U.S.)	
		Limb-scattered light: profile of aerosol optical depth	OMPS on SNPP (2011) and NOAA-20 (2018)	
Gravity-Based Measurements	Glaciers, sea ice, ice caps	Ice mass when combined with measure of topography		GRACE-FO (2018)
	Groundwater	Large-scale groundwater (requires in situ auxiliary observations)		
	Ocean surface, subsurface currents	Subsurface or barotropic mass shifts (computed in conjunction with surface altimeter measurements)		