# The role of satellite remote sensing in climate change studies

Jun Yang1, Peng Gong1,2,3\*, Rong Fu4, Minghua Zhang5, Jingming Chen6,7, Shunlin Liang8,9 Bing Xu8,10, Jiancheng Shi2, Robert Dickinson4

1 Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing, China, 100084

2 State Key Lab of Remote Sensing Science, Jointly Sponsored by Institute of Remote Sensing Applications, Chinese Academy of Sciences, and Beijing Normal University, Beijing, China, 100101

3 Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, USA

4 Jackson School of Geosciences, University of Texas, Austin, TX 78712, USA

5 School of Marine and Atmospheric Sciences, State University of New York, Stony Brook, NY 11794, USA

6 International Institute for Earth System Science, Nanjing University, Nanjing, China, 210093

7 Department of Geography and City Planning, University of Toronto, Toronto, Ontario, Canada, M5S 3G3

8 College of Global Change and Earth System Science, Beijing Normal University, Beijing, China 100875

9 Department of Geography, University of Maryland, College Park, MD 20742, USA

10 College of Environmental Science and Engineering, Tsinghua University, Beijing, China, 100084

## Abstract

Satellite remote sensing plays a significant role in improving our understanding of the climate change. [In this review, some important discoveries about the climate system provided by satellite observations are highlighted, e.g., the effect of aerosols on the energy budget of Earth.] While satellite remote sensing offers unparalleled spatial and temporal coverage of the Earth’s climate, the short duration of observation series and uncertainties pose major barriers unique to satellite data for capturing robust long-term trends of most climate variables. We point out what improvements are needed in future work and future systems to fully realize the potential of satellite remote sensing in climate change studies.

Observational data and model simulations are the foundations of our understanding of the climate system[1](#_ENREF_1). Satellite remote sensing (SRS), which acquires information about the Earth’s surface and its atmosphere remotely from sensors deployed on satellites, plays an important role in climate system observations. Since the first space observation of solar irradiance and cloud reflection was made with radiometers onboard the Vanguard-2 satellite in 1959[2](#_ENREF_2), SRS has gradually become a leading research method in climate change studies[3](#_ENREF_3).

SRS allows the observation of statues and processes of the atmosphere, land, and ocean at multiple spatial and temporal scales. For instance SRS is one of the most efficient approaches to map land cover and its change in time over a variety of spatial scales[4](#_ENREF_4),[5](#_ENREF_5). Satellite data are frequently used to evaluate and validate climate models[6](#_ENREF_6" \o "Ghent, 2011 #241). Satellite data contribute significantly to the improvement of meteorological reanalysis products that are widely used for climate change research such as the National Centers for Environmental Prediction (NCEP) reanalysis[7](#_ENREF_7). The Global Climate Observing System (GCOS) has listed 26 out of 50 essential climate variables (ECVs) as significantly dependent upon satellite observations[8](#_ENREF_8). SRS is also widely used for developing prevention, mitigation and adaptation measures to cope with the impact of climate change[9](#_ENREF_9).

Despite the aforementioned contributions of SRS, there are concerns about the suitability of satellite data for monitoring and understanding climate change[10](#_ENREF_10). Climate change studies require calibrated/validated, consistent, and adequate temporally and spatially sampled observations over a long period of time[11](#_ENREF_11). Satellite data often contain uncertainties caused by biases in sensors and data retrieval algorithms. Therefore the use of satellite observations in climate change studies requires a clear identification of their limitations.

In this article we review the contribution of SRS to our understanding of climate change and the processes involved. We focus on SRS-enabled discoveries that have substantiated or challenged our fundamental knowledge of climate change. The main goal is to reveal the unique contributions and major limitations of SRS through these studies. Technical details of instrumentation and data retrieving methods can be found in a recent review[12](#_ENREF_12).

## Observations of the climate system

Conventional land based observations are typically collected at fixed intervals with limited spatial coverage whereas SRS allows for continual monitoring on a global scale. This continuous global coverage has greatly enhanced our understanding of the climate system and its variations (Fig.1).

### Global warming

The warming trend of the Earth’s mean surface temperature in the last century has played a significant role in the debate of anthropogenic influences on global climate[13](#_ENREF_13). This trend was first identified through analyzing anomalies in time series of near- surface air temperature over the land recorded by weather stations[14](#_ENREF_14), but it was consistently challenged due to the biases in weather records[15](#_ENREF_15). SRS provides an independent way to reveal the global temperature trend, particularly on the ocean surface and the atmospheric temperature.

The sea surface temperatures (SST) of the global oceans, which are directly related to heat transfer between the atmosphere and oceans, serve as important indicators of the state of the climate system[16](#_ENREF_16). The Advanced Very High Resolution Radiometer (AVHRR) data and the passive microwave sensing data provide us with the capacity to monitor the SST on a global scale. An increase in SST has been observed in all ocean basins since the 1970s, with an average estimated increase of 0.28oC from 1984-2006[17](#_ENREF_17). The global mean SST trend is similar to that of near-surface air temperature over the lands, thus providing a decisive corroboration to the warming trend identified from weather records even though the magnitude of the detected trend still has considerable uncertainty[18](#_ENREF_18" \o "Zhang, 2009 #286). Satellite observations also reveal an uneven warming pattern. The warming trend is the highest in the middle latitudes of both hemispheres[19](#_ENREF_19). Stronger east-to-west zonal SST gradients have been detected across the Equatorial Pacific Ocean[20](#_ENREF_20). The regional variability of SST are tightly linked with the variability of other climate variables, such as precipitation[21](#_ENREF_21). All these discoveries have led to a better understanding of the variability of the regional and global oceans.

Surface and tropospheric warming has been predicted as a major response of the climate system to escalating greenhouse gases [22](#_ENREF_22), but initial analyses found no obvious trend in tropospheric temperature records obtained using Microwave Sounding Unit (MSU) on polar-orbiting satellites[23](#_ENREF_23), a finding that has challenged both the reliability of surface temperature records and our understanding of the response of the climate system to increased greenhouse gases[24](#_ENREF_24). However, after removing known problems with the sensors, accounting for the influence of stratospheric cooling, and reducing biases in retrieving methods[25](#_ENREF_25), new versions of satellite time series all show a warming trend in the troposphere except in the Antarctic region[26](#_ENREF_26) (Fig.2). This progress together with improved climate models has led to the conclusion that there is no fundamental disagreement between observed and modeled tropospheric temperature trends of warming when uncertainties in both are accounted for[24](#_ENREF_24). Nevertheless, some questions remain. The observed scaling ratio, the ratio of atmospheric trend to surface trend, is still significantly lower than model projections[27](#_ENREF_27). The differences between observed temperatures in the tropical upper and lower middle troposphere are significantly smaller than those simulated by climate models[28](#_ENREF_28). These remaining differences indicate that either model deficiencies or observational errors identified in previous studies are still yet to be resolved.

### Snow and ice

The retreat of snow and ice covers is an important indicator of global warming. Melting of snow and ice cover can cause a positive feedback through lowering the albedo of the Earth surface and contribute to sea level rise (SLR)[13](#_ENREF_13). Monitoring the dynamics of snow and ice cover is, therefore, an important part of climate observations. SRS has played a crucial role in it.

Snow cover extent (SCE) over the Northern Hemisphere has been routinely monitored by using visible band sensors and passive microwave band sensors carried by satellites since 1967[29](#_ENREF_29). Reconstructed time series based on the National Oceanic and Atmospheric Administration (NOAA) SCE data set and in situ measurements showed that overall the SCE over the Northern Hemisphere had reduced by 0.8 million km2 decade-1 in March and April during the 1970-2010 period. A comparison with pre-1970 values shows a 7% and 11% decrease in March and April SCE respectively[30](#_ENREF_30). This trend is consistent with observed global surface warming. The satellite observations also display strong regional patterns of SCE affected by regional climate variability. No significant decrease was observed over North America in March between 1970-2010[30](#_ENREF_30) and the decrease of SCE inside Russia ceased after 1990[31](#_ENREF_31).

The extent of sea ice and ice sheets are primarily monitored by using passive microwave sensors such as the Special Sensor Microwave Imagers (SSMI). The latest trend identified from the satellite records shows that the Antarctic sea ice extent has increased by 1.5±0.4% decade-1 from 1979 to 2010[32](#_ENREF_32). Researchers hypothesize that this slight increase was caused by reduced upward ocean heat transport and increased snowfall[33](#_ENREF_33). The situation is reversed in the Arctic where satellite observations show an overall negative trend of -4.1±0.3% decade-1 in that period[34](#_ENREF_34). The observed trend concurs with climate model projections but the magnitude of the observed trend is larger than model projections[35](#_ENREF_35). Whether the Arctic as a whole has reached a “tipping point” is still a matter of debate but some researchers believe that at least a “regional tipping point” has been reached based on satellite observations[36](#_ENREF_36).

The mass losses of the Antarctic and Greenland ice sheets have been studied by measuring changes of surface elevation with satellite altimetry data or measuring changes of gravity with Gravity Recovery and Climate Experiment (GRACE) satellite data. Results from these studies confirm that the Antarctic and Greenland ice sheets are losing mass[37](#_ENREF_37),[38](#_ENREF_38). The polar ice sheets are estimated to contribute an average of 0.59±0.2 mm year-1 to the rate of global SLR since 1992 according to the latest study[38](#_ENREF_38). However, it should be noted that the estimates of the mass loss rates are highly divergent (Supplementary table 1). Both GRACE-based and altimeter-based methods have limitations and the efforts to combine the strengths of the two have achieved partial success[37](#_ENREF_37). Along with the mean trend, the acceleration of ice discharge in Antarctic and Greenland was revealed by using active Interferometric Synthetic-Aperture Radar (InSAR) records[39](#_ENREF_39). This finding and subsequent studies indicate that ice-ocean interaction drives much of the recent increase in mass loss from Antarctic and Greenland ice sheets[40](#_ENREF_40).

The retreat of glaciers in high-altitude regions has been cited as a clear sign of global warming. However, satellite observations show that the extent and magnitude of melt are less than predicted. Based on Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Satellite Pour l' Observation de la Terre (SPOT) data, dynamics of glaciers in the Himalaya region were highly variable from 2000-2008. While 65% of the monsoon-influenced glaciers were retreating, 50% of the glaciers in northwestern Himalaya’s Karakoram region were advancing or stable[41](#_ENREF_41). The mass loss of glaciers in the high mountains of Asia during 2003-2010 was estimated to be only 0.01±0.06 m yr-1 water equivalent based on GRACE measurements, significantly lower than the 0.13-0.15 m yr-1 water equivalent estimated by earlier studies[42](#_ENREF_42). In the Karakoram region, the mass balance of glaciers was positive at 0.11±0.22 m yr-1 water equivalent between 1999 and 2008[43](#_ENREF_43). While some of these findings are disputed[44](#_ENREF_44), they show glacier retreat in high-altitude regions is not uniform but has strong regional variations. Causal factors other than surface temperature must be considered when making future predictions. The results also show that the estimated contribution of water from melting glaciers to SLR may be less than predicted in certain regions.

### Sea level change

Sea level is closely related to climate because the main factors that cause sea level changes are driven by climate change and variability[45](#_ENREF_45). Based on sites with good-quality tide gauge records, the global mean SLR was estimated as 1.9±0.4 mm yr-1 since 1961[46](#_ENREF_46). Satellite altimetry observations beginning with the TOPEX/Poseidon satellite mission indicate an accelerated SLR since the end of the 20th century, with a global mean SLR around 3.2±0.8 mm yr-1 in 1992-2010[47](#_ENREF_47). Satellite altimetry observations have also been combined with in situ measurements to form long-term time series. The added spatial details reveal strong regional SLR variations (Fig.3). The western Pacific showed the highest SLR, 12 mm yr-1,while the eastern Pacific had a slower than the global average SLR and even slightly negative trend [45](#_ENREF_45). The prevalence of mesoscale eddies (radius around 100 km or smaller) in oceans has also been picked up by satellite altimetry observations. This finding has profoundly changed our understanding of the relationship between SLR and ocean circulations[48](#_ENREF_48).

Verification of altimetry observations against tide gauge data has ruled out the possibility of a spurious trend resulting from biases in satellite data. Tide gauge calibrations did not show any drift trend in the combined 18-year satellite altimetry data[47](#_ENREF_47). The global mean SLR estimated from tide gauge records alone was 2.8±0.8 for the period of 1993-2009, not significantly different from values estimated from satellite altimetry[46](#_ENREF_46).

SLR contains steric change, due to alterations of total heat content and salinity, and mass change components. Therefore in studies of sea-level budget the total SLR measured from satellite altimeters should be equal to the sum of the SLR equivalent of mass changes observed by GRACE and the steric sea level change measured by the in situ network of sensors such as the Argo system. Initial results show a general agreement in regions where all three observation systems are working. The sea-level budget could not, however, be fully closed with existing data sets. Systematic errors in each observation system must be addressed and longer observation periods are needed to fully close the budget[47](#_ENREF_47) and to distinguish the inter-annual and decadal variability from the climate trend in the sea level records. Satellite altimetry products of mean sea level for regions outside of the 66oN-66oS zone are not readily available[49](#_ENREF_49). A recent effort to use multi-satellite altimetry data covering the ice-free ocean to generate weekly gridded sea level data for regions between 66oN to 82oN has offered a partial solution[50](#_ENREF_50).

### Solar radiation

Tracking changes in the Sun’s luminosity, measured in total solar irradiance (TSI) is important to answer whether natural variations of solar radiation contribute significantly to recent climate change. TSIClimate model simulations predict that the variation of TSI has little influence on global warming since 1880[51](#_ENREF_51). However, a study found that the sun might contribute to 25-35% of the 1980-2000 global warming using two alternative satellite TSI composites[52](#_ENREF_52). A nearly negligible influence was found in a later study using the same data and limitations of the methodology used by the former was suggested to be the source of overestimation[53](#_ENREF_53).

A possible influence of the solar spectral irradiance variability on climate change has been raised in recent years[54](#_ENREF_54),[55](#_ENREF_55). Measurements from the Spectral Irradiance Monitor (SIM) onboard the Solar Radiation and Climate Experiment (SORCE) satellite showed that the decrease in ultraviolet radiation is four to six times larger than expected from model calculations. This reduction is partially compensated by an increase in radiation at visible wavelengths[54](#_ENREF_54). These spectral changes were linked to a significant decline in stratospheric ozone below an altitude of 45 km from 2004 to 2007. The impact rippled throughout the atmosphere and contributed to global surface warming[55](#_ENREF_55). The variation of solar ultraviolet irradiance is also linked to cold winters in northern Europe and Canada by using the SIM measurements as inputs to run climate models[56](#_ENREF_56). However, others believe that the observed variation is a consequence of under-correction of instrument response to changes during early on-orbit measurements or undetected instrument sensitivity drifts[57](#_ENREF_57). The true change of the solar spectrum and its impact can only be confirmed when longer SIM measurements become available and more factors are considered in climate model simulations[58](#_ENREF_58).

### Aerosols

Aerosols are important agents of climate change and they can counteract the warming effects of anthropogenic greenhouse gases by affecting both atmospheric radiation and cloud/precipitation processes[59](#_ENREF_59),[60](#_ENREF_60). Recent atmospheric aerosol concentration changes have been identified through satellite observations. Aerosol optical depth (AOD) derived from observations recorded by visible and infrared optical sensors onboard different satellites since 1982 show a negative trend in the troposphere over North America and most of Europe and a positive trend over South and East Asia, with the combined effect of these regional changes apparently amounting to a small trend, although probably negative[61](#_ENREF_61),[62](#_ENREF_62). These changes are attributed to air pollution control efforts in North America and Europe and rapid industrialization in Asian countries[62](#_ENREF_62). The findings are important as aerosols in the troposphere produce direct and indirect radiative forcing that can significantly alter the regional patterns of climate change caused by an increase of greenhouse gases. In the stratosphere the concentration of aerosols has increased by as much as 10% from 2000, in contrast to the basic assumption of climate models, that the background stratospheric aerosol layer is constant. This increase of aerosols in the stratosphere might cause a negative radiative forcing of about -0.1 W m-2, implying a global cooling of about -0.07 oC and consequently about 10% less SLR from 2000[63](#_ENREF_63). The increase was attributed to small-scale volcano emissions[64](#_ENREF_64).

Satellite observations of the direct and indirect climate forcing by aerosols provide independent comparisons for climate models. The direct radiative forcing by anthropogenic aerosols is estimated by combining satellite observations of radiation budget and AOD. It is around -0.65 W m-2 to -1.0 W m-2 using this approach, magnitudes that are larger than the -0.5±0.4 W m-2 IPCC AR4 ‘consensus’ value and most model estimates. Explanations suggested for this disagreement include both biases in satellite data and deficiency of models in simulating the physical, chemical and optical properties of aerosols[60](#_ENREF_60). The indirect effects of aerosols estimated from satellite data are found to range from -0.2 to -0.5 W m-2, which is 3 to 6 times smaller than model estimates[65](#_ENREF_65). One reason for the difference is that satellite-based methods use the present-day relationship between observed cloud drop number concentrations (*Nc*) and AOD to determine the preindustrial values of *Nci*, but the primary reason is likely due to overestimation by models because they still cannot accurately simulate the cloud processes[*66*](#_ENREF_66).

### Clouds

Climate forcing and feedbacks of clouds adjust the energy flow throughout the Earth’s system. The net cloud forcing (NCF) is estimated to be -21 W m-2 by combining model simulations with the Earth Radiation Budget Satellite (ERBS) and Clouds and Earth’s Radiant Energy System (CERES) observations[67](#_ENREF_67). The cloud feedback to short-term climate variations is estimated to be a positive value of 0.54±0.74 W m-2 K-1 based on satellite observations of top-of-atmosphere radiation budget[68](#_ENREF_68). Those estimates provide good constraints on climate models. The model outputs of short-term (decadal scale) cloud feedback are in the same range of satellite observations, which indicate that climate models can simulate the response of clouds to short-term climate variations[68](#_ENREF_68). However, cloud feedback is considered the most complex and least understood climate phenomenon. Satellite cloud products still lack the accuracy and duration for detecting trends in cloud properties that are critical to understand the long-term (centennial-scale) feedback to climate changes[69](#_ENREF_69).

Some recent satellite measurements offered new insights on the complex relationship between clouds and Earth energy flows. The global effective cloud height measured using the Multiangle Imaging SpectroRadiometer (MISR) onboard the Terra satellites shows a negative trend from 2000 to 2010 of -44±22 m decade-1. If this observed ten-year trend were sustained, the decrease of cloud height would provide a negative cloud feedback[70](#_ENREF_70). Cloud laser data from the Aqua satellite show that dust particles lifted to the cold cloud layer effectively promote the formation of ice crystals in supercooled clouds and decrease the albedo of clouds, which in turn leads to decreased reflection of solar radiation and decreased cooling effects[71](#_ENREF_71). The interactions among cloud, aerosols, and precipitation are also better understood with the simultaneous multi-sensor observation capability provided by A-train, a formation of four Earth-observing satellites. The suppression effect on precipitation of ice clouds by aerosols has been identified from analyzing the aerosol and precipitation satellite data[72](#_ENREF_72).

### Water vapor and precipitation

Water vapor is an important greenhouse as it contributes to around 50% of the present-day global greenhouse effect[73](#_ENREF_73). Models predict that climate warming will increase the atmospheric specific humidity resulting in a positive feedback and, in turn, strongly amplify the warming[74](#_ENREF_74). From 1988 to 2003, an increase of 0.4±0.09 mm per decade of precipitable water in the troposphere over the ocean has been observed using the special sensor microwave imager (SSM/I) data[75](#_ENREF_75). A strong inter-annual correlation between tropospheric water vapor content and surface temperature over the ocean-land combination was also detected during the period of 1988-2008 by using a combination of SSM/I and radiosonde data[76](#_ENREF_76). In the upper troposphere, High-Resolution Infrared Radiation Sounder (HIRS) records from 1979 to 2009 showed an average increase of water vapor content in the equatorial tropics[77](#_ENREF_77). While regional, seasonal, inter-annual variations, and even longer variations responding to decadal climate events such as the El Niño Southern Oscillation (ENSO) have been observed[77](#_ENREF_77),[78](#_ENREF_78), satellite observations consistently support a positive tropospheric water vapor feedback at a long-term scale[74](#_ENREF_74). A different trend was detected in observations of stratospheric water vapor content. Based on satellite data sets from the HALogen Occulation Experiment (HALOE), Stratospheric Aerosol and Gas Experiment II (SAGEII), and the Microwave Limb Sounder (MLS), the water vapor content in stratospheric was found to increase persistently from 1980 to 2000 and then decreased by 10% between 2000 and 2009, contributing to the flattening of the global warming trend since then[79](#_ENREF_79). Satellite observations also support the theory that the stratospheric water vapor content is tightly regulated by the tropical tropopause temperature[80](#_ENREF_80), even though decoupling may occur at short time scale[81](#_ENREF_81). These results provided powerful validations of climate models in simulating the climate feedbacks of water vapor.

Precipitation plays a primary role in the global water and energy cycle. Its variations are closely linked to climate change. The spatial and temporal variability of precipitation at global scale can be retrieved from observations made by infrared sensors onboard the geostationary satellites, passive microwave sensors carried by the polar-orbiting satellites, and recently active radars onboard the Tropical Rainfall Measuring Mission (TRMM) satellite and its successors. SSMI records between 1987 and 2006 showed that the response of precipitation to global warming was 7% K-1 of surface warming, much higher than the 1-3% k-1 of surface warming predicted by climate models[82](#_ENREF_82). The observation has generated an intense debate on whether a large discrepancy exists between observed and modeled trends of precipitation. Studies that used longer satellite time series produced lower rates of increase but these results are still regarded as inconclusive due to the brevity of satellite time series[83](#_ENREF_83),[84](#_ENREF_84). At inter-annual scale, the correlation between the satellite observed precipitations and global surface temperature anomalies was also found to be weak during 1988-2008 if large-scale forcings including ENSO and volcanic eruptions were removed[76](#_ENREF_76). A survey of available satellite-based long-term precipitation products showed mostly little or no trend in global precipitation[85](#_ENREF_85). These divergent findings display the challenge to detect a robust global mean trend of precipitation, which is still impeded by the high variability of the precipitation, systematic biases associated with the instrument, and inadequate interpretation of the surface and atmospheric properties in the retrieving algorithms[84](#_ENREF_84),[86](#_ENREF_86). While the uncertainty in a general trend is still high, satellite observations have greatly enhanced the understanding of the climate processes that control the variability of precipitation. For example, the effect of SST on the regional precipitation pattern at multi-annual and multi-decadal time scale[21](#_ENREF_21) and the promotion of a “wet-gets-wetter” and “dry-gets-direr” trend pattern in tropical region by the intensification of summer monsoon were detected using satellite precipitation products[87](#_ENREF_87).

**Limitations and solutions**

Three recurring limitations can be identified from discussed studies: shortness of the satellite data sets, biases associated with instrument, and uncertainties of the retrieval algorithms.

### Shortness of satellite data sets

Researchers who use short time series of satellite data may have the trouble to reliably separate the long-term trend from inter-annual and decadal variability. In order to detect the trend of climate change satellite observations should have long-term continuity[88](#_ENREF_88). A uniform requirement on the time length that is applicable to detect all important climate trends does not exist currently. A few studies have specified minimum requirements for some climate variables, ranging from 40 years for tracking the change of satellite ocean color[89](#_ENREF_89) to 60 years for determining SLR[90](#_ENREF_90). GCOS suggested duration of 30 years for satellite observation of the climate system[8](#_ENREF_8). More studies are needed to find out the lengths of satellite time series required for detecting reliable trends in other climate variables. An examination on the lengths of ECVs constructed from satellite observations shows that some time series are already longer than 30 years (Table 1). Availability of more time series with adequate length will depend on the efforts to maintain the continuity of existing satellite missions.

### Biases associated with instrument

So far observations on many climate variables are made by satellite sensors originally designed for meteorological observations. The coarse-resolution sensors carried by some satellites are not able to capture climate processes occurring at finer spatial scales. For example, no satellite sensor can provide high spatial resolution observations needed for characterizing the small-scale “turbulence” in thermodynamic profile associated with the fine-scale variability of temperature and water vapor in atmosphere[91](#_ENREF_91). Also, satellite sensors do not have the required accuracy to detect the trend of cloud properties[69](#_ENREF_69). This requires new sensors with sufficiently high spatial resolution and accuracy suitable for observing the interested climate phenomena. At the same time, the inadequate temporal frequency of coverage of the current systems need to be addressed, which impede the ability to study some fast-evolving climate processes. Constellation of small satellites that observe the same location at a time interval is a solution[9](#_ENREF_9),[69](#_ENREF_69).

For satellite records that are used for trend detection and retrieval of the absolute levels of climate variables, the findings are greatly affected by how well the uncertainties associated with the sensors are resolved. This key step is exemplified well in the debate on the trend of solar radiation. Undetected sensor sensitivity drifts have been cited as a main reason for exposed spectrum change[57](#_ENREF_57). Satellite sensors will gradually lose the radiometric sensitivity and stability during the operation; so good calibration is indispensable. Some satellite sensors cannot be recalibrated after launch due to a lack of onboard or on-orbit calibrations with the required level of accuracy. Procedures have been developed to calibrate this type of sensors but may still contain uncertainties[92](#_ENREF_92). Biases caused by orbit drifting of satellite platforms are also common in satellite data. Satellites go through a slow change of local equator crossing time and a decay of orbital height due to drag by the upper atmosphere. Orbit drifting can add a spurious effect to detected trends[93](#_ENREF_93). This type of biases need to be addressed by applying a diurnal correction procedure to the data[93](#_ENREF_93) or by determining the precise orbit position of the satellites[94](#_ENREF_94).

Uncertainties can also rise from combining observations obtained from different satellite systems to form Long-term records. If the procedures to merge data from different systems are not well developed and calibrated, the uncertainties can be potentially high in combined data sets. The report of an abrupt increase of Antarctic sea ice area was found to be a false detection caused by the shift from the Special Sensor Microwave Imager (SSMI) system to the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSRE)[95](#_ENREF_95). This type of problem can be reduced by allowing an overlap of operating time between instruments so inter-instrument calibrations can be conducted to find out the relative bias[96](#_ENREF_96). For instance, the Topex/Poseidon satellite and its successors have been launched in a way to allow for tandem measurements and inter-satellite calibrations. Many planned new satellite missions are adopting this approach[12](#_ENREF_12).

### Uncertainties in retrieval algorithms

Retrieval algorithms are key for converting the electromagnetic signals from satellite sensors to measurements of climate variables. Uncertainties in retrieval algorithms can affect the magnitude of detected trends and even change their direction, e.g. the positive and negative trends of tropospheric temperature derived from the same satellite data by using different retrieving algorithms[23](#_ENREF_23),[93](#_ENREF_93). Multiple satellite data sets of climate variables should be developed independently and intercomparison studies needed to be conducted to help identify potential problems.

Some recent studies also showed that the common inputs used in retrieving algorithms are an important source of uncertainties. One main factor for the divergent estimates of the mass loss rate of ice sheets discussed earlier is the different GIA values adopted by different research groups[38](#_ENREF_38). In studies of the concentrations of aerosols in the atmosphere, inputs used for deriving aerosol optical thickness from satellite data are one of the main sources of uncertainties. Surface emissivity and albedo, cloud information, and aerosol properties are several highly cited inputs that significantly affect the accuracy of retrieved AOD[97](#_ENREF_97). Researchers face with huge selections of these common inputs. For example, just for the land cover data needed for land surface models, seven types of global land cover data derived from satellite data are now available[5](#_ENREF_5). Studies are needed to evaluate the quality of common inputs used in satellite retrieval algorithm and quantify their effects on the uncertainties in final products.

Besides making improvements on instrumentation and retrieval algorithms, validation data with good quality will help researchers to calibrate instrument, tune retrieval algorithms and gauge the level of uncertainties in satellite data sets[21](#_ENREF_21),[94](#_ENREF_94). There is an urgency to construct more global reference networks for calibrating satellite data and validating data products[11](#_ENREF_11). However, the spatial and temporal mismatch between the satellite observations and the validation data sets must be noted and accounted for in this process[98](#_ENREF_98). Guided by better knowledge on errors in instrument and algorithms, rigorous reanalysis should be conducted regularly to remove errors in long-term remotely sensed data. This approach provides the best hope to produce high-quality climate records from data collected by existing satellites and their predecessors. For example, a temporally consistent global product of LAI has been developed using a well calibrated algorithm[99](#_ENREF_99).

**Conclusions**

In this review we have demonstrated that SRS has made a unique and crucial contribution to our understanding of the climate system and its variations. It provides an independent source of observations to validate climate models and climate theories. Although the shortness of and the uncertainties in time series derived from satellite records have limited the detection of robust long-term trends of many climate variables at the moment, the progresses made in both instrumentation and retrieval algorithms accompanied with the accumulation of satellite records will make more detections possible. By combining the strength of passive and active remote sensing, e.g., the formation of A-train, better insights into the complicated climate system have been obtained. Innovative use of existing satellite data is also a direction to produce long-term climate records. A good example is the 30-year atmospheric brightness temperature data produced by the NOAA by using archived geostationary satellite data, which are not frequently used to produce climate records as polar-orbiting satellite data[100](#_ENREF_100).

Besides working to advance the science and technology of SRS, strong international collaboration and governmental support are also necessary for enhance its role in climate change studies. Several international initiatives, notably the Global Observing Systems Information Center (GOSIC) and the Global Earth Observation System of Systems (GEOSS), have been implemented to coordinate the efforts to produce and disseminate high-quality satellite climate records. United Sates, European Union, and several other countries have planned new satellite missions for climate observation. Seventeen satellite missions that can provide improved climatological measurements are scheduled to be launched by 2020[12](#_ENREF_12). However, the recent cancelation of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) and the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) missions show that such important initiatives are vulnerable to poor governmental commitments. Clearly, our "Eyes in Space" would contribute more towards capturing real trends of climate change were the aforementioned activities fully implemented.

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F**igure 1. Remote sensing of the climate system.** SRS is capable of providing frequent and repetitive coverage over a large area.

**Figure 2. Upper atmosphere temperature trends between 1979 and 2012 based on MSU data sets.** University of Alabama at Huntsville (UAH) data set and Remote Sensing Systems (RSS) data set are drawn here. A 6-month moving window smoothing has been applied to the data sets. UAH and RSS data sets now both show a warming trend in the troposphere while UAH formerly reported a cooling trend in the lower troposphere[23](#_ENREF_23). (Data source: National Climate Data Center, NOAA)

**Figure 3. Zonal patterns of global SLR between 1993 and 2012.** Panel *a* is based on combined data sets (66oN to 66oS) of TOPEX/Poseidon, Jason-1, and Jason-2 produced by the Laboratory for Satellite Altimetry (LSA), NOAA. Panel *b* is mapped using data sets (85oN to 85oS) from the same three satellites produced by the Archiving, validation and interpretation of satellite oceanographic data (Aviso). Panel *c* shows that LSA/NOAA and Aviso have similar estimates of global mean SLR, 3.2±0.4 and 3.2±0.6, respectively. However, the estimated magnitudes of regional SLR were different in two data sets.

Table 1 Time lengths of climate ECVs retrieved from satellite observationsa.

|  |  |  |  |
| --- | --- | --- | --- |
| Time length (yr) | Atmospheric ECV | Oceanic ECV | Terrestrial ECV |
| 0~9 |  | Ocean salinity | Biomass, Glacier and ice caps |
| 10~19 | Wind speed and direction(Upper air), Carbon dioxide, Ozone | Ocean color, Sea state | Land cover, Albedo, fAPAR, Fire disturbance |
| 20~29 | Radiation budget, Wind speed and direction(surface), Water vapor, Cloud properties, Aerosol properties | Sea level | Lakes, LAI |
| 30~39 | Precipitation, Upper air temperature | Sea surface temperature, Sea ice | Soil moisture |
| 40~49 |  |  | Snow cover |

1. Data sets, holders, and access URLs for these ECVs are listed in the supplementary table 2.





