nature climate change

REVIEW ARTICLE

PUBLISHED ONLINE: 15 SEPTEMBER 2013 | DOI: 10.1038/NCLIMATE1908

The role of satellite remote sensing in climate change studies

Jun Yang[1], Peng Gong[1,2,3*], Rong Fu[4], Minghua Zhang[5], Jingming Chen[6,7], Shunlin Liang[8,9], Bing Xu[8,10], Jiancheng Shi[2] and Robert Dickinson[4]

Satellite remote sensing has provided major advances in understanding the climate system and its changes, by quantifying processes and spatio-temporal states of the atmosphere, land and oceans. In this Review, we highlight some important discoveries about the climate system that have not been detected by climate models and conventional observations; for example, the spatial pattern of sea-level rise and the cooling effects of increased stratospheric aerosols. New insights are made feasible by the unparalleled global- and fine-scale spatial coverage of satellite observations. Nevertheless, the short duration of observation series and their uncertainties still pose challenges for capturing the robust long-term trends of many climate variables. We point out the need for future work and future systems to make better use of remote sensing in climate change studies.

Observational data and model simulations are the foundations of our understanding of the climate system[1]. Satellite remote sensing (SRS) — which acquires information about the Earth's surface, subsurface and atmosphere remotely from sensors on board satellites (including geodetic satellites) — is an important component of 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], SRS has gradually become a leading research method in climate change studies[3].

The use of satellites allows the observation of states and processes of the atmosphere, land and ocean at several spatio-temporal scales. For instance, it is one of the most efficient approaches for monitoring land cover and its changes through time over a variety of spatial scales[4,5]. Satellite data are frequently used with climate models to simulate the dynamics of the climate system and to improve climate projections[6]. Satellite data also contribute significantly to the improvement of meteorological reanalysis products that are widely used for climate change research, for example, the National Center for Environmental Prediction (NCEP) reanalysis[7]. The Global Climate Observing System (GCOS) has listed 26 out of 50 essential climate variables (ECVs) as significantly dependent on satellite observations[8]. Data from SRS is also widely used for developing prevention, mitigation and adaptation measures to cope with the impact of climate change[9].

Despite the aforementioned contributions of SRS, there are concerns about the suitability of satellite data for monitoring and understanding climate change[10]. Climate change studies require observations to be calibrated/validated and consistent, and to provide adequate temporal and spatial sampling over a long period of time[11]. However, satellite data often contain uncertainties caused by biases in sensors and retrieval algorithms, as well as inconsistencies between continuing satellite missions with the same sensors. The use of satellite observations in climate change studies requires a clear identification of such limitations.

In this Review we discuss 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. Our main goal is to reveal the unique contributions and major limitations of SRS as used in these studies. Technical details on instrumentation and retrieval methods can be found in a recent review[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 the global scale. This 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 since the late nineteenth century has provided evidence for anthropogenic influences on global climate[13]. This trend was first identified by analysing anomalies in time series of near-surface air temperature over the land that were recorded by weather stations[14]. However, the existence of the trend was consistently challenged due to the biases in weather records[15] caused by such things as poor siting of the instrumentation and the influence of land-use/land-cover changes. Satellite data provides an independent way to investigate global temperature trends, particularly at the ocean surface and in the atmosphere.

The sea surface temperatures (SSTs) of the 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]. The Advanced Very High Resolution Radiometer on board the National Oceanic and Atmospheric Administration (NOAA) satellites allows us to monitor the SST worldwide. An increase in SST has been observed in all ocean basins since the 1970s, with an average estimated increase of 0.28 °C from 1984 to 2006[17]. This

[1]Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing 100084, China, [2]State Key Lab of Remote Sensing Science, jointly sponsored by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Science, and Beijing Normal University, Beijing 100101, China, [3]Department of Environmental Science, Policy and Management, University of California, Berkeley, California 94720, USA, [4]Jackson School of Geosciences, University of Texas, Austin, Texas 78712, USA, [5]School of Marine and Atmospheric Sciences, State University of New York, Stony Brook, New York 11794, USA, [6]International Institute for Earth System Science, Nanjing University, Nanjing 210093, China, [7]Department of Geography and City Planning, University of Toronto, Toronto, Ontario M5S 3G3, Canada, [8]College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China, [9]Department of Geography, University of Maryland, College Park, Maryland 20742, USA, [10]College of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China. *email: penggong@berkeley.edu

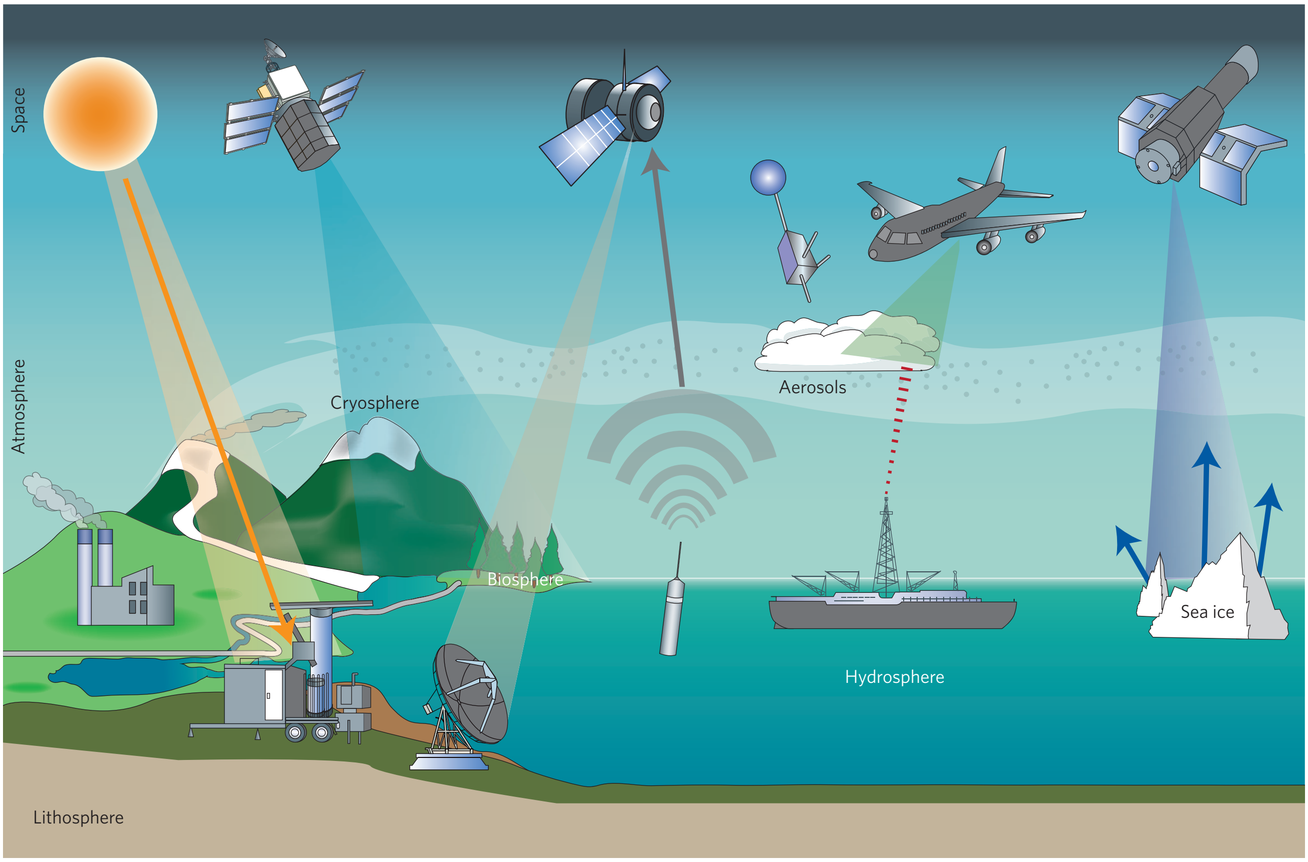

Figure 1 | Remote sensing of the climate system. Remote sensing is carried out by sensors aboard different platforms, including plane, boat and Argo floats. Ground-based instruments are also used, for example, sun spectral radiometers measure solar radiation. However, satellite remote sensing is capable of providing more frequent and repetitive coverage over a large area than other observation means . Figure courtesy of R. He, Hainan University.

global trend is similar to that of the near-surface air temperature over land, thus providing a decisive corroboration of the warming identified from weather records, although the magnitude still has considerable uncertainty[18]. Satellite observations also reveal an uneven warming pattern. The ocean warming trend is highest in the middle latitudes of both hemispheres[19], stronger east–west zonal SST gradients have been detected across the equatorial Pacific Ocean[20]. The regional variability of SST is closely linked with that of other climate parameters, such as precipitation[21]. All of these discoveries have led to a better understanding of the role of the oceans in influencing global climate.

Surface and tropospheric warming has been predicted as a major response of the climate system to escalating concentrations of greenhouse gases[22], but initial analyses found no obvious trend in the tropospheric temperature records obtained using microwave sounding units (MSUs) on polar-orbiting satellites[23] — a finding that has challenged both the reliability of surface temperature records and our understanding of the reaction of the climate system to increased greenhouse gas concentrations[24]. However, after removing known problems with the sensors, accounting for the influence of stratospheric cooling and reducing biases in retrieval methods[25], new versions of satellite time series all show a warming trend in the troposphere, except in the Antarctic region[26] (Fig. 2). This progress, together with improved climate models, has led to the conclusion that there is no fundamental disagreement between observed and modelled tropospheric temperature trends of warming (provided that uncertainties in both are accounted for)[24]. Nevertheless, some questions remain. The observed scaling ratio (that is, the ratio of atmospheric trend to surface trend) is still significantly lower than model projections[27]. The differences between observed temperatures in the tropical upper- and lower-middle troposphere are also significantly smaller than those simulated by climate models[28]. These remaining differences indicate that either model deficiencies or observational errors that were identified in previous studies have not been fully resolved.

Snow and ice. The retreat of snow- and ice-cover is an important indicator of global warming. Melting of seasonal snow- and ice-cover can cause a positive feedback by lowering the albedo of the Earth's surface, and the latter contributes to sea-level rise (SLR)[13]. Data from SRS has played a crucial role in monitoring the dynamics of snow extent and ice covers.

Snow-cover extent (SCE) over the Northern Hemisphere has been routinely monitored since 1967 using visible-band sensors and passive microwave-band sensors carried by satellites[29]. Reconstructed time series based on the NOAA SCE data set and *in situ* measurements have shown that, overall, the SCE over the Northern Hemisphere has been reduced by 0.8 million km^2 per decade in March and April from 1970–2010. A comparison of recent SCE with pre-1970 values indicates a 7% and 11% decrease in March and April, respectively[30]. This trend is consistent with observed global surface warming. The satellite observations also display strong regional patterns of SCE that are affected by regional climate variability. No significant decrease was observed over North America in March from 1970–2010[30], and the decrease of SCE inside Russia ceased after 1990[31].

The extent of sea ice is primarily monitored by passive microwave sensors such as the special sensor microwave/imagers (SSM/I). The latest pattern identified from the satellite records shows that the Antarctic sea-ice extent has increased by 1.5±0.4% per decade from

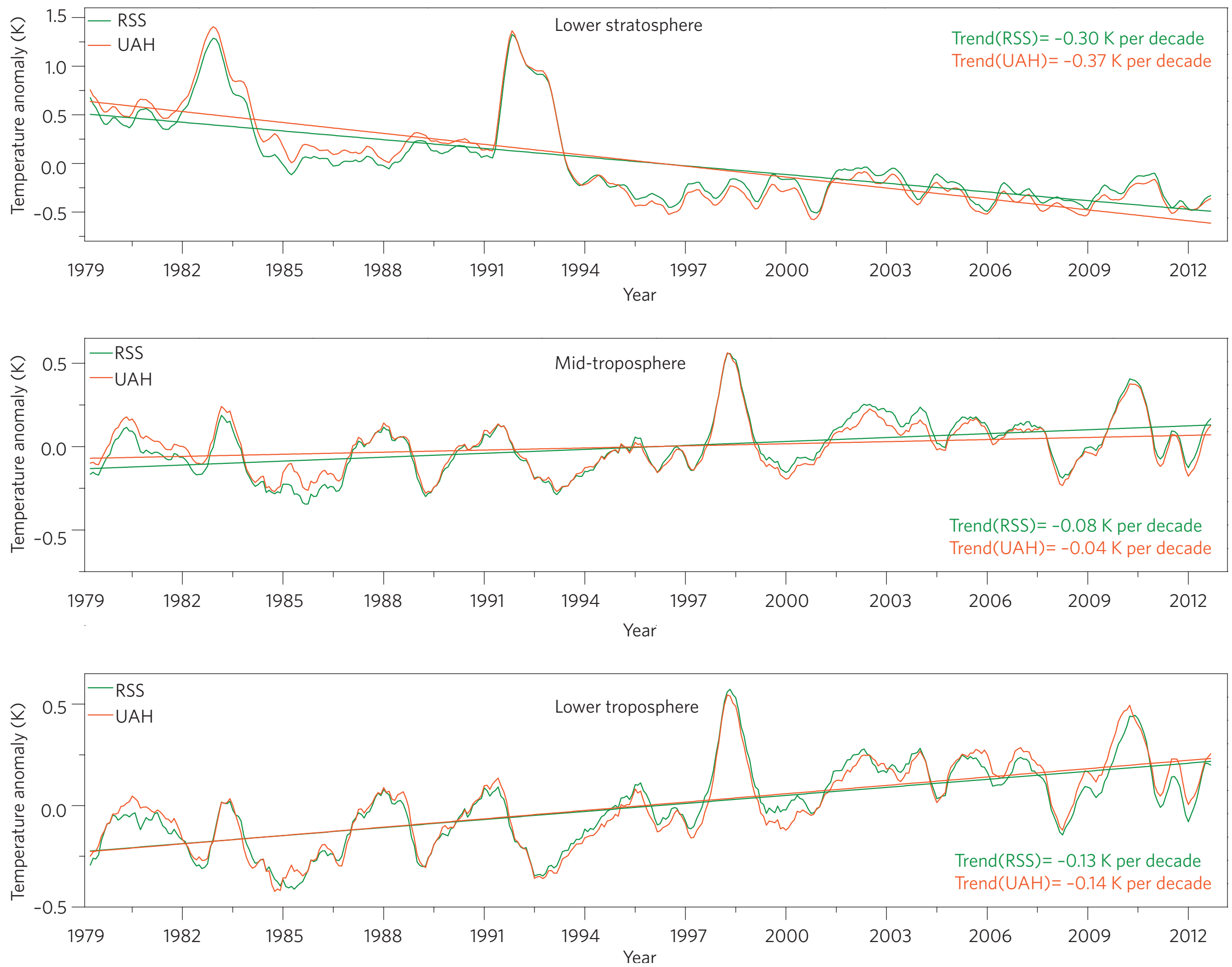

Figure 2 | Upper atmosphere temperature trends between 1979 and 2012 based on MSU data sets. Data from the University of Alabama at Huntsville (UAH) and the Remote Sensing Systems (RSS) are shown here. A 6-month moving window smoothing has been applied to the data sets. Both data sets now show a warming trend, whereas UAH formerly reported a cooling trend in the lower troposphere[23]. Data from the National Climate Data Center; http://vlb.ncdc.noaa.gov/temp-and-precip/msu. Figure courtesy of C. Huang, Beijing Forestry University.

1979 to 2010[32]. Researchers hypothesize that this slight increase was caused by reduced upward heat-transport in the oceans and increased snowfall[33]. The situation is reversed in the Arctic, where satellite observations show an overall negative trend of −4.1±0.3% per decade in that period, with the largest negative trend occurring in summer[34]. This concurs with climate model projections, but its magnitude is larger[35]. Whether the Arctic as a whole has reached a 'tipping point' (a point in time when the decrease of ice in the Arctic cannot be reversed) is still a matter of debate, but some researchers believe that satellite observations show that a 'regional tipping point' has been reached, given that the average age of multi-year ice is decreasing, and the percentage of oldest ice declined from 50% of the multi-year ice pack to 10% from 1980 to 2011[36].

The mass losses of the Antarctic and Greenland ice-sheets have been estimated by measuring surface elevation changes from satellite altimetry data (collected by satellites such as ERS-1/-2, Envisat, ICESat and CryoSat-2) or by measuring ice-mass changes using the Gravity Recovery and Climate Experiment (GRACE) satellite data. Both estimates show that the Antarctic and Greenland ice-sheets are losing mass[37,38]. The latest studies find that these polar ice-sheets contributed an average of 0.59±0.2 mm yr^{-1} to the rate of global SLR since 1992[38]. However, 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 only partial success[37]. Along with the mean trend, the acceleration of ice discharge in the Antarctic and Greenland was revealed through the satellite-borne interferometric synthetic-aperture radar records[39]. This finding and subsequent studies indicate that ice–ocean interaction drives much of the recent increase in mass loss from the Antarctic and Greenland ice-sheets[40].

The retreat of global mountain glaciers and ice caps (GICs) has been cited as a clear sign of global warming. However, satellite observations show that the extent and magnitude of melt for some glacier systems have been less than predicted. Based on Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Satellite Pour l' Observation de la Terre (SPOT) data, the dynamics of glaciers in the Himalayan region were highly variable from 2000–2008. Although 65% of the monsoon-influenced glaciers were retreating, 50% of the glaciers in the Karakoram region of the northwestern Himalayas were advancing or stable[41]. The mass loss of global GICs that was assessed using GRACE measurements during 2003–2010 (excluding the Greenland and Antarctic peripheral GICs) was 30% less than the *in situ* mass-balance result. In the high mountains of Asia, the glacier loss-rate in terms of sea-level contribution was estimated to be only 0.01±0.06 mm yr^{-1}, significantly lower than the 0.13–0.15 mm yr^{-1} calculated by other studies[42]. In the Karakoram region, the mass balance of glaciers was found to be positive, at 0.11±0.22 mm yr^{-1} of water equivalent between 1999 and 2008[43]. Although some of these evaluations still contain high uncertainties, they show non-uniform glacier retreat and regional variations that have been verified by *in situ* observations[44]. They also indicate that the estimated contribution of water from melting glaciers to SLR may be less than predicted in certain regions. Evidently, causal factors other than surface temperature must be considered in projecting the future evolution of glaciers.

Sea-level change. Sea level is driven by climate conditions which are influenced by climate change and variability[45]. On the basis of monitoring sites with good-quality tide-gauge records, the global averaged SLR was estimated as 1.9±0.4 mm yr^{-1} since 1961[46]. Satellite altimetry observations using the TOPEX/Poseidon satellite launched by NASA and Centre National d'Études Spatiales (CNES), which mapped ocean surface topography from 1992 to 2006, as well as its follow-on and other missions, observed a global mean SLR of around 3.2±0.8 mm yr^{-1} between 1992 and 2010[47]. Satellite altimetry observations have also been combined with *in situ* or tide-gauge measurements to reconstruct long-term sea-level time series with global coverage[46]. Strong regional SLR variations have been uncovered by satellite observations (Fig. 3). However, these spatial patterns were probably transient features influenced by El Niño/La Niña or longer-period signals [45]. The prevalence of mesoscale eddies (radius around 100 km or smaller) in oceans has also been detected by satellite observations, profoundly changing our understanding of the relationship between sea level and ocean circulations[48].

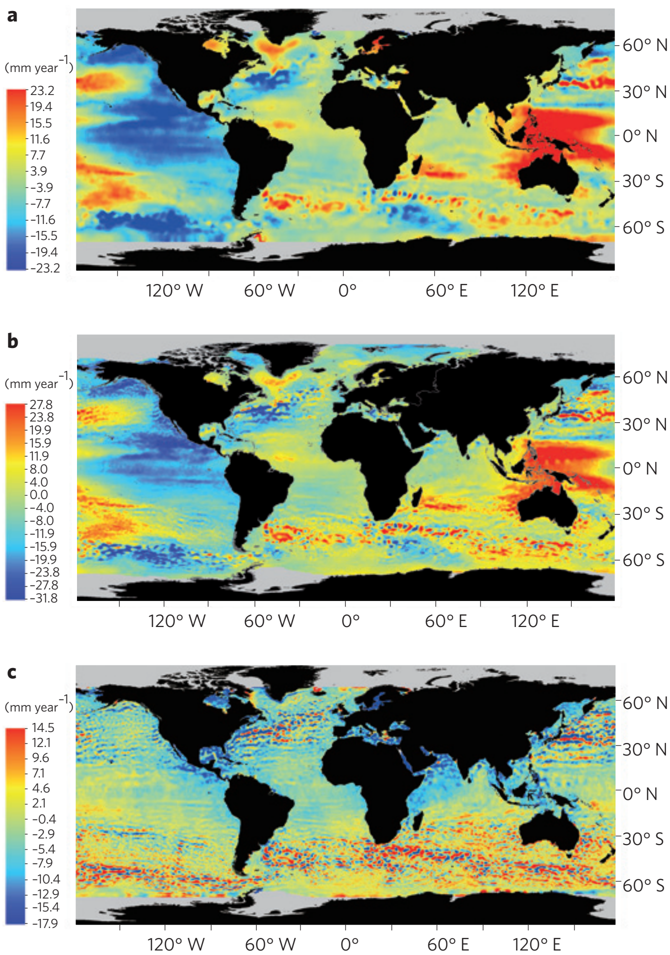

Figure 3 | Map of sea-level trends between 1993 and 2012. a, Combined data sets (66°N to 66°S) of TOPEX/Poseidon, Jason-1 and Jason-2 produced by the Laboratory for Satellite Altimetry, NOAA (http://ibis.grdl.noaa.gov/SAT/SeaLevelRise). **b**, Sea level trends for 85° N to 85° S from the same three satellites produced by the archiving, validation and interpretation of satellite oceanographic data (AVISO). Data from http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level. **c**, The difference between the LSA/NOAA and AVISO data. AVISO and LSA/NOAA have close estimates of global mean SLR (without GIA corrections), 2.72±3.01 and 2.71±2.30 mm yr^{-1}, respectively. However, the estimated magnitudes of regional SLR were different in the two data sets.

The global mean SLR since the last decade of the twentieth century estimated from satellite data has been much higher than that calculated from tide-gauge data during the twentieth century. However, owing to the short data span (~2 decades) of satellite altimetry, the higher estimated rate of SLR could be influenced by interannual or longer oceanic variations, and not necessarily accelerated SLR. Knowing why the rate of SLR has changed is important for its robust future projections[46,47]. Verification of altimetry observations against tide-gauge data has ruled out the possibility that this change in the trend is spurious, or resulting from biases in satellite data. Tide-gauge calibrations did not show any trend drift in the combined 18-year satellite altimetry data[47]. The global mean SLR from tide-gauge records alone was 2.8±0.8 mm yr^{-1} for the period of 1993–2009, which is not significantly different from the values estimated from satellite altimetry[46]. Values of SLR contain steric change (from alterations in 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 hydrography data collected, for example, by the Argo system (a global array of 3,000 free-drifting profiling floats that measure the temperature and salinity of the upper 2,000 m of the ocean). Initial results show a general agreement in regions where all three observation systems are in operation. However, the sea-level budget cannot be fully closed with existing data sets. Systematic errors in each observation system, and the error in the glacial isostatic adjustment (GIA) modelling (accounting for post-glacial rebound of the Earth's surface), must be addressed, and, longer observation periods are needed[47,49].

Accurately estimating trends in global mean SLR is still a challenging task. A longer period of observation is needed to distinguish the interannual and decadal variability from the long-term trend in sea-level records. Satellite altimetry measurements of mean sea level for regions outside the 66° N–66° S zone are not readily available[47]. A recent effort to use multisatellite altimetry data covering the ice-free ocean to generate weekly gridded sea-level data for regions between 66 and 82° N has offered a partial solution[50].

Solar radiation. It is important to track changes in the sun's luminosity (measured in total solar irradiance; TSI), to determine whether the natural variation in solar radiation has contributed significantly to recent climate change. Satellite observation of TSI started in 1978 using active-cavity electrical-substitution radiometers. Climate simulations indicate that the variation in TSI has had little influence on global warming since 1880[51]. One study determined that the sun might have contributed 25–35% of the 1980–2000 global warming on the basis of two alternative satellite TSI composites[52]. A nearly negligible influence was found in a later study using the same data, and limitations of the retrieval methodology that was previously used were suggested to be the source of the overestimation[53].

Recent studies have identified possible ways that variability in solar spectral irradiance influences climate[54,55]. Measurements from the spectral irradiance monitor (SIM) on board the Solar Radiation and Climate Experiment (SORCE) satellite showed that ultraviolet radiation has decreased over the solar magnetic energy cycle four to six times more than had been expected from model calculations. This reduction is partially compensated by an increase in radiation at visible wavelengths[54]. These spectral changes were linked to a significant decline in stratospheric ozone below an altitude of

45 km from 2004 to 2007, which caused a ripple effect throughout the atmosphere and contributed to global surface warming[55]. The variation in solar ultraviolet irradiance has also been linked to cold winters in northern Europe and Canada by using the SIM measurements as inputs to run climate models[56]. However, others believe that the observed variation is a consequence of undercorrection of instrument response to changes during early on-orbit measurements or undetected drifts in the sensitivity of instruments[57]. The true change in the solar spectrum and its impact can only be confirmed when longer-period SIM measurements become available and more factors are considered in climate model simulations[58].

Aerosols. Particles in the atmosphere known as aerosols can generate a cooling effect on the climate system, counteracting the warming effects of anthropogenic greenhouse gases by affecting both atmospheric radiation and cloud–precipitation processes[59,60]. Recent changes in atmospheric aerosol concentration have been identified through aerosol optical depth (AOD), which is derived from observations recorded by visible and infrared optical sensors on board various satellites. Since 1982 these data show a negative trend in the troposphere over North America and most of Europe, and a positive trend over South and East Asia. The overall combined effect of these regional changes probably amounts to a small negative trend[61,62], which is attributed to efforts in North America and Europe to control air pollution and rapid industrialization in Asian countries[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. The concentrations of aerosols in the stratosphere have increased by as much as 10% since 2000, in contrast to assumptions used in climate models that the background stratospheric aerosol layer is constant. This increase might have caused a negative radiative forcing of about -0.1 W m^{-2}, implying a global cooling of about -0.07 °C and consequently about 10% less SLR since 2000[63]. The increase was attributed to small-scale volcano emissions[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 calculated by combining satellite observations of the radiation budget and AOD. The estimated value is around -0.65 W m^{-2} to -1.0 W m^{-2}, greater than the -0.5 ± 0.4 W m^{-2} 'consensus' value from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change and most model results. Explanations for this disagreement include biases in satellite data and the deficiency of models in simulating the physical, chemical and optical properties of aerosols[60]. The indirect effects of aerosols that are assessed using satellite data range from -0.2 to -0.5 W m^{-2}, which is three to six times smaller than model estimates[65]. One reason for this difference is that satellite-based methods use the present-day relationship between observed cloud water content (droplet number) and AOD to determine the preindustrial values for droplet concentration but the primary reason is probably overestimation by models, because they still cannot accurately simulate cloud processes[66].

The interactions between cloud, aerosols and precipitation are also better understood with SRS observations. Cloud–aerosol lidar data show that dust particles lifted to the cold cloud layer promote the formation of ice crystals in supercooled clouds and decrease cloud albedo — which, in turn, leads to decreased reflection of solar radiation and decreased cooling effects[67]. The simultaneous multisensor observation capability provided by the A-train mission (a formation of six Earth-observing satellites) has allowed the detection of the suppression effect of aerosols on precipitation of ice clouds[68].

Clouds. Climate forcing and feedback of clouds adjust the energy flow throughout the Earth's system. Net cloud forcing (NCF) is estimated to be -21 W m^{-2} by combining model simulations with the Earth Radiation Budget Experiment (ERBE) and Clouds and the Earth's Radiant Energy System (CERES) observations[69]. The cloud feedback to short-term climate variations is calculated to be a positive value of 0.54 ± 0.74 W m^{-2} K^{-1} on the basis of satellite observations of the top-of-atmosphere radiation budget[70]. These estimates provide good constraints for climate models. The model outputs of short-term (decadal scale) cloud feedback are in the same range as the satellite observations, indicating that climate models can simulate the response of clouds to short-term climate variations[70]. However, cloud feedback is considered to be the most complex and least understood climate phenomenon. For example, measurements made with the Multiangle Imaging SpectroRadiometer (MISR) on board the Terra satellite showed a decreasing global effective cloud height between 2000 and 2010. Such a cloud top lowering could lead to a negative cloud feedback not previously considered[71]. However, satellite cloud products still lack the accuracy and duration required to detect trends in cloud properties that are critical for understanding the long-term (centennial-scale) feedback to climate changes[72]. To better understand cloud feedback, long-term stable satellite observations of cloud types and their physical properties, as well as radiative effects, are needed.

Water vapour and precipitation. Water vapour is an important greenhouse gas as it contributes around 50% of the present-day global greenhouse effect[73]. Models predict that climate warming will increase atmospheric specific humidity (resulting in a positive feedback) and, in turn, strongly amplify the warming[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 SSM/I data[75]. A strong interannual correlation between tropospheric water-vapour content and surface temperature over the ocean–land combination was also detected during the period of 1988–2008 using a combination of SSM/I and radiosonde (instrumentation hosted on weather balloons) data[76]. High-Resolution Infrared Radiation Sounder (HIRS) records from 1979 to 2009 showed an average increase in water-vapour content in the upper troposphere over the equatorial tropics[77]. Although regional, seasonal, interannual and even longer-period variations that respond to decadal climate events such as the El Niño Southern Oscillation (ENSO) have been observed[77,78], satellite observations consistently support a positive tropospheric water-vapour feedback on a long timescale[74]. A different trend was detected in observations of stratospheric water-vapour content. Satellite data sets from the HALogen Occulation Experiment (HALOE), Stratospheric Aerosol and Gas Experiment II (SAGEII) and the Microwave Limb Sounder (MLS) indicated that the stratospheric water-vapour content increased persistently from 1980 to 2000, and then decreased by 10% between 2000 and 2009, contributing to the flattening of the global warming trend[79]. Satellite observations also support the theory that the stratospheric water-vapour content is tightly regulated by the tropical tropopause temperature[80], even though decoupling may occur on a short timescale[81]. These results provided powerful validation of the abilities of climate models to simulate the feedback of water vapour.

Precipitation plays a primary role in the global water and energy cycle, and its variations are closely linked to climate change. The spatial and temporal variability of precipitation on the global scale can be retrieved from observations made by infrared sensors on board geostationary satellites, passive microwave sensors carried by the polar-orbiting satellites and recently active radars on board the TRMM satellite and its successors. Satellite records between 1987 and 2006 indicated that the response of precipitation to global warming was 7% K^{-1} of surface warming, much higher than the 1–3% K^{-1} predicted by climate models[82]. The observation has generated an intense debate on whether a large discrepancy exists between observed and modelled trends of precipitation. Although studies

Table 1 | Time span of climate ECVs retrieved from satellite observations.

Time span (yr)	Atmospheric ECV	Oceanic ECV	Terrestrial ECV
0~9		Ocean salinity	Biomass, glacier and ice caps
10~19	Wind speed and direction (upper air), CO_2 and ozone	Ocean color, sea state (including wave height, direction, wavelength and time period)	Land cover, fire disturbance
20~29	Radiation budget, wind speed and direction (surface), water vapour, cloud properties and aerosol properties	Sea level	Albedo, lakes (water levels and areas)
30~39	Precipitation, upper air temperature	SST, sea-ice extent	Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) LAI, soil moisture
40~49			Snow cover

*Data sets, providers and access links for these ECVs are listed in the Supplementary Table 2.

using longer satellite time series did produce smaller rates of increase, these results are still regarded as inconclusive due to the brevity of the series[83,84]. The correlation between satellite observed precipitation and global surface temperature anomalies at inter-annual scale was also found to be weak during 1988–2008 if large-scale forcing including ENSO and volcanic eruptions were removed[76]. A survey of available satellite-based long-term precipitation products showed mostly little to no trend in global precipitation[85]. These divergent findings illustrate the problems of detecting a robust global mean trend of precipitation, a consequence of high variability of precipitation, systematic biases associated with instruments, and inadequate interpretation of the surface and atmospheric properties in the retrieval algorithms[84,86]. Although there is still uncertainty regarding a general trend, satellite observations have greatly enhanced our 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 multidecadal timescales[21], and the prevalence of 'wet-gets-wetter' and 'dry-gets-drier' trends in tropical regions that are caused by the intensification of summer monsoons, were detected using satellite precipitation products[87].

Limitations and solutions

Three recurring limitations can be identified from these studies: short data spans of satellite records, biases associated with instruments and uncertainties in retrieval algorithms.

Short spans of satellite data sets. Researchers who use short time series of satellite data might have trouble reliably separating the long-term trends from inter-annual and decadal variability. Intuitively, to most accurately detect trends in climate change, satellite observations should have long-term continuity[88], consistency, and homogeneity (here this means that the non-climatic factors such as instruments and observing methods have homogeneous influences on all observed data). However, there is no uniform requirement for observation length. Some studies have specified minimum requirements for climate variables, ranging from 40 years for tracking the change of ocean colour[89] to 60 years for determining SLR[90]. The GCOS suggested 30 years for satellite observation of the climate system[8]. More studies are needed to determine the lengths of satellite time series required for detecting reliable trends in other climate variables. An examination of the lengths of ECVs constructed from satellite observations shows that some time series are already longer than 30 years (Table 1). The availability of more time series with adequate length will depend on our ability to maintain the continuity of existing satellite missions.

Biases associated with instruments. Observations of many climate variables are made by satellite sensors that were originally designed for meteorological observations. The coarse-resolution sensors carried by some satellites cannot capture climate processes occurring at finer spatial scales. For example, satellite sensors are unable to provide the observations at high enough resolutions to characterize the small-scale 'turbulence' that is associated with the variability of atmospheric temperature and water vapour[91]. In addition, satellite sensors do not have the required accuracy for detecting cloud-property trends[72]. This requires new sensors with sufficiently high spatial resolution and accuracy for observing the climate phenomena of interest. Existing systems provide inadequate temporal coverage with which to study quickly evolving climate processes. This shortfall must be addressed. A possible solution is a constellation of small satellites that observe the same location over a given time interval[9,72].

The findings of satellite records that are used for trend detection and retrieval of the absolute levels of climate variables are greatly affected by how well the uncertainties associated with the sensors are resolved. This important step is underscored in the debate on the trend in solar radiation. Undetected drifts in sensor sensitivity have been cited as the main reason for the apparent spectrum of change[57]. Satellite sensors gradually lose radiometric sensitivity and stability during their operation, so good calibration is essential. Some satellite sensors cannot be recalibrated after launch due to the lack of accurate on-board or on-orbit calibrations. Procedures have been developed to calibrate these types of sensors but may still contain uncertainties[92]. Biases caused by instrument drifts are also common in satellite data. Satellites go through a slow change of crossing time at the local equator and a decay of orbital height, adding a spurious effect to detected trends[93]. Such biases must be addressed by applying a diurnal correction procedure to the data[93] or by determining the precise orbit position of the satellites[94].

Uncertainties can also increase when combining observations from different satellite systems to form long-term records. If the procedures for merging data from different systems are not well developed and calibrated, the uncertainties can potentially be high in combined data sets. The report of an abrupt increase in Antarctic sea-ice area was found to be a false detection caused by the shift from the SSM/I system to the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSRE)[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]. For instance, launch times of the Topex/Poseidon satellite and its successors allow for tandem measurements and intersatellite calibrations. Many new satellite missions are adopting this approach[12].

Uncertainties in retrieval algorithms. Retrieval algorithms are key for converting the electromagnetic signals from satellite sensors to measurements of climate variables. Uncertainties can therefore affect the magnitude of detected trends and even change their direction — for example, the positive and negative trends of tropospheric temperature derived from the same satellite data by using different retrieval algorithms[23,93]. Practices such as producing several satellite data sets of climate variables independently and conducting intercomparison studies should continue and be expanded to help identify potential problems.

Recent studies show that the common inputs used in retrieval algorithms are an important source of uncertainty. One main factor in the divergent estimates of the mass-loss rate of ice sheets discussed earlier is the different GIA values adopted by different research groups[38]. In studies of the concentrations of aerosols in the atmosphere, surface emissivity and albedo, cloud information and aerosol properties are frequently cited inputs that significantly affect the accuracy of retrieved AOD[97]. Researchers are faced with many choices for these common inputs. For example, seven types of global land-cover data derived from satellite data are available for land surface modelling[5]. Studies are needed to evaluate the quality of the common inputs used in retrieval algorithms and to quantify their effects on the uncertainties in the final products.

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

Conclusions

In this Review we have demonstrated that SRS has made crucial contributions 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 satellite time series and associated uncertainties have so far limited the detection of robust long-term trends in some climate variables, the progress made in both instrumentation and retrieval algorithms, accompanied by the accumulation of satellite records, can remedy this. By combining the strength of passive and active remote sensing — for example, the formation of A-train — better insights into the complicated climate system have been obtained. Innovative use of existing satellite data is also a path to production of long-term climate records. A good example is the NOAA's use of archived geostationary satellite data (which are not used as frequently as polar-orbiting satellite data in producing climate records[100]) to produce 30-year brightness temperature data — that is, the effective temperature of a black body radiating the same amount of energy per unit area at the same wavelengths as the observed body.

Along with advancing the science and technology of SRS, strong international collaboration and governmental support are needed to enhance its role in climate change studies. Several international initiatives — notably the Global Observing Systems Information Center (GOSIC), the Global Geodetic Observing System (GGOS) and the Global Earth Observation System of Systems (GEOSS) — have been implemented to coordinate efforts to produce and disseminate high-quality satellite climate records. The USA, European Union and several other countries have planned new satellite missions for climate observation: in total, 17 satellite missions that can provide improved climatological measurements are scheduled for launch by 2020[12]. However, the recent cancellation of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) and the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) missions show that these initiatives depend on a high level of government commitment. Clearly, our 'eyes in space' would contribute more towards capturing real trends of climate change if the aforementioned activities are fully implemented.

Received 23 October 2012; accepted 23 April 2013; published online 15 September 2013.

References

1. Overpeck, J. T., Meehl, G. A., Bony, S. & Easterling, D. R. Climate data challenges in the 21st century. *Science* **331,** 700 (2011).
2. Yates, H. W. Measurement of the Earth radiation balance as an instrument design problem. *Appl. Opt.* **16,** 297–299 (1977).
3. Li, J., Wang, M. H. & Ho, Y. S. Trends in research on global climate change: A Science Citation Index Expanded-based analysis. *Glob. Planet. Change* **77,** 13–20 (2011).
4. Bontemps, S. *et al.* Revisiting land cover observations to address the needs of the climate modelling community. *Biogeosci. Discuss.* **8,** 7713–7740 (2011).
5. Gong, P. *et al.* Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. *Int. J. Remote Sens.* **34,** 2607–2654 (2013).
6. Ghent, D., Kaduk, J., Remedios, J. & Balzter, H. Data assimilation into land surface models: The implications for climate feedbacks. *Int. J. Remote Sens.* **32,** 617–632 (2011).
7. Saha, S. *et al.* The NCEP climate forecast system reanalysis. *Bull. Am. Meteorol. Soc.* **91,** 1015–1057 (2010).
8. Global Climate Observing System *Systematic Observation Requirements for Satellite-based Data Products for Climate: 2011 Update* GCOS-154 (World Meteorological Organization, 2011).
9. Joyce, K. E., Belliss, S. E., Samsonov, S. V., McNeill, S. J. & Glassey, P. J. A review of the status of satellite remote sensing and image processing techniques for mapping natural hazards and disasters. *Prog. Phys. Geog.* **33,** 183–207 (2009).
10. Trenberth, K. & Hurrell, J. How accurate are satellite thermometers—Reply. *Nature* **389,** 342–343 (1997).
11. Karl, T. R. *et al.* Observation needs for climate information, prediction and application: Capabilities of existing and future observing systems. *Procedia Environ. Sci.* **1,** 192–205 (2010).
12. Thies, B. & Bendix, J. Satellite based remote sensing of weather and climate: Recent achievements and future perspectives. *Meteorol. Appl.* **18,** 262–295 (2011).
13. Pachauri, R. K. & Reisinger, A. (eds) *IPCC Climate Change 2007: Synthesis Report* (IPCC, 2007).
14. Hansen, J. & Lebedeff, S. Global trends of measured surface air temperature. *J. Geophys. Res.* **92,** 345–313 (1987).
15. Pielke, R. A. *et al.* Unresolved issues with the assessment of multidecadal global land surface temperature trends. *J. Geophys. Res.* **112**, D24S08 (2007).
16. Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C. & Wang, W. An improved *in situ* and satellite SST analysis for climate. *J. Clim.* **15,** 1609–1625 (2002).
17. Large, W. G. & Yeager, S. G. On the observed trends and changes in global sea surface temperature and air-sea heat fluxes (1984–2006). *J. Clim.* **25,** 6123–6135 (2012).
18. Zhang, H. *et al.* An integrated global observing system for sea surface temperature using satellites and *in situ* data: Research to operations. *Bull. Am. Meteorol. Soc.* **90,** 31–38 (2009).
19. Deser, C., Phillips, A. S. & Alexander, M. A. Twentieth century tropical sea surface temperature trends revisited. *Geophys. Res. Lett* **37**, L10701 (2010).
20. Karnauskas, K. B., Seager, R., Kaplan, A., Kushnir, Y. & Cane, M. A. Observed strengthening of the zonal sea surface temperature gradient across the Equatorial Pacific Ocean. *J. Clim.* **22,** 4316–4321 (2010).
21. Schwaller, M. R. & Robert Morris, K. A ground validation network for the global precipitation measurement mission. *J. Atmos. Ocean. Tech.* **28,** 301–319 (2011).
22. Manabe, S. & Wetherald, R. T. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci.* **24,** 241–259 (1967).
23. Spencer, R. W. & Christy, J. R. Precise monitoring of global temperature trends from satellites. *Science* **247,** 1558–1562 (1990).
24. Thorne, P. W., Lanzante, J. R., Peterson, T. C., Seidel, D. J. & Shine, K. P. Tropospheric temperature trends: History of an ongoing controversy. *WIREs Clim. Change* **2,** 66–88 (2011).

25. Mears, C. A. & Wentz, F. J. Construction of the remote sensing systems V3. 2 atmospheric temperature records from the MSU and AMSU microwave sounders. *J. Atmos. Ocean. Tech.* **26,** 1040–1056 (2009).
26. Xu, J. & Powell, A. Jr Uncertainty of the stratospheric/tropospheric temperature trends in 1979–2008: Multiple Satellite MSU, radiosonde, and reanalysis datasets. *Atmos. Chem. Phys. Discuss.* **11,** 10727–10732 (2011).
27. Christy, J. R., Spencer, R. W. & Norris, W. B. The role of remote sensing in monitoring global bulk tropospheric temperatures. *Int. J. Remote Sens.* **32,** 671–685 (2011).
28. Fu, Q., Manabe, S. & Johanson, C. M. On the warming in the tropical upper troposphere: Models versus observations. *Geophys. Res. Lett.* **38**, L15704 (2011).
29. Frei, A. A new generation of satellite snow observations for large scale earth system studies. *Geog. Compass* **3,** 879–902 (2009).
30. Brown, R. D. & Robinson, D. A. Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *Cryosphere.* **5,** 219–229 (2011).
31. Bulygina, O., Groisman, P. Y., Razuvaev, V. & Korshunova, N. Changes in snow cover characteristics over Northern Eurasia since 1966. *Environ. Res. Lett.* **6,** 045204 (2011).
32. Parkinson, C. & Cavalieri, D. Antarctic sea ice variability and trends. *Cryosphere Discuss.* **6,** 931–956 (2012).
33. Liu, J. & Curry, J. A. Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. *Proc. Natl Acad. Sci. USA* **107,** 14987 (2010).
34. Cavalieri, D. & Parkinson, C. Arctic sea ice variability and trends, 1979–2010 *Cryosphere.* **6,** 881–889 (2012).
35. Kattsov, V. M. *et al.* Arctic sea ice change: A grand challenge of climate science. *J. Glaciol.* **56,** 1115–1121 (2011).
36. Maslanik, J., Stroeve, J., Fowler, C. & Emery, W. Distribution and trends in Arctic sea ice age through spring 2011. *Geophys. Res. Lett.* **38**, L13502 (2011).
37. Horwath, M., Legresy, B., Remy, F., Blarel, F. & Lemoine, J.-M. Consistent patterns of Antarctic ice sheet interannual variations from ENVISAT radar altimetry and GRACE satellite gravimetry. *Geophys. J. Int.* **189,** 863–876 (2012).
38. Shepherd, A. *et al.* A reconciled estimate of ice-sheet mass balance. *Science* **338,** 1183–1189 (2012).
39. Rignot, E. *et al.* Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophys. Res. Lett.* **31**, L18401 (2004).
40. Joughin, I., Alley, R. B. & Holland, D. M. Ice-sheet response to oceanic forcing. *Science* **338,** 1172–1176 (2012).
41. Scherler, D., Bookhagen, B. & Strecker, M. R. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.* **4,** 156–159 (2011).
42. Jacob, T., Wahr, J., Pfeffer, W. T. & Swenson, S. Recent contributions of glaciers and ice caps to sea level rise. *Nature* **482,** 514–518 (2012).
43. Gardelle, J., Berthier, E. & Arnaud, Y. Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geosci.* **5**, 322–325 (2012).
44. Yao, T. *et al.* Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Clim. Change* **2,** 663–667 (2012).
45. Cazenave, A. & Remy, F. Sea level and climate: Measurements and causes of changes. *WIREs Clim. Change* **2,** 647–662 (2011).
46. Church, J. A. & White, N. J. Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.* **32,** 585–602 (2011).
47. Leuliette, E. W. & Willis, J. K. Balancing the sea level budget. *Oceanography* **24,** 122–129 (2011).
48. Fu, L. L., Chelton, D. B., Le Traon, P. Y. & Morrow, R. Eddy dynamics from satellite altimetry. *Oceanography* **23,** 14–25 (2010).
49. Willis, J. K., Chambers, D. P., Kuo, C. Y. & Shum, C. K. Global sea level rise: Recent progress and challenges for the decade to come. *Oceanography* **23,** 26–35 (2010).
50. Prandi, P., Ablain, M., Cazenave, A. & Picot, N. A new estimation of mean sea level in the Arctic ocean from satellite altimetry. *Mar. Geod.* **35,** 61–81 (2012).
51. Hansen, J. *et al.* Climate simulations for 1880–2003 with GISS modelE. *Clim. Dynam.* **29,** 661–696 (2007).
52. Scafetta, N. & West, B. J. Phenomenological solar contribution to the 1900–2000 global surface warming. *Geophys. Res. Lett.* **33,** L05708 (2006).
53. Benestad, R. & Schmidt, G. Solar trends and global warming. *J. Geophys. Res.* **114**, D14101 (2009).
54. Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C. & Woods, T. N. Trends in solar spectral irradiance variability in the visible and infrared. *Geophys. Res. Lett.* **36**, L07801 (2009).
55. Haigh, J. D., Winning, A. R., Toumi, R. & Harder, J. W. An influence of solar spectral variations on radiative forcing of climate. *Nature* **467,** 696–699 (2010).
56. Ineson, S. *et al.* Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geosci.* **4,** 753–757 (2011).
57. Lean, J. L. & DeLand, M. T. How does the Sun's spectrum wary? *J. Clim.* **25,** 2555–2560 (2012).
58. Matthes, K. Atmospheric science: Solar cycle and climate predictions. *Nature Geosci.* **4,** 735–736 (2011).
59. Quaas, J., Boucher, O., Bellouin, N. & Kinne, S. Satellite-based estimate of the direct and indirect aerosol climate forcing. *J. Geophys. Res* **113**, D05204 (2008).
60. Zhao, T. X. P., Loeb, N. G., Laszlo, I. & Zhou, M. Global component aerosol direct radiative effect at the top of atmosphere. *Int. J. Remote Sens.* **32,** 633–655 (2011).
61. Cermak, J., Wild, M., Knutti, R., Mishchenko, M. I. & Heidinger, A. K. Consistency of global satellite-derived aerosol and cloud data sets with recent brightening observations. *Geophys. Res. Lett.* **37**, L21704 (2010).
62. De Meij, A., Pozzer, A. & Lelieveld, J. Trend analysis in aerosol optical depths and pollutant emission estimates between 2000 and 2009. *Atmos. Environ.* **51,** 75–85 (2012).
63. Solomon, S. *et al.* The persistently variable "Background" stratospheric aerosol layer and global climate change. *Science* **333,** 866–870 (2011).
64. Vernier, J. P. *et al.* Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade. *Geophys. Res. Lett.* **38**, L12807 (2011).
65. Penner, J. E., Xu, L. & Wang, M. Satellite methods underestimate indirect climate forcing by aerosols. *Proc. Natl Acad. Sci. USA* **108,** 13404–13408 (2011).
66. Quaas, J., Boucher, O., Bellouin, N. & Kinne, S. Which of satellite- or model-based estimates is closer to reality for aerosol indirect forcing? *Proc. Natl Acad. Sci. USA* **108**, E1099-E1099 (2011).
67. Choi, Y. S., Lindzen, R. S., Ho, C. H. & Kim, J. Space observations of cold-cloud phase change. *Proc. Natl Acad. Sci. USA* **107,** 11211–11216 (2010).
68. Jiang, J. H. *et al.* Clean and polluted clouds: Relationships among pollution, ice clouds, and precipitation in South America. *Geophys. Res. Lett.* **35**, L14804 (2008).
69. Allan, R. P. Combining satellite data and models to estimate cloud radiative effect at the surface and in the atmosphere. *Meteorol. Appl.* **18,** 324–333 (2011).
70. Dessler, A. E. A determination of the cloud feedback from climate variations over the past decade. *Science* **330,** 1523–1527 (2010).
71. Davies, R. & Molloy, M. Global cloud height fluctuations measured by MISR on Terra from 2000 to 2010. *Geophys. Res. Lett.* **39**, L03701 (2012).
72. Taylor, P. C. The role of clouds: An introduction and rapporteur report. *Surv. Geophys.* **33,** 609–617 (2012).
73. Schmidt, G. A., Ruedy, R. A., Miller, R. L. & Lacis, A. A. Attribution of the present-day total greenhouse effect. *J. Geophys. Res.* **115**, D20106 (2010).
74. Dessler, A. E. & Davis, S. M. Trends in tropospheric humidity from reanalysis systems. *J. Geophys. Res.* **115** (2010).
75. Trenberth, K. E., Fasullo, J. & Smith, L. Trends and variability in column-integrated atmospheric water vapor. *Clim. Dynam.* **24,** 741–758 (2005).
76. Gu, G. & Adler, R. F. Large-scale, inter-annual relations among surface temperature, water vapour and precipitation with and without ENSO and volcano forcings. *Int. J. Climatol.* **32,** 1782–1791 (2012).
77. Shi, L. & Bates, J. J. Three decades of intersatellite-calibrated high-resolution infrared radiation sounder upper tropospheric water vapor. *J. Geophys. Res. D Atmos.* **116** (2011).
78. Jin, X., Li, J., Schmit, T. J. & Goldberg, M. D. Evaluation of radiative transfer models in atmospheric profiling with broadband infrared radiance measurements. *Int. J. Remote Sens.* **32,** 863–874 (2011).
79. Solomon, S. *et al.* Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science* **327,** 1219 (2010).
80. Randel, W. J. Variability and trends in stratospheric temperature and water vapor. *Geophys. Monog. Series* **190,** 123–135 (2010).
81. Fueglistaler, S. Stepwise changes in stratospheric water vapor? *J. Geophys. Res. D Atmos.* **117,** D13302 (2012).
82. Wentz, F. J., Ricciardulli, L., Hilburn, K. & Mears, C. How much more rain will global warming bring? *Science* **317,** 233–235 (2007).
83. Liepert, B. G. & Previdi, M. Do models and observations disagree on the rainfall response to global warming? *J. Clim.* **22,** 3156–3166 (2009).
84. Liu, C. & Allan, R. P. Multisatellite observed responses of precipitation and its extremes to interannual climate variability. *J. Geophys. Res.* **117**, D03101 (2012).
85. Gruber, A. & Levizzani, V. *Assessment of Global Precipitation Products WCRP-128* 50 (World Climate Research Programme, 2008).
86. Gebregiorgis, A. S. & Hossain, F. Understanding the dependence of satellite rainfall uncertainty on topography and climate for hydrologic model simulation. *IEEE Trans. Geosci. Remote Sens.* **51,** 704–718 (2013).
87. Wang, B., Liu, J., Kim, H. J., Webster, P. J. & Yim, S. Y. Recent change of the global monsoon precipitation (1979–2008). *Clim. Dynam.* **39,** 1123–1135 (2012).
88. Trenberth, K. E., Moore, B., Karl, T. R. & Nobre, C. Monitoring and prediction of the earth's climate: A future perspective. *J. Clim.* **19,** 5001–5008 (2006).

89. Henson, S. A. *et al.* Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences* **7,** 621–640 (2010).
90. Douglas, B. C. Global sea rise: A redetermination. *Surv. Geophys.* **18,** 279–292 (1997).
91. Kahn, B. H. *et al.* Temperature and water vapor variance scaling in global models: Comparisons to satellite and aircraft data. *J. Atmos. Sci.* **68,** 2156–2168 (2011).
92. Datla, R., Kessel, R., Smith, A., Kacker, R. & Pollock, D. Review Article: Uncertainty analysis of remote sensing optical sensor data: Guiding principles to achieve metrological consistency. *Int. J. Remote Sens.* **31,** 867–880 (2010).
93. Mears, C. A. & Wentz, F. J. The effect of diurnal correction on satellite-derived lower tropospheric temperature. *Science* **309,** 1548 (2005).
94. Mei, L. *et al.* Validation and analysis of aerosol optical thickness retrieval over land. *Int. J. Remote Sens.* **33,** 781–803 (2012).
95. Screen, J. Sudden increase in Antarctic sea ice: Fact or artifact? *Geophys. Res. Lett.* **38**, L13702 (2011).
96. Ohring, G., Wielicki, B., Spencer, R., Emery, B. & Datla, R. Satellite instrument calibration for measuring global climate change: Report of a workshop. *Bull. Am. Meteorol. Soc.* **86,** 1303–1313 (2005).
97. Li, Z. *et al.* Uncertainties in satellite remote sensing of aerosols and impact on monitoring its long-term trend: A review and perspective. *Ann. Geophys* **27,** 2755–2770 (2009).
98. Crow, W. T. *et al.* Upscaling sparse ground-based soil moisture observations for the validation of coarse-resolution satellite soil moisture products. *Rev. Geophys.* **50,** 1–20 (2012).
99. Liu, Y., Liu, R. & CHen, J. M. Retrospective retrieval of long-term consistent global leaf area index (1981–2010) maps from combined AVHRR and MODIS data *J. Geophys. Res.* **117**, G04003 (2012).
100. Knapp, K. R. *et al.* Globally Gridded Satellite observations for climate studies. *Bull. Am. Meteorol. Soc.* **92,** 893–907 (2011).

Acknowledgements
This work was supported by the National High-tech Research and Development Program of China (Grant No. 2009AA12200101) and the National Key Basic Research Program of China (Grant No. 2010CB530300).

Author contributions
J.Y. and P.G. designed the framework of the Review. All authors contributed to writing.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to P.G.

Competing financial interests
The authors declare no competing financial interests.