Satellite Contributions to Climate Change Studies[1]

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Introduction

This year, well-deserved attention has been given to longtime NASA employee Katherine Johnson (Figure 1) for her crucial calculations for the flights of the Mercury and Apollo astronauts in the 1960s—attention that has come through the best-selling book *Hidden Figures* by Margot Lee Shetterly and the Oscar-nominated movie based on the book. Johnson is still alive, now 98 years old, and has relayed how thrilled she was with her NASA job and the privilege it afforded her of being part of the grand enterprise of sending human explorers into space. I too, for the past 38 years, have been thrilled to be a part of NASA and to have the privilege to be a participant in one of NASA's other grand enterprises, this one being to use satellites to observe Earth from space, monitor and analyze its changes, and benefit humanity through the knowledge obtained.

Observing Earth from space is loaded with immediate practical benefits, like being able to see hurricanes form and intensify well before landfall, to see the spread of forest fires, dust storms, and volcanic emissions, and to help with weather forecasting. However, when it comes to climate studies, the fact that the satellite era did not begin until 1957, with the launch of the first artificial satellite, does create a notable limitation, as satellites cannot provide the deep-time records possible with ice cores, tree rings, and other paleoclimate data sets. Additionally, they cannot, by themselves, predict the future, as can be done—with varying levels of success—through the use of computer models. What satellites can do, however, is collect frequent, repetitive observations and do so on a global basis.[2] They can provide us with a

1 Read on 28 April 2017 as part of the *Observed Climate Change* symposium.

2 See https://aqua.nasa.gov/sites/default/files/references/aqua_modis_h264.mov for a one-minute animation of the scanning of a sample instrument—the Moderate Resolution Imaging Spectroradiometer—during the orbiting of a sample Earth-observing satellite, Aqua.

FIGURE 1. Katherine Johnson. Courtesy of NASA.

global picture of changes occurring now and in the recent past far better than any other available technology.

Satellites can monitor radiation inputs and outputs at the top of the atmosphere, numerous phenomena and layers within the atmosphere, a wide range of features on Earth's surface, and even some phenomena below the surface. They can see clouds and, with proper selection of wavelengths, can see through clouds to monitor the surface underneath. In this paper, I will provide a selection of illustrative examples of how and what we are learning from satellite data about Earth's changing climate.

Satellite Contributions

Greenhouse Gases

Among the topics most frequently included in discussions of climate change in recent decades are greenhouse gases; satellite data are allowing us to map many of these gases on a global or near-global basis. Greenhouse gases readily allow radiation from the sun that reaches Earth's outer atmosphere to pass through to Earth's surface, but they hinder some of Earth's radiation from getting out, hence keeping the Earth system warmer than it would be without them. These gases have been a crucial component of the Earth system for billions of years, helping to keep much of Earth comfortably habitable. However, there is considerable concern that human activities are increasing the concentration of these gases to a point where the projected resulting additional warming is likely to be far more damaging than beneficial.

Satellites cannot determine whether further increases in greenhouse gases will be good or bad, but they do give us a means of monitoring those gases. Water vapor is the most abundant greenhouse gas, and satellite monitoring of water vapor has tremendous benefits for weather forecasting and water management. For climate change considerations, however, the gas that has received the most attention is not water vapor but instead the second most abundant greenhouse gas, which is carbon dioxide, as atmospheric carbon dioxide has quite measurably increased in recent history, largely due to human activities.

Ground-based carbon dioxide (CO_2) measurements have been made at the Mauna Loa Observatory in Hawaii since 1958, when Charles David Keeling began a remarkable record that continues to be maintained and extended. This record shows the expected seasonal cycle in atmospheric CO_2, with decreases each spring and summer as vegetation sucks in carbon dioxide for photosynthesis, followed by increases in late fall and winter, when far less photosynthesis is occurring and far more plant decomposition, releasing CO_2 to the atmosphere. In addition to the seasonal cycle, the Mauna Loa record, commonly called the Keeling Curve, shows a relentless upward trend, with each year having more atmospheric CO_2 than the year before, as correctly anticipated by Keeling and others.

The satellite record cannot come close to the Keeling Curve in terms of record length, but it can wonderfully complement that curve by showing the global picture (Figure 2). The Atmospheric Infrared Sounder (AIRS) on the Aqua satellite has within its large suite of infrared channels certain frequency bands that undergo strong absorption by carbon dioxide, allowing estimated atmospheric CO_2 concentrations to be calculated from the infrared record. Like the Mauna Loa data, the satellite data show a prominent seasonal cycle and a strong overall upward trend, but they show these two dominant features for the entire globe, not just for individual ground stations.[3] This allows global averages to be calculated and regional differences to be clearly identified.

Atmospheric Temperatures

It has long been recognized that the increases in atmospheric carbon dioxide and other greenhouse gases provide a forcing in the direction

3 See a 58-second animation of the near-global AIRS CO_2 record for the period from September 2002 to September 2016, overlaid with the Keeling Curve, at https://svs.gsfc.nasa.gov/4533.

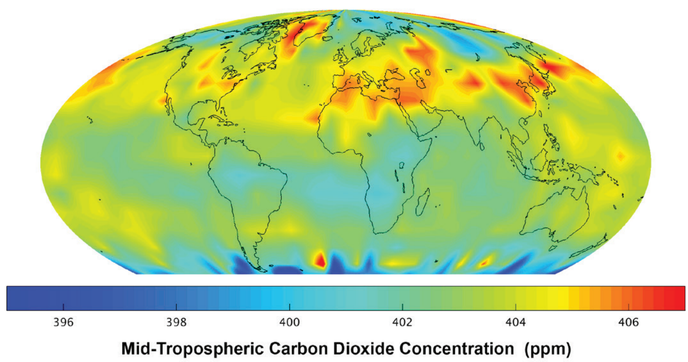

FIGURE 2. Atmospheric carbon dioxide concentrations in the mid-troposphere in February 2017, in units of parts per million (ppm) by volume, as derived from the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite. Courtesy of Ed Olsen of the AIRS Science Team.

of increased atmospheric temperatures. Satellite data are quantifying that increase for the period of the satellite record. When averaged globally, the satellite record shows considerable interannual variability but a definite upward trend in the temperatures of the lower atmosphere (the troposphere) and a downward trend in the temperatures higher in the atmosphere (in the lower stratosphere) (Figure 3). This contrast between warming in the troposphere and cooling in the stratosphere was well predicted through climate model simulations of the effects of increased greenhouse gases. The warming in the troposphere is what is referred to as "global warming"; the cooling in the stratosphere results in part because the increased trapping of terrestrial radiation in the lower atmosphere by greenhouse gases lessens the Earth's radiation that makes its way to the upper atmosphere.

The warming that has occurred in recent decades in the lower atmosphere and at Earth's surface varies greatly geographically, and in fact, as expected, some areas have experienced cooling while the globe as a whole has experienced warming. Global maps of warming and cooling reveal particularly high warming in the Arctic. This polar amplification was anticipated, as the ice and snow covers of the Arctic provide strong enhancing (or "positive") feedbacks to the changing temperatures. For instance, under warming conditions, the expectation is for less sea ice to form and more sea ice to melt, so that sea ice coverage decreases; but because sea ice is a highly reflective surface, as

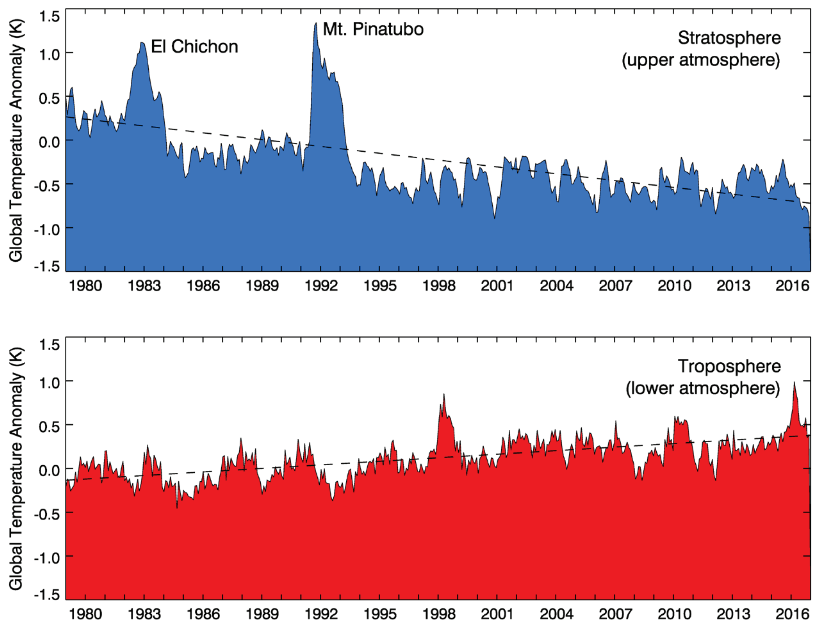

FIGURE 3. Near-global temperature trends in the lower stratosphere and lower troposphere, 1979–2016, from Microwave Sounding Unit (MSU) and Advanced MSU (AMSU) instruments on satellites of the National Oceanic and Atmospheric Administration (NOAA), NASA, and the European Space Agency. Major vertically explosive volcanic eruptions, such as the eruptions of El Chichon in 1982 and Mt. Pinatubo in 1991, result in temporary warming of the stratosphere and cooling of the troposphere, because of the absorption and reflection of solar radiation in the stratosphere by the volcanic emissions. Plots were constructed from data obtained from http://www.remss.com, with tropospheric data for 70.0°S–82.5°N and stratospheric data for 82.5°S–82.5°N.

the sea ice coverage lessens and is replaced by the far less reflective liquid ocean, less of the sun's radiation that reaches the Arctic Ocean gets reflected back to space and more gets retained within the Earth system, further warming the system and leading to even more sea ice retreat and more warming.

Polar Sea Ice

Satellites have been used to monitor sea ice since the 1970s. As long as conditions are cloud-free and well-lit, instruments measuring radiation at visible wavelengths provide wonderful images of the sea ice cover as our eyes would see it. Such instruments, however, have the same limitations that our eyes have, greatly limiting the collection of sea ice or other surface data under dark or cloudy conditions. Hence, climate change studies of sea ice typically use microwave radiation instead.[4] The microwave radiation comes from within the Earth system and hence does not require sunlight; and, with proper choice of wavelengths, the microwave radiation can pass through clouds, allowing the satellite instrument to provide a record of sea ice and other phenomena at Earth's surface irrespective of cloud cover.

Sea ice currently spreads over a vast area, in wintertime in the Arctic typically reaching an extent of approximately 15 million square kilometers, which exceeds one and a half times the area of the United States. Even in 2017, when the maximum Arctic wintertime ice extent was the lowest in the satellite record, it still reached 14.4 million square kilometers. This provides a large, highly reflective insulating cap over the Arctic Ocean and surrounding seas. In the Antarctic, the wintertime sea ice coverage is even greater, typically reaching an extent of approximately 18 million square kilometers.

By now we have a reasonably consistent satellite microwave record of polar sea ice that extends back to the late 1970s. For both polar regions, this record shows considerable interannual variability, but in the Arctic case it also shows a prominent downward trend in sea ice extents that was apparent by the end of the 20th century and that has accelerated since then (Figure 4). This downward trend is evident in all seasons and all months of the year. The decreasing sea ice coverage is also evident in almost all regions of the Arctic, as is clear from mapping the length of the sea ice season in each year and calculating the trends in how long the ice season lasts at each location (Figure 5).

The same methodology used for examining Arctic sea ice from satellite data is also used for examining Antarctic sea ice. As in the Arctic, the satellite microwave record reveals considerable interannual variability in Antarctic sea ice coverage; but in the Antarctic case, the overall trend, at least until 2015, was toward increased rather than decreased sea ice extents (Figure 6). The increases in Antarctic sea ice were unexpected, leading to many attempts at an explanation. These attempts include tie-ins with atmospheric circulation, ocean circulation, melt from the Antarctic land ice, and even the stratospheric ozone hole. However, starting in mid-2015, there has been a striking change in Antarctic sea ice coverage, with major decreases in ice extents. These additional satellite data, and the data to be added in the next few years, will provide scientists with important evidence for testing the various

4 See a 39-second animation from satellite microwave data of the Arctic sea ice cover from its 2016 ice-extent minimum on September 10, 2016 to its 2017 ice-extent maximum on March 7, 2017, at https://svs.gsfc.nasa.gov/4564.

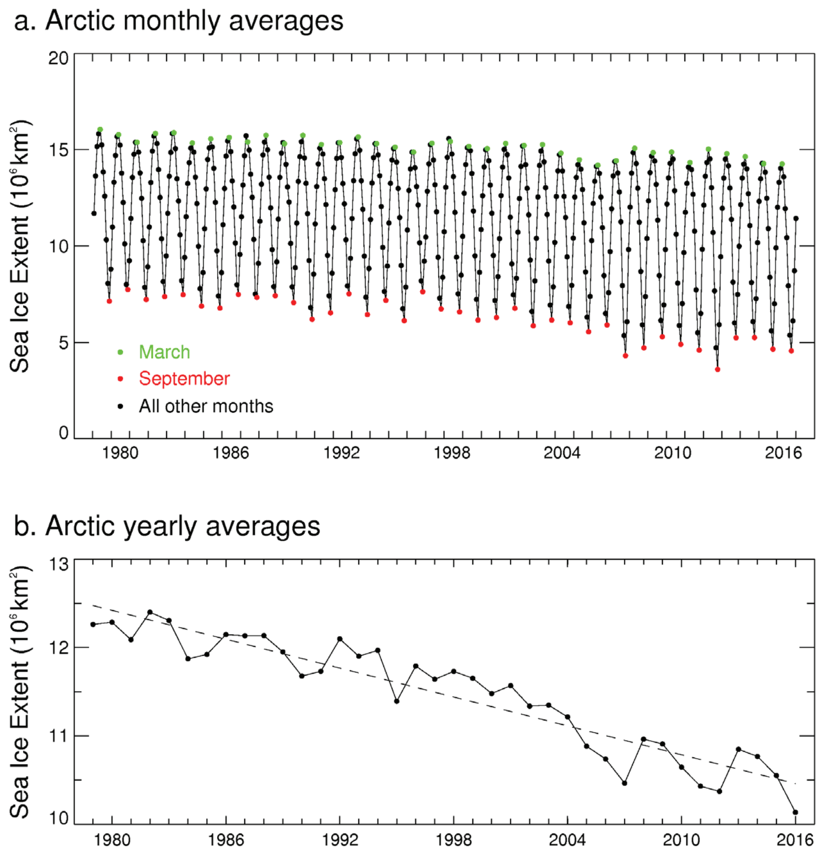

FIGURE 4. (a) Monthly average Arctic sea ice extents derived from satellite microwave data, November 1978–December 2016, and (b) yearly average Arctic sea ice extents for 1979–2016, along with the line of linear least squares fit. The data come from passive-microwave instruments on NASA's Nimbus 7 satellite and satellites of the Defense Meteorological Satellite Program (DMSP). The slope of the trend line for the yearly averages is -54,500±3,300 km^2/yr (-4.4±0.3%/decade).

attempted explanations of why the Antarctic sea ice was increasing, overall, over the 37 years from 1979 to 2015.

Land Ice

Satellites are also providing us with a record of land ice, which is less expansive than sea ice but overwhelmingly thicker and more massive. The mass of land ice on Earth today is roughly a third of the mass of ice at the peak of the last ice age. This mass is dominated by the ice in the two remaining large ice sheets, covering most of the continent of

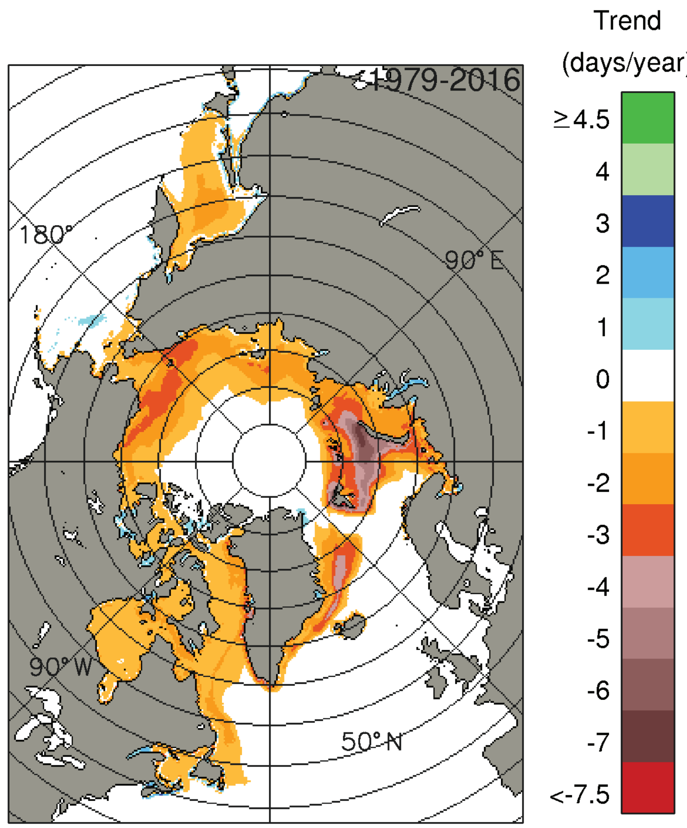

FIGURE 5. Trends in the length of the sea ice season in the Arctic, 1979–2016, as derived from data from passive-microwave instruments on NASA's Nimbus 7 satellite and satellites of the DMSP. Oranges, browns, and reds all show shortening sea ice seasons over the 38-year period.

Antarctica and most of the island of Greenland. These ice sheets are gigantic, so much so that over large areas of Greenland the ice thickness exceeds one mile, and over large areas of Antarctica the ice thickness exceeds two miles. Together, these two ice sheets have a volume of ice that equates to approximately 65–70 meters of sea level rise globally. Hence the potential exists that if major decays of the Greenland and/or Antarctic ice sheets were to occur, the resulting sea level rise could drown entire island nations and coastal areas around the world.

Several types of satellite instruments have been used to measure changes in the ice sheets and other land-based ice. Visible imagery has shown the calving off of icebergs (e.g., Figure 7), advancing and retreating glaciers, and other changes in the extent of land-based ice, as well as visible surface features on the ice. Satellite radar and laser

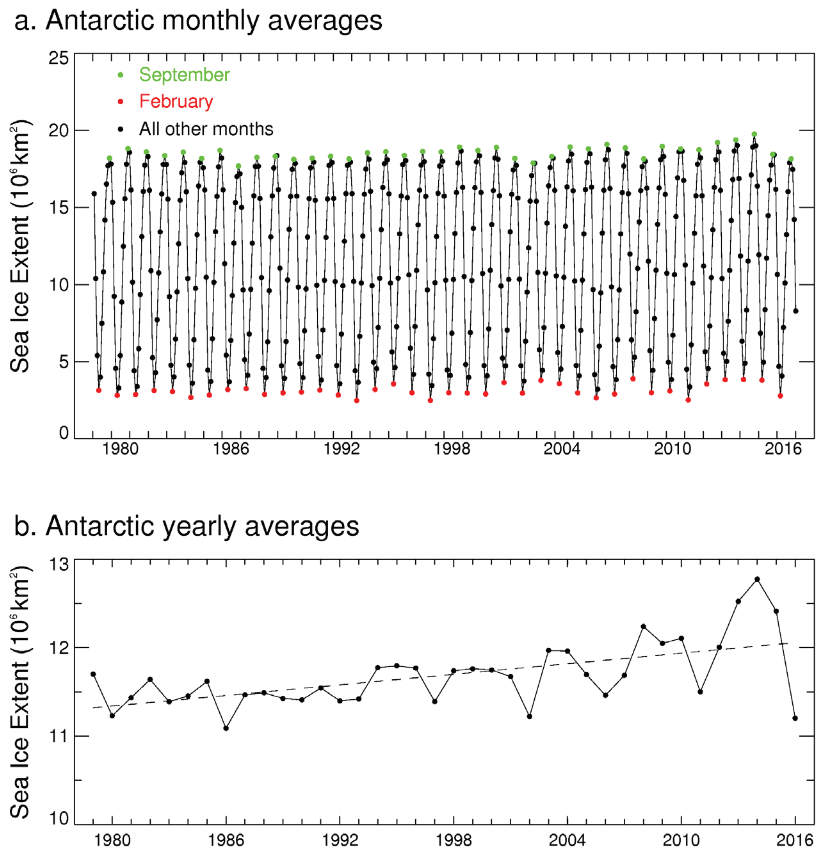

FIGURE 6. (a) Monthly average Antarctic sea ice extents derived from satellite microwave data, November 1978–December 2016, and (b) yearly average Antarctic sea ice extents for 1979–2016, along with the line of linear least squares fit. The data come from passive-microwave instruments on NASA's Nimbus 7 satellite and satellites of the DMSP. The trend line slope for the yearly averages is 19,900±4,500 km^2/yr (1.8±0.4%/decade).

altimeters determine the altitude of the top surface of the ice through sending a signal down and timing its return. Repeat measurements by satellite altimeters have revealed a thinning around the edges of the Greenland ice sheet and a thickening in its center, plus a pattern of thinning and thickening in the Antarctic ice sheet that shows particularly large thinning in the region of the Thwaites and Pine Island Glaciers to the west of the Antarctic Peninsula.

The basic pattern of thinning and thickening on the Greenland and Antarctic ice sheets found by satellite altimeters has been confirmed (Figure 8) by a remarkable pair of satellites in the Gravity Recovery and Climate Experiment (GRACE) mission (joint between NASA and

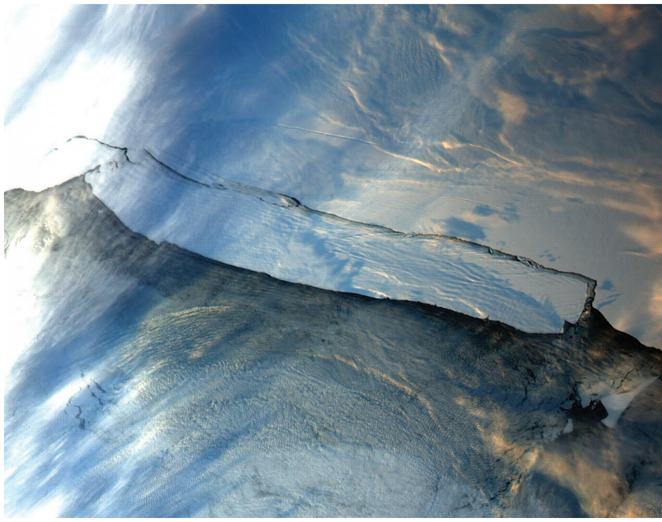

FIGURE 7. Formation of Iceberg B15 as it breaks off from the Ross Ice Shelf at the edge of the Antarctic ice sheet, as imaged by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite on March 28, 2000. This iceberg had an area exceeding the combined area of Delaware and Rhode Island. For a higher resolution satellite image of the entire Antarctic continent from visible data, see the Landsat Image Mosaic of Antarctica at https://lima.usgs.gov.

the German Aerospace Center), each orbiting Earth on its own, with one trailing behind the other by about 220 kilometers. Neither of the GRACE satellites has data-collecting instruments pointed at Earth. Instead, Earth information is determined through measuring the distance between the two satellites. This distance is related to the underlying gravity field, as the leading satellite speeds up when overflying a strong gravity field, increasing the distance between the satellites, followed by a decrease in the distance as the trailing satellite overflies the same area. The resulting gravity calculations are converted to ice mass changes, revealing overall mass losses for both the Greenland and Antarctic ice sheets (Figure 9).

Sea Level

Much of the ice mass lost by the ice sheets and other land ice in recent decades has gone into the ocean, either as ice or as melt water. This additional mass in the oceans contributes to sea level rise, with the other main contributor being the thermal expansion of the water as it

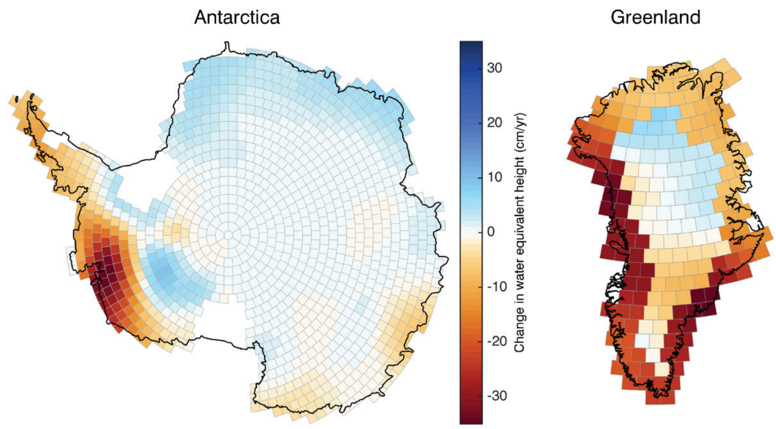

FIGURE 8. Spatial distribution of the ice mass changes in the Antarctic and Greenland ice sheets from 2004 to 2016, as derived from Gravity Recovery and Climate Experiment (GRACE) satellite data and expressed in units of changes in the water equivalent height at each grid cell, in centimeters per year (cm/yr). The prominent region of ice mass losses in the lower left of the Antarctic image is the region of the Thwaites and Pine Island Glaciers. Courtesy of Scott B. Luthcke and Bryant Loomis from the GRACE Science Team, with relabeling. Details are provided at https://ssed.gsfc.nasa.gov/grace/.

warms. A sequence of satellite radar altimeters has provided a record of sea level since the early 1990s.

Changes in sea level vary from location to location; global maps of sea level changes since 1992, as derived from satellite data, show some areas of sea level fall, including in the Gulf of Alaska and in portions of the North Atlantic's Gulf Stream (Figure 10). However, the areas of sea level fall are far outweighed by the areas of sea level rise, which are particularly high in the low latitudes of the western Pacific and also quite high in several other large regions scattered around the globe (Figure 10). Globally averaged, sea level time series reveal an upward trend rising well above the noise of year-to-year variability, with a globally averaged sea level rise of over 8 centimeters over the period of 1993–2016, equating to a rise of about 3.4 centimeters per decade (Figure 11). This rate of rise is concerning, not so much for Earth, which has experienced periods with much higher sea level than now and periods with much lower sea level than now, but for humans, who have constructed so much at coastal locations near sea level that rises in sea level could cause major disruptions to human societies (and also to other species).

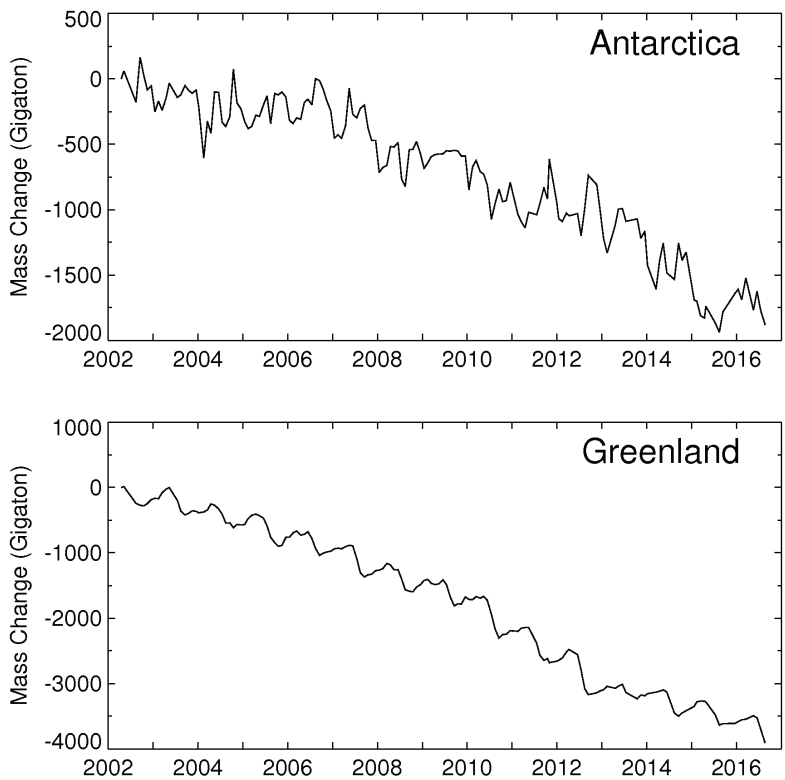

FIGURE 9. Time series of Antarctic and Greenland ice sheet mass changes since April 2002, as derived from GRACE satellite data for April 2002–August 2016. Over this period, Antarctica lost on average approximately 125 gigatons of ice per year and Greenland lost on average approximately 285 gigatons of ice per year. Tick marks are at the start of the year. Plots were created from data obtained from https://climate.nasa.gov.

Stratospheric Ozone

For a final example, I return to the atmosphere, although this time to the upper atmosphere and a topic that is often not discussed in connection with climate change, namely, the Antarctic ozone hole. The ozone hole is a region of lessened stratospheric ozone (not an actual hole) that has elicited concern because of the protection that stratospheric ozone provides to life at Earth's surface against dangerous levels of ultraviolet radiation from the sun. Although the ozone hole results from chemical reactions in the stratosphere, Earth's climate system is so interconnected that stratospheric ozone conditions are probably

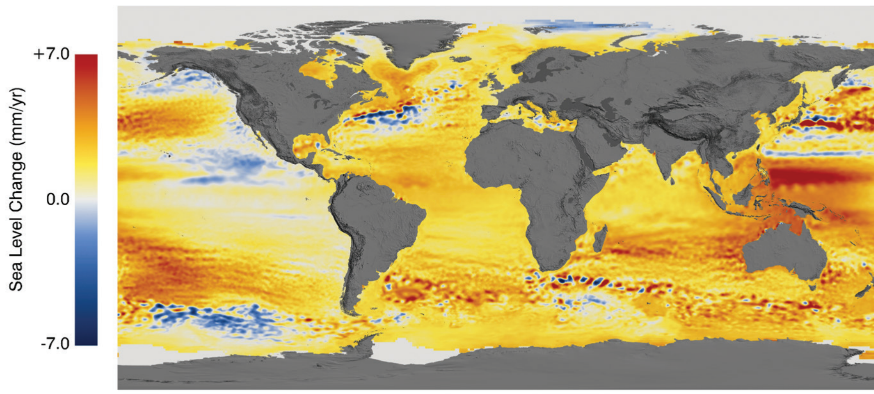

FIGURE 10. Globally mapped rates of sea level rise (in yellow and red) and sea level fall (in blue) in millimeters per year (mm/yr) over the period of 1992–2014, as derived from radar altimetry data from the TOPEX/Poseidon, Jason-1, and Jason-2 satellites. Courtesy of Josh Willis and the NASA Scientific Visualization Studio.

affecting the circulation of the upper atmosphere, which affects the circulation of the lower atmosphere and thereby has propagating influences throughout the global climate system.

The ozone hole was first discovered through Antarctic station data by members of the British Antarctic Survey. Although satellite data were not involved in the initial discovery, it quickly became apparent that satellite data provide the best means of mapping the full extent of the ozone hole and monitoring its changes over time. It is the satellite data record—largely based on measurements of ultraviolet radiation—that has allowed a clear depiction of the size, spatial distribution, and variability of the ozone hole.

When viewing images of stratospheric ozone over time (e.g., Figure 12), it is not readily apparent that progress has been made in reducing the size and depth of the ozone hole, despite the deservedly celebrated 1987 Montreal Protocol aimed at reversing the damage to stratospheric ozone through restricting the production of ozone-destroying chlorofluorocarbons. However, in moving from the images to plotted time series, significant progress becomes apparent. The time series show that the area of the ozone hole increased considerably over the years 1979–1993, followed by considerable interannual variability over the succeeding years but no continuing strong upward trend (Figure 13a). Similarly, the rapid deepening of the ozone hole from 1979 to 1994 also ceased, with the minimum levels of ozone even increasing somewhat since 1994 (Figure 13b). With the known ozone-depleting

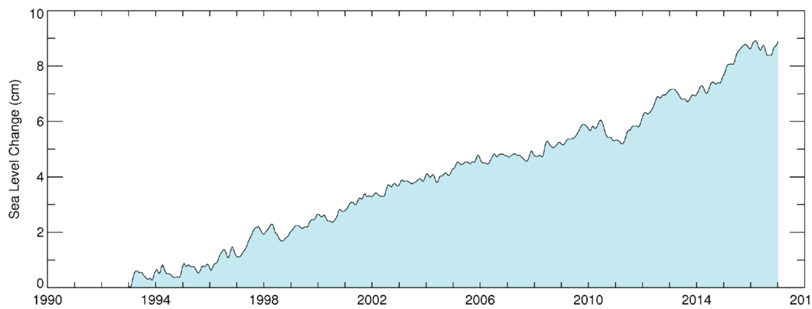

FIGURE 11. Globally averaged sea level change, 1993–2016, from radar altimetry data from the TOPEX/Poseidon, Jason-1, and Jason-2 satellites. Tick marks are at the start of the year. Plot was constructed from data obtained from NASA Goddard Space Flight Center at https://climate.nasa.gov/vital-signs/sea-level.

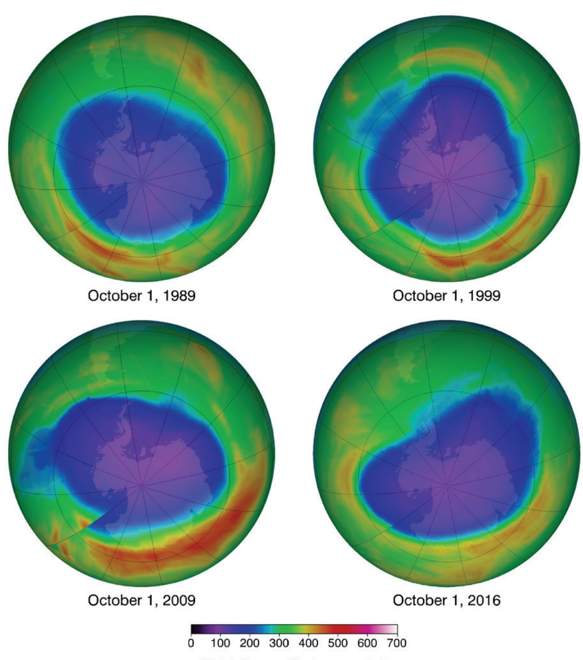

FIGURE 12. Southern Hemisphere atmospheric ozone amounts on October 1 of 1989, 1999, 2009, and 2016, highlighting the Antarctic ozone hole in blue and purple, as derived from ultraviolet data from NASA's Total Ozone Mapping Spectrometer (TOMS) on the Nimbus 7 satellite (1989 image) and the TOMS Earth Probe satellite (1999 image) and from the Netherlands' Ozone Monitoring Instrument (OMI) on NASA's Aura satellite (2009 and 2016 images). A Dobson unit represents a thickness of 0.01 mm of pure ozone at standard temperature and pressure. Images from https://ozonewatch.gsfc.nasa.gov, with relabeling.

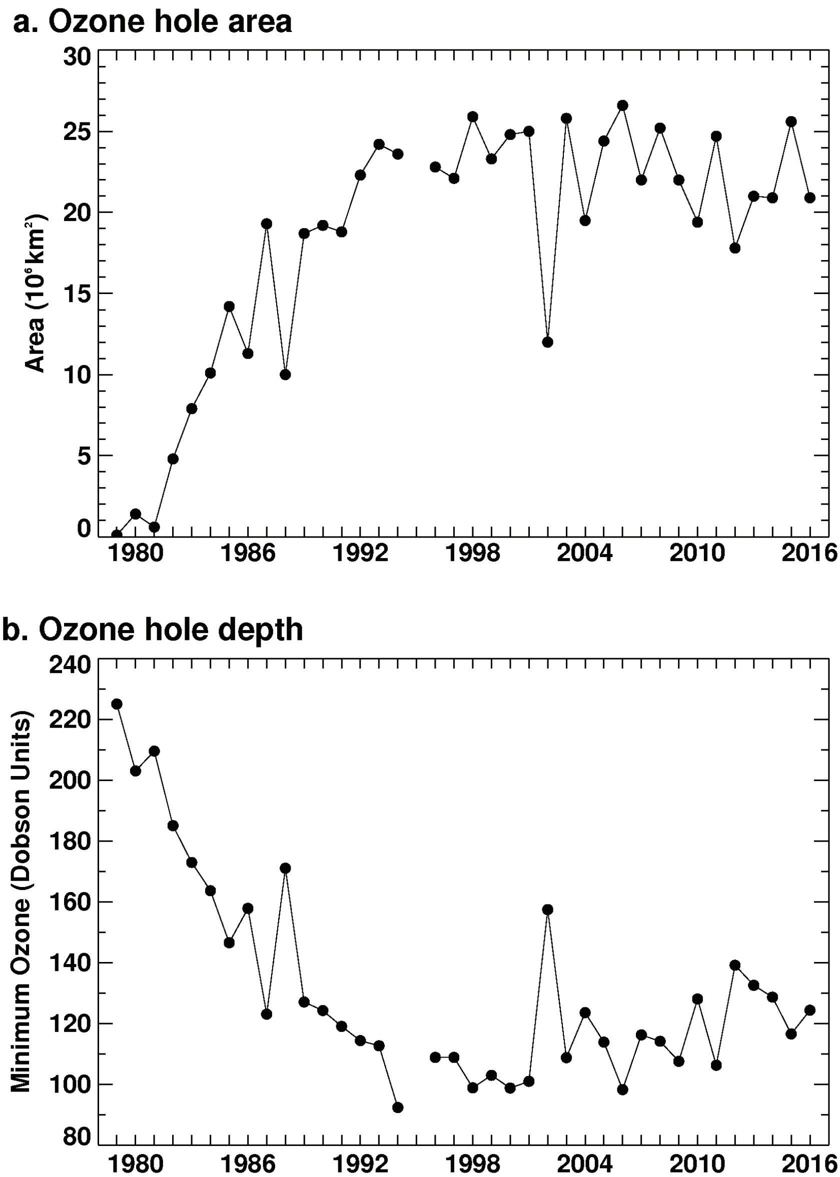

FIGURE 13. (a) Area of the Antarctic ozone hole, 1979–2016, averaged over the period of September 7–October 13 for each year, as derived from data from the TOMS and OMI satellite instruments. (b) Depth of the Antarctic ozone hole, 1979–2016, as determined by the minimum ozone value in the map of average ozone values for September 21–October 16 of each year, as derived from TOMS and OMI data. Plots were created from data provided at https://ozonewatch.gsfc.nasa.gov.

substances no longer being added to the atmosphere in large quantities, it is thought likely that stratospheric ozone levels will fully recuperate, some studies predicting that a full recuperation to 1980 ozone levels could occur by about the year 2070.

Conclusion

Like all data sets, satellite data sets are far from perfect. In addition to the fact that satellite records are no more than a few decades long, there is also the complication that the satellite instruments are often not making direct measurements of the Earth variables they are being used to examine. For example, altimeters measure the timing of the return radar or laser pulse, and that needs to be converted to topographic information. The GRACE mission measures the distance between the two GRACE satellites, and that needs to be converted to a gravity measurement and then further to changes in such geophysical quantities as the mass of the ice sheets. Other satellite instruments measure the amount of radiation the instrument receives at specific wavelengths or wavelength bands, and these radiation measurements need to be converted into geophysical information through algorithms with varying degrees of sophistication. Even the best algorithms cannot incorporate all the complexities of the Earth system. Hence, adjustments to the algorithms are common, as more is learned about not just how the variable of interest affects the wavelengths of radiation being measured but how various components of the atmosphere affect them as well. Furthermore, the instruments can decay over time, the satellite orbits can change, and all instruments have finite life-spans, so that for their data sets to be extended, they need to be replaced by new instruments, necessitating careful matching of the old and new data records for consistency over time.

Still, despite the many imperfections, satellites are making major contributions to improved monitoring and understanding of our constantly changing planet. Prior to satellites, measurements were generally taken only in locations where people were—in or near human settlements, along shipping routes, at expedition campsites, etc., or at locations where they went and set up instruments to retrieve later. With satellites, we can now get measurements for the surface waters of the central Pacific just as easily as for San Francisco Bay.[5] We can measure the Arctic sea ice in the harsh conditions of the cold, dark polar night just as easily as in the warmer, sunlit conditions of summer. We can measure the Sahara desert or the Amazon rainforest without having to

5 See a 98-second animation of two years of global sea surface temperatures from satellite data at https://podaac.jpl.nasa.gov/AnimationsImages/Animations?page=3.

suffer the conditions of those locations or harming them in any way. Satellites provide a level playing field for data collection, with distance from human settlements, unfavorable surface conditions, or political boundaries all irrelevant. With satellites we can monitor variables at all latitudes and longitudes, allowing us both to see the regional differences in how Earth's climate is changing and to obtain global averages, the latter being of crucial importance in lessening the confusions brought about by the regional differences.

Even in this short survey, focused only on climate change and not on everything else that satellites contribute, I have been able to illustrate that satellite data quantify increases in atmospheric carbon dioxide, global warming in the troposphere, cooling in the stratosphere, decreases in Arctic sea ice coverage, increases in Antarctic sea ice coverage, decreases in the masses of the Greenland and Antarctic ice sheets, global sea level rise, and depletion of stratospheric ozone in the 1980s and early 1990s, followed by a leveling off of the depletion.

The serious attention now being given to proposed attempts to geoengineer large-scale aspects of Earth's climate vastly increases the importance of getting correct information about current climate changes—and satellite technology is one of the major tools to help us do that. Satellites provide the best means for obtaining a repetitive, global view. But for fully understanding the global climate system and the changes occurring in it, many other products are also needed, including in situ instrumental records, anecdotal records, deep-time records from ice cores, deep-sea cores, tree rings, and other paleoclimate sources, and the very different products generated by computer models that allow a sophisticated peering into cause and effect and a projection into the future. All of these products are important, and all of them are contributing in a major way to our improved recognition, quantification, and understanding of Earth's constantly changing climate. Such understanding is vital to help ensure that we, the human society, have the information available to make appropriately informed decisions regarding how best to preserve and protect the amazing pale blue planet that is Earth, the singular, isolated dot in the vastness of space (Figure 14) that is, so far, our only home.

Acknowledgments

The author thanks NASA Headquarters for funding this work through the Aqua mission; Nick DiGirolamo of Science Systems and Applications, Inc., for his assistance in generating several of the plots; and the American Philosophical Society for the opportunity to present this talk at their April 2017 Meeting.

FIGURE 14. Earth as imaged from 898 million miles away by NASA's Cassini spacecraft while in the vicinity of Saturn. A portion of Saturn is visible in the upper left of the image and the Saturn rings in the upper right. The arrow points to the pale blue planet that is Earth. Courtesy of NASA, the Jet Propulsion Laboratory, and the Space Science Institute.