

An update on human-induced climate change: global warming: coming, ready or not.

Dr. Kevin E. Trenberth^{*}
National Center for Atmospheric Research^{**}

In 2007 the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), known as AR4, clearly stated that “Warming of the climate system is unequivocal” and it is “very likely” due to human activities. Since the IPCC report, nature continues to provide evidence that it is under duress with impacts affecting people and animals. Increasing rates of carbon dioxide emissions raise the specter that future climate changes could be much larger and come much quicker than IPCC suggests. Meanwhile global actions to address the problem are ineffective and there is a crisis of inaction.

The IPCC reports are the gold standards for the science of climate change, however, by the consensus nature of the reports, they are inherently conservative. The IPCC working groups are made up of participants from the United Nations countries, and for the 2007 assessment there were over 450 lead authors, 800 contributing authors, and over 2,500 reviewers from over 130 countries. The IPCC process is very open. For the 2007 report, two major reviews were carried out, and climate “skeptics” can and do participate, some as authors. All comments were responded to in writing and by changing the report. The process is overseen by two Review Editors for each chapter. The Summary for Policy Makers was approved line by line by governments. The rationale is that the scientists determine what can be said, but the governments help determine how it can best be said. Negotiations occur over wording to ensure accuracy, balance, clarity of message, and relevance to understanding and policy.

Observed Climate Change

* Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the National Science Foundation.

** The National Center for Atmospheric Research (NCAR) is sponsored by the National Science Foundation.

The following includes a summary of aspects of the IPCC report, which mostly takes account of observations through 2005, but with updates on more recent changes and developments in the context of the IPCC findings.

Carbon dioxide concentrations in the atmosphere have increased such that current values of about 385 ppmv are over 36% higher than pre-industrial values of 280 ppmv and over half that increase has occurred since 1970 (Fig.1). Of particular note is the clear evidence that carbon dioxide concentrations are increasing at rates beyond the highest of the IPCC scenarios in spite of the Kyoto Protocol, suggesting that climate changes are apt to become larger than any IPCC projections. Large increases in emissions from China and India contribute to the acceleration, and in 2007 China supposedly surpassed the U.S. as leader in annual emissions. Carbon dioxide comes primarily from burning of fossil fuels in association with energy production and industrial activity. There is no doubt that carbon dioxide is a greenhouse gas and causes warming, and it has a long lifetime which is why amounts are increasing in the atmosphere. Other greenhouse gases also contribute significantly to warming, while aerosols and dust more often cause cooling and regionalize some of the radiative forcing. A direct consequence of the escalating level of carbon dioxide in the atmosphere is the world's ocean becoming more acidic, dramatically altering ocean chemistry and threatening corals and other marine organisms that secrete skeletal structures.

Since 1979, measurements from space have been made of changes in the sun and, as there are no changes of consequence during the period to date, changes in the sun are not responsible for the large changes observed in climate since the 1970s.

The iconic summary statement of the observations section of the 2007 IPCC report is “**Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level.**” The language was carefully chosen to reinforce the view that there is an increasing body of evidence showing physically consistent discernable changes.

This finding fundamentally changes the way we think about and approach climate change. Previously, we have always supposed (scientists refer to it as a null hypothesis) that the climate is not changing and the onus has been to prove that global warming is having an effect. Now this switches to an underlying hypothesis that global warming is affecting all aspects of weather and climate, and the onus is on showing this is not the case. We are often asked, “Is a particular event caused by global warming or natural variability?” The answer is that it is always both.

a. Temperature

Instrumental observations over the past 158 years show that temperatures at the surface (Fig. 1) have risen globally. Warming in the last century occurred in two phases, from the 1910s to the 1940s (0.35°C), and more strongly from the 1970s to the present (0.55°C) at a rate of about 0.16°C per decade. The last 7 years are among the warmest 8 on record. The total warming since the 1800s is about 0.76°C. Globally 2006 ranks 6th, while 2007 ranks as 8th warmest. Sea surface temperatures (SSTs) are also increasing, however land areas are warming much faster than the oceans since 1970.

Urban heat island effects are real but local, and have a negligible influence on the overall surface temperature record. New analyses of balloon-borne and satellite measurements of tropospheric temperature show warming rates that are similar to the surface and consistent within their respective uncertainties.

Regional temperature observations do not track the global average warming because of atmospheric wave patterns, as well as increased natural variability at smaller geographic scales. For example, the eastern half of the United States has not warmed as much as other areas such as Europe, especially during the daytime, owing to increases in cloud and precipitation associated with changes in atmospheric circulation as the climate changes. On the other hand, average Arctic temperatures increased at almost twice the global average rate in the past 100 years and also since 1960. However, a warm Arctic was observed from 1925 to 1945, but that was focused in the North Atlantic and was not global as in the recent warming.

Since 1950, the number of heat waves globally has increased and widespread increases have occurred in the numbers of warm nights. Cold days, cold nights and frost have generally become rarer.

b. Temperature related

The average atmospheric water vapor content has increased over land and ocean as well as above the surface, and over the global oceans this is estimated to be 4% since 1970. The increase is broadly consistent with the extra moisture that warmer air can hold and amounts to a fairly constant relative humidity. The water vapor adds to the greenhouse effect and roughly doubles that due to carbon dioxide, providing a powerful positive feedback to climate change.

Decreases are found in the length of the freeze season of river and lake ice. Temperature at the top of the permafrost layer has increased by up to 3°C since the 1980s in the Arctic. The maximum area covered by seasonally frozen ground has decreased by about 7% (15% in spring) in the Northern Hemisphere since 1900.

Sea-ice extents have decreased in the Arctic since 1978, particularly in spring and summer (7.4% per decade through 2005), and patterns of the changes are consistent with regions showing a temperature increase, although changes in winds are also a major factor. The IPCC only included data through 2005 and sea-ice extents were at record low values in 2005, which was also the warmest year since records began in 1850 for the Arctic north of 65°N. This record has since been smashed in 2007 when Arctic sea ice dropped to over 20% below the 2005 value. There have also been decreases in sea-ice thickness. The result in 2008 is an unprecedented amount of first year ice in the Arctic that is very vulnerable to melting.

In contrast to the Arctic, Antarctic sea ice did not exhibit any significant trend from the end of the 1970s through 2006, which is consistent with the lack of trend in surface temperature south of 65°S over that period. However, along the Antarctic Peninsula, where significant warming has occurred, progressive break up of ice shelves occurred beginning in the late 1980s, culminating in the break up of the Larsen-B ice shelf in 2002. In 2008 there was a marked expansion of Antarctic sea ice in association with changes in atmospheric winds.

The observed surface temperature increases are consistent with the observed nearly worldwide reduction in glacier and small ice cap mass and extent in the 20th century. In addition, flow speed has recently increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior, and melting of Greenland and West Antarctica has increased after about 2000. Critical changes are occurring in the ocean and ice shelves that buttress the flow of glaciers into the ocean. Glaciers and ice caps respond not only to temperatures but also to changes in precipitation, and both winter accumulation and summer melting have increased over the last half century in association with temperature increases.

Global average sea level rose at an average rate of 1.8 mm per year from 1961 to 2003 and increases in temperature of global ocean water indicate that the ocean is absorbing most of the heat being added to the climate system causing seawater to expand. The sea level rise was faster after 1992 (Fig. 2), when truly global values have been measured from altimeters in space, at about 3.2 mm per yr from 1993 to early 2008. About 60% of this is from ocean warming and expansion, and 40% is from melting land ice, adding to the ocean volume. The observation of consistent sea level rise over several decades, and also an increasing rate of sea level rise in the last decade or so, is probably the single best metric of the cumulative global warming that we have experienced to date. There is really no explanation other than global warming for the observed sea level rise. A consequence is increasing risk of coral bleaching and coastal storm surge flooding.

In the northern winter of 2007-08, a strong La Niña event dominated the patterns of weather especially around the Pacific and had major influences across the United States. It also affected sea ice in the southern oceans. The cooling of the tropical Pacific Ocean amounts to a redistribution of heat within the ocean and it affects the jet stream and tracks of cyclones around the world. Only in northern Europe and Asia was the weather pattern not identified with La Niña, and the pattern called the North Atlantic Oscillation played a role there in making conditions much warmer than normal. The net result was a very snowy winter and above normal snow cover in North America, but much below normal snow cover for Eurasia, and much below for the hemisphere as a whole. Even sea level rise leveled off after mid-2007 (Fig. 2), suggesting a loss of heat from the ocean and/or a slowing of melting of glaciers and the ice sheets. This is exactly as expected and a counter example is in 1997/98 (Fig. 2) when a major El Niño occurred. Such natural variability is to be expected: global warming does not mean relentless warming at every place and time.

The observed surface warming at global and continental scales is consistent with observed changes in sub-surface ocean water temperature; decreases in sea-ice extent and thickness; decreases in glacier and small ice cap extent and mass; sea-level rise; reduced duration of freeze seasons, increased heat waves; and increased atmospheric water vapor content. Hence the Earth is warming, and major components of the Earth's climate system are already responding to that warming. This wide variety of observations gives a very high degree of confidence to the overall findings.

c. Precipitation, drought and storms

A key ingredient in changes in character of precipitation is the observed increase in water vapor and thus the supply of atmospheric moisture to all storms, increasing the intensity of precipitation events. Indeed, widespread increases in heavy precipitation events and risk of flooding have been observed, even in places where total amounts have decreased. Hence the frequency of heavy rain events has increased in most places but so too has episodic heavy snowfall events that are thus associated with warming. Snow cover has decreased in many Northern Hemisphere regions, particularly in spring, and more precipitation is falling as rain instead of snow.

Long-term trends from 1900 to 2005 have been observed in total precipitation amounts over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally. The pattern of precipitation change is one of increases generally at higher northern latitudes (because as the atmosphere warms it holds more moisture) and drying in the tropics and subtropics over land. Basin-scale changes in ocean salinity provide further evidence of changes in the Earth's water cycle, with freshening at high latitudes and increased salinity in the subtropics.

More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying due to higher temperatures and decreased precipitation have contributed to these changes, with the latter the dominant factor. The regions where droughts have occurred are determined largely by phenomena such as El Niño. In Australia and Europe, direct links to warming have been inferred through the extreme nature of high temperatures and heat waves accompanying drought.

Satellite records suggest a global trend towards more intense and longer lasting tropical cyclones (including hurricanes and typhoons) since about 1970, correlated with observed warming of tropical oceans. There is no clear trend in the annual number of tropical cyclones globally although a substantial increase has occurred in the North Atlantic after 1994. In the Atlantic, many records were broken in the 2004 and 2005 hurricane seasons, with unprecedented damage in Katrina. It has been estimated that heavy rains in tropical storms and hurricanes (including Katrina) have increased by 6 to 8% as a result of higher SSTs and more water vapor in the atmosphere. In 2007, a record number of two category 5 hurricanes made landfall in the Americas, both hitting Central America. Widespread damage has also occurred in 2008 from typhoons Nargis in Myanmar and Fengshen in the Philippines. In the Atlantic, Bertha has broken several records for how early and how far east it formed, and it has also been the longest-lasting July tropical storm.

d. Synthesis across variables

In summary, global mean temperatures have increased since the 19th century, especially since the mid-1970s. However, global warming does not mean that temperatures increase steadily or uniformly. The atmospheric circulation has also changed: in particular increasing westerly wind flow is observed in most seasons in both hemispheres. In the Northern Hemisphere this brought milder maritime air into Europe and much of high-latitude Asia from the North Atlantic in winter, enhancing warming there. In the Southern Hemisphere, where the ozone hole has played a role, it has resulted in cooling since 1971 for parts of the interior of Antarctica but large warming in the Antarctic Peninsula region and Patagonia..

Over land in low latitudes and in summer more generally, there is a strong tendency for either hot and dry or cool and wet. Hence areas that have become wetter, such as the eastern United States and Argentina, have not warmed as much as other land areas. Increased precipitation is associated with increases in cloud and surface wetness. Thus more heat goes into increased evapotranspiration and less into raising temperature at the surface in wetter conditions.

Warming promotes increases in both drought and temperature. Changes in both come as the heat goes into raising temperature or drying (evaporation) and, as the temperatures increase, the water holding capacity of the atmosphere goes up at 4% per deg F. Hence warmer temperatures have the effect of drawing moisture out of plants and soils. Droughts have increased over many tropical and mid-latitude land areas, in part because of decreased precipitation over land since the 1970s but also from increased drying arising from increased atmospheric demand associated with warming. Even as rains have become heavier (more intense), so dry spells have also become longer. The two go hand in hand and relate to how precipitation changes: more intense but less frequent, and the amount changes less. After a certain point where the ground is dry and the plants have reached wilting point, all the heat goes into raising temperature and creating heat waves, and then wild fire risk goes up substantially and "dry lightning" is disastrous, especially in areas where trees are damaged such as by bark beetle. Wild fires in California early in 2008 and again this summer are direct evidence of the impacts. As of June 30, more than 2.1 million acres have burned this year according to the U.S. National Interagency Fire Center, the third highest on record after 2006 and 2002. Of course the risk of wild fire does not necessarily translate into a wild fire if care has been taken in managing the risk by building wild fire breaks, cutting down on litter, removing diseased and dead trees and vegetation near buildings, etc. A key question in recognizing that global warming is happening, is whether adequate preparation for the changes (whether heavy rains, drought, or wild fire risk) has been made?

A consequence of these findings is that what were once 500 year flood events are now more like 30 or 50 year events. A particular example has been seen in the central U.S in the first 6 months of 2008 as record heavy rains have occurred in Iowa, Ohio, and Missouri, with associated flooding through overtopped levees along the Cedar River in Iowa and the Mississippi. This follows from similar flooding in 1993, just 15 years ago. The record breaking numbers of tornadoes and deaths in the U.S. in 2008 probably also has a modest global warming component. Tornadoes are most common in the spring and early summer in weather systems moving across the U.S. that bring warm moist low-level air flowing from the Gulf of Mexico into the storms, while drier westerly winds aloft create wind shear that leads to rotation and thus tornadic thunderstorms. Because the Gulf air is warmer and moister than it would otherwise have been 30 or more years ago, the instability of these storms is enhanced. The effect is not measurable owing to the nature of tornado statistics which mainly reflect increasing numbers of people in more places.

Consequences of the changes in climate include those given above from changes in heat, cold, storms (including hurricanes and tornadoes), drought, and wild fires. In 2008 preliminary counts through June are that 119 people have died in tornadoes in the United States. The drought-related heat wave in Europe in summer 2003 killed as many as 35,000 people. On the other hand fewer cold waves reduce mortality. Safe drinking water is jeopardized by more intense rains and runoff which can lead to contamination and increased microbial loading, sometimes overwhelming water treatment plants (if they exist). Hence water-borne diseases have been observed to increase. Also drought and observed earlier snow melt and runoff jeopardize water supplies, especially in summer. Changes in temperatures, humidity and precipitation also affect the environment for pests and disease, and have increased risk of certain problems in plants, animals and humans. Changes in phenology, reproduction, and geographic range are occurring, disrupting predator-prey relationships. Some species have become extinct. For instance, pine beetle that has devastated huge tracts of lodge-pine forest in the U.S. flourishes and spreads in warmer temperatures. Evidence of climate change effects is also evident in fish, such as salmon. Air quality is also changing from pollution, and ground level ozone and particulate matter are increasing in most regions, with increased hospital admissions for respiratory disease. The capacity to adapt to these changes varies greatly regionally.

Modeling climate change and projections

Many of the above observed changes are now simulated in climate models run for the past 100 years, adding confidence to understanding of the relationship with the agents that alter the climate, and human-induced changes in atmospheric composition. In particular, when anthropogenic forcings are included, the models simulate the observed global and continental-scale temperature records with impressive fidelity. The models can then be used to simulate the record without anthropogenic forcings, and the results are similar up till about 1970, and it is only since then that the human influence has emerged above the levels of natural variability. Also, the models indicate that volcanic and anthropogenic aerosols have offset some of

the additional warming that would have resulted from observed increases in greenhouse gas concentrations alone.

A climate model is a tool; often a very sophisticated tool that encapsulates much of our understanding about the complex climate system. But it is still a model that makes assumptions and approximations, and is a grossly simplified version of the real world. Faster computers that can permit much higher resolution are required, for one thing, to merely capture our current understanding about the role of currently unresolved phenomena such as hurricanes. The main way models have been used is to examine the change in response to future emissions into the atmosphere and not worrying about specifying the starting point. It means the result is not a prediction and instead it is referred to as a projection. Climate models have crude representation of aerosols and their forcing, and clouds are the biggest source of uncertainty. George Box is credited with saying “*All models are wrong, some are useful*”. It applies to climate models especially well.

Owing to the long lifetime of carbon dioxide and other greenhouse gases, even if no further emissions occurred into the atmosphere we are guaranteed to have further warming of the planet, amounting to about 0.6°C according to IPCC, but possibly quite a bit larger if feedbacks not accounted for in models kick in (such as outgassing of carbon dioxide by the oceans as they warm).

Over the next two decades, all models produce similar warming trends in global surface temperatures, regardless of the emissions scenario. The rate of the projected warming is near 0.2°C per decade. Decadal-average warming over each inhabited continent by 2030 is insensitive to the emission scenario; but by the middle of the 21st Century the choice of scenario becomes more important for the magnitude of surface warming, and by the end of the 21st Century there are clear consequences for which scenario is followed. The best estimate of the global surface temperature change from today to the end of the century is +1.8°C for the low emission scenario (corresponding to a carbon dioxide equivalent concentration of 600 ppm by 2100) and +4.0°C for the highest emission scenario (corresponding to 1,550 ppm). This result highlights the long lead times required before measures taken are effective in reducing the threat of global warming.

Geographical patterns of warming show greatest temperature increases at high northern latitudes and over land, with less warming over the southern oceans and North Atlantic, as has been observed in recent decades. In spite of a slowdown of the meridional overturning circulation and changes in the Gulf Stream in the ocean across models, there is still warming over the North Atlantic and Europe due to the overwhelming effects of the increased concentrations of greenhouse gases.

Sea ice coverage is projected to shrink in polar regions. In 2006 a model suggested that there are real prospects for the Arctic becoming ice free in late summer by about the 2040s and the record low Arctic sea ice observed in 2007 suggest that this may be happening a lot faster than most models suggest. The IPCC models fail to capture these dramatic changes. Snow cover is projected to contract, with widespread increases in thaw depth over most permafrost regions. Another recent study with a climate model suggests that permafrost may melt much faster than previously thought partly as a consequence of the diminishing sea ice, with consequences for the carbon cycle.

It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent. It is likely that tropical storms and hurricanes will become more intense and with much heavier rainfalls, and thus risk of flooding. The observed patterns of precipitation change in recent decades is projected to continue, with increases over northern continents but decreases over subtropical regions, increasing risk of drought. At the same time, dry spells are expected to increase everywhere. Water resources will be a major issue and perhaps the biggest source of stress on society.

Projections of sea level rise by the end of the century in IPCC range from 30 to 40 cm, but do not include possible ice sheet collapse. These climate models have very primitive modeling of ice sheets and the role of buttressing ice shelves, leading to considerable uncertainty in possible future sea level rise. The IPCC estimates of future sea level rise could be low by a factor of 2 or more.

Models can be exceedingly useful if used wisely. Observed climate changes are now sufficiently large, and models in IPCC have now improved to the point that they simulate many of the observed changes going on. As shown by recent sea ice and ice sheet changes, the IPCC conclusions are quite conservative. We very much need to improve models and have access to faster bigger computers.

Some implications

The scientific understanding of climate change is now sufficiently clear to show that specific global and regional changes resulting from global warming are already happening, possibly faster than IPCC has projected. Uncertainties remain, and new efforts at reprocessing past satellite records for phenomena such as hurricanes are required, but the 2007 IPCC report definitively shows that the climate is changing. “Warming is unequivocal” and it is “very likely” caused by human activities.

In my personal opinion as a climate scientist, there is a need for a three pronged approach of mitigation, adaptation, and maintaining and improving climate observing and information systems.

While there are uncertainties (although these cut both ways) and some changes arising from global warming may be benign or even beneficial, at least in some places and in the short run, the IPCC report shows that the rate of change as projected exceeds anything seen in nature in the past 10,000 years. Moreover, the inertia of the climate system and the long life of carbon dioxide in the atmosphere mean that we are already committed to a significant level of climate change. I believe that mitigation actions are certainly needed to significantly reduce the build-up of greenhouse gases in the atmosphere and lessen the magnitude and rate of climate change. Action taken now to reduce significantly the build-up of greenhouse gases in the atmosphere will lessen the magnitude and rates of climate change. In fact I believe there is a crisis of lack of adequate action in this regard.

At the same time, the 2007 IPCC report makes clear that even aggressive mitigation would yield benefits decades in the future, and that no amount of mitigation can avoid significant climate change. It is apt to be disruptive in many ways. Hence it is also vital to plan to cope with the changes, such as enhanced droughts, heat waves and wild fires, and stronger downpours and risk of flooding. Managing water resources will be a major challenge in the future. Adapting to climate change and reducing vulnerability is essential. This means that we should adapt to climate change by planning for it and making better predictions of likely outcomes on several time horizons.

There is a great need to address the considerable shortcomings in our observing systems. Weather stations come and go and changes are made without regard to the effect on the climate record. Changes in observing systems, especially from satellites, as new satellites and instruments are launched, create artifacts in the climate record. Loss of Earth observing satellites is also of concern. Ground based observations are not being adequately kept up in many countries. Calibration of climate records is critical. Small changes over long times are characteristic of climate change but they occur in the midst of large variations associated with weather and natural climate variations such as El Niño. Yet the climate is changing and an imperative is to track the changes and the causes as they occur. We need to build a system based on these observations to inform decision makers on what is happening, and why, and what the predictions are for the future on several time horizons.

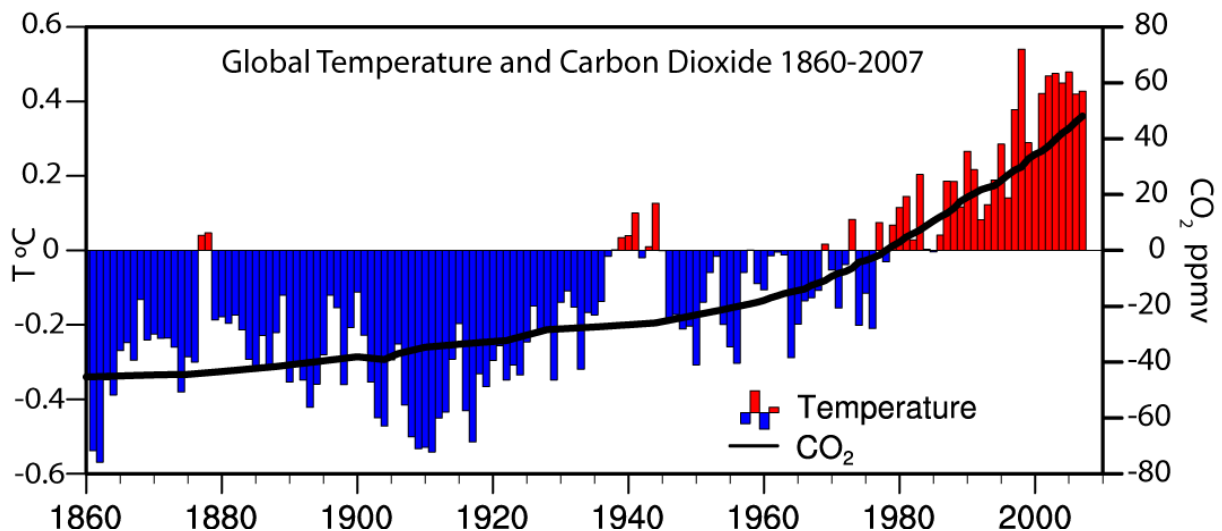


Figure 1. Time series of annual global mean temperature departures for 1861-2007 from a 1961-90 mean (bars), left scale, and the annual mean carbon dioxide from Mauna Loa after 1957 linked to values from bubbles of air in ice cores prior to then. The zero value for 1961-90 for temperature corresponds to 14°C and for carbon dioxide 334 parts per million by volume (ppmv).

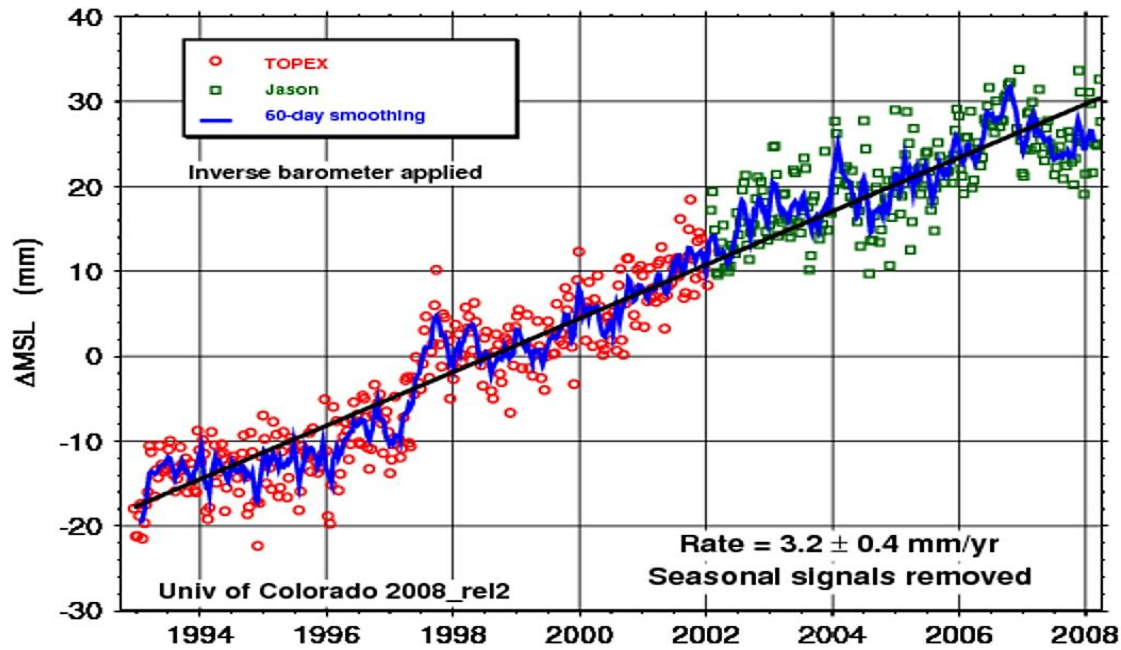


Figure 2. Sea level changes based on altimetry from space from the TOPEX/Poseidon and Jason measurements, processed to remove the mean annual cycle and with an inverse barometer correction applied (to account for changing sea level pressure over the oceans). From Univ. Colorado http://sealevel.colorado.edu/current/sl_ib_ns_global.jpg courtesy Steve Nerem.