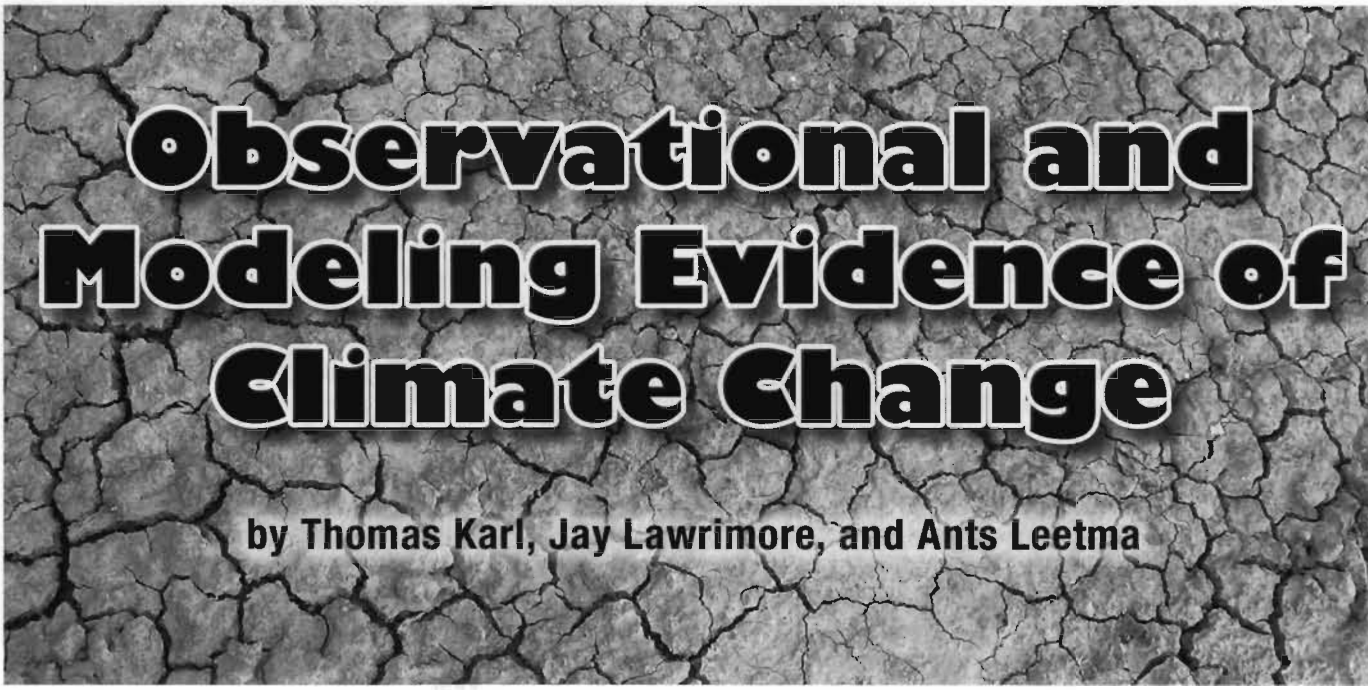

Observational and Modeling Evidence of Climate Change

by Thomas Karl, Jay Lawrimore, and Ants Leetma

Scientific understanding of past changes and variability in the Earth's climate comes from the analysis of numerous sources of instrumental and proxy data, as well as computer model simulations of the Sun/Earth/atmosphere processes causing the changes. Subject to certain limitations and uncertainties, instrumental data are available to assess climate change and variability from the late 1800s to present. The study of climate in the preceding centuries is possible primarily through paleoclimate reconstructions using proxy sources such as tree rings, marine and lake sediments, ice cores, corals, and borehole records.

Improvements in monitoring systems have been made with technological advances such as radar and satellite instruments, but climate research continues to be affected by a number of limitations, including inadequate spatial coverage of many variables and systems with inadequate instrument calibration methods. Model simulations of the Earth's changing climate over many centuries are possible by numerical solutions of time-dependent equations on supercomputers. The following are brief summaries of observed changes in the Earth's climate resulting from studies of instrumental and proxy records, as well as simulated climate from global climate models. We also include a discussion of inherent problems in observing systems and future solutions that will further enhance the scientific understanding of the Earth's climate.

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CLIMATE FORCING FACTORS

The Earth's climate system derives its energy from the Sun, and any variations in the amount or geographic distribution of solar energy can result in changes in distinct climates. The most obvious manifestations are the geographic differences in mean climate (e.g., tropics, midlatitudes, polar regions) and the seasonal cycles. Changes in Earth–Sun geometry happen on periods of 20,000–100,000 years and have been shown to be the primary drivers responsible for the occurrence of ice ages and the intervening interglacial periods.

> Paleoclimate studies suggest that even small changes in radiative forcing, such as those induced by anthropogenic GHGs, can produce major changes in the global climate.

Volcanic eruptions, an abrupt forcing, introduce large amounts of aerosols into the upper atmosphere. By reflecting incoming solar radiation, these aerosols reduce the solar energy reaching the Earth's surface. Studies have shown that important multi-decadal climate variations in the Northern Hemisphere over the past 1000 years were driven by prolonged periods of volcanic activity, as well as subtle variations in solar output. The changes in solar energy received at the Earth's surface during these periods are of the order of a few watts per square meter (w/m^2).

Greenhouse gases (GHGs) are trace constituents in the atmosphere that absorb outgoing radiation from the Earth's surface and then re-emit the radiation back to Earth. This trapping of radiative energy raises the temperature of the Earth's surface, causing what is known as the greenhouse effect. The main natural GHGs are water vapor, carbon dioxide, ozone, methane, and nitrogen. The amount of radiative forcing depends on the concentration of the gas, its radiative properties, and the presence of other such gases. The lifetimes of some of these gases extend to centuries; therefore, the consequences of increasing long-lived GHGs, which have been occurring since the start of the Industrial Revolution, will persist long into the future.

Anthropogenic aerosols (i.e., micron-sized particles with atmospheric lifetimes up to one week) resulting from fossil fuel and biomass burning often reflect more solar radiation than they absorb and, hence, contribute to cooling the climate system. However, for some aerosols the opposite occurs, causing warming. Aerosols can also affect cloud formations and reflectivity; these indirect effects are poorly understood. Indirect evidence from the rate of warming of the global oceans during the past 50 years suggests a net positive radiative forcing (e.g., the sum of GHGs and aerosols on the order of 1 w/m^2).

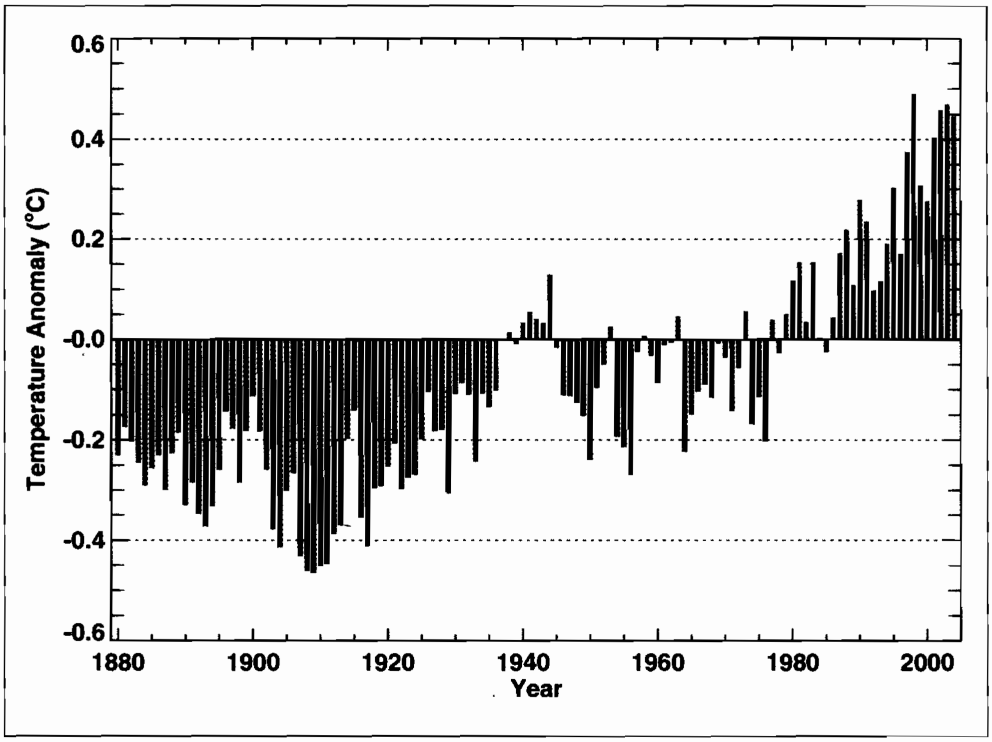

Figure 1. Time series of annual global surface temperature departures from the 1961–1990 base period mean of 14.0 °C.[3]

The lesson from the past is that the climate is sensitive to numerous forcings, which can have profound effects on regional and global climate. Paleoclimate studies suggest that even small changes in radiative forcing, such as those induced by anthropogenic GHGs, can produce major changes in the global climate.

OBSERVATIONAL EVIDENCE OF CLIMATE CHANGE

A wide range of climate observations forms the basis for understanding the Earth's climate. The following sections provide a sample of key variables and indicators related to climate variability and change. Included are century-long measurements of monthly mean temperature and total precipitation and shorter records of data with daily resolution, which are useful in addressing changes in the frequency and severity of heavy precipitation events, drought, and heat waves. Also provided are trends from 50 years of global in situ tropospheric temperature records and a 26-year record of upper-air temperatures from satellite measurements. Other important indicators of global climate change are also included, such as Northern Hemisphere snow cover extent, polar sea ice extent, and sea level. Brief summaries of the major findings resulting from the study of paleoclimate data for surface temperature and drought are included to provide a longer-term perspective on these important climate indicators.

Temperature

Multi-proxy reconstructions of Northern Hemisphere temperature for the past 2000 years reveal an oscillation between warm conditions 1000–1100 AD (the Medieval Warm Period) and cooler temperatures, which reached a minimum around 1600 AD (the Little Ice Age), and an increase in temperature from around the middle 1800s to the present.[1] Based on these analyses we can state that the temperature over the past decade and a half, averaged for the Northern Hemisphere, is likely warmer than any other 15-year period observed during the past 2000 years. Although different paleoclimate proxies yield different results, most indicate a temperature increase of between 0.5 and 1.0 °C since the 16th Century, with much of this occurring in the past 100 years.[2]

Instrumental observations of surface temperature[3] reveal two multi-decadal periods of rapidly warming global temperatures in the 20th Century that are part of an overall warming trend of approximately 0.06 °C decade^{-1} from 1900 to 2004 (see Figure 1). The warming trend was 0.13 °C decade^{-1} from 1910 to 1945, but only 0.02 °C decade^{-1} during the ensuing 30 years. This was followed by an unprecedented period of warming that brought the 1976–2004 trend to 0.17 °C decade^{-1}. The recent rise in temperatures is believed to be the fastest since the end of the last Ice Age.[4] Numerous analyses have addressed possible contamination of these records by factors such as changes in instruments, urban heat island growth, and observing methods. Nevertheless, multiple research teams using similar but different methods of correcting for these potential biases generally find very similar results.

The warming trend is seen in both daily maximum and minimum temperatures, with minimum temperatures increasing at a faster rate than maximum temperatures up to 1970 and the diurnal temperature range decreasing in many areas of the world. Since the mid-1970s, both maximum and minimum temperatures have risen equally when averaged across the worldwide land areas. Widespread reductions in the number of days below freezing occurred during the latter half of the 20th Century in the United States, as well as most land areas of the Northern Hemisphere and areas of the Southern Hemisphere having sufficient data for analysis.

The smaller rise in maximum temperatures observed earlier has been related to increases in atmospheric water vapor, cloud cover, and precipitation, which have a differential effect on maximum and minimum temperatures. Apparent temperature, a measure that combines the effects of humidity and temperature and is a contributor to heat stress, has been found to have increased in some regions of the world. There is also evidence of increases in the incidence and duration of heat waves, but the occurrences are less widespread and persistent than the rise in mean temperature.[5]

Temperature measurements have been made above the Earth's surface over the past half-century in the troposphere (surface to 10–16 km) and stratosphere (10–50 km above sea level). Widespread data collection from balloon-borne instruments (radiosondes) began in 1958, and reliable measurements from satellites began in 1979. Radiosonde measurements of global tropospheric temperatures averaged within the middle troposphere (~3–10 km above the Earth's surface)[6] from 1958 to 2004 increased at a rate of 0.13 °C decade^{-1}, which was similar to trends in global surface temperature (0.11–0.12 °C decade^{-1}). For the period beginning in 1979, when satellite measurements of troposphere temperatures began, various satellite datasets compiled for a similar layer of the atmosphere show similar rates of warming compared to global surface temperatures.[7] Although some of the satellite-derived datasets produce global tropospheric trends larger than surface trends, others do not.

Precipitation

Warming global temperatures may induce changes in the Earth's hydrologic cycle and alter precipitation patterns across the globe. There are inadequate data available over the oceans to be confident of trends in these areas although several approaches are currently being refined based on blended satellite and in situ data. Over land areas, observations provide indications that changes in precipitation amounts, intensity, and frequency have already occurred. Best estimates suggest that worldwide land precipitation increased approximately 2% during the 20th Century, although there

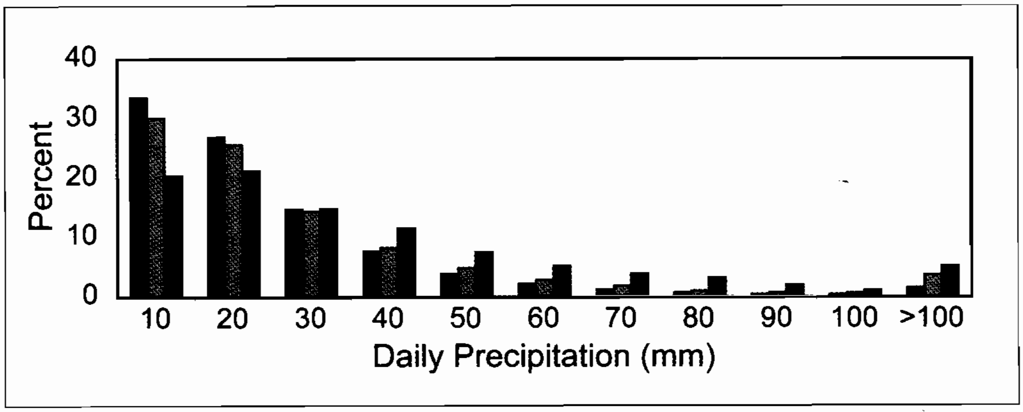

Figure 2. Climatology of the intensity of daily precipitation as a percentage of total amount in 10 mm/day categories for different temperature regimes, based on 51, 37, and 12 worldwide stations, respectively: blue bars = -3–19 °C; pink bars = 19–29 °C; dark red bars = 29–35 °C. By selection, all stations have the same seasonal mean precipitation amount of 230 + 5 mm. As temperatures and the associated water-holding capacity of the atmosphere increase, more precipitation falls in heavy (more than 40 mm/day) to extreme (more than 100 mm/day) daily amounts.[12]

was significant year-to-year variability and several multi-year periods of unusually wet and dry conditions.[2]

The worldwide land increase in precipitation is not spatially uniform; and although increases generally predominate, negative trends are prevalent in large parts of the Northern Hemisphere tropics. This is most notable in much of West Africa south of the Sahara (i.e., the Sahel region), stretching to western areas of the Greater Horn of Africa. Precipitation increases were largest in the mid- and high-latitude Northern Hemisphere especially during the autumn and winter seasons. On an annual basis, precipitation increased at a rate of approximately 6% century^{-1} in the United States, more than 10% in Canada, and 5% in the former USSR. Areas of increasing precipitation in the Southern Hemisphere include Australia, where total annual rainfall increased 15–20% across large areas of the continent from 1910 to the late 1990s.[2]

In these and other countries, long-term positive trends in precipitation were interrupted by periods of drought. In the United States, severe and widespread multi-year droughts occurred in the 1930s and 1950s. Severe droughts have also occurred since that time, but none have been as widespread and persistent; and there is little overall trend in the severity or expanse of drought in the United States since 1900.[8] Paleoclimatic data indicate the existence of droughts in the more distant past. An analysis of reconstructed tree-ring data for the past five centuries shows a dozen droughts similar to the 1950s drought, in terms of severity and spatial footprint across the southwestern United States, several of which lasted longer.[9] In contrast, the 1930s drought does not appear to have a close analog matched in duration, severity, and regional coverage.

While devastating droughts were not a new phenomenon of the 20th Century, there are, nonetheless, indications that warming temperatures and the associated increase in evapotranspiration make periodic, naturally occurring droughts more severe than they would be otherwise in a steady-state climate. On a global basis, the areas that have experienced severe to extreme drought have increased from ~ 12% to 30% since the 1970s.[10] Increases in surface air temperature, which act to increase the water-holding capacity of air and, thus, its demand for moisture, are believed to be the primary cause of the observed surface drying.

Because of the increased water-holding capacity of the atmosphere, an enhanced hydrologic cycle ensues, leading to more frequent heavy and very heavy precipitation events (in the upper 5 and 1 percentiles). Higher atmospheric water vapor content and an earlier onset of spring- and summer-like conditions have been shown to contribute to increases in the frequency of thunderstorm-producing cumulonimbus clouds in the United States.[11] These and other factors can be related to a shift in the distribution of precipitation to a greater frequency of heavy events at the expense of light to moderate precipitation events.

An assessment of observed changes of the characteristics of very heavy precipitation events in more than 50% of the world's land areas found greater changes in heavy precipitation frequencies than changes in precipitation totals in every region. These increases in heavy and very heavy precipitation events, which occurred as the temperature of the Earth increased, have been found to be consistent with the distribution of precipitation between warm and cold climates, whereby even for regions with the same seasonal or annual precipitation, those regions with warmer climates have more heavy daily precipitation events than those having colder climates (see Figure 2).[12] Moreover, this effect is enhanced as annual precipitation amounts increase as detected in many mid- and high-latitude areas as noted above.

Other Indicators of Climate Change

Warming global temperatures are also closely linked with other parts of the Earth's climate system. Sea ice extent (SIE) and snow cover extent (SCE) have declined as temperatures have increased, creating the potential for positive climate feedbacks that can produce even warmer surface temperatures. Less solar radiation is reflected back into space as the highly reflective white snow and ice surfaces are replaced by darker land and ocean surfaces that more readily absorb solar radiation. Spring and summer Northern Hemisphere SCE have decreased more than 15% since satellite observations began in 1966, primarily due to reductions since the mid-1980s over the Eurasian and North American continents.[13] SIE in the Northern Hemisphere has decreased at a rate of approximately 10% decade^{-1} since reliable measurements began in 1978. The lowest extent on record occurred in September 2002, and in each of the following two years Northern Hemisphere SIE was near the record low.[14]

Warming has not been as widespread in the high latitude Southern Hemisphere during the past 25–30 years, and as a result there have not been large drops in SIE around

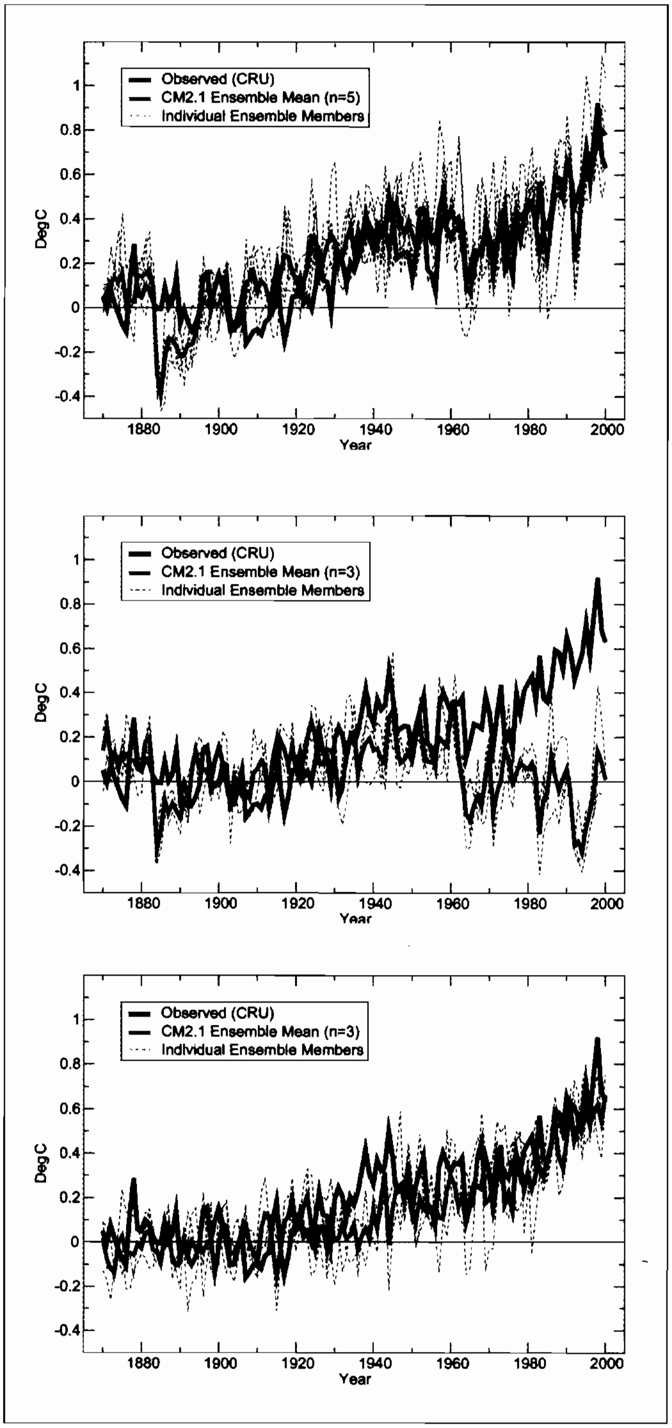

Figure 3. Global annual mean temperature time series for the observations (black curves) and model historical forcing runs: top panel = all forcings; middle panel = natural forcings only (solar plus volcanic); lower panel = anthropogenic forcings only. The heavy red curves are model ensemble means and the green dashed curves are individual ensemble members. All curves are referenced to the period 1881–1920.

Antarctica similar to those observed in the Arctic. However, there are indications that rapid thinning of ice sheets caused by pronounced regional warming has occurred on parts of the Antarctic continent; for example, the large buttressing ice shelves Larsen A and Larsen B were lost consecutively in 1995 and 2002.[15] Melting and thinning ice sheets can lead to higher sea level and may be the dominant cause of global sea level changes in future centuries. However, the biggest contributor to rising sea levels during the 20th Century was thermal expansion of warming ocean waters, which is also expected to be the primary contributor to sea level rise during this century. Data collected from coastal tide gauges provide an estimated global average sea level rise of between 0.1 and 0.2 m during the last century.[2]

Uncertainties and Observing Issues

It has long been recognized that observational records used to study the Earth's climate suffer from deficiencies that, if left unresolved, can compromise the climate signal. These deficiencies are the result of a number of factors, including inadequate spatial coverage of observing stations, insufficient historical documentation of station characteristics, changes in observing methods, and instruments without adequate calibration. These limitations require that adjustments be applied to remove the influences that can artificially amplify or diminish trends. An array of statistical and physically based adjustment techniques have been developed over the past two decades for this purpose and include, but are not limited to, adjustments for the effects of urbanization and local land use changes, instrument changes, and station observing or location changes.

Although adjustments improve the climate record, a level of uncertainty remains, particularly in the early part of the instrumental record. Efforts to quantify the uncertainties are being made, and to date, the most successful have focused on global temperature. Uncertainties in annual global temperature approach values as large as 0.15 °C in the late 1800s, but decrease to 0.05 °C in the latter part of the century.[3] These uncertainties result in a statistical uncertainty range (95% confidence interval) of possible 20th Century global temperature trends between 0.03 and 0.09 °C decade^{-1}.

In recognition of these inadequacies, as well as the fact that existing systems have deteriorated over the past few decades in many parts of the world, new efforts have emerged to help improve observing and reporting systems. A series of Earth Observation Summits have been held since July 2003 to promote the development of a comprehensive, coordinated, and sustained observation system among the international community. A 10-year implementation plan for developing a Global Earth Observing System of Systems (GEOSS) has emerged from these summits. This plan would, among other goals, help assure data utility and usability; assist developing countries in improving and maintaining observing systems; and create full, open, and expeditious exchange of observational data.[16]

The new standard is to deploy, at an adequate spatial density, readily accessible and integrated systems of well-calibrated instrumentation that are free from unresolved influences such as changes in environment. The success of these efforts will greatly enhance the ability of the scientific community to monitor the global climate. The end result will be reduced uncertainties and the availability of data and information that will provide for better resolution of climate change issues.

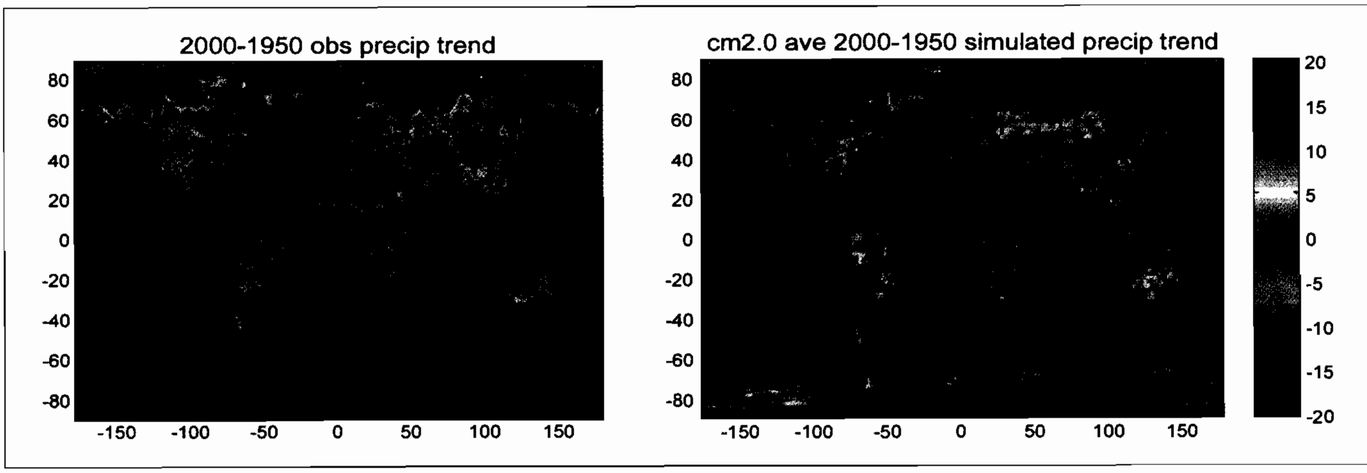

Figure 4. Linear trends from 1950 to 2000 in the observed (left panel) and modeled (right panel) July–Aug–Sept rainfall over land in mm/month/50 yr. Blue areas correspond to a trend toward drier conditions, and yellow and red toward wetter climates. Model trends are for the average of a three-member ensemble.

MODELING EVIDENCE OF CLIMATE CHANGE

Models are sets of mathematical equations that simulate the complex interactions between the atmosphere, ocean, land, snow, and ice by taking into account the laws of physics, thermodynamics, and chemistry. Because of the complexity of the equations and the interactions between the components, the equations need to be solved using computer programs. Climate change simulations can be hundreds to thousands of years long, and because of the long timescales involved and the complexity of the Earth system, the largest supercomputers are required for these studies.

In the real world, significant processes that transfer heat, momentum, and water, and phenomena that influence radiation balances such as clouds, convection, eddies, and turbulence occur on much finer scales than can be resolved in models. Hence, their effects are parameterized in terms of the larger-scale fields, which the models do resolve. Many of the differences between model simulations result from differences and uncertainties in the parameterizations. Testing and making improvements to the parameterizations is an integral part of model development. Additionally, the steady progress in increasing model resolutions has led to closer agreement between model simulations and observations.

Model Results for the 20th Century

Any human-induced impacts on climate variability and change will be part of a broader spectrum that includes natural climate variations on a variety of space and time scales. Detecting the anthropogenic signal in the presence of energetic natural variability is a significant research challenge. Furthermore, the anthropogenic effects might produce changes in natural variability itself, as is suggested above. In the most recent model-based studies of the climate of the 20th Century, the model's radiative forcing takes into account observations/estimates of changes in the well-mixed GHGs (i.e., carbon dioxide, methane, nitrous oxide), tropospheric ozone, sulfate and carbonaceous aerosols, stratospheric ozone and aerosols, solar irradiance, and land use. Projections for the 21st Century and beyond require estimates of future scenarios for these forcing factors. Because this involves projections of future population growth, energy usage, and new technologies, the uncertainty level of what future climates might look like increases and, therefore, can only be considered as plausible scenarios, not real forecasts.

Temperature

Assessments of historical climate simulations (1861–2000) with observations are valuable tests of the credibility of climate models. Such simulations are forced with observed/estimated effects of changes in the well-mixed GHGs, ozone, sulfates, black and organic carbon, volcanic aerosols, solar flux, and land cover. Multiple simulations were run to average over the variability that is present in the model runs and in nature. Additional simulations were also run using only the changes in natural forcings (e.g., solar and volcanoes) over this period. The difference between these simulations represents the climate change resulting from anthropogenic effects.

Extensive analyses for global and regional effects for these runs are reported in Knutson et al.[17] The warming trends on global scales are simulated realistically (see Figure 3). The warming trend during the 20th Century takes place in two stages: 1910–1945 and, more dramatically, 1975–2000. The top panel model simulations capture these increases. The middle panel shows that simulations using only natural forcing partly capture the early century warming; however, these natural forcings do not contribute at all to the warming since 1975. The lower panel shows that the simulations using only anthropogenic changes in radiative forcing capture the late century warming well. These simulations support previous findings that 20th Century global warming resulted from a combination of natural and anthropogenic forcing. Additionally, the model simulations capture the observed change in oceanic heat content during the latter part of the century. This suggests that the net radiative imbalance present because of the various natural and anthropogenic forcings is reasonably simulated.

The regional results[18] provide evidence for an emergent anthropogenic forcing warming signal over many, if not most, regions of the globe. This signal has emerged rather monotonically in the Indian Ocean/Western Pacific near equatorial regions during the past half-century. The tropical and subtropical Atlantic and the tropical eastern Pacific are also regions where the anthropogenic warming signal now appears to be emerging from a background of substantial natural multi-decadal variability. A full understanding of the details of these regional trends will require a better understanding of this natural multi-decadal signal, which was dominant during the middle of the last century.

Rainfall

The patterns of change for precipitation have more spatial structure than those for temperature. A prominent feature is the drying trend in the Sahel region during the latter half of the last century. The observations suggest that this is part of a broader pattern in the Eastern Hemisphere. Not only is there drying in the Sahel, but also over large parts of southern Africa, the Mediterranean, India, and Southeast Asia. The model-simulated trends for this period show a similar pattern. The model also captures the trend toward enhanced rainfall in Western Australia. In all these regions, the model trends are weaker than the observed trends. Over the Sahel, the model trend is approximately half that observed. In the Western Hemisphere and areas outside the tropics and subtropics, the agreement between the observed and modeled trends is less satisfactory. In general, models simulate changes in mean precipitation more poorly than temperature. This is because there is considerable uncertainty in the parameterizations of convection, and rainfall patterns are strongly influenced by small-scale features in the model solutions.

Rainfall variations over the Sahel and the neighboring regions appear to be caused by a myriad of factors.[19] Sea surface temperature variability in the Atlantic, which is partly a result of the natural multi-decadal oscillation, plays a role as do the changing sea surface temperatures in the tropical Indian and Pacific Oceans. As in the case of temperature variability during the last century, both natural and anthropogenic effects seem to play important roles in producing these trends. Further research is needed to fully understand the relevant mechanisms and the reasons for the lack of consensus among the models.

CONCLUSIONS

Climate models are our most complete tools for projecting what the Earth's climate might look like in the future as a result of anthropogenically produced changes in radiative forcings and land use. These models are necessarily complex because they need to accurately represent phenomena, such as midlatitude storms, the annual cycle, and natural variability on multiple timescales. To achieve this accuracy, these models must take into account interactions between the ocean, atmosphere, land, snow, and ice and how these might change due to subtle variations in radiative forcing resulting from both natural and anthropogenic causes. The models are far from perfect; hence, whenever possible, the answers they produce need to be verified by observations. As a minimum requirement, models should reproduce the trends observed during the 20th Century; otherwise, the case for believing future projections is inadequate. This short discussion suggests that the current generation of models is not only capable of simulating global-scale trends, but that it is also useful for starting to explore regional variations. The simulations provide additional evidence for a substantial human-induced effect on late 20th Century global and regional climates. However, the effects of natural variability on regional trends are substantial, and credible projections of such trends into the future will require an improved understanding of both natural variability and anthropogenic effects. **em**

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