Kevin E. Trenberth

The Earth's climate system variability and change

We experience weather every day in all its wonderful variety. Most of the time, it is familiar, yet it never repeats exactly. We also experience the changing seasons and associated changes in the kind of weather. In summer, fine sunny days are interrupted by outbreaks of thunderstorms, which can be violent. Outside of the tropics, as winter approaches the days get shorter, it gets colder, and the weather typically fluctuates from warm, fine spells to cooler and snowy conditions. These seasonal changes are the largest changes we experience at any given location. Because they arise in a well-understood way from the regular orbit of the Earth around the Sun, we expect them, we plan for them, and we even look forward to them. We readily and willingly plan (and possibly adapt) summer swimming outings or winter ski trips. Farmers plan their crops and harvests around their expectation of the seasonal cycle. By comparison with this cycle, variations in the average weather from one year to the next are quite modest, as they are over decades or human lifetimes. Nevertheless, these variations can be very disruptive and expensive if we do not expect them and plan for them. Anomalous weather patterns constitute a short-term climate variation or fluctuation. If they repeat or persist over prolonged periods, then they become a climate change.

The distribution of solar radiation absorbed on Earth is very uneven and largely determined by the geometry of the Sun-Earth orbit and its variations. This incoming radiant energy is transformed into various forms moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation. The requirement for an equilibrium climate mandates a balance between the incoming and outgoing radiation and further mandates that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate. And they can be perturbed, causing climate change.

The climate system has several internal interactive components. The atmosphere does not have very much heat capacity but is very important, as the most volatile component of the climate system, in moving heat and energy around. The oceans have enormous heat capacity and, being fluid, also can move heat and energy around in important ways. Other major components of the climate system include sea ice, the land and its features (including the vegetation, albedo (reflective character), biomass, and ecosystems), snow cover, land ice (including the semi-permanent ice sheets of Antarctica and Greenland and glaciers), and rivers, lakes and surface and subsurface water.

Changes in any of the climate system components, whether internal and thus a part of the system, or from the external forcings, cause the climate to vary or to change. Thus climate can vary because of alterations in the internal exchanges of energy or in the internal dynamics of the climate system. An example is El Niño-Southern Oscillation (ENSO) events, which arise from natural coupled interactions between the atmosphere and the ocean centered in the tropical Pacific. Most of the interannual variability in climate in the tropics and a substantial part of the extratropical variability is related through the El Niño phenomenon. El Niño events involve a warming of the surface waters of the tropical Pacific. Ocean warming takes place from the International Dateline to the west coast of South America and results in changes in the local and regional ecology. Historically, El Niño events have occurred about every 3–7 years and alternated with the opposite phases of below average temperatures in the tropical Pacific, dubbed La Niña. In the atmosphere, a pattern of change called the Southern Oscillation is closely linked with these ocean changes, so that scientists refer to the total phenomenon as ENSO. Then El Niño is the warm phase of ENSO and La Niña is the cold phase.

Because convection and thunderstorms preferentially occur over warmer waters, the pattern of SSTs determines the distribution of rainfall in the tropics, and this in turn determines the atmospheric heating patterns through the release of latent heat. The heating drives the large-scale monsoonal-type circulations in the tropics, and consequently determines the winds. If the Pacific trade winds relax, the ocean currents and upwelling change, causing temperatures to increase in the east, which decreases the surface pressure and temperature gradients along the equator, and so reduces the winds further. This positive feedback leads to the El Niño warming persisting for a year or so, but the ocean changes also sow the seeds of the event's demise. The changes in the ocean currents and internal waves in the ocean lead to a progression of colder waters from the west that may terminate the El Niño and lead to the cold phase La Niña in the tropical Pacific. The El Niño develops as a coupled ocean–atmosphere phenomenon and, because the amount of warm water in the tropics is redistributed, depleted and restored during an ENSO cycle, a major part of the onset and evolution of the events is determined by the history of what has occurred one to two years previously. This means that the future evolution is potentially predictable for several seasons in advance.

Planet Earth is habitable because of its location relative to the sun and the natural greenhouse effect of its atmosphere. Various atmospheric gases contribute to the greenhouse effect, whose impact in clear skies is about 60% from water vapor, 25% from carbon dioxide, 8% from ozone, and the rest from trace gases including methane and nitrous oxide. Clouds also have a greenhouse effect. On average the energy from the sun received at the top of the Earth's atmosphere amounts to 175 Petawatts (PW) (or 175 quadrillion watts), of which about 31% is reflected by clouds and from the surface. The rest (120 PW) is absorbed and ultimately emitted back to space as infrared radiation. Over the past century, infrequent volcanic eruptions of gases and debris into the atmosphere have significantly perturbed these energy flows, causing cooling but for only a few years. Inferred changes in total solar irradiance appear to have increased global mean temperatures by perhaps 0.2°C in the first half of the Twentieth Century, but measured changes in the past 25 years are of little consequence. Over the past 50 years human influences have been the dominant detectible influence on climate change. The main way in which humans alter global climate is to interfere with the natural flows of energy by changing the composition of the atmosphere, not by the actual heat generated in energy usage. On a global scale, even a 1% change in the energy flows, which is the order of the estimated change to date, dominates all other direct influences humans have on climate. For example, just one PW is the energy output equivalent to that of a million of the biggest power stations of 1000 megawatts capacity, and total human usage of energy is about a factor of 9000 less than the natural flow.

Global changes in atmospheric composition occur from anthropogenic emissions of greenhouse gases, such as carbon dioxide that results from the burning of fossil fuels, and methane and nitrous oxide from multiple human activities. Because they have long (decades to centuries) atmospheric lifetimes, the result is an accumulation in the atmosphere and a build up in concentrations that are clearly shown both from instrumental observations and from bubbles of air trapped in ice cores. Carbon dioxide has increased 31% since pre-industrial times, from 280 ppmv to over 370 ppmv today and half of the increase has been since 1965. The greenhouse gases trap outgoing radiation from the Earth to space, creating a warming of the planet. Because radiative forcing from greenhouse gases dominates over the net cooling forcings from aerosols, the popular term for the human influence on global climate is "global warming", although it really means global heating, of which the observed global temperature increase is only one consequence. Already it is estimated that the Earth's climate has exceeded the bounds of natural variability, and this has been the case since about 1980. A major consequence is sea level rise, and global sea level has only been monitored accurately since 1992, but it has risen at an average rate of 3 mm/year.

Reading

Kiehl, J. T., and K. E. Trenberth, 1997: Earth's annual global mean energy budget. *Bull. Amer. Met. Soc.*, **78**, 197–208.

Trenberth, K. E., and T. J. Hoar, 1997: El Niño and climate change. *Geophys. Res. Lttrs.,* **24**, 3057–3060.

Trenberth, K. E., and J. M. Caron, 2000: The Southern Oscillation revisited: Sea level pressures, surface temperatures and precipitation. *J. Climate*, **13**, 4358–4365.

Trenberth, K. E., 2001: Stronger Evidence for Human Influences on Climate: The 2001 IPCC Assessment, *Environment*, **43**, 4 (May), 8–19.

Karl, T. R., and K. E. Trenberth, 2003: Modern global climate change. *Science*, **302**, 1719–1723.

Background

Dr. Kevin E. Trenberth is Head of the Climate Analysis Section at the National Center for Atmospheric Research. From New Zealand, he obtained his Sc. D. in meteorology in 1972 from Massachusetts Institute of Technology. He was a lead author of the 2001 IPCC Scientific Assessment of Climate Change and serves on the Scientific Steering Group for the Climate Variability and Predictability (CLIVAR) program and the Joint Scientific Committee of the World Climate Research Programme. He is a fellow of the American Meteorological Society (AMS) and American Association for Advancement of Science, and an honorary fellow of the Royal Society of New Zealand. In 2000 he received the Jule G. Charney award from the AMS and in 2003 he received the NCAR Distinguished Achievement Award.

Contact:

National Center for Atmospheric Research
P. O. Box 3000
Boulder, Colorado 80307
email: trenbert@ucar.edu