

## Chapter 2: Climate Change – State of the Science

The purpose of this chapter is to provide historical context for the current state of climate change science, with an emphasis on references to more recent journal articles, historically important scientific literature and major synthesis documents. A large, and rapidly growing, amount of scientific literature on climate change and an unprecedented collection of climate change syntheses are available for this purpose.

Science involves the systematic combination of what we know from observation and what we understand from analyses of those observations. We use what we know and understand about the past and the present as a basis for what we expect in the future. When we predict future events, there will always be an element of irreducible uncertainty (Stewart 2000). That uncertainty cannot be resolved until the event either occurs or does not occur at the predicted time. Since climate is not a single event but a statistical measure of a large ensemble of meteorological events, climate prediction involves statistical analyses that yield a range of potential climate outcomes (e.g. 2° to 11° C warming) that we expect for the future (Stainforth et al. 2005). Gains in climate change knowledge over the past few decades have substantially reduced the uncertainty of climate change projections and thus decreased the range of expected future climate outcomes (IPCC WG I 2007).

### Basis for Climate Change Science

Three areas of knowledge form the basis for current climate change science. **First** is the instrumental record that includes surface meteorological conditions, available for ~140 years, and atmospheric Carbon Dioxide (CO<sub>2</sub>) concentrations, available for ~50 years (Compo et al. 2011; Keeling et al. 1976). The instrumental record provides clear observational evidence of global greenhouse gas (GHG) and surface temperature increases and trends. The geographic and temporal coverage of instrumental observations has increased significantly since the mid-1950s, especially with the advent of satellite observing technologies. **Second** is the paleoclimate record of observations from tree rings, ice cores and several other techniques, which now provide a rapidly increasing body of knowledge that extend GHG and temperature observations backward in time and allow us to see how ecosystems evolved over the geologic history of the planet. CO<sub>2</sub> and CH<sub>4</sub> (methane) GHG concentrations have increased over the last several thousand years of the Holocene epoch (~10,000 years ago to present) (Ruddiman, Kutzbach, and Vavrus 2011). Earth has experienced significantly different GHG concentrations, climates, and fire regimes over the past 420 million years (Bowman et al. 2009). Our rapidly expanding paleoclimate knowledge base is perhaps the most useful component for increasing our understanding of fire history and climate change. The **third** area of knowledge involves our ability to explain how various forcing factors, including GHG growth, affect the coupled circulation and energy fluxes of Earth's atmosphere and oceans, called the General Circulation, to influence weather and climate. Our knowledge of the General Circulation allows us to combine instrumental and paleoclimate observations with other information sources to provide an integrated understanding of past climate, present climate, ongoing climate change and projections for additional climate change likely in the 21<sup>st</sup> Century and beyond. This is the realm of General Circulation Models (GCMs).

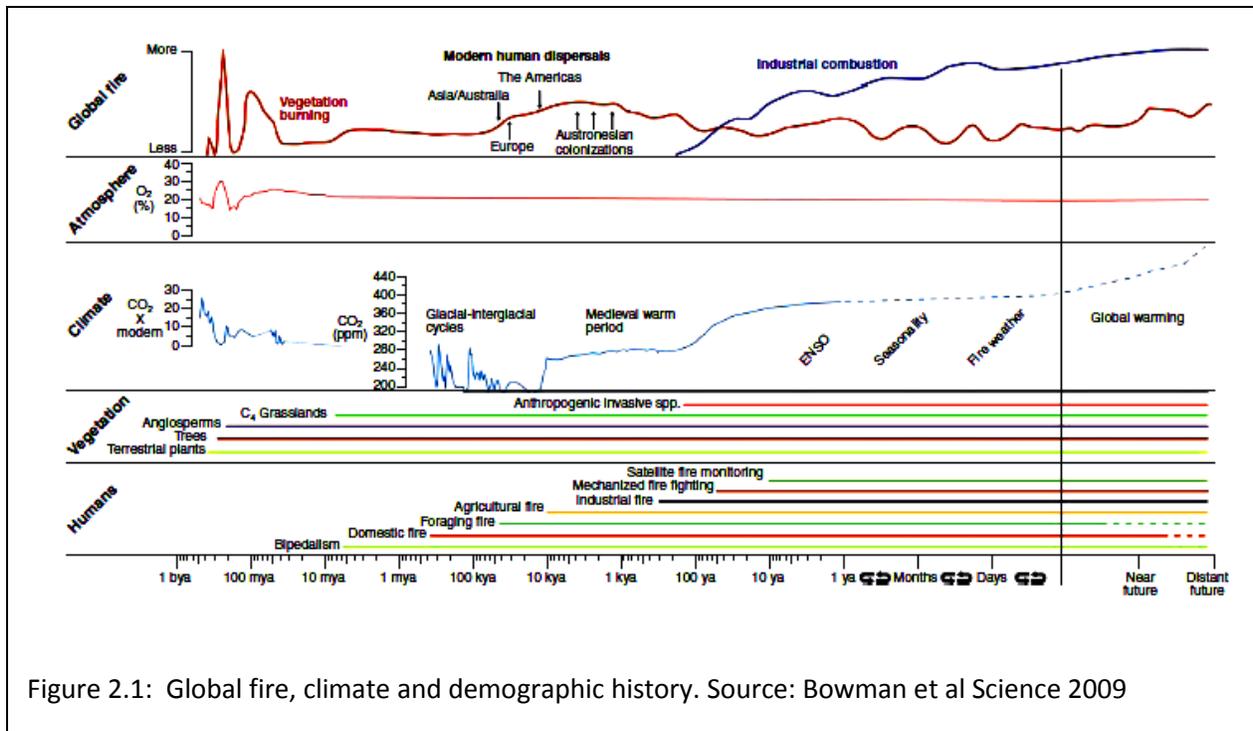


Figure 2.1: Global fire, climate and demographic history. Source: Bowman et al Science 2009

We understand and can numerically describe (model) the General Circulation of the Earth's atmosphere and oceans. General Circulation movements of the atmosphere (wind) and oceans (currents) are constantly redistributing heat received from the sun (solar radiation) and unevenly captured or reradiated by Earth. The General Circulation of the atmosphere determines all of the weather and climate variables (temperature, precipitation, wind, etc.) we experience. Major forcing factors determining the General Circulation and its variation are:

- 1) solar radiation -- generated, received and captured
- 2) orbital geometry of the Earth -- eccentricity, obliquity and axial precession
- 3) plate tectonics -- placement of continents and oceans and land surface height
- 4) albedo (reflectance due to vegetation cover, snow cover, etc.) of the land surface (includes Anthropogenic Land Cover Change (ALCC))
- 5) chemical and thermodynamic nature of our atmosphere and oceans (includes greenhouse gas (GHG) emissions and aerosols)

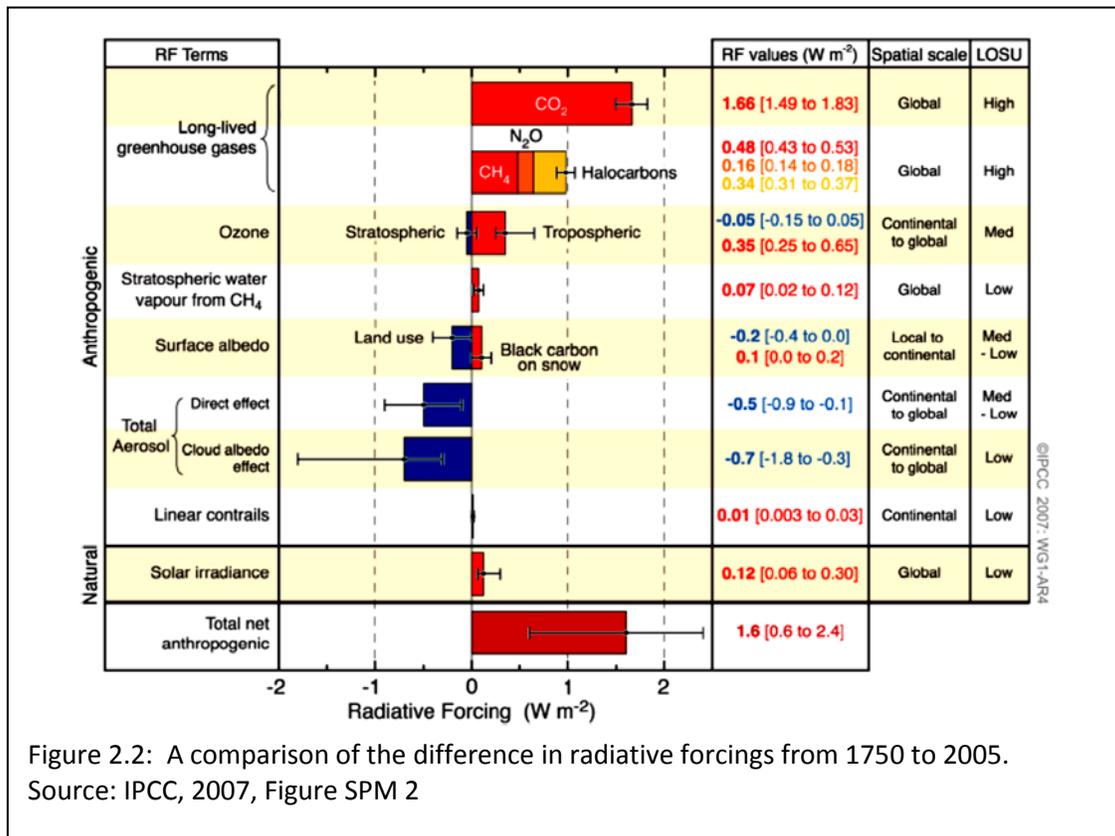
The first three forcing factors are stable over time scales of individual human lives, but have varied over geologic time scales<sup>3</sup> of Earth history. General Circulation forcing factors 1, 4 and 5 have varied over multiple time scales during both Earth history and human societal history (Kiehl 2011).

<sup>3</sup> Geologic time is divided into Eons, Eras, Periods, Epochs, and Ages. Eons last half a billion years or more and Ages millions of years. We are currently in the Holocene Epoch, which began 11,700 years ago. See: [http://en.wikipedia.org/wiki/Geologic\\_time\\_scale](http://en.wikipedia.org/wiki/Geologic_time_scale) and <http://en.wikipedia.org/wiki/Holocene> (last accessed July 6, 2011)

The Sun is the source of energy that heats the Earth by absorption of incoming and reflected radiation (IPCC WG I 2007). Total solar irradiance (TSI) from the Sun is the Earth's dominant energy input, providing 10,000 ( $10^4$ ) times more energy than any other source (Kopp and Lean 2011). There are only three ways to cause a lasting increase in the Earth's surface temperature (Pearson 2010):

- 1) increasing heat from the Sun (forcing factors 1 and 2 above)
- 2) reflecting less sunlight back into space (forcing factor 4 above)
- 3) trapping more heat in the atmosphere (forcing factor 5 above)

Radiative forcing, reported in  $\text{Wm}^{-2}$ , is a measure that allows comparison of variability in these three factors and comparison of their contribution to observed surface global temperature change (IPCC WG I 2001).



Measured variability of incoming solar radiation over the 11-year maximum to minimum sunspot cycle is about  $1 \text{ Wm}^{-2}$ , with a measured 30 year drift of  $0.017 \text{ Wm}^{-2} \text{ decade}^{-1}$  that is associated with changes in energy from the sun (Gray et al. 2010). Solar forcing appears to have dominated long-term regional climate changes during the pre-industrial era (Shindell et al. 2003). Solar activity during the current sunspot minimum has fallen to levels unknown since the start of the 20th century, with solar activity expected to continue to decline in the years ahead, contributing to some regional winter cold periods within an overall warming climate (Lockwood et al. 2011).

Albedo-related radiative forcing changes due to anthropogenic vegetation changes (mainly conversion of forest to agriculture land use) from pre-agriculture times to present are now estimated as  $-0.09 \text{ Wm}^{-2}$  (Myhre, Kvalevåg, and Schaaf 2005). In comparison, radiative forcing from trapping of heat by GHG is currently increasing at the rate of  $0.30 \text{ Wm}^{-2} \text{ decade}^{-1}$  (Hofmann, Butler, and Tans 2009), and has increased by about  $2.7 \text{ Wm}^{-2}$  since 1750 as measured by the Annual Greenhouse Gas Index (AGGI) (Hofmann et al. 2006). Variability in solar radiative forcing is therefore smaller than estimated radiative forcing due to changes in albedo (forcing factor 4 above) and much smaller than estimated radiative forcing from heat trapping GHG and aerosols (forcing factor 5 above). Albedo-related radiative forcing changes are inherently more regional in scale than those associated with solar variability and GHG (Pielke Sr. et al. 2002).

Past climate change occurring over millions ( $\sim 10^5$  to  $10^7$ ) of years has resulted from plate tectonics (forcing factor 3 above). Modern (Holocene epoch) biomes, and the climatic factors governing them, depend heavily on the distribution of oceans and landmasses, and the topography of those landmasses, all resulting from plate tectonics (Prentice and Webb III 1998; Prentice et al. 1992). Modern land distributions and mountain building began to be shaped with the breakup of the super continent Pangaea starting  $\sim 225$  to 200 Mya during the transition from the Permian to the Triassic, and proceeded through the Jurassic (150 Mya) reaching a recognizably modern distribution in the Cretaceous (65 Mya), when a period of warmer temperatures began (Keating-Bitonti et al. 2011)<sup>4</sup>. Climatically driven, latitudinal dependent biogeographic provinces sorted terrestrial biota on Pangaea where topographic barriers were largely absent. Pangaeian biogeographic provinces changed as biota migrated in response to  $\sim 20,000$ -year climate variations caused by cyclical variations in the Earth's orbit (Whiteside et al. 2011).

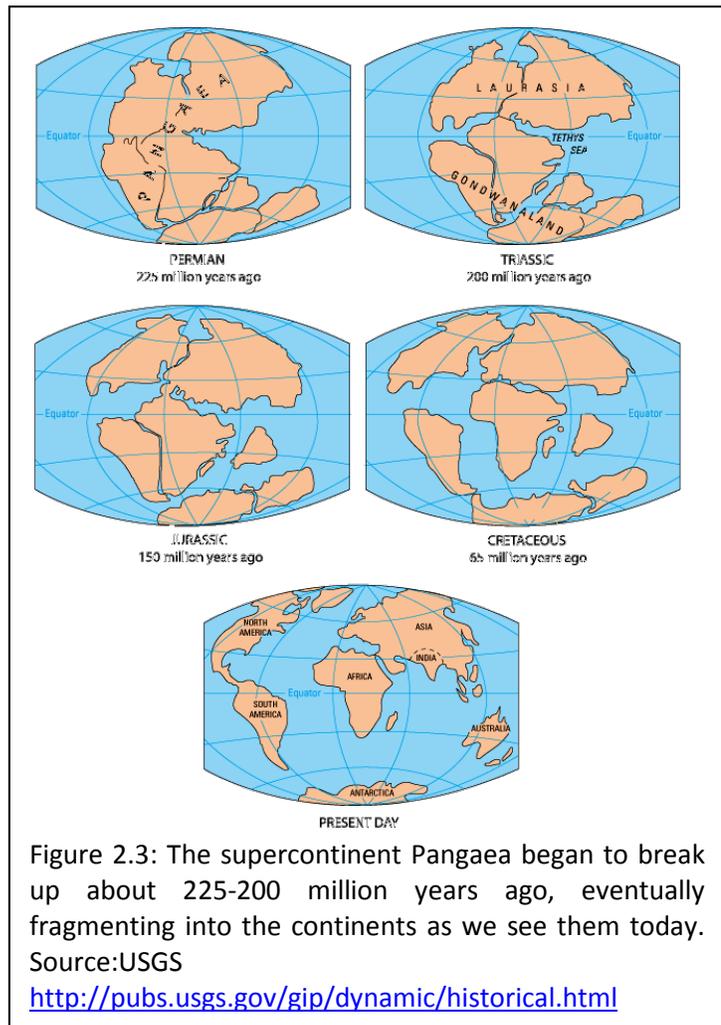


Figure 2.3: The supercontinent Pangaea began to break up about 225-200 million years ago, eventually fragmenting into the continents as we see them today.

Source:USGS

<http://pubs.usgs.gov/gip/dynamic/historical.html>

<sup>4</sup> For additional description of these changes, see <http://pubs.usgs.gov/gip/dynamic/historical.html>.

## Earth Orbit Variability

The Earth rotates around an axis that tilts relative to the plane of its elliptical orbit around the Sun. These orbital factors give us our days, seasons, and annual climate cycles, and vary over long periods. Climate change occurring over tens to hundreds of thousands ( $10^4$  to  $10^5$ ) years has resulted from quasi-periodic oscillations in the Earth's movement around the Sun (orbital parameters - forcing factor 2 above) (Zachos et al. 2001). The orbital *components* and their perturbation periods are<sup>5</sup>:

- *eccentricity* (400,000 and 100,000 years) - The shape of the Earth's orbit changes from a nearly perfect circle to an oval shape on a 100,000-year cycle
- *obliquity* (41,000 years) - Earth's axis is tilted, and the angle of the tilt varies between 22 and 24 degrees every 41,000 years
- *axial precession* (23,000 years) - gravity-induced slow change in the Earth's rotational axis relative to the Sun over the span of 19,000 to 23,000 years, observed as a movement of the equinoxes relative to fixed stars

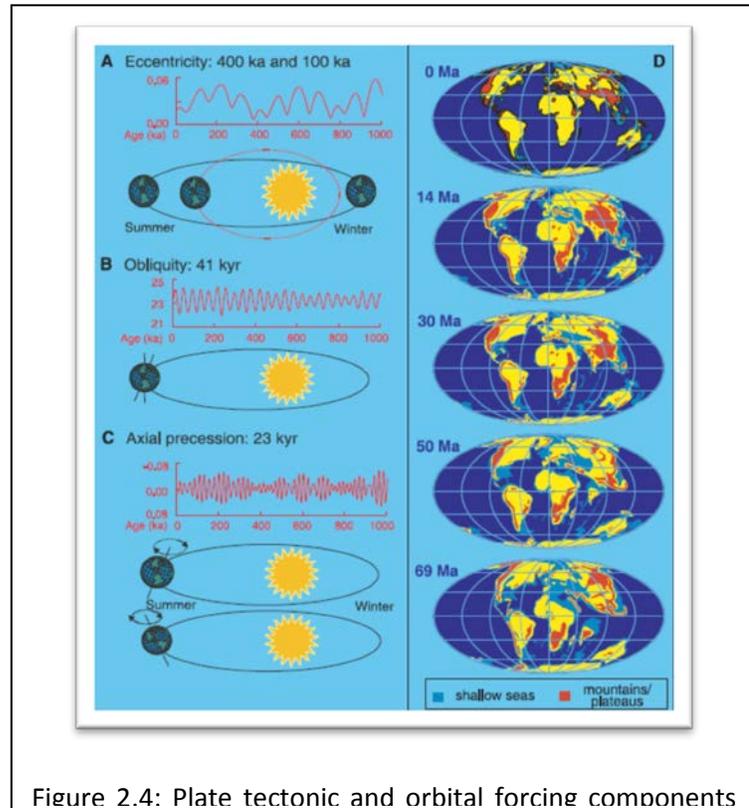


Figure 2.4: Plate tectonic and orbital forcing components

General Circulation Models (GCMs)

accurately account for orbital variations (factor 2) and plate tectonics (factor 3), which are important factors needed to study the paleoclimatic record of Earth. The time scale of their variability means, however, that they are not important factors driving short-term 21<sup>st</sup> Century climate change. The important factors determining 21<sup>st</sup> Century climate change relate to natural events and anthropogenic causes acting via GHG, aerosol and albedo forcing factors, with a minor contribution related to variation of solar radiation. The amount of surface warming or cooling produced during a solar minimum to maximum cycle is 0.1°C, compared to warming produced by an ENSO (El Nino Southern Oscillation) event of 0.2°C and cooling following large volcanic events of ~0.3°C (Lean and Rind 2009). All of these natural events affect climate, often in a cyclical manner (warming then cooling), for a limited period. ENSO and other observed periodic patterns of ocean and atmosphere circulation, such as the North Atlantic Oscillation (NAO), are known to have significant influence on weather and short-term climate variability (Hurrell and van Loon 1997). ENSO type events have been associated with changes in fire patterns and are considered to be a potentially important feedback mechanism of climate change (Swetnam and Betancourt 1998; Beckage et al. 2003; Kitzeberger et al. 2007; van der Werf et al.

<sup>5</sup> See [http://earthobservatory.nasa.gov/Features/Paleoclimatology\\_Evidence/](http://earthobservatory.nasa.gov/Features/Paleoclimatology_Evidence/) for further detail

2008; Macias Fauria, Michaletz, and Johnson 2011; Jinbao Li et al. 2011; Wenhong Li et al. 2011). ENSO and similar events are features of the General Circulation that affect weather patterns from periods of weeks to several years, and lie in the computational zone between Numerical Weather Prediction (NWP) technologies that support daily weather forecasts and GCM technologies that provide long-term climate simulations. As discussed elsewhere in this synthesis, improvements in computational and observational capacity are expected to yield significant improvements in our ability to predict short-term climate variability caused by ENSO type patterns and close the coverage gap between NWP and GCM in the decade ahead (Keenlyside and Ba 2010; Meehl et al. 2009; Scroxtion et al. 2011).

While it is important to understand the broad context under which long-term climate change occurs, our primary focus is on those General Circulation forcing factors that directly relate to the current rapid warming. Primary among these are anthropogenic emissions of GHG which are causing atmospheric warming at the rate of  $\sim 0.2^{\circ}\text{C}$  per decade and this rate is accelerating (Easterling and Wehner 2009). Previous uncertainty about the relative importance of various contributors to the forcing factors has been reduced as a result of:

- improved accuracy of Total Solar Irradiance (TSI) monitoring from satellite systems (Kopp and Lean 2011),
- improved quantification of Anthropogenic Land Cover Change (ALCC)<sup>6</sup> emissions (Reick et al. 2010), and
- improved understanding of how atmospheric chemistry favors removal of non- $\text{CO}_2$  GHG but long term retention of  $\text{CO}_2$  (Montzka et al. 2011).

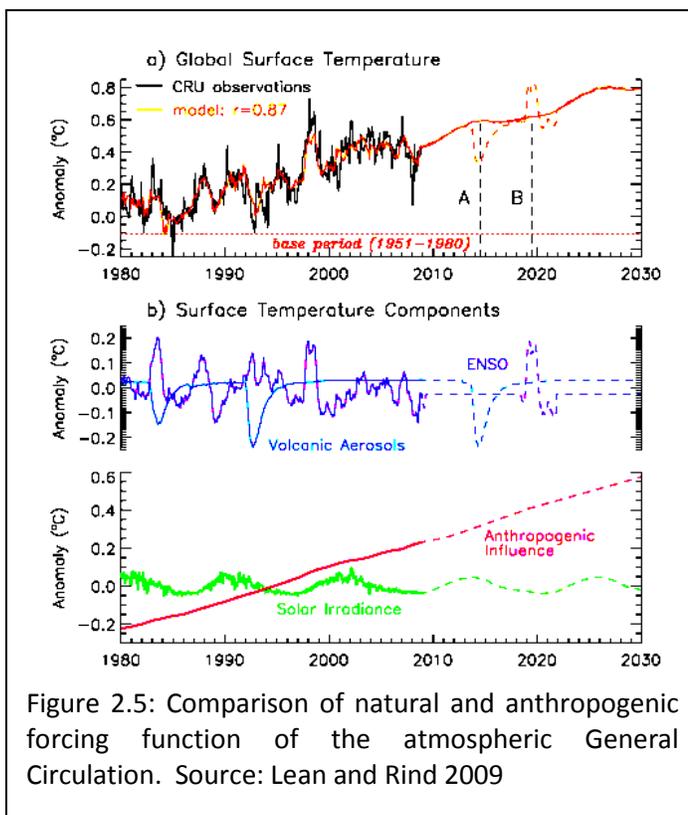


Figure 2.5: Comparison of natural and anthropogenic forcing function of the atmospheric General Circulation. Source: Lean and Rind 2009

## Carbon Dioxide

The role of  $\text{CO}_2$  as the dominant GHG and continuing primary cause forcing surface temperature increases is now clearly established (Lacis et al. 2010). The more variable impact of aerosols is gradually becoming better understood (Kaufmann et al. 2011; Solomon et al. 2011). The two main causes of anthropogenic GHG gas emissions over human history are anthropogenic land cover change (ALCC) and fossil fuel consumption (Kaplan et al. 2010). ALCC was the major

<sup>6</sup> Readers may be more familiar with the terminology Land Cover and Land Use Change (LCLUC), but we use ALCC here as due to its more common usage in cited studies describing long-term history of human induced changes in vegetative cover.

contributor of GHG emissions for most of human history through the early days of the industrial revolution. Current estimates are that tropical land-use change emissions, consisting of a gross tropical deforestation emission partially compensated by a sink in tropical forest regrowth, are more than offset elsewhere to yield an overall total forest sink of  $2.4 \pm 0.4 \text{ Pg C yr}^{-1}$  globally for 1990–2007 (Pan et al. 2011). The influence of fossil fuel emissions became increasingly dominant from the beginning of large-scale industrialization (~ AD 1850) onward (Vitousek et al. 1997). The Earth will warm by  $2^\circ\text{C}$  above pre-industrial temperature levels when a cumulative total of  $3,670 \text{ Pg C}^7$  of anthropogenic  $\text{CO}_2$  is emitted to the atmosphere, with about half of that amount already having been emitted since ~1750 when industrialization began (Allen et al. 2009). The growth rate of atmospheric  $\text{CO}_2$  has increased from  $\sim 1 \text{ ppmv yr}^{-1}$  prior to 1970 to more than  $\sim 2 \text{ ppmv yr}^{-1}$  at present. Atmospheric  $\text{CO}_2$  concentration is now increasing exponentially; it has been doubling every 30 years since about 1930 and on track to reach 560 ppmv (double pre-industrial levels) by 2050 (Hofmann, Butler, and Tans 2009). The exponential growth of  $\text{CO}_2$  emissions driven by fossil fuel consumption, and the persistence of  $\text{CO}_2$  in the atmosphere, cause it to be the main forcing factor for the 21<sup>st</sup> Century climate change (Solomon et al. 2010).  $\text{CO}_2$ , and other GHG, do not condense and precipitate from the atmosphere, while water vapor does.  $\text{CO}_2$ , and other noncondensing GHG, account for 25% of the total terrestrial greenhouse effect, and serve to provide the stable temperature structure that sustains current levels of atmospheric water vapor and clouds via feedback processes that account for the remaining 75% of the greenhouse effect. While  $\text{CO}_2$  is not subject to removal from the atmosphere by chemical reactions, the other noncondensing GHG are. Methane ( $\text{CH}_4$ ), the second most important anthropogenic influenced GHG, is subject to greater (and not fully explained) observed variability than  $\text{CO}_2$  (Heimann 2011; Kai et al. 2011; Aydin et al. 2011). Without the radiative forcing supplied by  $\text{CO}_2$  and the other noncondensing greenhouse gases, the terrestrial greenhouse would collapse (Lacis et al. 2010).  $\text{CO}_2$  growth and persistence means we are committed to irreversible warming in the 21<sup>st</sup> Century, and for centuries beyond, with  $\text{CO}_2$  likely to exceed 1,000 ppmv by 2100 (Gillett et al. 2011; Solomon et al. 2009).

## Climate Change Prediction

Quantitative climate change prediction is based on our knowledge of atmospheric chemistry and atmospheric dynamics (motion). The roots of both of those aspects of modern atmospheric science date to the same era when the Big Burn of 1910 (Egan 2009) was shaping future fire management in the United States. Swedish scientist Svante Arrhenius combined his interests in atmospheric chemistry and cosmology to explain how water vapor and certain trace gases in the atmosphere acted like the glass panels in a greenhouse to warm our atmosphere and make Earth habitable, concluding that a doubling of  $\text{CO}_2$  would cause a  $4^\circ\text{C}$  increase in global surface temperature (Arrhenius 1908). Current estimates are that a doubling of  $\text{CO}_2$  will result in a  $2^\circ\text{C}$  to  $4.5^\circ\text{C}$  warming (IPCC 2007) which is likely to occur by the mid 21<sup>st</sup> Century (Betts et al. 2011). Observations of modern and past climates help us understand climate dynamics and provide a baseline for predicting future responses to GHG emissions (Zachos, Dickens, and Zeebe 2008). The current state of the science of climate dynamics, represented in GCM climate simulations (also called global climate models by some), built upon a practical need to better navigate by winds and currents at a time when wind power drove ocean commerce. Hadley, in 1735, “... explained the trade winds and prevailing westerlies by noting that heating should

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<sup>7</sup> 1 Petagram (Pg) =  $10^{12}$  (1 trillion) kg =  $10^9$  (1 billion) metric tons = 2,204.62 billion pounds

*produce a direct meridional cell in each hemisphere. The equatorward current at low levels should be deflected by the Earth's rotation to become the trade winds.*" (Lorenz 1967). In the 275 years since Hadley described this theory, we have seen the industrial revolution replace wind and water power with fossil fuel power, human population expand exponentially and human enterprise continue to alter the albedo of the Earth's surface. As human society and ecosystems have co-evolved in the 10,000 years since the peak of the last glacial period, plate tectonic and orbital factors determining the General Circulation have remained relatively stable. Measured perturbations in received solar radiation have been minor. Effects of human activity, manifested as changes in atmosphere/ocean chemistry and in land cover, are the basis for attributing observed and expected future climate change to anthropogenic causes (Hegerl and Zwiers 2011; IPCC WG I 2007). Those changes are altering the thermodynamic drivers of the General Circulation. Science is increasingly able to quantify the causes and amount of thermodynamic alteration, and numerically describe (model) resulting and future changes of the circulation patterns of the atmosphere and oceans, which determine patterns of weather and climate. These are the two bases for quantitative climate change prediction. Thermodynamic forcing caused by past, present and future GHG emissions serves as input to the GCMs to describe future climate conditions.

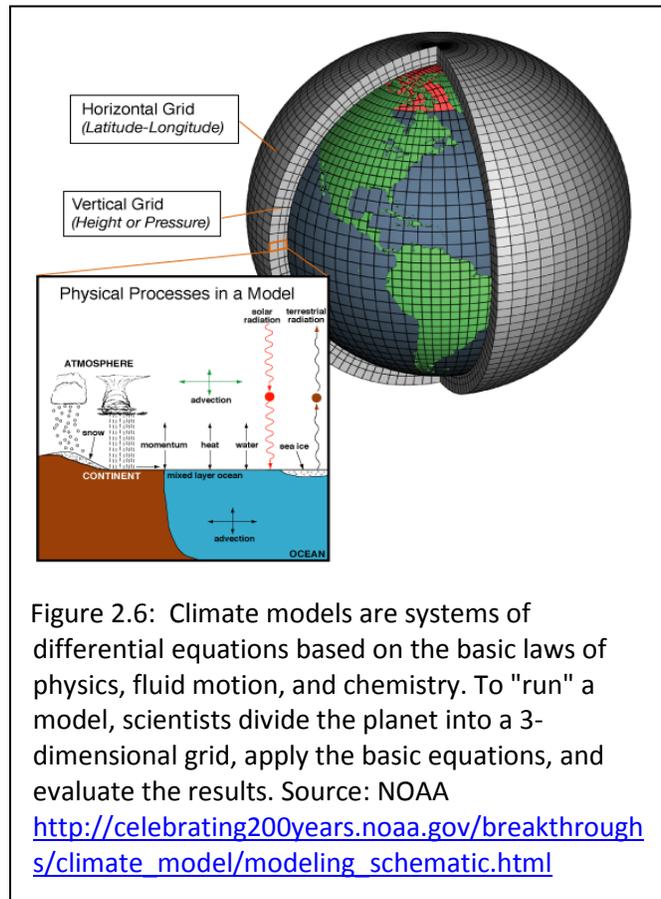
## **NWP and GCM Development**

Our understanding of atmospheric dynamics has grown from the early 20<sup>th</sup> Century work of Norwegian scientist Vilhelm Bjerknes and his colleagues at the Bergen (Norway) School, who developed the frontal model of extratropical cyclones that remains the centerpiece for today's public forecasts that ascribe daily weather conditions to the movement of pressure systems and fronts. Shortly after Arrhenius provided his greenhouse explanation, Bjerknes began applying mathematical equations governing the motions of the atmosphere that, if solved in real time, would advance weather forecasting (Gedzelman 1994; Lorenz 2006). Soon after, Lewis Richardson proposed how those three dimensional equations could be solved through time using numerical methods (Richardson 1922). Richardson's methods for Numerical Weather Prediction (NWP) had no practical application until modern digital computers became available after World War II. Weather forecasts were one of the first uses of the new digital computers starting in 1950 (Lorenz 2006). Those NWP methodologies are the basis of both current daily weather predictions and the General Circulation Models (GCMs) used for climate change forecasting (Phillips 1956). By the mid-1960s several groups were conducting general circulation model research, which developed the ancestors of GCMs used today (see Edwards (Edwards 2011) for a definitive history). NWP (weather forecasts) and GCMs (climate models) diverged during this period of development because of lack of sufficient computer capacity. As each advance in computing capacity became available, meteorologists focused on improving operational weather forecasts (out to 96 hours/4 days) and used additional computing capacity to increase spatial and temporal resolution of the computations to reduce forecast errors. The long-term nature of climate forecasting (30 years to centuries) required GCM scientists to parameterize many variables to gain the computational stability necessary for computer runs over long time periods required for climate modeling. GCMs remained more of research than operational or policy interest until observational evidence of increasing atmospheric CO<sub>2</sub> indicated to the research community that the potential for anthropogenic climate change was a serious possibility (Keeling et al. 1995).

## The IPCC

The concern raised by scientists over the potential for substantial climate change from recorded increases in CO<sub>2</sub> led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 by two United Nations Organizations, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) (Revelle 1982). The purpose of the IPCC was to assess “*the scientific, technical and socioeconomic information relevant for the understanding of the risk of human-induced climate change.*” (<http://www.ipccfacts.org/history.html>). In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted as the basis for a global response to the climate change problem with the goal of preventing “dangerous” human interference with the climate system (<http://unfccc.int>).

The IPCC has been an essential sponsor of GCM development and improvement, in addition to issuing four comprehensive and authoritative assessment reports (AR)<sup>8</sup> and various additional reports in support of the UNFCCC process. While several individual laboratories in different countries continue development of their own GCMs, the IPCC through its continuing assessment process and supporting functions uses these various GCMs to support integrated GCM-based products. As models are improved, the outputs from many of the available individual GCMs used by IPCC have increasingly converged through the four assessment reports issued to date (IPCC WG I 2007), eliminating earlier concerns that the GCMs “did not agree”. IPCC model comparison efforts are strongly supported by the Coupled Model Intercomparison Project (CMIP) organized by the World Climate Research Program (WCRP). This project integrates data from 23 models, run by 16 modeling groups, from 11 countries (Meehl et al. 2007).



<sup>8</sup> IPCC released the First Assessment Report (FAR) in 1990, the Second Assessment Report (SAR) in 1995, the Third Assessment Report (TAR) in 2001, and most recently, Assessment Report 4 (AR4) in 2007. AR5 is currently in development and due for publication in 2014 (<http://www.ipcc.ch/activities/activities.htm>)

## GCMs

So how do GCMs actually work? They basically apply a system of equations (the Navier-Stokes equations<sup>9</sup>) that describe the motion of fluids in time and space. These analytical equations, along with equations and parameterizations that represent myriad physical processes, are translated into numerical models, which are then solved for a series of time steps at points (grid points) on a three-dimensional lattice that represents the Earth's atmosphere (Fig. 2.6). A typical modern GCM grid lattice using ~20 vertical levels and a horizontal grid point spacing of ~100 km models the atmosphere at 2.5 million grid points. At a typical time step of ~10 to 20 minutes, a one-year simulation requires processing data 27,000 times at each of the 2.5 million grid points. For climate simulations extending a century forward, extremely large and fast computer systems are necessary.

Supercomputer speeds have increased by a factor of over a million since the 1970s, enabling remarkable progression of GCM technology (Figs. 2.6 and 2.7). This progress has permitted a corresponding increase in model complexity (by including more and more components and processes), in the length of the simulations, and in spatial resolution (IPCC WG I 2007). As GCMs have added more Earth system components they are now, on occasion, called atmosphere-ocean general circulation models (AOGCMs) and, with inclusion of carbon cycle and other dynamics, Earth system models (ESMs) (Hibbard et al. 2007). We will retain the simple GCM terminology in this synthesis, unless we need to emphasize a specific point regarding model development. Each succeeding IPCC AR has relied on both higher resolution and more complete GCMs.

Several important processes that control climate sensitivity or abrupt climate change (e.g., clouds, vegetation, and oceanic convection) depend on very small spatial scales that, even with decades of computational advancement, are still treated by using simplified parameters to represent complex biophysical processes or with less than desirable resolution even within the most powerful GCMs. Likewise, GCM outputs do not approach the time and space scales of weather forecasts that fire and other land managers are accustomed to working with. Improvements are expected in the decades ahead (see Chapter 7 of this synthesis), particularly in

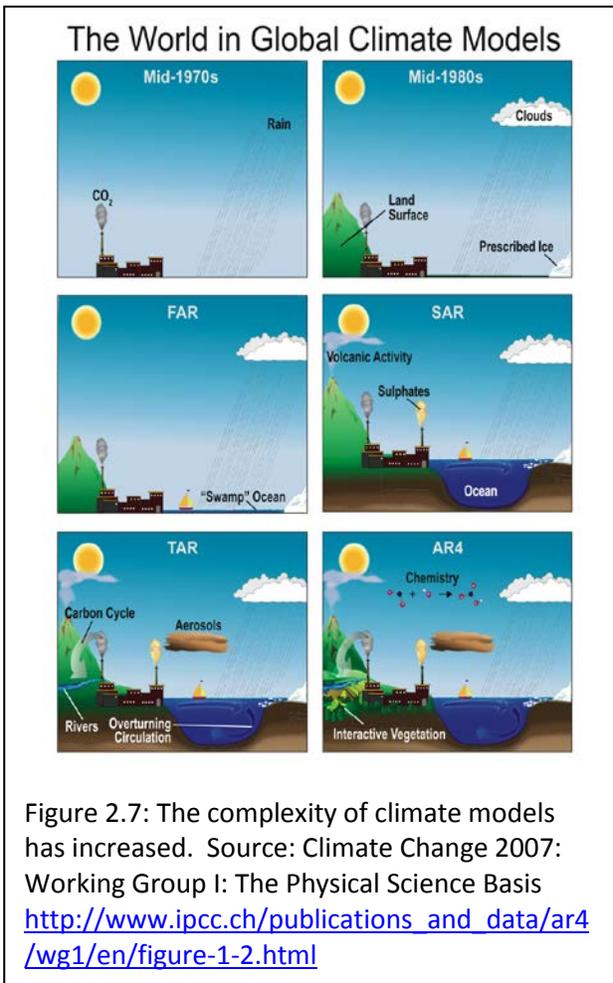


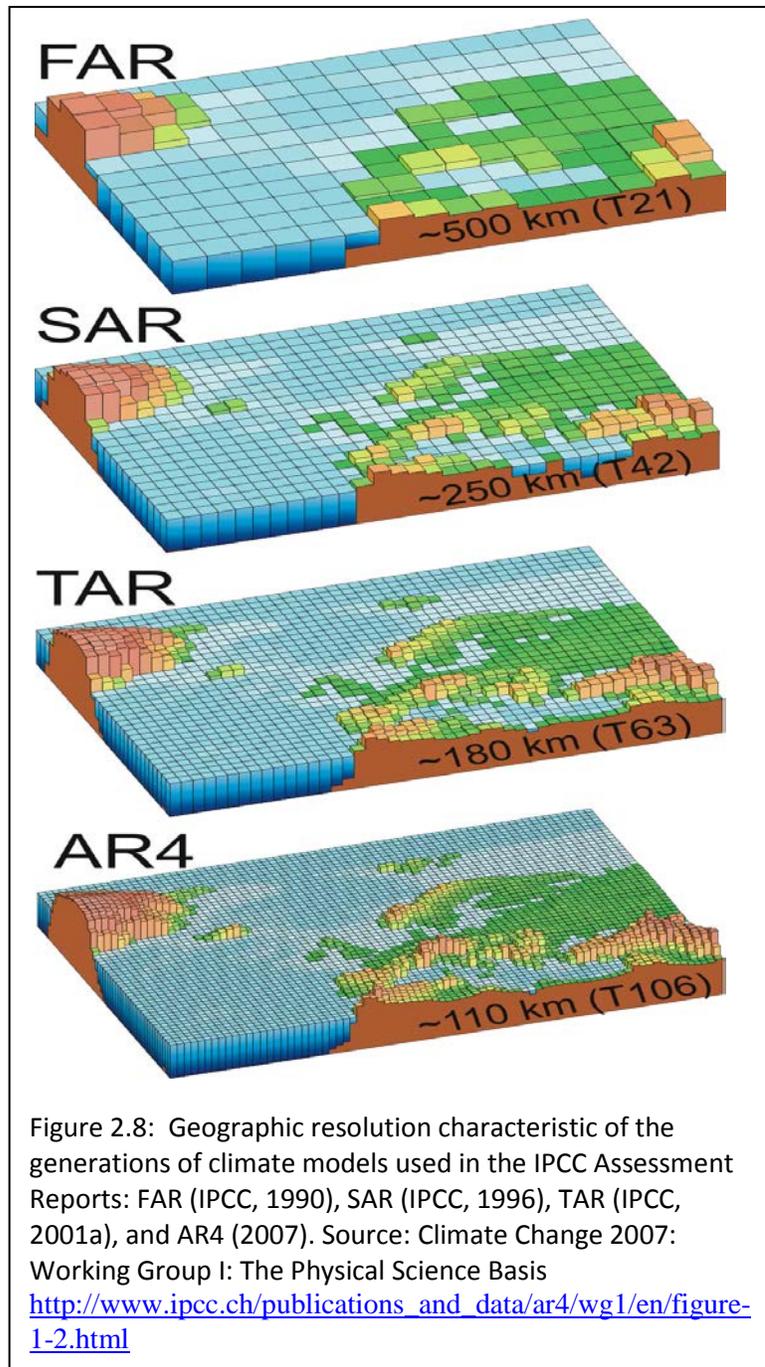
Figure 2.7: The complexity of climate models has increased. Source: Climate Change 2007: Working Group I: The Physical Science Basis [http://www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/figure-1-2.html](http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-1-2.html)

<sup>9</sup> The Navier–Stokes equations, named after Claude-Louis Navier and George Gabriel Stokes, describe the motion of fluid substances

[http://en.wikipedia.org/wiki/Navier%E2%80%93Stokes\\_equations](http://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations)

shorter range (months to decadal time scales) climate simulations that will help those managers, and including more physical and biological processes in the actual computations (see Chapter 7 of this synthesis).

Longer term (beyond several decades) climate projections will not be as likely to improve because the greatest uncertainty in the use of GCMs for climate prediction does not derive from shortfalls of the models themselves, but from uncertainty in needed input to the models of future GHG emissions that are dependent on socio-economic and policy factors (Knutti et al. 2008). Climate science frequently refers to “business as usual” as the default emissions scenario, meaning no effective international treaty will come into affect that would mitigate GHG emissions expected from fossil fuel energy consumption associated with normal population growth and economic development. Although the IPCC is developing alternative approaches in support of CMIP modeling, it has relied on emissions scenarios to drive GCMs in all four assessments issued to date (Moss et al. 2010).



## Emissions Scenarios

The IPCC has used data from a study of emissions scenarios for future GHG emissions commonly referred to as SRES (Special Report on Emission Scenarios), to generate radiative forcing data for GCM input (Nakićenović and Swart 2000). The SRES scenarios incorporate a wide range of the main demographic, economic, and technological driving forces of GHG to produce 40 scenarios grouped under four storylines or “families”. Four “families” or groups of scenarios (A1, A2, B1, and B2) represented low, high, low and medium population growth

respectively. Other characteristics used to define different scenarios were GDP growth, energy use, land-use change, resource availability, technological change and change of energy source. In practice, only a few of the 40 scenarios have been used because it was not practical to multiply the already huge computational load of GCM runs by 40. The SRES also did not include a “business as usual” or a “best guess” scenario. Business as usual is a terminology meant to indicate that economic, population and energy use growth take place driven solely by business dynamics and in the absence of carbon reducing technologies and/or policies. In the decade since SRES release, business as usual has been the norm and GHG emissions have systematically exceeded most of the SRES scenarios. SRES did identify 6 ‘marker scenarios’ (A1FI, A1B, A1T, A2, B1 and B2), but practical computational costs and capacity resulted in IPCC AR4 consideration of only 3 of these scenarios (A1B (A

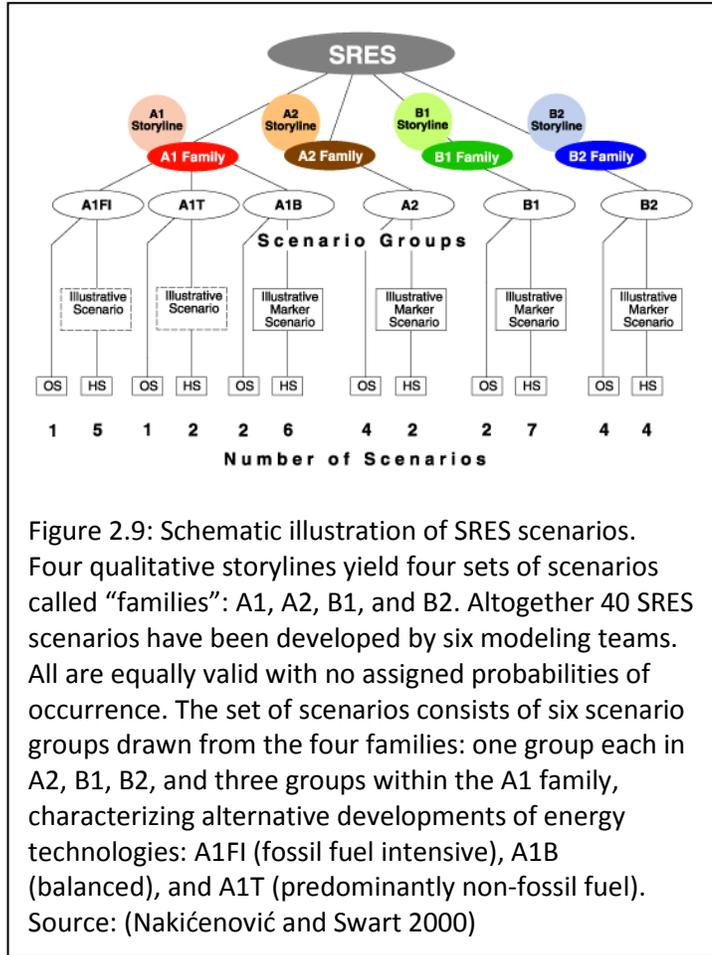


Figure 2.9: Schematic illustration of SRES scenarios. Four qualitative storylines yield four sets of scenarios called “families”: A1, A2, B1, and B2. Altogether 40 SRES scenarios have been developed by six modeling teams. All are equally valid with no assigned probabilities of occurrence. The set of scenarios consists of six scenario groups drawn from the four families: one group each in A2, B1, B2, and three groups within the A1 family, characterizing alternative developments of energy technologies: A1FI (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel). Source: (Nakićenović and Swart 2000)

*balanced emphasis on all energy sources*), A2 (*A world of independently operating, self-reliant nations, with continuously increasing population*) and B1 (*An emphasis on global solutions to economic, social and environmental stability*)) by all of the participating complex GCM modeling groups. The highest emissions scenario A1F1 (*fossil fuel intense*) was run only under simplified GCMs. The ‘likely range’ of warming for the B1, A1B and A2 scenarios is 1.6–5.9°C relative to pre-industrial, and with the A1FI projection considered, the likely range extends to 6.9°C relative to pre-industrial (Betts et al. 2011). The IPCC is preparing a new approach to providing emission inputs to the GCM runs in preparation for AR5 that should more accurately represent actual radiative forcing measures (Pitcher 2009). This new emissions estimation approach identifies radiative forcing characteristics to support CMIP GCM runs and brings a new term, Representative Concentration Pathways (RCPs), selected from the scientific literature (Moss et al. 2010). In 2010, global CO<sub>2</sub> emissions were 96% of those estimated by the A1F1 scenario, and concern remains that even the A1F1 scenario (the most carbon intense used by the IPCC) underestimates high-end 21<sup>st</sup> Century GHG concentrations. Recent GCM runs using carbon futures that enhance the A1F1 scenario by increasing population growth and fossil fuel consumption yielded 2100 global mean temperatures 0.5°C to 1.2°C greater than projected for the IPCC A1F1 scenario (Sanderson et al. 2011).

There are three approaches for predicting the future. One involves process models that use numerical solutions of physical equations and supporting input information to provide quantitative predictions of future conditions that may be entirely different from those existing at present or in the past. As discussed above, GCMs represent this approach. The second approach is to project current conditions unchanged into the future, or to, perhaps, extend current trends into the future allowing for some change from the present. The third approach uses knowledge and understanding of current and past conditions and processes to project what systems would look like in the future, when certain variables are expected to change. This empirical approach, heavily used in natural resource science and management, can be especially useful if there is sufficient information on a range of past conditions. A good example is using fire history information to inform how future fire regimes are likely to evolve as climate changes in the 21<sup>st</sup> Century. While not so much in the public eye as GCM technology, information relating paleoclimate and paleo-vegetation to fire regimes has grown tremendously over the past several years and now offers the opportunity to inform projections of future fire regimes.

## Paleoclimate

We have to look back 35 million years to see the last time atmospheric CO<sub>2</sub> concentrations reached 1,000 ppmv (Kiehl 2011; Keating-Bitonti et al. 2011). Paleoclimate observations (tree rings, ice cores, sediment cores, pollen, and charcoal, for example) have now provided a good record of the climate history of Earth, especially during the Cenozoic Era, which began 65 Mya (Long et al. 1998). The modern distribution of our continents and oceans, the diversification of mammals and plants (including the evolution of grasses) and the geologically recent appearance of humans characterize the Cenozoic Era. Continuing climate change has also characterized the Cenozoic. Paleoclimate studies covering the Quaternary Period (1.8 Mya to today) and the Holocene Epoch (11,000 years ago to today – the time since the last glacial maximum) of the Cenozoic Era have greatly increased our understanding of how past changes in our atmosphere, oceans and land cover have related to changes in climate (Geological Society of London 2010).

During the Cenozoic Era, the Earth’s climate has experienced the warm extreme of ice-free poles and the cold extreme of continental ice sheets and polar ice caps. Our current ecosystems and human civilization have co-evolved during the Holocene Epoch. This period has seen increasing human impacts on climate change through ALCC and fossil fuel GHG emissions. From 8000 years ago to the start of the industrial revolution (circa AD 1750), atmospheric CO<sub>2</sub> increased by ~22 ppmv (Ruddiman

<u>Era</u>	<u>Period</u>	<u>Epoch</u>	<u>Began (Ma)</u>
<b>Cenozoic</b>	<b>Quaternary</b>	<b>Holocene</b>	<b>.01</b>
		Pleistocene	1.8
		Pliocene	5.3
		Miocene	23
		Oligocene	34
		Eocene	54
	Tertiary	Paleocene	65
Mesozoic	Cretaceous		145
	Jurassic		200
	Triassic		251
Paleozoic	Permian		299
	Carboniferous		359
	Devonian		416
	Silurian		443
	Ordovician		488
	Cambrian		542

Figure 2.10: Geological timescale  
Source: adapted from Pausas and Keeley, 2009

2007). Inefficient agriculture and growing human populations led to extensive clearing of forestland by fire, with associated increases in atmospheric GHG concentration (Springer et al. 2010; Bowman and Haberle 2010; McWethy et al. 2010).

Increases in agricultural efficiency and a large decrease in per capita land use followed (Kaplan et al. 2010). Exponential population growth began ~ AD 1500, continuing until present. Events that decreased population locally or regionally, such as the European conquest of the Americas with accompanying fire reduction and reforestation (Nevle and Bird 2008), are reflected in ice core CO<sub>2</sub> records (Faust et al. 2006), but those and other local emission reductions were offset by increased emissions in other parts of the world (Pongratz et al. 2011). Paleoclimate records are also helping to explain historical susceptibility of human societies to climate variability as regional and seasonal manifestations of climate change (Büntgen et al. 2011; Hegerl et al. 2011). By AD 1850, ALCC during the Holocene had produced an increase in atmospheric CO<sub>2</sub> of ~ 25 ppmv (Kaplan et al. 2010). Western hemisphere ALCC is likely the main driver of a steep increase in atmospheric CO<sub>2</sub> between AD 1750 and 1850 (Reick et al. 2010). Fossil fuel emissions gained significance after 1850 and are now responsible for a rapidly growing 84% of global GHG emissions, with ALCC responsible for the remaining 16% (Raupach et al. 2007). Current projections are for CO<sub>2</sub> to increase from the current level of 390 ppmv to reach atmospheric concentrations of ~ 900 to 1100 ppmv by the end of the 21<sup>st</sup> Century (IPCC WG I 2007). The last time Earth experienced ~1000 ppmv CO<sub>2</sub> levels was 35 Mya when paleogeography did not differ much from current alignments and solar radiation was ~0.4% less than today. At that time of the Cenozoic mean annual temperatures were 5° to 10°C warmer in the tropics and 15° to 20°C warmer at the poles than they are today (Kiehl 2011). While anthropogenic GHG increases, and associated surface warming, have occurred throughout the Holocene, the current rate of increase is unprecedented.

Measurements of CO<sub>2</sub> concentrations in air trapped in ice cores show a strong correlation between changes in atmospheric CO<sub>2</sub> (and methane) concentrations and changes in surface temperature for the past 420,000 years (Petit et al. 1999). A comparison of CO<sub>2</sub> from ice cores and surface temperatures with estimated and measured carbon emissions shows more short-term variability in the temperature record compared to the smoother CO<sub>2</sub> and carbon curves. The ice core data show that CO<sub>2</sub> concentrations at some times in the past were higher than pre-industrial

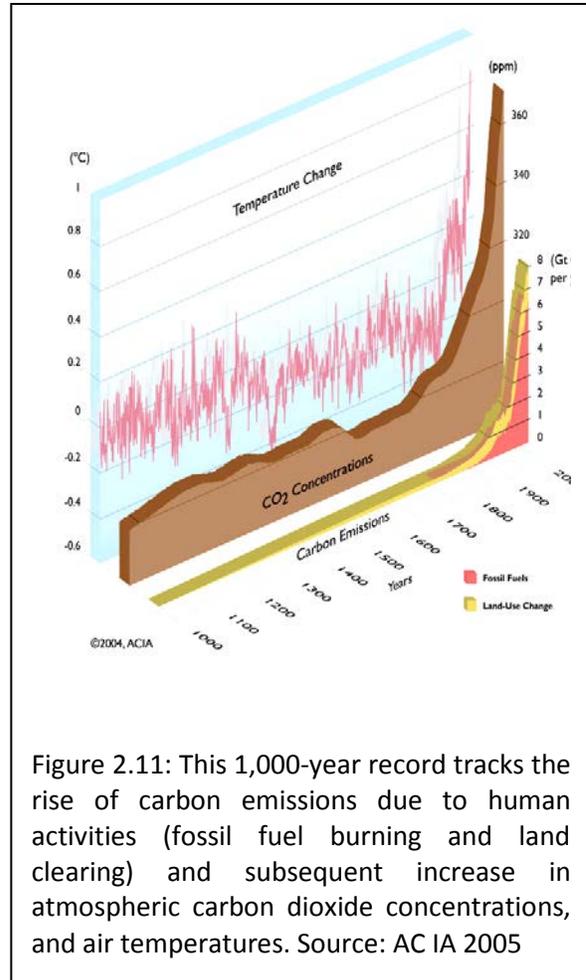


Figure 2.11: This 1,000-year record tracks the rise of carbon emissions due to human activities (fossil fuel burning and land clearing) and subsequent increase in atmospheric carbon dioxide concentrations, and air temperatures. Source: AC IA 2005

levels. Nonetheless, the long-term changes in CO<sub>2</sub>, carbon emissions and temperature correlate well and the rates of increase in all these variables since the mid-1800s are unprecedented.

Deeper drilling of ice cores is providing longer periods of record and improved analysis techniques are providing higher resolution and measures of more atmospheric variables trapped in the air bubble and ice cores. Ice core data are producing increasingly more detailed evidence of past abrupt climate change events, adding significantly to our knowledge of climate variability and change during the Holocene (Steffensen et al. 2008). Ice core contents of various atmospheric trace gases and other variables, such as soot and pollen, are used to explore past fire events and fire regime changes such as those that occurred during the Younger Dryas climate event of ~8,000 years ago (Alley et al. 1997). We apply this understanding of the importance of past interactions between CO<sub>2</sub> and climate to the rapidly expanding record of paleoclimate measurements that quantify the Earth's past climate, including information of varying fire regimes in relation to past climate (Bijl et al. 2010; Bowman et al. 2009). While ice core data are a critical source for our increasingly detailed descriptions of past climate, other paleoclimate approaches have added more significantly to our specific understanding of the relationship of past fire regimes to climate.

Of particular importance to understanding past fire in relation to climate are techniques that employ tree ring widths (dendrochronology) and fire scars (Swetnam 1993), sediment cores (Brunelle and Whitlock 2003), pollen (Delcourt et al. 1998) and charcoal (fusain) studies (Whitlock and Larsen 2001). Because these studies are typically based on samples from one or a few sites, they have tended to be site specific, but syntheses of data from different investigators and research groups are providing increasing information at regional through global scales (Enache and Cumming 2009; Swetnam and Anderson 2008; Marlon et al. 2008). Our knowledge of fire during the last ~500 years in certain regions (such as the western United States) has been greatly enhanced by findings showing regional fire histories based on fire scar tree ring data (Brown et al. 2008; Heyerdahl, Morgan, and Riser II 2008; Sherriff and Veblen 2008). Charcoal studies, extend our record of direct fire evidence back many millennia, with developing regional and global coverage (Crickmay 1935; Scott 1989; Enache and Cumming 2009; Power et al. 2008). A very useful, but still not complete, source for paleoclimatological data sets is World Data Center for Paleoclimatology (<http://www.ncdc.noaa.gov/paleo/paleo.html>) maintained by

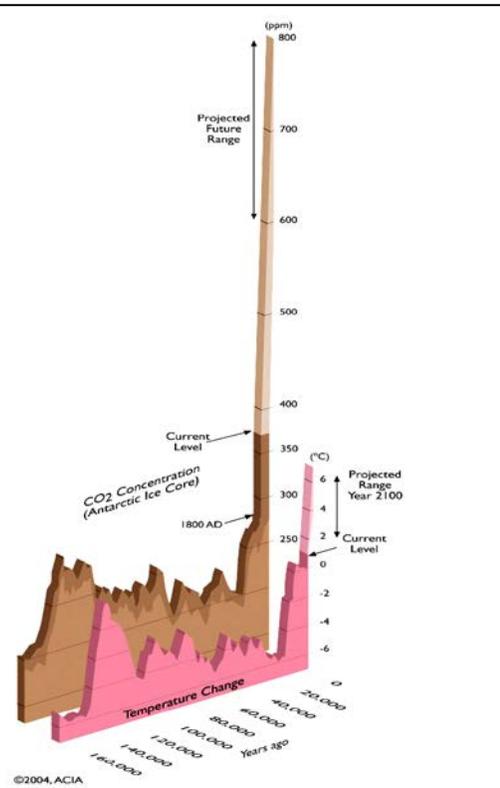


Figure 2.12: This record illustrates the relationship between temperature and atmospheric carbon dioxide concentrations over the past 160,000 years and next 100 years. Source: ACIA 2005

NOAA. Paleoclimate studies affirm the strong correlations, and feed-backs between fire and atmosphere and vegetation conditions. This is consistent with our understanding of current fire regimes and fire-atmosphere interactions (Harrison, Marlon, and Bartlein 2010). These studies show that fire has been prevalent since the atmosphere became sufficiently oxygenated (13% to 35%) to support combustion and there was fuel to burn (Scott and Glasspool 2006; Belcher et al. 2010). Fire has been a major factor in GHG emissions for the last 420 million years (My) of Earth history (Pausas and Keeley 2009). Paleoclimate studies show that fire in turn influenced atmospheric CO<sub>2</sub> prior to the rise of humans and increasingly during the Holocene with human use of fire a principal tool for ALCC (Grasby, Sanei, and Beauchamp 2011; Marlon et al. 2008). Fire associated with ALCC forest clearing is considered a main cause of GHG emissions through most of recorded human history, while others considered climate the other important driver of fire (Michael Williams 2008; Pechony and Shindell 2010). There is a rich and growing library of paleoclimate-based information that help us understand fire history and fire regimes in relation to varying atmospheric CO<sub>2</sub> concentrations, including levels were last at levels being experienced in the 21<sup>st</sup> Century.

### **Instrumental Record**

The instrumental record that informs current climate change science is well described elsewhere (IPCC WG I 2001) and is being continually augmented (NOAA NCDC @ <http://www.ncdc.noaa.gov/oa/ncdc.html>, CDIAC @ <http://cdiac.ornl.gov/>, NASA GISS @ <http://data.giss.nasa.gov/gistemp/>), so will be only briefly covered here. Instruments have measured temperatures at the surface of the Earth for over 130 years. Observed temperatures have increased 0.8° C globally since 1880 (IPCC WG I 2007), with two-thirds of the warming occurring since 1975, at a rate of ~0.15-0.20°C per decade (<http://earthobservatory.nasa.gov>). Seven of the eight warmest years since 1880 have occurred since 2001 and the 10 warmest years have all occurred since 1995 (NOAA NCDC <http://www.ncdc.noaa.gov>), with 2010 approaching or equaling the 2005 record (Hansen et al. 2010). Methodology concerns with earlier reporting (Hansen et al. 1981) have been resolved (Thorne et al. 2011). Global surface temperatures have risen at an increasing rate over the last two decades, with temperatures in the United States increasing by a comparable amount (Karl, Melillo, and Peterson 2009). The 2009 Copenhagen Accord (<http://unfccc.int/>) agreed that to avoid “harmful” warming *‘the increase in global temperature should be below 2 degrees Celsius...with an intent to consider a lower 1.5°C target in 2015’* (New et al. 2011). A comprehensive reanalysis of the historical instrumental meteorological records is now available in numeric and map based formats for all global weather events from 1871 to the present day, and from the earth's surface to the jet stream level (Compo et al. 2011).

Carbon dioxide (CO<sub>2</sub>) is the leading GHG and its current atmospheric concentration of ~390 ppmv (<http://www.esrl.noaa.gov/gmd/ccgg/trends/>) is higher than it has been in at least 800,000 years (National Research Council 2010). The importance of the concentration of CO<sub>2</sub> in the atmosphere, and the suspicion that global fossil fuel consumption was affecting that concentration, lead to the establishment of a long term monitoring program for atmospheric CO<sub>2</sub> at Mauna Loa Observatory in Hawaii in 1957 (Keeling 1973). At the beginning of the 20<sup>th</sup> Century, Arrhenius noted that global coal combustion (then the major source of GHG emissions) had reached about 900 million tons and he estimated that it would take about 3,000 years for atmospheric CO<sub>2</sub> concentration to double (Arrhenius 1908).

Growth in global fossil fuel use by the middle of the 20<sup>th</sup> Century lead Charles Keeling to estimate CO<sub>2</sub> emission values from 1800 to 1969, and conclude that atmospheric CO<sub>2</sub> concentrations had increased by 18% over the projections of Arrhenius (Keeling 1973). Based on the long-term record at the Mauna Loa observatory in Hawaii, annual average CO<sub>2</sub> concentration rose by 3.4% between 1959 and 1971 (Keeling et al. 1976). More recent Mauna Loa CO<sub>2</sub> measurements<sup>10</sup> show that atmospheric CO<sub>2</sub> concentration rose from 315.98 ppmv (parts per million volume) in 1959 to 387.50 ppmv in 2009, a 22.6% increase in 50 years and an increase of 45% over levels estimated for 1800. In the years since the Mauna Loa observations began climate change science has established an unequivocal relationship between atmospheric CO<sub>2</sub> and global temperature throughout Earth history (Solomon et al. 2009). Successive international scientific assessments (IPCC 2007) have, with increasing certainty, attributed ongoing global warming to anthropogenic forcing caused by emission of GHG, principally CO<sub>2</sub>.

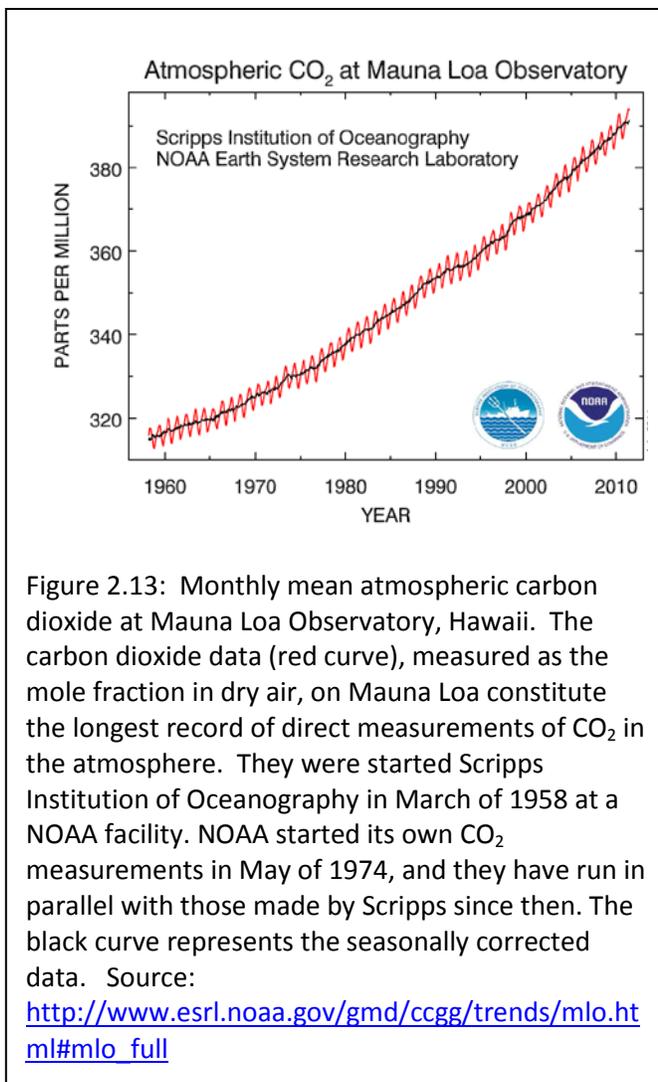
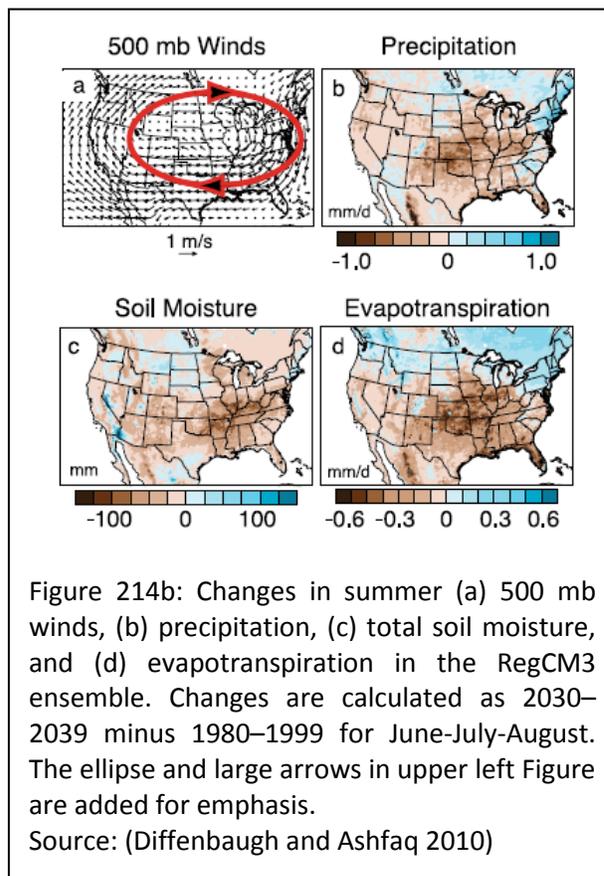
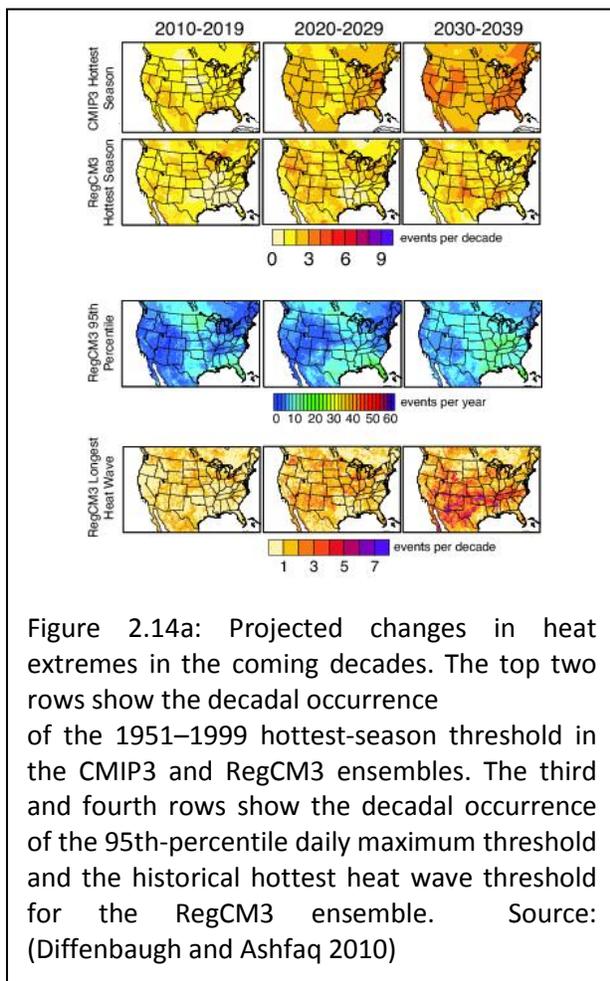


Figure 2.13: Monthly mean atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii. The carbon dioxide data (red curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO<sub>2</sub> in the atmosphere. They were started Scripps Institution of Oceanography in March of 1958 at a NOAA facility. NOAA started its own CO<sub>2</sub> measurements in May of 1974, and they have run in parallel with those made by Scripps since then. The black curve represents the seasonally corrected data. Source: [http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html#mlo\\_full](http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html#mlo_full)

## 21<sup>st</sup> Century Climate

Since the exceptional atmospheric persistence of CO<sub>2</sub> means that irreversible warming for more than 1,000 years is nearly certain (Solomon et al. 2010), the cumulative emissions of CO<sub>2</sub> are of paramount importance (Bowerman et al. 2011). Because CO<sub>2</sub> is so long lived in the atmosphere compared to non-CO<sub>2</sub> GHG and aerosols, an immediate cessation of anthropogenic emissions, followed by washing of aerosols out of the atmosphere, would result in an immediate upward spurt in global surface temperatures resulting from a rapid diminution of aerosol cooling relative to GHG warming effects (Armour and Roe 2011). Changes in the heat trapping capacity of the Earth's atmosphere have been closely associated with changes in surface temperatures during the past 400 years and throughout much of earth's history (Mann, Bradley, and Hughes 1998; Petit et al. 1999; Joos and Spahni 2008). For example, a 4° C to 6° C global warming took place over a 400,000-year period about 40 Mya. This coincided with a doubling of atmospheric CO<sub>2</sub> (Bijl et al. 2010). With continuation of current emissions we will experience a similar CO<sub>2</sub> doubling and 4° C warming this Century after ~ 300 years.

<sup>10</sup> [ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2\\_mm\\_mlo.txt](ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_mlo.txt)



The average mean annual temperature at the Earth’s surface was 14°C (57°F) in the 20<sup>th</sup> Century (<http://www.ncdc.noaa.gov/cmb-faq/>). The instrumental record shows that 20th century, atmospheric carbon dioxide increased more than an order of magnitude faster than any sustained change during the past 22,000 years (Joos and Spahni 2008). Atmospheric carbon dioxide is the “principal control knob” governing our Earth’s temperature, and its accelerating atmospheric concentration increase over the first decade of the 21<sup>st</sup> Century correlates with measured increases of global surface temperature and increasingly with measured climate related changes in fire regimes in the United States (Lacis et al. 2010; Westerling et al. 2006).

GCM outputs are continually improving in terms of resolution and completeness of process inclusion. In the opening of this chapter, we directed the reader to the IPCC AR4 and other scientific consensus reports for more in depth coverage of climate change science and the model outputs available. Now to illustrate the type of information available, we show some model results for the United States that focus on summer heat and drought, variables shown to be of importance to fire (Heyerdahl et al. 2008). Drier conditions existed over the central United States and northern Rockies during the mid-Holocene (~ 8,000 to 3,000 years ago). These

periods were dominated by changes in large-scale atmospheric processes, such as enhanced anti-cyclonic circulation aloft over mid-continent, attributed to insolation<sup>11</sup> forcing and insolation-induced changes in sea surface temperature (Diffenbaugh et al. 2006). Recent studies indicate a similar shift towards more anti-cyclonic atmospheric circulation over the United States during the warm season with resultant intensification of hot extremes (Diffenbaugh and Ashfaq 2010). A permanent 21<sup>st</sup> Century heat regime shift, in which the coolest warm-season of the 21<sup>st</sup> century is hotter than the hottest warm-season of the late 20th century, is increasingly likely (Diffenbaugh and Scherer 2011). Figures 2.14 a, b illustrate this potential.

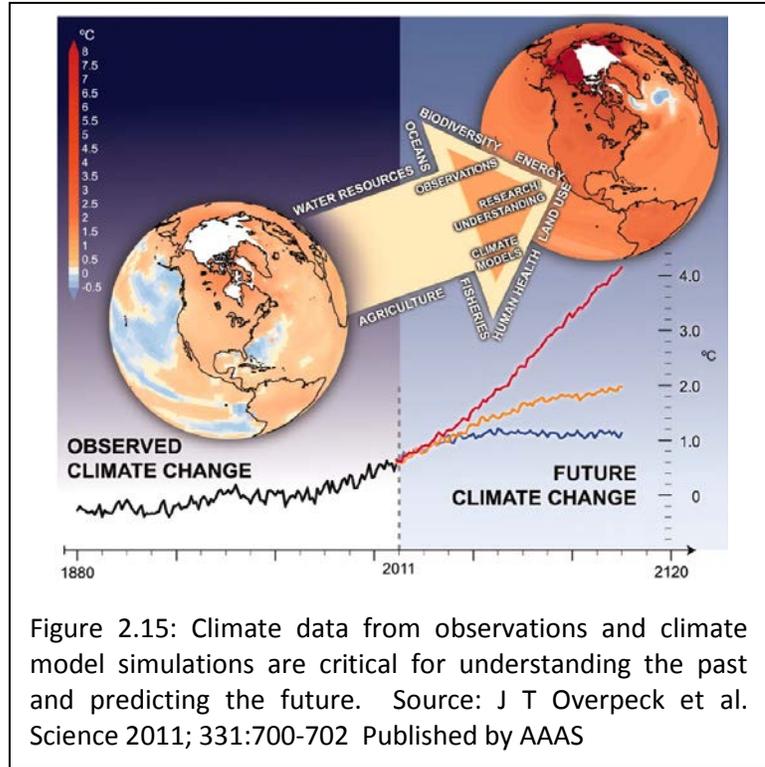


Figure 2.15: Climate data from observations and climate model simulations are critical for understanding the past and predicting the future. Source: J T Overpeck et al. Science 2011; 331:700-702 Published by AAAS

## Climate Information Growth

While we have emphasized the enormous growth of climate change science by focusing on instrumental, paleoclimate and model supported knowledge; we may be hiding a fundamental facet of the state of climate change science by our focus on the “trees” rather than the “forest”. The volume of worldwide climate data is expanding rapidly and becoming directly available to a wide user community that goes far beyond climate science specialists (Overpeck et al. 2011). Major growth in model and remote sensing (satellite) data will greatly supplement in situ (observational) data over the next 30 years. Data volume is expected to expand from the Terabyte (1 Tb = 10<sup>12</sup> Bytes) to the Petabyte (1 Pb = 10<sup>15</sup> (2<sup>50</sup>))

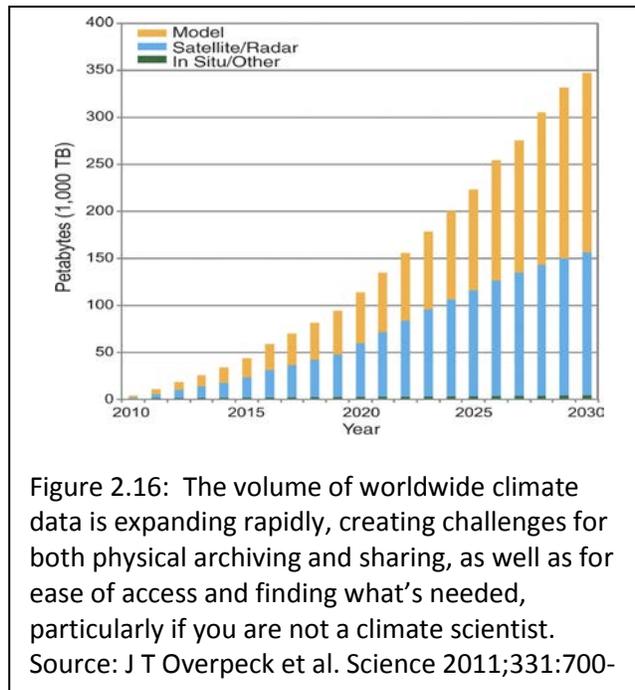


Figure 2.16: The volume of worldwide climate data is expanding rapidly, creating challenges for both physical archiving and sharing, as well as for ease of access and finding what’s needed, particularly if you are not a climate scientist. Source: J T Overpeck et al. Science 2011;331:700-

<sup>11</sup> Insolation is a measure of [solar radiation](http://en.wikipedia.org/wiki/Insolation) energy received on a given surface area in a given time.

Bytes) range, specifically from ~ 1 Pb to 350 Pb, compared to the Gigabyte (1 Gb =  $10^9$  ( $2^{30}$ ) Bytes) volumes we are used to commonly deal with. These data must meet the needs of a wide range of users (including those concerned with fire) and be useful for purposes beyond traditional climate change science (or within a significantly enlarged concept of what is included in climate change science). “... *two major challenges for climate science revolve around data: ensuring that the ever expanding volumes of data are easily and freely available to enable new scientific research, and making sure that these data and the results that depend on them are useful to and understandable by a broad interdisciplinary audience.*” (Overpeck et al. 2011). Meeting those challenges will enable us to apply our knowledge, based on observation, understanding and modeling of past and present climate, to help us understand fire history and fire regimes, and to shape fire and fuel management decisions in the face of 21<sup>st</sup> Century climate change.

## Further Reading

The reader seeking a more comprehensive understanding of the development of climate change science over the last few decades should begin by accessing:

- Assessment (4) reports issued to date by the Intergovernmental Panel on Climate Change (IPCC; <http://www.ipcc.ch/>),
- Synthesis and Assessment Products (21) issued to date by the United States Global Change Research Program (USGCRP; <http://www.usgcrp.gov/usgcrp/default.php>)
- America’s Climate Choices publications series issued by the National Research Council of the National Academies (NRC; <http://americasclimatechoices.org/>).
- State of the climate in 2010. The *State of the Climate* report is peer-reviewed and published annually as a special supplement to the Bulletin of the American Meteorological Society (BAMS). (BAMS; <http://www.ncdc.noaa.gov/bams-state-of-the-climate/2010.php>)

## IPCC AR4 WGI

### Frequently Asked Questions

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) Working Group I (WGI) Report "The Physical Science Basis" (IPCC WG I 2007) is the most useful, currently available, comprehensive reference for the state of the science of climate change. The Report extracts information from its 11 component Chapters to provide a [Frequently Asked Questions](#) section that serves as an excellent source for understanding the basics of climate science. The 19 questions are listed below, and the complete answers to them can be found by clicking [HERE](#).

What Factors Determine Earth's Climate?

What is the Relationship between Climate Change and Weather?

What is the Greenhouse Effect?

How do Human Activities Contribute to Climate Change and How do They Compare with Natural Influences?

How are Temperatures on Earth Changing?

How is Precipitation Changing?

Has there been a Change in Extreme Events like Heat Waves, Droughts, Floods and Hurricanes?

Is the Amount of Snow and Ice on the Earth Decreasing?

Is Sea Level Rising?

What Caused the Ice Ages and Other Important Climate Changes Before the Industrial Era?

Is the Current Climate Change Unusual Compared to Earlier Changes in Earth's History?

Are the Increases in Atmospheric Carbon Dioxide and Other Greenhouse Gases During the Industrial Era Caused by Human Activities?

How Reliable Are the Models Used to Make Projections of Future Climate Change?

Can Individual Extreme Events be Explained by Greenhouse Warming?

Can the Warming of the 20th Century be Explained by Natural Variability?

Are Extreme Events, Like Heat Waves, Droughts or Floods, Expected to Change as the Earth's Climate Changes?

How likely are Major or Abrupt Climate Changes, such as Loss of Ice Sheets or Changes in Global Ocean Circulation?

If Emissions of Greenhouse Gases are Reduced, How Quickly do Their Concentrations in the Atmosphere Decrease?

Do Projected Changes in Climate Vary from Region to Region?