Science of Climate Change

Climate change has been defined as a long-term change to the attributes that constitute the state of the climate; e.g. surface and air temperatures, atmospheric composition, and radiation absorption. What makes climate change significant is that the change to climatic conditions persists over long periods of time (at scales larger than several decades). Short-term climate variability that occurs because of periodic fluctuations such as teleconnection patterns; e.g. El Nino, La Nina, and Pacific Decadal Oscillation (PDO), are therefore not considered contributors of climate change due to their shorter durations (several years).

Some of the literature uses the term climate change synonymously with global warming; however there is a distinction between the two terms. Climate change refers to a shift in climatic conditions that is attributable to any type of source (anthropogenic or natural) and can occur in any direction (warming or cooling). Global warming tends to refer strictly to heating patterns that are attributable to man-made causes and is linked to the content level of carbon dioxide and other greenhouse gases in the earth's atmosphere.

It is important to recognize that climate can change towards a cooling trend or a warming trend, and each shift can take place and alter the existing climate in different ways. Climate is primarily determined by the amount of radiation absorbed or reflected by the earth's surface and atmosphere. This in turn is determined by the presence of certain types of particles in the earth's atmosphere that enhance solar absorption or reflection (e.g. carbon dioxide or volcanic ash), the albedo on the earth's surface (albedo determines the fraction of radiation absorbed or reflected at the surface), and physical characteristics of the earth that hinder or promote radiation retention (e.g. orbital patterns and geographic locations of oceans and landmasses). Therefore it becomes clear that the different feedbacks and relationships between climatic parameters can be complex and difficult to predict. However, the study of climate change has advanced to a stage that modeling the state of the climate, along with examining historical records of climate, has become a customary exercise for climate scientists.

Sources of Climate Change

Solar Radiation and the Energy Balance

The energy balance, the equilibrium of incoming and outgoing radiation in earth's atmosphere, is driven by the magnitude of solar output from the sun. The level of radiation absorbed by the earth dictates the type of climate it will experience (warmer vs. cooler). Variation in solar energy produced by the sun may change over time. The frequency and number of sunspots; magnetic storms that occur on the sun, have shown to increase the emission of energy from the sun. The occurrence of sunspots tends to follow a quasi-periodic cycle; where the maximum number and size of the sunspots coincide with the length of the cycle. The two most commonly found cycles in solar observations are 11-year and 22-year cycles. Even though these short-term periods may not fall under a significant portion of time to represent climate change, historical records have shown that a 70 year period in the past (between 1645 to 1715) called the Maunder minimum exhibited a significant lack of sunspots that resulted in a net decrease of half a degree Celsius when compared to the long term average. In addition, approximately four billion years ago, the sun produced 30% less solar power than it does today, validating the possibility of solar variation as a source of climate change.

Earth's Orbital Patterns

Changes in climate have also been attributed to variations in the earth's orbit, which affect the distribution of incoming sunlight along seasonal and geographic lines. According to the Milankovitch theory (named after astronomer Milutin Milankovitch), the combined effect of variations to three different orbital cycles can lead to changes in the amount of solar radiation received by the earth's surface. These three Milankovitch cycles are directly associated with the shape of the earth's orbit around the sun (eccentricity), the axial tilt of the earth's axis (obliquity), and the earth's 'wobble' as it rotates along its axis (precession).

The earth's eccentricity is altered over time as the earth continues to orbit around the sun. This orbit tends to alternate from a circular shape to an elliptical shape and back every 100,000 years. Adjustments to the earth's eccentricity due to this cycle translate to differences in incoming solar energy due to the earth's proximity to the sun during its orbit. At periods of low eccentricity (more circular orbit), the earth's closest approach to the sun during orbit (called the perihelion) receives approximately 7% more radiation than the earth's furthest approach to the sun during orbit (called the aphelion). Conversely, at periods of high eccentricity (more elliptical orbit), the earth's atmosphere during a perihelion stage receives approximately 20% more radiation than at an aphelion stage. Furthermore, extreme eccentricity causes a subsequent change in the length of the seasons since more of the duration of the earth's orbit occurs near the aphelion than the perihelion.

The earth's obliquity; or angle of axial tilt also undergoes a cycle every 41,000 years. In that period, the angle of tilt shifts from 22 degrees to 24.5 degrees and back. When the axial tilt is larger, there is increased solar irradiation during the summer and less during the winter. The net result of this effect is larger seasonal variability due to warmer summers and colder winters. However, when the axial tilt is decreased, there is less seasonal variation as summer receives less irradiation while winters receive more, causing summers to be cool and winters to be mild.

The earth's precession refers to the gyroscopic motion, or 'wobble', the earth makes as it rotates around its axis (similar to a spinning top toy). This axial precession induces different seasonal variability between the northern and southern hemispheres. During this cycle (which lasts between 23,000 to 25,000 years), the hemisphere that is closer to the sun due to the precession will receive increased solar radiation and as such will have greater variability in its seasons (e.g. hotter summer and colder winter). In contrast the other hemisphere will have more temperate seasons (e.g. warmer winters and cooler summers).

<u>Ocean Circulation and Heat Redistribution</u>

Oceans play a large role in regulating the earth's climate; they store heat during the summer and release heat during the winter, contributing towards milder winters and temperate summers. Since more of the earth is covered by oceans rather than land (~70%), a significant portion of the solar radiation reaching earth is absorbed by its oceans. Furthermore, the oceans also circulate and transport this absorbed heat around the earth before it is released into the atmosphere. Ocean heat transport is possible through two types of circulation patterns: wind-driven surface currents and the density-driven thermohaline circulation.

Wind-driven currents that transport absorbed solar heat at the water surface only move a limited volume of water (~10% of the earth's oceanic water), and consequently a smaller portion of the absorbed heat. Thermohaline circulation is propelled by deep water currents and affects the majority of the earth's ocean water (~90% of the ocean). Deep waters develop where the air temperature is cold and the salt content of the water is high. The combination of these two effects is denser water; since dense water tends to be colder and possesses a higher salinity. As water moves towards the poles, and becomes more saline and cold, the water's density increases and it sinks into deep ocean basins. Dense water that is pushed away from the poles eventually moves into latitudes that allow for the gradual warming of the water and its subsequent rise to the ocean surface; where the circulation cycle repeats. This process of conversion of warm shallow currents (wind-driven) and cold and salty deep currents (density-driven) and vice-versa is akin to an ocean circulation conveyer belt; which is the nickname given to the thermohaline circulation it represents. Changes to the thermohaline circulation can contribute to large-scale changes to the climate due to the large volumes of ocean water and stored heat it entails.

<u>Chemical Composition of the Atmosphere</u>

The chemical composition of the atmosphere and the presence of different types of particles and/or gases in the atmosphere can impact climate in different ways depending on the effect these atmospheric particles have with respect to incoming solar radiation; some may inhibit the absorption of solar radiation and instigate a cooling effect, others may promote solar absorption and induce a warming effect. Additionally, the warming and cooling effects that these particles may cause can differ between the atmosphere and the earth's surface.

Sulfate Aerosols

Examples of particles that reflect and scatter incoming sunlight include soil dust and sulfate aerosols. Sulfate aerosols are produced from the combustion of fossil fuels that contain sulfur. When released into the atmosphere these sulfate aerosols only last a few days and as such do not spread far from their point of origin. Therefore most sulfate aerosol concentrations in the atmosphere can be found near high sulfate pollution production zones (primarily in the northern hemisphere). Additionally, sulfate aerosols assist in cloud formation as sulfate particles act as cloud condensation nuclei (the atmospheric material upon which clouds form). In addition to reducing the amount of sunlight reaching the earth's surface, clouds may also produce droplets that help to scatter incoming radiation. The net effect of this scattering and reflecting of sunlight by sulfate aerosols is the cooling of surface temperatures.

Volcanic Eruptions

Other particles in the atmosphere have the opposite effect of absorbing incoming sunlight; prime examples of this are smoky soot and volcanic dust or ash. Volcanic eruptions release ash and dust into the atmosphere which can have a profound impact on climate, particularly if the eruption is heavily laden with sulfur gases. The combination of volcanic eruption material and water vapor in the atmosphere produces a dense layer of haze which can last for several years. This haze is then able to absorb incoming solar radiation as well as reflect some of it back. This causes the surrounding air to be warmed but surface temperatures to become cool since a diminished amount of sunlight reaches the earth's surface.

Greenhouse Gases and Global Warming

The presence of greenhouse gases in the atmosphere also helps to absorb incoming radiation but produces a different result than that of volcanic ash. Green house gases include (in order of their contribution to the greenhouse effect of warming) water vapor, carbon dioxide, methane, and ozone. Greenhouse gases have the effect of absorbing incoming solar radiation and emitting some of that absorbed radiation as infrared energy to the earth's surface. Therefore the increased presence of greenhouse gases warms both atmospheric and surface temperatures. The rise of greenhouse gases in the earth's atmosphere have been linked with global warming due to human-induced anthropogenic activities such as the increased burning of fossil fuels and deforestation (which reduces the number of plants that can convert carbon dioxide on the earth into oxygen).

Depletion of the Ozone Layer

The depletion of the ozone layer has in the past been mistakenly linked with global warming. The loss of ozone is due to increased levels of chlorofluorocarbons (CFCs) in the atmosphere; which are produced from cooling units such as air conditioners, the release of aerosol spray propellants, and other chemical processes.

Plate Tectonics

The slow (at a rate of millions of years) and constant shifting of the earth's tectonic plates have a long-term impact on the earth's topography by helping to shape the configuration of continents and oceans. These changes in the earth's sea to landmass makeup can alter the existing mechanism of heat transport; especially the thermohaline circulation pattern. Additionally, the ocean's capacity to regulate surface temperatures becomes impacted if plate tectonics cause an increase in the earth's landmass and a decrease in ocean water volume. Geologic evidence during the presence of the supercontinent Pangaea 300 million years ago illustrate that climate behaved much differently than how it does today; with the prevalence of large-scale monsoon circulation patterns and higher temperature variations.

Clouds and Surface Albedo

In addition to these major sources of climate change, the presence of other factors plays a role in how a climate takes shape. The formation of clouds can influence the climate significantly as the presence of low clouds may alter the energy balance of the earth. Clouds act like atmospheric buffers that can reflect a large portion of incoming solar radiation. Thus, the abundance of low clouds supports a cooling effect. Conversely, the lack of clouds can contribute to a warming effect; as more solar radiation is able to reach the surface of the earth.

Albedo, or reflectivity, then plays a role in determining how much incoming solar radiation that reaches the earth's surface is absorbed or reflected. Different types of land cover/surfaces (water, snow, grass, etc) have different albedo values distinguishing its reflectivity with respect to solar radiation; e.g. snow has a significantly higher albedo than bare soil.

Indicators of Climate Change

The primary indicator of climate change is temperature measurements. However, current instrumental temperature measurements only go as far back as the 19^{th} century. To look at historical records before that period for a longer duration of years (centuries to millenniums), scientists need to look at secondary and indirect indicators of climate change (referred to as climate proxies) that enable them to reconstruct a climate image of conditions in the past.

Another useful indicator of climate change is the change in global sea level. Much like temperature measurements, current records using tide gauge measurements only go so far (19^{th} century) with satellite data only being recently used. Longer historical records of sea level changes can be determined by dating geological objects in the ocean such as coral reefs and coast sediments using carbon and uranium-thorium dating methods.

Linked to changes in temperature and sea level are changes in precipitation and vegetation. Precipitation can be determined using networks of precipitation gauges that are supplemented by satellite observations. However for historical records that predate current precipitation gauges, scientists need to look at other methods such as tree ring analysis or the sampling of ice cores.

Besides inferences on climate based on types of vegetation that grow and thrive in warmer vs. cooler climates, the rate of change of climate has some consequence on the state of vegetation. Climate change that is more radical, faster, or larger can cause stress to plants and vegetation loss to the extent of desertification. Evidence of this occurring in the past is provided through the Carboniferous Rainforest Collapse that took place 300 million years ago. During this event, rapid climate change caused much of the expansive tropical rainforests that covered Europe and the Americas to decline into pockets of forests that led to the extinction of much plant- and animal-life.

Dendroclimatology or tree ring analysis is one of the most reliable and extensive pieces of climate data available that stretches back for thousands of years. By taking core samples from trees that have been in existence for a remarkably long time, tree ring scientist can determine the local climate of different time periods. These scientists are able to do this by looking at the growth pattern of tree rings. Wetter climates are generally indicated by wide tree rings while drier climates can be inferred from narrow tree rings.

The drilling of ice cores in long-preserved ice sheets (such as in Antarctica) can provide even more quantitative evidence of climate change. Through the use of isotope analysis, an ice core sample can provide information on temperature, sea level, precipitation, and atmospheric composition of the time periods that the ice core represents. Depending on the length of the ice core, some samples can trace back to 800,000 years. Of particular interest when it comes to ice core analysis, is the ability to establish the changes to the level of carbon dioxide in the atmosphere in time periods before the large increase in recent decades. This information helps to provide a comparison point for evaluating the impact carbon dioxide in the atmosphere may have in global warming.

Several other indicators are also linked to the condition of ice. The decline in the ice of the Arctic sea is a strong indicator of a warming phase of climate change. In comparison to the Antarctic sea ice, which melts and reforms completely with little to no loss, very little of the ice lost from the Arctic sea reforms. Recent observations indicate a declining Arctic sea ice rate of 12% per decade (based on comparison to a 20-year average from 1980 to 2000).

Glaciers' sensitivity to temperature makes them reliable indicators of climate change. In warming periods brought about by higher temperatures and lower precipitation, glaciers will shrink in size and retreat. Conversely during cooling periods where temperatures remain low and precipitation is present, glaciers may grow and advance. As such, establishing when a glacier advances or retreats also establishes whether the climate is changing or not; especially when compared to some long-term mean of record to quantify the magnitude of the change. In addition, glaciers produce moraines during their advance and retreat that provide organic material and minerals that can be dated to correlate the time periods when a glacier advanced or retreated; thus attaching a climate setting to an actual period of time.

Additionally, other evidence of climate change can be established using less rigorous and more scientifically subjective methods. This includes examining archeology to determine the adverse effects of climate change on prior populations and peoples, the examination of animal remains (e.g. beetles) and species productivity (e.g. fishes) that are linked to different climatic patterns , and the analysis of pollen (called palynology) and the changes to their type and size that may correspond to a changing climate.