INTRODUCTION TO CLIMATE CHANGE

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1. INTRODUCTION

Climate of a region represents the long-term average of weather (more than thirty years). It is a resultant of extremely complex system consisting of different meteorological variables, which vary with time. Climate in a narrow sense is defined as "average weather", or more rigorously, as the statistical description in terms of mean and variability of relevant quantities of weather parameters over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by WMO. These parameters are most often surface variables such as temperature, precipitation and wind.

The climate change is a very common word in the present day world. The common man, media and scientists all seem to be concerned with this phenomenon. It is generally because the mean global temperature of earth is showing an increasing trend. However, this might not be true in a regional scale, but enough evidences have been gathered showing this increasing trend of temperature. The important evidences include worldwide retreat of glaciers in all latitudes, rising of the mean sea level, breaking of Antarctic ice sheets etc. Such changes may have severe impact on mankind and all other living species. Such scenarios of projection have urged researchers from all over the world and of all fields of science to study the problem in a greater depth.

Climate change refers to a statistically significant variation in either the mean state of the climate or in other statistics (such as standard deviations, the occurrence of extremes, etc.), persisting for an extended period particularly decades or longer. Climate change may be due to natural internal processes or external forcings, or to anthropogenic changes in the composition of the atmosphere or in the land use. Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that of UNFCCC which defines climate change as, "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". Climate change is not only a major global environmental problem, but also an issue of great concern to a developing country like India.

The earth's atmosphere - the layer of air that surrounds the earth - contains many gases. Short-wave radiation from the sun passes through the earth's atmosphere. Partly this radiation is reflected back into space, absorbed by the atmosphere and remainder reaches the earth's surface, where it is either reflected or absorbed. In turn the earth's surface, emits long-wave radiation toward space. The greenhouse gases (GHGs) available in the atmosphere principally include carbon dioxide (CO_2), nitrous oxide (NO_2), methane (CH_4), and chlorofluorocarbons (CFCs) and ozone (O_3). These GHGs absorb some of this long-wave radiation emitted by the Earth's surface and re-radiate it back to the surface. Ever since the industrial revolution began about 150 years ago, human activities have added significant quantities of GHGs to the atmosphere. An increase in the levels of GHGs could lead to greater warming which, in turn, could have major impact on the world's climate, leading to accelerated climate change. Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased from 280 ppm to 379 ppm, 715 ppb to 1774 ppb and 270 ppb to 319 ppb respectively, between pre-industrial period and 2005 (IPCC, 2007). Thus GHGs modify the heat balance of the Earth by retaining long-wave radiation that would otherwise be dispersed through the Earth's atmosphere to space.

This effect is known as the greenhouse effect. Evidently, GHG have an important role in controlling the temperature of the earth and an increase in their concentration in the atmosphere would increase the temperature of the Earth. In addition, presence of excess quantities of CFCs affects the protective ozone layer which deflects the harmful short wave rays.

Global warming arising from the anthropogenic-driven emissions of greenhouse gases has emerged as one of the most important environmental issues ever to confront humanity in last two decades. Concern over global climatic changes caused by growing atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and global climate systems has improved. Scientists have learnt a great deal in recent decades about the climate and its response to the human activities, particularly emission of the greenhouse gases such as carbon dioxide, methane, nitrous oxide etc. Nevertheless the global climate system is so vast and complex that it is difficult to understand very accurately. Consequently, some uncertainty remains in the outcome of the analysis. There is focus on scientific research along with probable impact on society. This problem is inextricably linked to the process of development and economic growth itself. This concern arises from the fact that our everyday activities may be leading to changes in the earth's atmosphere that have the potential to significantly alter the planet's heat and radiation balance. It could lead to a warmer climate in the next century, which may have adverse effect on the resources and society.

With an economy closely linked to its natural resource base and climatically sensitive sectors such as agriculture, water and forestry, India may face a major threat because of the projected change in climate. With climate change, there would be increasing scarcity of water, reduction in yields of forest biomass, and increased risk to human health. India released its National Action Plan on Climate Change (NAPCC) on 30th June, 2008 to outline its strategy to meet the Climate Change challenge. The National Action Plan advocates a strategy that promotes, firstly, the adaptation to Climate Change and secondly, further enhancement of the ecological sustainability of India's development path. India's National Action Plan stresses that maintaining a high growth rate is essential for increasing the living standards of the vast majority of people of India and reducing their vulnerability to the impacts of climate change. Accordingly, the Action Plan identifies measures that promote the objectives of sustainable development of India while also yielding to benefits for addressing climate change. Eight National Missions, which form the core of the National Action Plan, represent multi-pronged, long term and integrated strategies for achieving key goals in the context of climate change. The focus is on promoting understanding of Climate Change, adaptation and mitigation, energy efficiency and natural resource conservation.

Recent decades have seen record-high average global surface temperatures. Thermometer readings sufficient to provide reliable global averages are available back to 1850. In the past century, global surface temperature increased by about 1.4 °F (Fig. 1). In the past quarter-century, according to satellite measurements, the lower atmosphere warmed by 0.22-0.34 °F per decade, equivalent to 2-3 °F per century (Christy and Spencer 2005; Mears and Wentz 2005). The past 20 years include the 18 warmest years on record (Hadley Centre 2005).

This well-documented warming trend could result from several factors that influence the earth's climate, some of which are natural, such as changes in solar radiation and volcanic activity. Others, particularly the release of certain gases to the atmosphere and land-cover changes, are manmade. This lecture describes recent scientific progress in identifying the causes and has drawn material from Pew (2005).

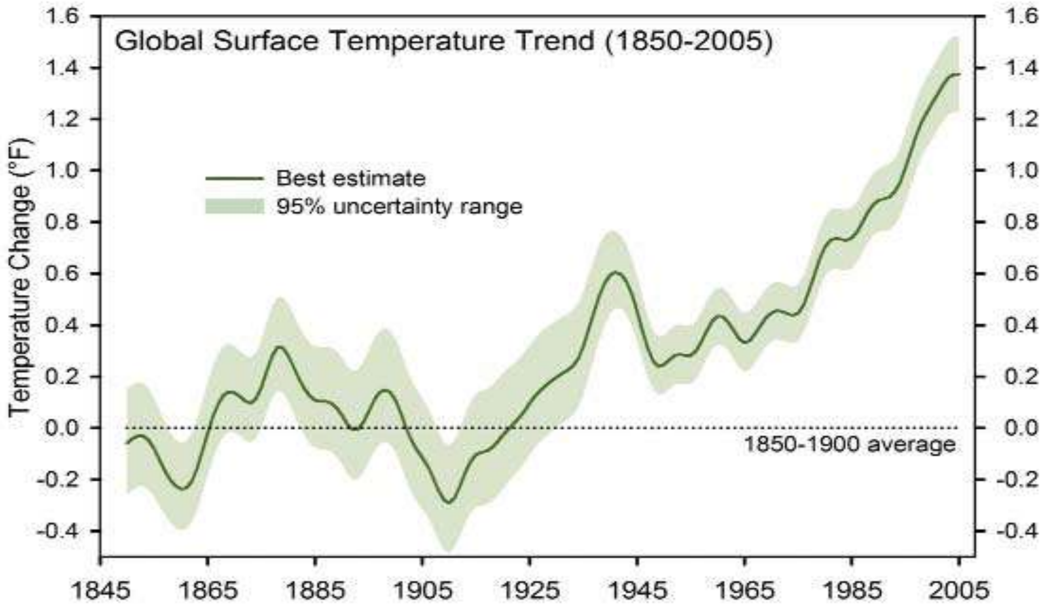

Figure 1. Average global surface temperature based on instrumental measurements (Adapted from Brohan et al. 2006). Temperature rise during the twentieth century is much larger than the uncertainty range.

The **greenhouse effect** is a natural phenomenon whereby certain gases in the earth's atmosphere, known as **greenhouse gases (GHGs)**, absorb heat that would otherwise escape to space. This heat originates from visible sunlight that warms the earth's surface. Subsequently, heat radiates from the surface to the atmosphere, where some of it is absorbed by greenhouse gases and radiated back to the surface (Fig. 2). Recent progress in climate modeling has generated a consensus among climate scientists that GHGs emitted by human activities are likely (66-90% chance) to have caused most of the observed global temperature rise over the past 50 years (Mitchell et al. 2001). The increase in the strength of the greenhouse effect as a result of man-made greenhouse gases is known as the enhanced greenhouse effect.

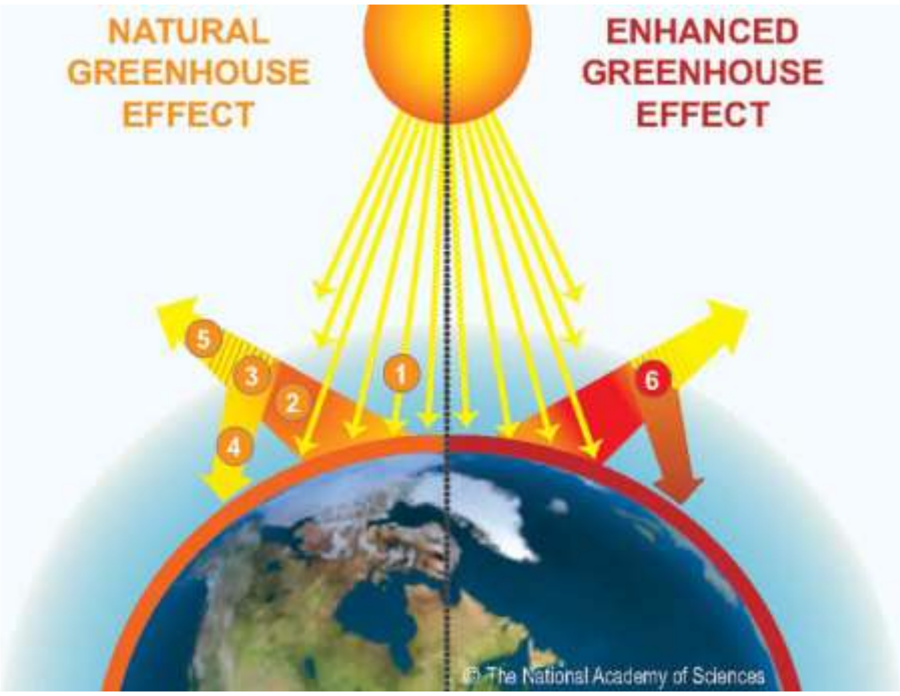

Figure 2. Illustration of the greenhouse effect (Courtesy: National Academy of Sciences). Visible sunlight passes through the atmosphere without being absorbed. Some of the sunlight striking the earth is (1) absorbed and converted to infrared radiation (heat), which warms the surface. The surface (2) emits infrared radiation to the atmosphere, where some of it (3) is absorbed by GHGs and (4) re-emitted toward the surface; some of the infrared radiation is not trapped by GHGs and (5) escapes into space. Human activities that emit additional GHGs to the atmosphere (6) increase the amount of infrared radiation that gets absorbed before escaping to space, thus enhancing the greenhouse effect and amplifying the warming of the earth.

Factors Influencing Global Temperature

Global climate varies over time in response to climate forcings—physical factors external to the climate system that force a net increase (positive forcing) or net decrease (negative forcing) of heat in the climate system as a whole (Hansen, Sato et al. 2005). This type of change is distinct from internal climate variability, in which heat is transported by winds or ocean currents between different components of the climate system with no net change in the total heat within the system. The El Niño–Southern Oscillation is a well-known example of internal climate variability. Because the observed climate change over the twentieth century results from a net increase of heat in the entire climate system, it can only be explained by external forcing (Hansen, Nazarenko et al. 2005). Hence, the task for climate change scientists is to identify one or more external forcing(s) — natural or manmade — that can explain the observed warming.

Until recent centuries, climate forcings were exclusively natural, such as changes in the amount of sunlight reaching the earth's surface and changes in emissions of dust from volcanoes. During modern times, human activities have introduced a mix of additional forcings, such as increases in atmospheric GHGs that cause warming (positive forcing), and sulfate aerosols, miniscule particles that reflect sunlight and cause cooling (negative forcing). The histories and magnitudes of various forcings are estimated from direct observations, such as satellite measurements of solar radiation in recent decades, or from proxies, such as sunspots for solar radiation in earlier decades (Foukal et al. 2004). The histories of individual forcings (Fig. 3) are then examined for the potential to cause the observed pattern of climate change (Hansen, Sato et al. 2005).

Scientists employ records of various forcings in a "fingerprinting" approach to identify which forcings can account for observed patterns of climate change. A particular forcing imprints itself uniquely on the past climate record based on how the forcing works and how its strength varies over time.

Modeling to Identify Causes of Climate Change

Fingerprint matching between climate forcings and observed climate change is performed using physical climate models that calculate how each forcing should have affected climate over time, based on its history and how the physical mechanisms of each forcing is currently understood. These models are able to reproduce most of the major features of the global climate system, including the pattern of global warming over the past century (e.g., Stott et al. 2000). The models serve as controlled experiments that test alternative hypotheses about the causes of climate change. Each forcing depicted in Fig. 3 represents a hypothesized cause of observed climate change. Entering records of one or more forcings into a model, scientists assess whether the climate scenario generated by the model is similar to the observed climate record; no observed climate data are entered into the model. If the simulated climate matches observed climate, then the forcing(s) represented in the model have correctly explained the observed climate record. If not, the forcing(s) cannot explain the observed climate change. Of course, it is possible that more than one forcing is involved, so it is necessary to test all possible combinations of forcings to see if their combined influence can explain observed climate change (e.g., Meehl et al. 2004). Independent modeling of different components of the climate system demonstrates that man-made GHGs have been the dominant forcing of climate change over the past half century.

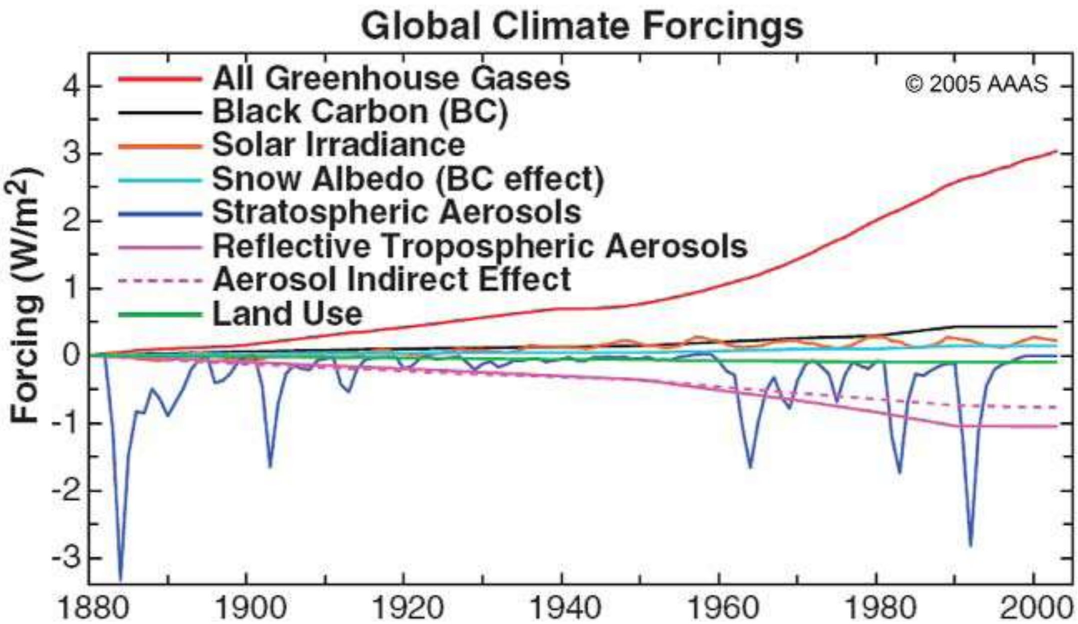

Figure 3. Forcings used to drive global climate simulations (Hansen et al. 2005). Records of forcing history are compiled from a wide variety of direct observations and proxies. Each forcing has a unique historical pattern that serves as its fingerprint of influence on observed climate change. Positive forcings exert a net warming effect (e.g., GHGs, red line), whereas negative forcings exert a net cooling effect (e.g., stratospheric aerosols from volcanic eruptions, dark blue line). GHGs exhibit the largest trend of all forcings shown.

The distinct fingerprint of man-made GHGs has been detected in records of surface temperature, ocean heat content, and the vertical structure of the atmosphere above the earth's surface.

Surface warming The twentieth-century warming trend at the earth's surface progressed in a distinct pattern, with a large warming during 1910-1940, moderate cooling during 1940-1975, and a large warming from 1975 to the present (Fig. 1). Scientists at the National Center for Atmospheric Research (NCAR) looked for fingerprints of various natural (solar radiation, volcanic particles) and man-made (GHGs, sulfate aerosols) forcings in this record of observed climate change (Meehl et al. 2004). The study employed a physical climate model that allowed individual or combinations of forcings to drive the simulated climate. The change in surface temperature calculated by the model for each forcing or combination of forcings was then compared with the observed record of surface temperature change over the twentieth century (Fig. 4).

The best fit of the model results to the observed climate was produced when all of the forcings were included, implicating all of the forcings in producing the overall pattern of change (Fig. 4A). However, different forcings dominated at different times during the century. For instance, the temperature rise in the early part of the century was dominated by natural forcings (Fig. 4B), whereas the warming after 1975 was dominated by man-made GHGs (Fig. 4C). The cooling during the mid-century was consistent with a combination of natural volcanic and man-made aerosols (Nagashima et al. 2006).

The results of this study implicate the enhanced GHG effect as the dominant cause of global warming over the past three decades. If not for the temporary cooling between 1940 and 1975 from volcanic and man-made aerosol emissions, the earth might be even warmer than it is today (Mitchell et al. 2001).

Ocean heat content. Oceans exhibit natural temperature cycles, with some oceans cooling at the same time that others warm. This natural internal variability of climate results from heat transport from one place to another, but it adds no new heat to the ocean as a whole. A major challenge for assigning a cause to temperature changes is distinguishing internal variability from external forcing, which adds new heat to the system. Scientists have demonstrated that the ocean as a whole has been warming for the past five decades (Levitus et al. 2005). The first principles of physics dictate that simultaneous warming of all the world's oceans could only occur through external forcing, as there is no other source of this much energy within the climate system (Hansen, Nazarenko et al. 2005). Using a fingerprinting-modeling approach similar to the one described above, scientists at Scripps Institution of Oceanography, Lawrence Livermore National Lab, NCAR, and the United Kingdom's Hadley Center, published a study showing that the oceans situated along the equator have warmed over the past five decades as a direct result of the enhanced GHG effect (Barnett et al. 2005). Observations show that the oceans have been warming from the surface downward (red dots, Fig. 5), which indicates heat transfer from the atmosphere. The vertical pattern of heat penetration with depth varies from ocean to ocean as a result of internal variability (i.e. currents transporting heat from one ocean to another). This complex pattern of vertical profiles provides a "fingerprint" of climate forcing. Modeling of internal variability alone or internal variability combined with solar and volcanic forcings did not produce temperature profiles that matched this fingerprint (Fig. 5A). However, the combined influence of human-induce forcings, natural forcings, and internal variability reproduced the pattern of heat penetration for each ocean (Fig. 5B). Man-made GHGs strongly dominated the overall forcing.

Vertical structure of the atmosphere. Another fingerprint of the enhanced greenhouse effect has been identified in the observed increase in the height of the **tropopause**, a region of the earth's atmosphere that represents the transition between the lower atmosphere (troposphere) and the upper atmosphere (stratosphere). Factors that either warm the troposphere or cool the stratosphere increase the tropopause elevation (Fig. 6), and climate models have long predicted that the elevation of the tropopause above the earth's surface should increase as a result of the enhanced greenhouse effect (Santer et al. 2003). Although this phenomenon may affect climate behavior, it is discussed here strictly as a tool for identifying causes of observed climate change. Scientists from several American, British, and German research institutions employed a fingerprinting-modeling approach to determine which climate forcings could explain observed changes in the height of the tropopause (Santer et al. 2003; Santer et al. 2004).

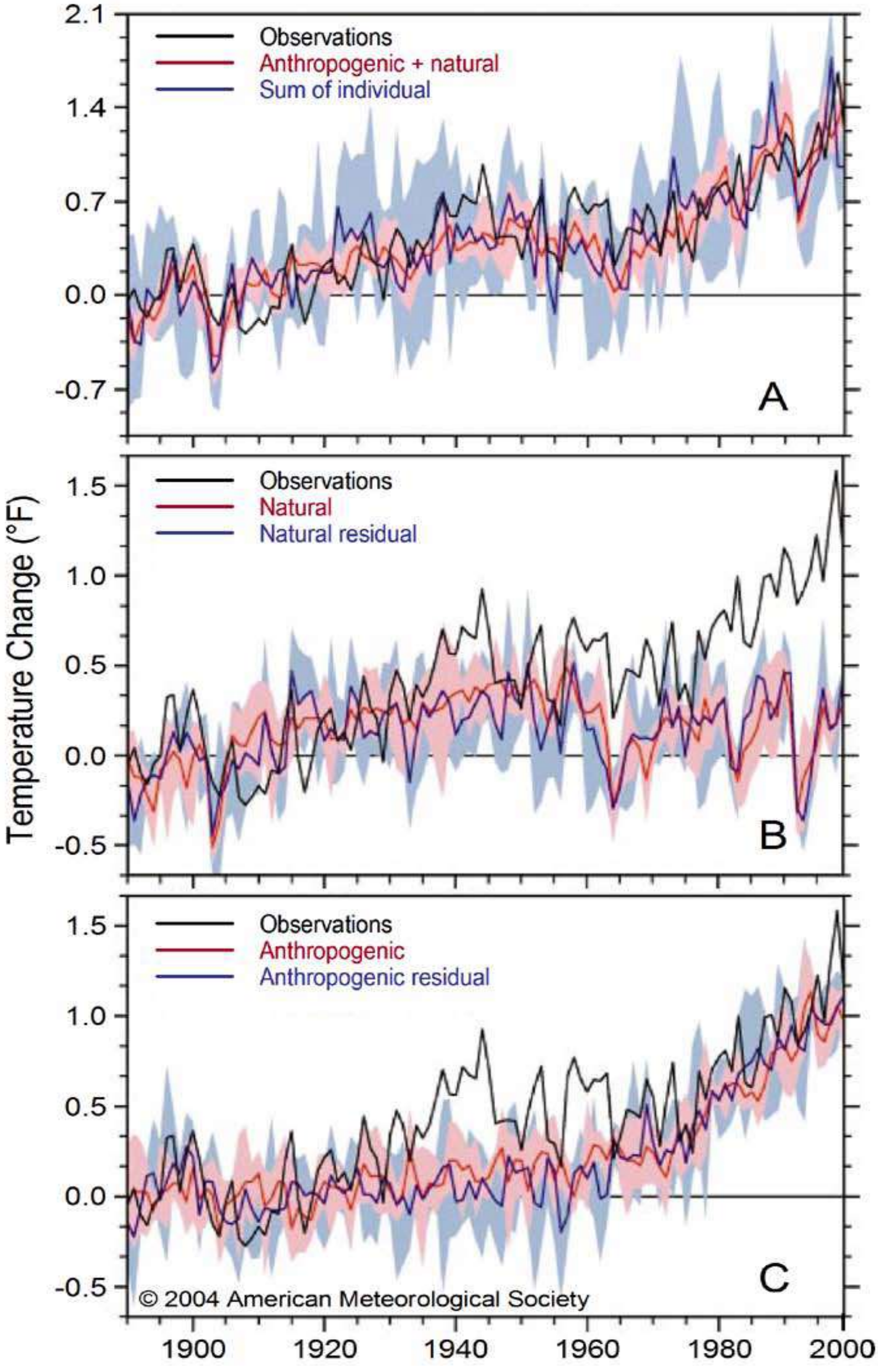

Figure 4. Fingerprint-modeling of global surface temperature change (Adapted from Meehl et al. 2004). (A) Model results with all forcings included. The combined forcings provided the best match to the fingerprint of climate change in the observed record. (B) Natural forcings alone explained much of the temperature change in the first half of the century. (C) Man-made forcings strongly dominated the temperature change after 1975.

Between 1979 and 2001, satellites monitoring the atmosphere recorded a 620-foot rise of the tropopause. In the model simulations forced by both natural and human-induced forcings, the tropopause elevation increased similarly (Fig. 7A). Manmade greenhouse gases, which warmed the troposphere, and stratospheric ozone depletion (by man-made chemicals), which cooled the stratosphere, dominated the forcing. Manmade greenhouse gases caused about 40 percent of the rise (Fig. 7B, green line), whereas ozone depletion caused about 60 percent (Fig. 7B, purple line). Overall, the effect of solar forcing, which contributed slightly (less than 10%) to the rise of the tropopause, was canceled by a small negative forcing (decrease in tropopause height) from volcanoes (Fig. 7B, gray line; note the transitory decreases corresponding to the eruptions of the Agung, El Chichón, and Pinatubo volcanoes).

Thus, human-induced forcings from GHGs and ozone-depleting chemicals provide the best explanation for the observed increase in the elevation of the tropopause over the past few decades.

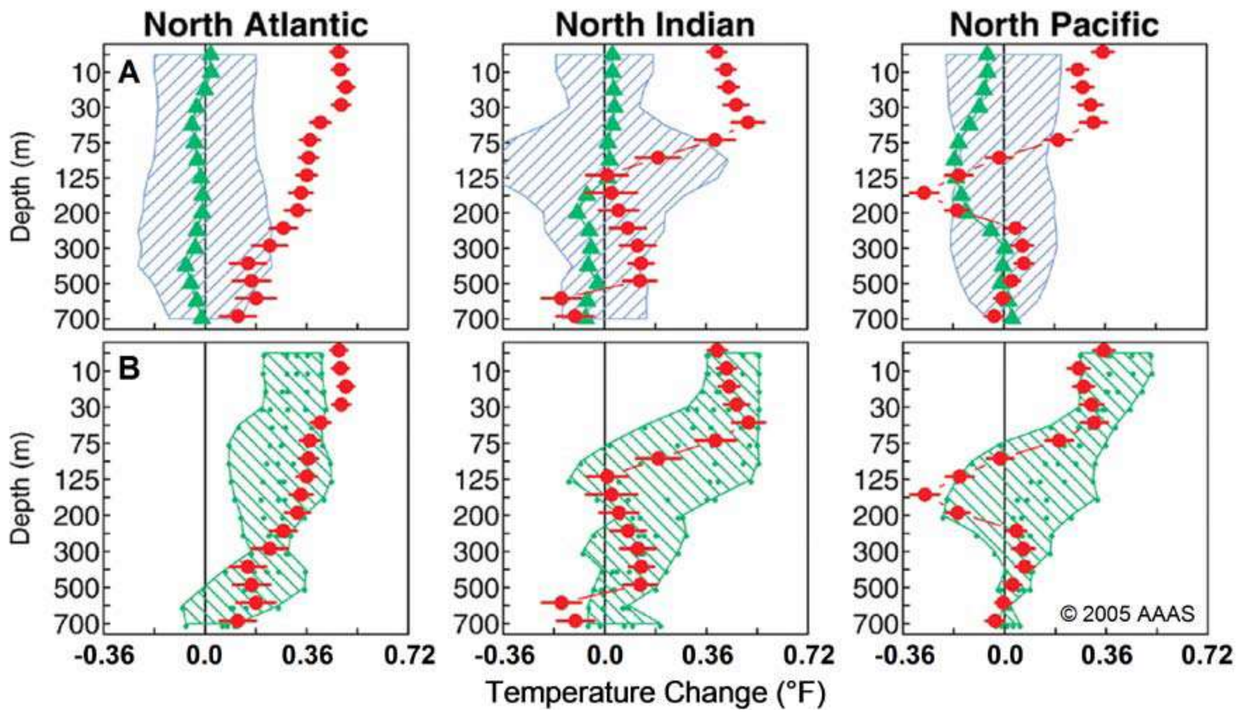

Figure 5. Observed and simulated heat penetration into three ocean basins (Adapted from Barnett et al. 2005; Reprinted with permission from AAAS). (A) The blue hatched region represents the 90% confidence limits of modeled natural internal variability resulting from heat exchange among different ocean basins. The observed record of temperature change (red dots) bears little resemblance to that expected from internal variability. The strength of the warming trend forced by observed solar and volcanic variability (green triangles) shows little agreement with the observed climate trend. (B) The modeled human-induced forcing from greenhouse gases and sulfate aerosols (green hatched region) shows substantial fingerprint matching with the observed heat penetration (red dots).

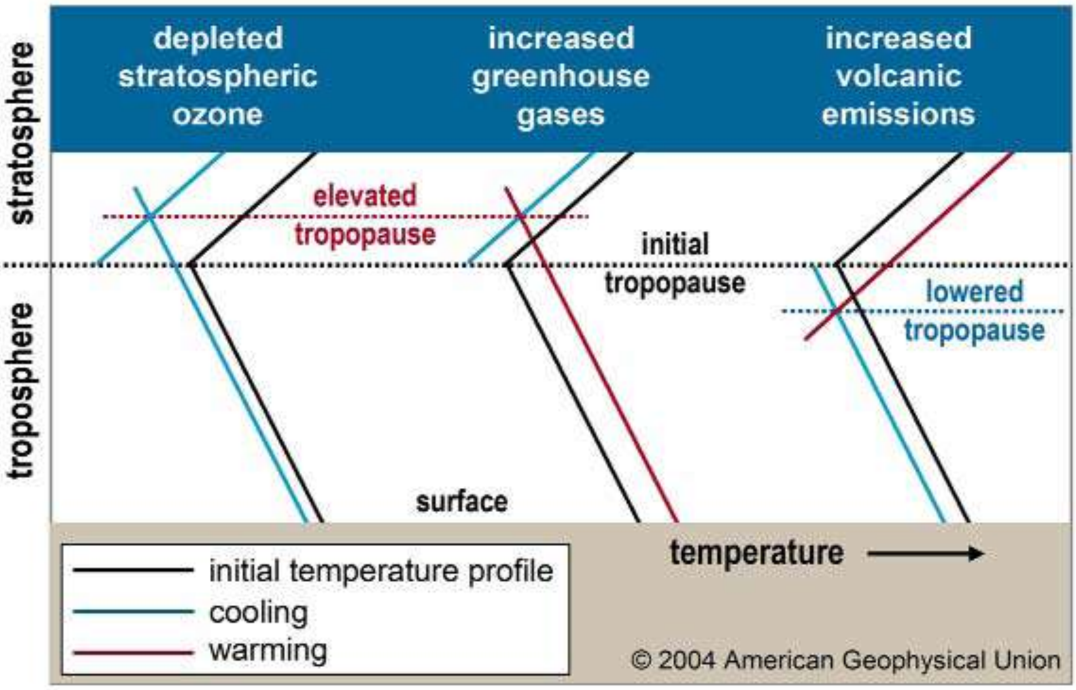

Figure 6. Conceptual model for the effects of three different forcings on tropopause height (Adapted from Santer et al. 2004). The solid black lines are the baseline atmospheric temperature profiles. Forcing by either stratospheric ozone depletion or increases in well-mixed atmospheric greenhouse gases increase tropopause height; volcanic forcing decreases tropopause height.

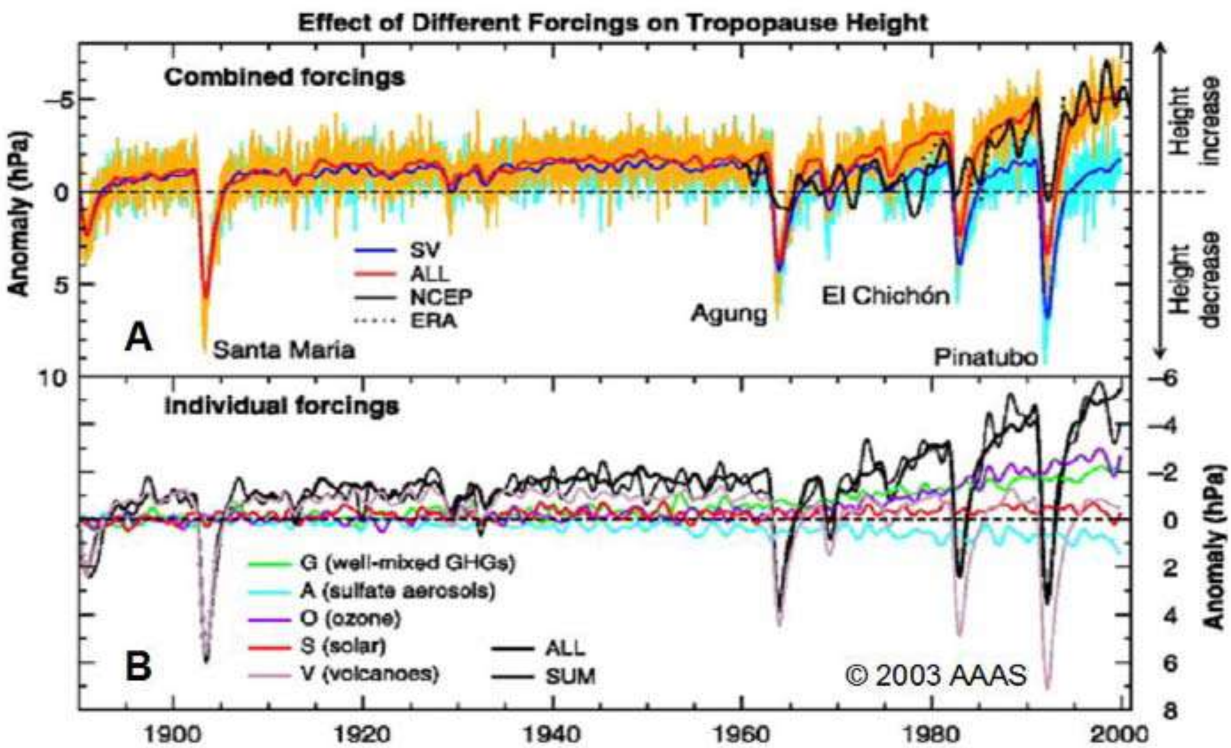

Figure 7. Global average change in tropopause height (From Santer et al. 2003; Reprinted with permission from AAAS). (A) Observations (NCEP and ERA) and model results driven by combined solar and volcanic forcing (SV) or combined natural and human-induced forcings (ALL). (B) Change in global

average tropopause height according to model results driven by individual forcings as compared to combined forcings (ALL and SUM). "ALL" refers to a single model realization with all forcings included. "SUM" refers to the sum of separate model realizations for individual forcings. Good agreement between ALL and SUM indicates that the influences of the different forcings are additive.

El Niño–Southern Oscillation (ENSO)

For hundreds of years, South American fishermen noticed the appearance of warm waters in the eastern Pacific Ocean along the coast of Ecuador and Peru. As the phenomenon typically appeared around Christmas time and lasted for several months, the name "El Niño" (El Niño is Spanish for "the little boy"), or the Christ Child was coined. El Niño events usually alternate with the opposite phase of below-normal water temperatures in the eastern & central tropical Pacific. The following description is based on internet resources including Wikipedia.

El Niño is defined by prolonged differences in Pacific Ocean Sea surface temperatures when compared with the average value. The accepted definition is a warming or cooling of at least 0.5 °C averaged over the east-central tropical Pacific Ocean. Typically, this anomaly happens at irregular intervals of 3–7 years and lasts nine months to two years. The average period length is 5 years. When this warming or cooling occurs for only seven to nine months, it is classified as El Niño/La Niña "conditions"; when it occurs for more than that period, it is classified as El Niño/La Niña "episodes".

The first signs of an El Niño are:

- Rise in surface pressure over the Indian Ocean, Indonesia, and Australia
- Fall in air pressure over Tahiti and the rest of the central and eastern Pacific Ocean
- Trade winds in the south Pacific weaken or head east
- Warm air rises near Peru, causing rain in the northern Peruvian deserts

Warm water spreads from the west Pacific and the Indian Ocean to the east Pacific. It takes the rain with it, causing extensive drought in the western Pacific and rainfall in the normally dry eastern Pacific. El Niño's warm rush of nutrient-poor tropical water, heated by its eastward passage in the Equatorial Current, replaces the cold, nutrient-rich surface water of the Humboldt Current. When El Niño conditions last for many months, extensive ocean warming and the reduction in Easterly Trade winds limits upwelling of cold nutrient-rich deep water and its economic impact to local fishing for an international market can be serious.

Southern Oscillation

During the 1920s, Sir Gilbert Walker, recognized patterns to the rainfall in South America. His discovery led him to theorize additional associations with the change in the ocean temperatures, and with atmospheric pressure changes measured at stations at different parts of the Pacific (Darwin-Australia and Tahiti). Noticing that as the atmospheric pressure rises in the east, there is typically an accompanying decrease in pressure in the west, with the reverse also true, he coined the term Southern Oscillation to categorize his findings. Further study led to the realization that Asian monsoon seasons under certain barometric conditions were often linked to drought in Australia, Indonesia, India, and parts of Africa and mild winters in western Canada.

The Southern Oscillation is the atmospheric component of El Niño. This component is an oscillation in surface air pressure between the tropical eastern and the western Pacific Ocean waters. The strength of the Southern Oscillation is measured by the Southern Oscillation Index (SOI). The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin, Australia. El Niño episodes are associated with negative values of the SOI, meaning that the pressure difference between Tahiti and Darwin is relatively small.

Low atmospheric pressure tends to occur over warm water and high pressure occurs over cold water, in part because of deep convection over the warm water. El Niño episodes are defined as sustained warming of the central and eastern tropical Pacific Ocean. This results in a decrease in the strength of the Pacific trade winds, and a reduction in rainfall over eastern and northern Australia.

In the late 1960s, Jacob Bjerknes, a meteorologist, established connection between the changes in sea surface temperatures, the weak trade winds from the east and heavy rainfall that accompany low atmospheric pressure in eastern tropical pacific ocean. Bjerknes' discovery led to the understanding that the warm waters of El Niño and the pressure variance of Walker's Southern Oscillation are interrelated, leading to naming of the phenomenon as **"*El Niño Southern Oscillation*"** (ENSO). The term El Niño has now come to refer to a much larger scale phenomenon associated with warmer-than-normal waters that occasionally form across the eastern & central tropical Pacific.

ENSO is a quasiperiodic climate pattern that occurs across the tropical Pacific Ocean. The Southern Oscillation refers to variations in the temperature of the surface of the tropical eastern Pacific Ocean (warming and cooling known as El Niño and La Niña respectively) and in air surface pressure in the tropical western Pacific. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific.

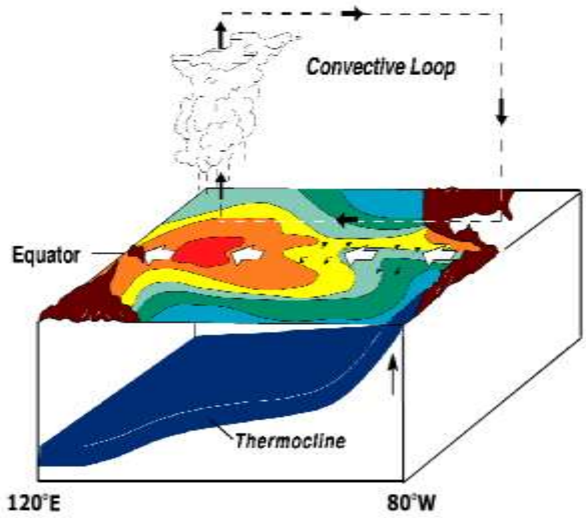	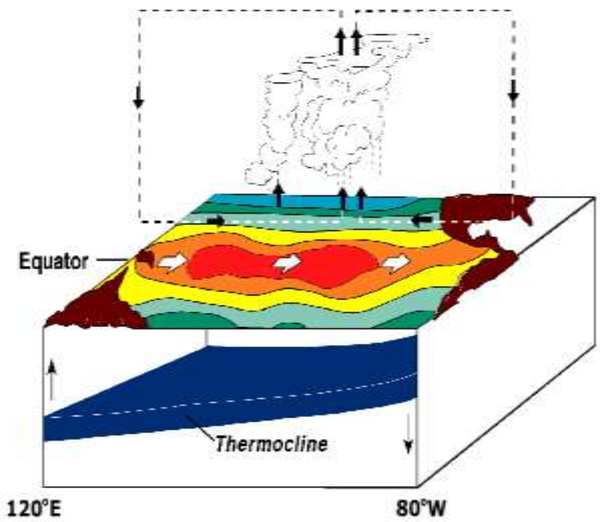
Normal Conditions: Winds from the east (indicated by white arrows) push water westward along the equator where solar radiation produces warmer sea surface temperatures. A convection circulation sets up producing abundant rain in the western tropical Pacific and drier conditions in the eastern tropical Pacific. Cold water upwells along South American coast.	**El Niño Conditions:** Winds from the west (indicated by white arrows) bring warmer water eastward. The convective circulation also shifts eastward producing abundant rains in the eastern and central tropical Pacific and drier conditions in the western tropical Pacific.Warm water pool approaches South American coast. Absence of cold upwelling increases warming.

Fig. Cross section in the tropical Pacific during normal and El Niño conditions.

Why El Niño Occurs ?

Although its causes are still being investigated, El Niño events begin when trade winds, part of the Walker circulation, falter for many months. A series of Kelvin waves—relatively warm subsurface waves of water a few centimetres high and hundreds of kilometres wide—cross the Pacific along the equator and create a pool of warm water near South America, where ocean temperatures are normally cold due to upwelling. The weakening of the winds can also create twin cyclones, another sign of a future El Niño. The Pacific Ocean is a heat reservoir that drives global wind patterns, and the resulting change in its temperature alters weather on a global scale. Rainfall shifts from the western Pacific toward the Americas, while Indonesia and India become drier.

Jacob Bjerknes in 1969 suggested that an anomalously warm spot in the eastern Pacific can weaken the east-west temperature difference, disrupting trade winds that push warm water to the west. The result is increasingly warm water toward the east. Several mechanisms have been proposed through which warmth builds up in equatorial Pacific surface waters, and is then dispersed to lower depths by an El Niño event. The resulting cooler area then has to "recharge" warmth for several years before another event can take place.

El Niño occurs perhaps due to changes in the normal patterns of trade wind circulation. Normally, these winds move westward, carrying warm surface water to Indonesia and Australia and allowing cooler water to upwell along the South American coast. For reasons not yet fully understood, these trade winds can sometimes be reduced, or even reversed. This moves warmer waters toward the coast of South America and raises water temperatures. Warmer water causes heat and moisture to rise from the ocean off Ecuador and Peru, resulting in more frequent storms and torrential rainfall over these normally arid countries.

Some Facts on El Niño

1. El Niño is the second largest driver of the world's weather, second only to normal seasonal warming and cooling, which also induces changes in precipitation patterns.
2. El Niños appear approximately every two to seven years. They typically last 12 to 18 months. In the early 1990s, a protracted El Niño persisted for four years.
3. El Niños have been documented since the early 1700s. More detailed observations from ships led to instrumental record keeping in the earlier half of the twentieth century. It is only since the 1970s, however, that scientists began linking El Niño to massive flooding and severe droughts around the world.
4. About every four to five years, a pool of cooler-than-normal water develops off South America. The effects of this cooler water are called La Niña. This usually brings colder winters to the Canadian west and Alaska and drier, warmer weather to the American southeast.

La Niña

La Niña (or the little girl), is the appearance of cooler than normal waters in the eastern and central Pacific Ocean. La Niña is the name for the cold phase of ENSO, during which the cold pool in the eastern Pacific intensifies and the trade winds strengthen; it is the antithesis of El Niño. A connection between La Niña, El Niño, and other weather patterns is yet to be established.

Why La Niña Occurs ?

La Niña is thought to occur due to increases in the strength of the normal patterns of trade wind circulation. Under normal conditions, these winds move westward, carrying warm surface water to Indonesia and Australia and allowing cooler water to upwell along the South American coast. For reasons not yet fully understood, periodically these trade winds are strengthened, increasing the amount of cooler water toward the coast of South America and reducing water temperatures. The increased amount of cooler water toward the coast of South America, causes increases in the deep cloud buildup towards southeast Asia, resulting in wetter than normal conditions over Indonesia during the northern hemisphere winter.

The changes in the tropical Pacific are accompanied by large modulations of the jet stream within the middle latitudes, shifting the point at which the stream normally crosses North America. The shifted jet stream contributes to large departures from the normal location and strength of storm paths. The overall changes in the atmosphere result in temperature and precipitation anomalies over North America which can persist for several months.

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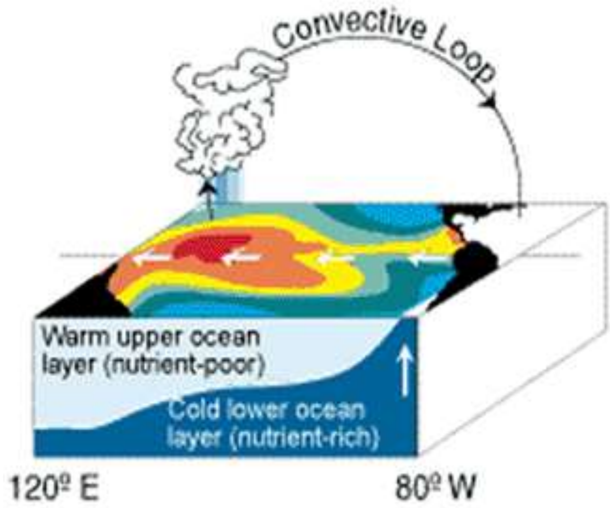
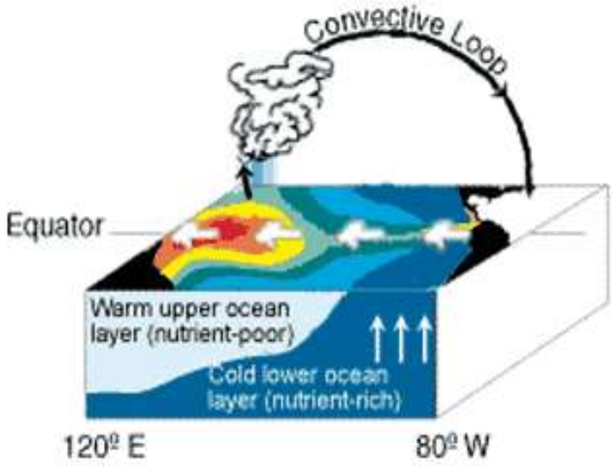
<td>

Normal Conditions: Winds from the east (indicated by white arrows) push water westward along the equator where solar radiation produces warmer sea surface temperatures. A convection circulation sets up producing abundant rain in the western tropical Pacific and drier conditions in the eastern tropical Pacific.</td>
<td>

La Niña Conditions: Winds from the east (indicated by white arrows) push water westward along the equator allowing deep sea cold waters to upwell along the coast of south America. Warmer-than-normal sea surface temperatures give rise to cloudiness in the western tropical Pacific. A convection circulation sets up producing abundant rain in western tropical Pacific and drier conditions in the eastern tropical Pacific.</td>
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Fig. Cross section in the tropical Pacific during normal and La Niña conditions.

The extremes of this climate pattern's oscillations, El Niño and La Niña, cause extreme weather (such as floods and droughts) in many regions of the world. Developing countries dependent upon agriculture and fishing, particularly those bordering the Pacific Ocean, are the most affected.

El Niño and Climate Change

Climate scientists are questioning whether climate change, as a result of anthropogenic effects such as the enhanced greenhouse effect, may be affecting the observed increase in strength and frequency of El Niño events since the late 1970s. These changes in El Niño are likely a reflection of warming of the eastern equatorial Pacific. In response to greenhouse gas increases, some model simulations show an increase in ENSO variability while others exhibit no significant increase. Thus, as yet there is no consistent picture of how ENSO variability might be expected to change in response to enhanced greenhouse gases. Further research is needed before scientists can provide confident answers.

RAINFALL TRENDS IN INDIA

Many studies have attempted to determine the trend in the rainfall on the country and regional scales. Most of these deal with the analysis of annual and seasonal series of rainfall for some individual stations or groups of stations. Some past studies related to changes in rainfall over India have concluded that there is no clear trend in average annual rainfall over the country. Though the monsoon rainfall in India exhibited no significant trend over a long period of time, particularly on the all India scale, pockets of significant long-term rainfall changes were identified in some studies.

Trend analysis of rainfall data of 135 years (1871-2005) indicated no significant trend for annual, seasonal and for any monthly rainfall on all-India basis (Kumar et al., 2010). Annual and monsoon rainfall decreased and pre-monsoon, post-monsoon and winter rainfall increased over the years, with maximum increase in pre-monsoon season. Monsoon months of June, July and September witnessed decreasing rainfall whereas August showed increasing trend on all-India basis. Further, analysis on sub-divisional basis (30 sub-divisions) indicated that half of them have increasing trend in annual rainfall but for only three sub-divisions namely Haryana, Punjab and Coastal Karnataka, this trend was statistically significant. Only the Chattisgarh sub-division had significant decreasing trend out of the 15 sub-divisions showing decreasing trend in annual rainfall. All the five regions showed non-significant trend in annual, seasonal and monthly rainfall for most of the months.

Kumar and Jain (2010b) carried out a detailed analysis to determine the trends in rainfall amount and number of rainy days in Indian river basins by using daily gridded rainfall data at $1^{o}\times 1^{o}$ resolution provided by the IMD. The magnitude of trend in annual and seasonal rainfall and rainy days was determined by the Sen's estimator. Six river basins had increasing trend in annual rainfall and fifteen river basins had the opposite trend whereas the Ganga basin had no trend. The increasing/decreasing trends for majority of the basins were non-significant. In the case of annual rainy days, 4 river basins had increasing trend, 15 river basins had decreasing trend and 3 had no change. The decreasing trend in annual rainy days in Godavari, WFR2 (West flowing river south of Tadri) and EFR5 (East flowing river south of Cauvery) river basins are statistically significant at 95% confidence level.

Analysis of seasonal trends shows that pre-monsoon rainfall increased over 9 river basins and decreased over 13; monsoon rainfall increased over 6 basins and decreased over 16; post-monsoon rainfall increased over 13 basins and decreased over 8; and winter rainfall increased over 18 basins and decreased over 2 of them. The Ganga basin, with no change in annual rainfall, has experienced a small decreasing trend in the monsoon and post-monsoon rainfall. There is some notion of weakening summer monsoon and strengthening in winter monsoon. In the seasonal rainy days, 4 river basins each in pre-monsoon, monsoon and post-monsoon season and 2 in winter season experienced an increasing trend. Eleven river basins in pre-monsoon, 3 in monsoon, 10 in post-monsoon and 19 in winter did not show change in rainy days.

Trends and magnitude of changes in annual rainfall and rainy days in terms of percentage of mean per 100 years for basins are shown in Fig. 3 (Kumar and Jain, 2010b). Direction of trend in rainfall and rainy days was similar for most river basins. For annual data, Mahanadi and Krishna have experienced decreasing trend in annual rainfall and increasing trend in rainy days, which means that droughts may become more recurrent in Krishna (a water stressed basin) whereas Barak+ and EFR4 (East flowing river between Pennar and Cauvery) have experienced increasing rainfall and decreasing rainy days which implies that floods may become more intense. Similarly, in the monsoon season, Barak+ and Brahmani, Baitarni & Subernarekha (BBS) (+ve trend in rainfall and –ve in rainy days) and Krishna (-ve trend in rainfall and +ve trend in rainy days) have experienced the opposite trend in rainfall and rainy days. Similar to annual data, these trends are non-significant.

EXTREME RAINFALL TRENDS IN INDIA

Using high resolution daily gridded rainfall data for the period 1951-2003, Goswami et al. (2006) showed that there are significant rising trends in the frequency and the magnitude of extreme rain events over central India (CI) during the monsoon season. They also found significant decreasing trend in the frequency of moderate events during the same period, thus leading to no significant trend in the mean rainfall. The results of this study were contradicted for some places in CI when analysis was performed at a finer resolution (1◦ latitude × 1◦ longitude) by Ghosh et al. (2009).

Variability and long-term trends of extreme rainfall events over central India was examined by Rajeevan et al. (2008) using 104 years (1901–2004) of high resolution daily gridded rainfall data. They found statistically significant long term trend of 6% per decade in frequency of extreme rainfall events. According to them, the increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend of sea surface temperatures and surface latent heat flux over the tropical Indian Ocean.

The long-term trend in monsoon season extreme rainfall events for 1951–2005 was analysed by Pattanaik and Rajeevan (2010). The average frequency of extreme rainfall events along with the contribution of extreme rainfall events to the seasonal rainfall showed a significant increasing trend (above the 98% confidence level) over India during monsoon season and also during June and July. It was also found that the increasing trend of contribution from extreme rainfall events is balanced by a decreasing trend in low rainfall events.

Kothawale et al. (2010) also investigated the association between El Niño Southern Oscillation (ENSO) and monsoon rainfall over India and reported a strong association between El Niño events and deficient monsoon rainfall. Nearly 60% of major droughts over India have occurred in association with El Niño events. Strong association between monsoon droughts and

El Niño events was noted by the authors. On the other hand, La Niña events were associated with more rainfall during monsoon and cooling. Earlier, Krishna Kumar et al. (1999) had shown that the relation between the Indian monsoon and ENSO weakened in recent decades.

TEMPERATURE TRENDS IN INDIA

The surface temperatures over a given region vary seasonally and annually depending upon latitude, altitude, and location in respect of geographical features such as a water body (river, lake, or sea), mountains, etc. Probably one of the most widely quoted aspect of climatic change and the one that will have important ramifications on a range of sectors including water is the significant increase in the global mean air temperature during the past century. Since the hydrologic cycle is a thermally driven system, rise in global temperature is likely to accelerate this cycle. Identification of the temperature trends and their projection has been the subject matter of a large number of studies.

The monthly maximum and minimum temperature data from 121 stations well distributed over the country for the period 1901–2007 were used by Kothawale et al. (2010) and from these data, they computed seasonal and annual trends in surface air temperature over the country and seven homogeneous regions (western Himalaya, northwest, north-central, northeast, east coast, west coast and interior peninsula) during 3 periods: 1901–2007, 1971–2007 and 1998–2007. Key findings of this comprehensive study are described here:

a) annual mean (average of maximum and minimum), maximum and minimum temperatures showed significant warming trends of 0.51, 0.72 and 0.27°C 100/year, respectively, during 1901–2007. The temperature has increased gradually and continuously over this period. This warming was mainly due to increasing temperatures in the winter and post-monsoon seasons. During the three decades from 1971 to 2007, annual mean temperature increased by 0.20°C per decade due to significant increases in both maximum and minimum temperatures. Also, increase in minimum temperature was much steeper than the maximum temperature. On the whole, winter and summer monsoon temperatures showed a significant increasing trend over almost the entire country, while post-monsoon temperatures significantly increased over relatively smaller number of regions.

b) On larger spatially aggregated scales, the temperature trends in India were found to be quite consistent and in agreement with global and hemispheric trends. However, on smaller regional scales and for different sub-periods, trends were not always consistent with Indian aggregated temperatures. Further, the trends were also influenced by the variability of rainfall in the monsoon and post-monsoon seasons. It was opined that the recent temperature changes in some parts of the country may also be due to the relative influence of greenhouse gases and aerosols.

c) Accelerated warming was observed during 1971–2007 and this was attributed mainly to intense warming in the decade 1998–2007. During 1998–2007, maximum temperature was significantly higher compared to the long-term (1901–2007) mean throughout India, with a stagnated trend during this period, whereas minimum temperature showed an increasing trend, almost equal to that observed during 1971–2007. It is pertinent to note that recently, the year 2010 has been reported to rank in the top three warmest years since the beginning of instrumental climate records in 1850, according to data sources compiled by the World Meteorological Organization (WMO).

d) On the seasonal scale, maximum temperature has significantly increased in all seasons during the period 1901–2007. On this scale, pronounced warming trends in mean temperature were observed in two seasons – winter and monsoon. However, for the recent period only, winter and post-monsoon temperatures showed significant warming trends and the other seasons showed a warming tendency (trend not significant). In contrast, minimum temperature showed a significant warming trend in most seasons during 1971–2007.

e) The global mean annual and seasonal (DJF, MAM, JJAS and ON) temperatures have significantly increased by 0.82, 0.89, 0.94, 0.72 and 0.76°C per 100 years, respectively, during the period 1901–2007. Indian mean annual and seasonal temperatures also showed a significant warming trend in all seasons. The magnitude of the warming trend of winter and post-monsoon seasons was almost the same for these two areas, while pre-monsoon and monsoon temperature trends for India were half that of the global trend (Fig. 4).

Kothawale et al. (2010) concluded that on inter-annual time scales, Indian mean temperatures are strongly correlated with SST in the eastern Pacific and the equatorial Indian Ocean. A strong interannual link between Indian temperatures and Indian Ocean SST was found. ENSO was found to be impacting Indian temperatures significantly. The composite maximum temperature anomalies of El Niño years were statistically significant and positive during monsoon and post-monsoon seasons over large areas of the country and the composite anomalies of La Niña years were almost opposite to El Niño years. Interestingly, the year 2010 was special for climate scientists since El Niño conditions prevailed in the tropical Pacific for the first four months but it quickly changed and a La Niña pattern had emerged by June.

7. IMPACT OF CLIMATE CHANGE ON INDIAN WATER RESOURCES

Availability of numerous water bodies and perennial rivers systems makes Indian sub-continent one of the wettest places in the world after South America. In India, large Himalayan Rivers including Indus, Ganga and Brahmaputra are perennial sources of fresh water though the flow is reduced during non-monsoon periods. The south peninsular are solely dependent on the monsoon rainfall and ground water recharge. Changes in temperature, precipitation and other climatic variables are likely to influence the amount and distribution of runoff into India river systems. The impact of future climatic change is expected to be more severe in developing countries such as India whose economy is largely dependent on the agriculture and is already under stress due to population increase and associated demands for energy, fresh water and food. The physical impacts of climate change are coupled with societal issues and management practices. The status of studies shows that the possible impacts of climatic changes on various aspects of hydrological cycle are not much studied in India.

Water resources are sensitive to the climate change. Temperature drives the hydrological cycle, influencing hydrological processes in a direct or indirect way. A warmer climate may lead to intensification of the hydrological cycle, resulting in higher rates of evaporation and increase of liquid precipitation. These processes, in association with a shifting pattern of precipitation, may affect the spatial and temporal distribution of runoff, soil moisture, groundwater reserves etc. and may increase the frequency of droughts and floods. The future climatic change, though, will have its impact globally but likely to be felt severely in developing countries with agrarian economies, such as India. Surging population, increasing industrialization and associated demands for freshwater, food and energy would be areas of concern in the changing climate scenarios. Increase in extreme climatic events will be of great consequence owing to the high vulnerability of the region to these changes. Water resources will come under increasing pressure in the Indian subcontinent due to the changing climate.

The Himalayan region, called the "*Water Tower of Asia"*, supports 9575 glaciers in India having an area of about 18000 km^2 and a volume of about 1300 km^3. The main river basins fed by glaciers are the Indus, the Ganga and the Brahmaputra. The importance of these river systems can be understood from the fact that these three river systems contribute more than 60% to the total annual runoff from all the rivers of India. These river systems hold immense potential as a future freshwater source and drain the major plains of the country. These major river systems consist of substantial contribution from the melting of snow and glaciers. The runoff of the Himalayan rivers is expected to be highly vulnerable to climate change because warmer climate will increase the melting of snow and ice. Melting of glaciers, reduction in solid precipitation in mountain regions would have direct impact of water resources affecting the drinking water, irrigation, hydropower generation and other applications of water. Glacial melt is expected to increase under changed climate conditions, which would lead to increased summer flows in some river systems for a few decades, followed by a reduction in flow in case glaciers retreat continuously.

The river systems of central, western and southern India are charged by groundwater and their flows are reinforced by the seasonal rainfall. The water potentials of these non- snow and glacier fed rivers are strongly associated with the conditions of monsoons. A poor monsoon rainfall leads to drought conditions and situation is further aggravated if monsoon fails for consecutive years and back-to-back drought occurs. Studies carried out on 12 river basins of India using SWAT model indicated that as a result of global warming, the conditions may deteriorate in terms of severity of droughts in some parts of the country and enhanced intensity of floods in other parts. A general overall reduction in the quantity of the available runoff is expected under the GHG scenario.

It is likely that the frequency of floods and droughts will increase during 21st century due to projected climate change, which would enhance the severity of water extreme events and may prove the greater challenge to society. Changes in the amount of rainfall, rainfall patterns and intensity would affect stream flow and the demand for water. According to country's report to the United Nations Framework Convention on Climate Change (UNFCCC), the global climate change is likely to result in severe droughts and floods in India - and have major impacts on human health and food supplies. High flood levels can cause substantial damage to key economic sectors: agriculture, infrastructure and housing. Although floods affect people of all socio-economic status, the rural and urban poor are hardest hit. Flood and drought management schemes have to be planned keeping in view the increase in severity of floods and droughts. It would be prudent to incorporate possible effects of climate changes in the design and management of water resources systems. The high magnitude floods are likely to bring more sediment and even dam failures. The design and management of both structural and non-structural water-resource systems should allow for the possible effects of climate change. It is clear that flood and drought management schemes have to be planned keeping in view the increase in severity of floods and droughts and expected changed climatic scenarios over the country. Despite these uncertainties, it is clear that even the possibility of changes in such extreme events is quite alarming.

Impact of climate changes on the ground water regime is also expected to be severe. It is to be pointed out that groundwater is the principle source of drinking water in the rural areas. About 85% of the rural water supply in India is dependent on groundwater. The projected climate change resulting in warming, sea level rise and melting of glaciers will adversely affect the water balance in different parts of India and quality of ground water along the coastal plains. Climate change is likely to affect ground water due to changes in precipitation and evapotranspiration. Rising sea levels may lead to increased saline intrusion into coastal and island aquifers, while increased frequency and severity of floods may affect groundwater quality in alluvial aquifers. Increased rainfall intensity may lead to higher runoff and possibly reduced recharge.

The water resources of the country are likely to be affected due to climate change. The adaptation strategies have to be considered in the water resources sector in view of these changes. Studies are required to be taken up for developing the modified methodologies for the assessment of water resources, hydrological design practices, flood and drought management, operation policies for the existing as well as proposed water resources projects and assessment of available water for irrigation including the land uses and cropping patterns.

Most of the studies carried out for projecting futuristic scenarios of water resources for different basins are very preliminary. The consequences of changes in climate on Indian water resources are poorly understood. It is felt to standardize the regional future climatic scenarios on regional/basin scale. Using these scenarios, an assessment of water availability in different basins in the context of future requirements taking particular account of the multiplying demands for water is critical for resource planning and sustainable development as a basis for economic and social development has to be carried out.

Issues on climate change impact on water resources

1. Determining extent of current climatic/hydro-meteorological variability and future projections in variability due to climate change including the impact on rainfall frequency and intensity.
2. Reliable downscaling of GCM (Global Circulation Model) projections to regional and basin level
3. Improvement required in hydro-meteorological network design for adaptation
4. Assessment of impact on surface and ground water interaction with specific emphasis on coastal areas
5. Impact of Climate Change on LandUse/LandCover and their coupled impact on water resources
6. Impact on Intensity-Duration-Frequency relationships in Urban Areas
7. Impact on magnitude-duration-frequency of drought (Agricultural, meteorological and hydrological)

8. Impact on sediment loads and their management implications

Issues on mitigation/adaptation measures

Some of the studies in this category may include

1. Updating the basin wise water availability
2. Coping with the variability in the water sector through development and regulation
3. Review of hydrological design and planning criteria under the changed scenario
4. Study of Water-Energy-Climate change relationships
5. Development of databases and associated tool-boxes for Integrated Water Resources Management (IWRM)

Summary

Scientific understanding of the causes of climate change has progressed dramatically in the past few years. Natural internal variability is an inherent feature of the climate system, but it cannot account for the net gain of energy that has been detected within the climate system as a whole. Based on physical principles, the modern increase in the heat content of the global ocean demonstrates that positive external forcing of the climate is underway. Changes in natural external forcings cannot explain the observed global warming of recent decades. Records of observed climate change at the earth's surface, in the global ocean, and in the atmosphere, bear the fingerprint of the enhanced greenhouse effect, which is caused by human activities associated with fossil fuel burning and land use.

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- projected over all states except Punjab, Rajasthan and Tamil Nadu, which show a slight decrease.
- Extreme rise in maximum and minimum temperatures is also expected and similarly extreme precipitation is also projected, particularly over the West Coast of India and West Central India.

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