Sea Level Rise due to Global Warming and Climate Variability

P. C. SINHA
Centre for Atmospheric Sciences
Indian Institute of Technology, New Delhi
E-mail: pcsinha@cas.iitd.ernet.in

Abstract

Global warming is likely responsible for the rising sea. Scientists have noticed an increase of greenhouse gasscs in our atmosphere, which help regulate the earth's temperature. The estimated 10% inciease over the last century is enough to altei the world's average temperature by 1-4 degree C. This increase causes the world's oceans to get warmer which will raise the entire world's atmospheric temperature.

Sea level rise is one of the projected changes that will accompany global waiming. Recent measurements show a sea-level rise of about 1 to 2 millimetres per year in the last century. Warmer temperatures are expected to raise sea level by expanding ocean water, melting mountain glaciers, and melting parts of the Greenland Ice Sheet. Global warming is also expected to increase the frequency of tropical cyclones, which have important bearing on the instantaneous sea level rise, the so-called storm surges. These sudden rises in the sea level can now be estimated quite accurately by several models which have been developed for many parts of the World. On such model which have been developed at IIT Delhi for the Bay of Bengal and the Arabian Sea of being used on an operational basis.

Climate influences sea level in two ways by moving the earth's water between glaciers and by changing the temperature of the ocean water and hence its volume. A warmer climate could also raise the sea even without any contribution from glaciers, although a warming of the entire ocean would take several centuries, the upper layers could warm and raise sea level as much as a meter by 2100. This shorter-term effect of a global warming is frequently overlooked..

Introduction

Global warming has emerged as one of the most important environmental issues ever to confront humanity. 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 coming years and whose possible effects would be mostly adverse.

According to the National Academy of Sciences, the Earth's surface temperature has risen by about 0.3-O.6°C (1°F) m the past century, with accelerated warming during the past two decades. There is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities. These activities have altered the chemical composition of the atmosphere through the buildup of greenhouse gases - primarily carbon dioxide, methane, and nitrous oxide. The heat trapping property of these gases is undisputed although uncertainties exist about exactly how earth's climate responds to them.

Assuming that all the effects of global wanning actually do occur, the consequences for the world economy for global warming - and hence for the insurance industry - are likely to be dramatic. The number and intensity of meteorological catastrophes will increase which means stronger circulation in the atmosphere and presumably also in the ocean. Tropical storms will be more frequent and more intensive, and their path will extend increasing towards the poles. At the same time there will be heavier rainfall, more serious floods and greater number of thunderstorms, hailstorms and tornadoes.

Sea level rise is one of the projected changes that will accompany global warming. Recent measurements show a sea-level rise of about 1 to 2 millimetres per year or 100 millimetres in the last century. Sources of error in these measurements come from intra-annual variations due to changing meteorological conditions, such as persistence of wind from a particular direction or at a particular speed. For instance, a stronger than normal wind from the west will cause an apparent sea level rise on the west coast of continents and lower sea level on the east coasts. A similar artificial change in sea level could arise from persistently anomalous ocean circulation. By use of historical records and numerical models, the contribution from these sources can be removed to more accurately reveal actual sea-level rise.

Also, a rise in temperature is likely to change cyclone activity; cyclone intensity, if not cyclone frequency, may increase. As a result, storm surges may also increase substantially. Sea-level rise, increase in cyclone intensity, and consequent increases in storm surge heights will have disastrous effects on a deltaic country like Bangladesh, which has several thickly populated islands many of which are not much above the mean sea-level. Many areas in and around the pacific will also have to face a severe increase in exposure. Billions of dollars will have to be spent on coastal defences to keep pace with these developments. Agricultural and forestry conditions will also change. In some areas they will be improved, not only because the climate will be warmer and moister but also on account of the higher concentration of carbon dioxide in then an Plants will not only grow better as result leading to an improvement in the harvest yields but will also make better use of the available water supply.

Global Warming

The term global warming describes the observed and projected increase in globally averaged temperatures over time. Because the global climate is a dynamic system, global warming has occurred in the past and will occur in the future. Using surface station temperature measurements and satellite based measurements researcher have identified an increasing trend in the global average surface an temperatures .The Intergovernmental Panel on Climate Change has determined that this increase can be attributed to a combination of natural climate variations and human factors. One of the leading causes undei investigation is the greenhouse effect of gasses in the atmosphere.

Climate modelling studies generally estimate that global temperatures will rise a few degrees Celsius (°C) in the next century Such a warming is likely to raise sea level by expanding ocean water, and melting glaciers and portions of the Greenland Ice Sheet .Warmer polar ocean temperatures could also melt poitions of the Ross and othei Antarctic ice shelves, which might increase the late at which Antarctic ice streams convey ice into the oceans. Warmer polar air temperatures however, would probably increase annual snowfall, which would partly offset the rise in sea level caused by warmer temperatures. Along much of the United States coast sea level is already rising 2. 5- 3.0 mm/yr (25.4 to 30.48 cm per century).

By ratifying the United Nations Framework Convention on Climate Change, more than 120 countries have agreed to implement measures for adapting to rising sea level and other effects of changing climate. Because the design and location of coastal structures involve decisions that cannot be easily reversed, people responsible for these activities must either plan now or risk losing the opportunity for a meaningful response. Nevertheless, the value of planning for sea level rise depends upon the probability that the sea will rise by a given magnitude.

Figure. 1. shows a probability based projection that can be added to local tide gauge trends to estimate future sea level at particular locations. It uses the same models employed by previous assessments of sea level rise. The key coefficients in those models are based on subjective probability distributions supplied by a cross section of climatologists oceanographers and glaciologists. The experts who assisted this effort were mostly authors of previous assessments

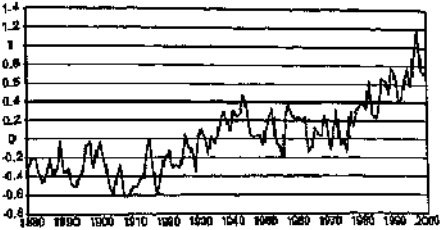

Fig. 1. *Global Temperature Changes (1980 - 2000).*
(Source:. US National Climatic Data Centre, 2001)

by the- National Academy of Sciences and the Intergovernmental Panel on Climate Change (IPCC, 1990).

Global mean surface temperatures have increased 0.2-0.5°C (0.5-1.0°F) since the late 19th century. The 20th century's 10 wannest years all occurred in the last 15 yeats of the century. Of these, the snow cover in the Northern Ilemisphcic and floating ice in the Arctic Ocean have decreased. Globally, sea level has risen 10.16-20.32 cm over the past century.

'['he evidence that human-induced global warming is real is increasingly clcai and compelling.

» Since **the** late 19th cenluiy, the mean surface temperature ot the earth Has :.........,.,,,! I,,, ..Kmil m-0 *f\°C. (I"* Ft.

• Over the last 40 years, which is the period with most reliable data, the temperature increased by about 0.2-0.3°C (0.5[s] F).

« Warming in the 20lh century is greater than al any time during the past 400-600 years.

• Seven of the ten warmest years *m* the 20th eentury occurred in_ the 1990s

measurements began.

in addition, changes m the natural environment support the evidence trom temperature records:

- mountain glaciers the world over are receding;
- the Arctic ice pack has lost about 40% of its thickness over the past four decades;
- the global sea level is rising about three times faster over the past 100 years compared to the previous 3,000 years; and
- there are a growing number of studies that show plants and animals changing their range and behaviour in response to shifts in climate.

As the Earth continues to warm, there is a growing risk that the climate will change in ways that will seriously disrupt our lives. While on average the globe will get warmer and receive more precipitation, individual regions will experience different climatic changes and environmental impacts. Among the most severe consequences of global warming are:

- a faster rise in sea level,
- more heat waves and droughts, resulting in more and more conflicts for water resources;
- more extreme weather events, producing floods and property destruction; and
- a greater potential for heat-related illnesses and deaths as well as the wider spread of infectious diseases carried by insects and rodents into areas previously free from them.

If climatic trends continue unabated, global warming will threaten our health, our cities, our farms and forests, beaches and wetlands, and other natural habitats.

The Impact of Global Warming in Asia

Over the past decade, emissions of the greenhouse gases suspected to be leading to global warming have only increased. According to official figures, the Canadians are up 31 per cent over the 1990 figures, Spain is up 22 per cent, France is up 13 per cent, Australia and New Zealand are up nine per cent each. According to 1990 figures, the US contributed 36 per cent of developed country emissions and this, too, has been going up.

Yet, despite the scientific uncertainty still surrounding the specifics of climate change links, the estimates are scary. Kirit Parikh of the Indira Gandhi Institute of Development Research says that a 2.5-4.9°C rise in temperatures could cut rice yields by between 15 and 42 per cent, and wheat yields by between 25 and 42 per cent.

Similarly, a one-metre rise in sea levels may hit India hard: A loss of 5,763 sq km land and 7.5 lakh houses, displacement of seven million people, loss of 4,000 km road network. In Bangladesh, it could lead to the displacement of 30-40 million people.

The Asian region spans polar, temperate, and tropical climates and is home to over 3 billion people. As the climate warms, many mountain glaciers may disappear, and the northern forests are likely to shift further north. Rapid population growth and development in countries like China and India will put additional pressures on natural ecosystems and will lead to a rapid rise in the release of greenhouse gases into the atmosphere unless steps are taken to curtail emissions.

Increasing Frequency and severity of Catastrophes

In the last couple of decades the frequency and magnitude of natural and/ or human-induced catastrophes has increased dramatically. Each month brings data on between twenty and fifty new loss events. Fortunately, only a few of these have to be added to the list of major catastrophes or those involving damage that requires substantial natural or international aid. This is generally the case if the number of dead runs into the hundred or thousands, if tens or hundred of thousands of people are rendered homeless and if the total economic loss approaches US$ 100 million. These catastrophes, about which we have fairly comprehensive data for those that occurred many years ago, numbered only fourteen in the 1960s but seventy in the 1980s; they therefore increased over a period of 30 years by a factor of five. The trend is also very clear when we consider the total economic loss, which - adjusted for inflation - increased during the same period from an average of US$3.7 billion per years to US$11.4 billion, i.e. by a factor of 3.1. The insured losses, finally, increased by as much as a factor of 4.8.

Sea Level Rise

Global warming is likely responsible for the rising sea. Scientists have noticed an increase of greenhouse gases in our atmosphere. Greenhouse gases cause the infrared rays emitted by the earth, in response to the sun's radiation, to reflect back to the earth's surface and increase the surface temperature. Greenhouse gases are found naturally and help regulate the earth's temperature. However, the estimated 10% increase over the last century is enough to alter the world's average temperature by an estimated 1-4°C. This increase causes the world's oceans to get warmer as well. The oceans of the world play a large role in stabilizing the entire world's atmospheric temperatures. Therefore when the ocean's temperatures increase, this causes an increase of overall temperatures as well.

This overall increase in temperatures of the oceans and the atmosphere influences the polar ice caps found on the north and south poles. As the temperatures increase it causes these ice caps to melt .In addition, over the last decade this glacial retreat has been observed all over the world Montana (US) Austria Himalayas (India) and Antarctica are just a few sites where recorded glacial retreats have been recorded in the last five years. As these glaciers melt they add large volumes of water to the oceans causing sea level rise Sea level also increases as seawater warms and expands.

Warmer temperatures are expected to raise sea level by expanding ocean water melting mountain glaciers and melting parts of the Greenland Ice Sheet. Warmer temperatures also increase precipitation Snowfall over Greenland and Antarctica is expected to increase by about 5 percent for every 0.3- 0.6°C (I°F). warming in temperatures Increased snowfall tends to came sea level to drop if the snow does not melt during the following summer because the only other place for the water to be is the ocean (The amount of water in the atmosphere is less than the water it takes to raise the oceans by one millimeter) .Considering all of these factors the IPCC estimates that sea level will use 9 to 88 cm by the year 2100 (figure 2) .A recent EPA study estimated that global sea level has a 50 percent chance ot using 45 cm (1- 1/2 ft) by the year 2100, but a 1- in -100 chance of a use of about 110 cm (over 3- 1/2 ft).

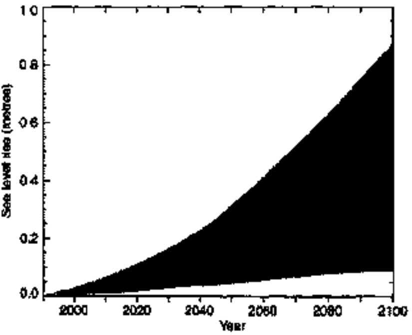

Fig. 2. *Estimate of Sea level use.*

The estimates of sea level rise are somewhat lower than those published by previous IPCC assessments, primarily because of lower temperature projections. This report estimates that global temperatures are most likely to rise 1°C by the year 2050 and 2°C by the year 2100, that there is a 10 percent chance that temperatures will rise more than 4°C in the next century, and a 90 percent chance that they will rise by at least the 0.6°C warming of the last century. By contrast, IPCC (1992) estimated that a warming of 2 8°C was most likely.

Sea Leval Rise Due to Tropical Cyclones

The global warming is expected to increase the frequency of the cyclones and their intensity which are responsible for a sudden rise in the sea level.

North Indian Ocean is one of the regions in the world which is frequently affected by storm surges associated with tropical cyclones. Statistics show that about 15 % of the global tropical cyclones form over the Bay of Bengal and the Arabian Sea, and on an average, 5 to 6 storms form in this region every year. Winds associated with tropical cyclones are the main driving force for accumulation of the water on the shoreline, which in turn, results in a sudden and substantial rise in sea level. This abnormal rise in sea level above the astronomical tide, which reaches a maximum on the coast, normally at the time of the landfall of the cyclone, is called storm surge. Storm surges are atmospherically forced oscillations of the water level in a coastal or inland water body, in the period range of a few hours to a few days, depending upon the speed of the cyclone. If the occurrence of storm surge coincides with normal astronomical tide the total rise in the water level may be spectacular. Storm surges cause heavy loss of life and property, damage to coastal structures, harbours, oil rigs and other residential complexes close to the coast. Most of the world's greatest human disasters associated with tropical cyclones have been directly attributed to the coastal flooding associated with storm surges.

A surge is caused by the interactions of air, sea and land. The cyclone provides the driving force in the form of a very high horizontal atmospheric pressure gradient and very strong winds. As a result the sea level rises and continues to rise as the cyclone approaches the shallow water, and reaches a maximum on the coast near the point of landfall.

The storm surge at any place may be divided into three stages: forerunner, the mam surge, and resurgence. A forerunner is the gradual rise of sea level preceding the storm; even when the cyclone is far from the coast, some broad scale disturbances seem to produce variations of coastal sea level. Thus a forerunner can be used as an indicator of the arrival of a cyclone.

Astronomical tide is another kind of rise of sea level which occurs, mainly, as a result of the periodical movements of the celestial bodies relative to the earth. The rise due to tide may be as high as 4.5 m above the mean sea level at some parts of Indian coasts. If the arrival of the surge coincides with the time of the high tides, worst devastation takes place. For instance, the most devastating surge recorded in Bangladesh, that of November 1970, in which several hundred thousand people were drowned, was an occasion where peak surge and high tide coincided.

The storm surges which occurred during 1977 and 1990 near Machilipatnam further support the vulnerability of Andhra coast to disastrous surges. In recent years, there has been considerable concern to estimate the vulnerability of coasts due to cyclones and associated surges in view of projected global warming and sea level rise. Head bay region, which covers part of Orissa, west Bengal and Bangladesh, is one of the most vulnerable regions for extreme sea levels associated with severe tropical cyclones, which cause extensive damage. Most of the deaths due to extreme water levels occur in this region. Shallow nature of the Bay, presence of Ganga-Brahmaputra-Meghna deltaic system and high tidal ranges are responsible for extreme water levels in this region.

Damages can be minimized if the surges are forecasted well in advance. This is being done routinely for many parts of the world using numerical models. Such models have also been developed at IIT Delhi for the Bay of Bengal and the Arabian Sea and these are capable of being used on an operational basis for storm surge forecast along the Indian coasts.

Long Term Trends in Sea Level Along the Indian Coast

The probable impacts of increased greenhouse gases in the Earth's atmosphere are well known. Charney (1979) estimated that if CO_2 concentration in the atmosphere doubles during the 21^{st} century, the increase in atmosphere temperature would be between 1.5°C and 4.5°C. An increase in global surface temperature would cause the expansion of upper layers of the world ocean. The melting of ice from high altitudes and polar caps will add to the total volume of the world ocean. Consequently, the mean sea level will increase (Titus and Bath, 1984; Emery and Aubrey, 1989; IPCC, 1990; Wigley and Raper, 1992; Gornitz, 1995; Singh et al., 2000 and 2001; Singh, 2001).

South Asian region due to its large population density is more prone to the sea level associated diasters. The Indian coast with a vast shoreline of 7516 km and Exclusive Economic Zone (EEZ) of about 20, 00000 km^2 constitutes the major portion of the South Asian coast. Thus it is essential to estimate the sea level trends along the Indian coast from a comprehensive scenario of expected sea level changes in South Asia. An indicator of the vulnerability of a coastal area to inundation is the topographic slope, i.e. increase in altitude with distance perpendicular to the coastline. Slopes determined from Indian maps reveal that from the point of view of shoreline retreat, the stretch of west coast of India between 12°-18°N is the safest. Topographic slopes decrease both to the north and the south of this region (Shetye et al., 1990). On the east coast of India the slopes are generally smaller making it more vulnerable to the inundation. Most of the tropical cyclones of the north Indian Ocean develop over the Bay of Bengal and strike east coast of India. Thus east coast of India is particularly vulnerable to the storm surges generated by the tropical cyclones.

Here some of the following points are given relating to the long terra trend in Sea Level:

- Long term trends in Mean Tidal Level at Mumbai, Kochi and Visakhapatnam indicate an annual rise, their values being 0.8 mm/year, 1.2 mm/year and 0.9 mm/year respectively. Though the observed sea level trends are rising, their magnitudes are comparable to the global mean trend.
- There are large seasonal variations of mean sea level at Kochi and Visakhapatnam with Kochi registering the highest rising trend of 1.8 mm/year during the pre-monsoon (hot weather) season and Visakhapatanam registering almost nil trends during the post-monsoon season. At Mumbai the sea level trends are very steady and therefore, the seasonal variation of mean sea level is negligible at this station.
- Intra-seasonal fluctuations of mean sea level are large at Kochi during the southwest monsoon season and at Visakhapatanam during the post-monsoon season. At Mumbai the intraseasonal variation of mean sea level is very less.
- The annual, seasonal and intra-seasonal trends of mean sea level vary significantly along the Indian coast. Thus the location of the station and the prevaining meteorological phenomenan play an important role in the sea level variability along the Indian coast.

Relationship Between Sea Leval and SST Along the Indian Coast

One of the important parameters in climate studies is the sea surface temperature (Houghton et al., 1990; Houghton et al, 1996; Casey and Cornillon, 1998; Singh, 1999 and Singh, 2000). But the size of the world ocean and difficulty in taking measurements at sea make it difficult to prepare consistent SST climatologies for different oceanic regions. For studies aimed at investigating the SST-sea level relationship in different ocean basins, it is necessary to have reliable SST observations with adequate distribution in time and space. Unfortunately, the conventional SST climatologies based on ship-borne observations are unable to provide required distribution. There is a need to estimate the SST trends over different coastal regions of the World and more so over the areas that are highly vulnerable to the sea level rise In some recent studies, Singh (2000) and Singh and Saiker (2000) have estimated the recent SST trends in the coastal regions of South Asia Singh (2001) has investigated the cause effect relationships between SST, precipitation and sea level along the Bangladesh coast

Summing up, the following points are pertinent

1 Annual sea suiface temperature has shown significant increasing trends along the Indian coast in recent times (1 e 1985 98) The highest increasing trends of 0 4°C/decade has been recorded over the southwest coast of India (I e at Kochi) which coincides with highest mean sea level tiend at Kochi

2 On seasonal scale the SSTs have risen considerably dunng the summer (le dunng pre monsoon and southwest monsoon seasons) Theie is a laige spatial and temporal variation in SST trends but a general using trend is established beyond doubt

3 ENSO scale variation is present in the interannual variation of both SST and sea level

4 There is a tendency for higher SSTs before a major La Nino epoch Mean sea levels ate generally higher along the Indian coast during the La Nino conditions

References

CASEY K S and CORNILLON P (1998) A comparison of satellite and in situ based sea surfxe temperature climatologies J Ch v 12 pp 1848 1863

CHARNEY J (1979) Carbon Dioxide and Climate A Scientific Assessment Washington D C NAS Press

DUBE S K RAO A D SINHA P C and CHITTIBABU P (1994) A real time storm surge prediction system An application to the east coast of Indn Proc Ind Nat Sci Acad 60A pp 157 170

DUBE S K RAO A D SINHA P C MURTY T S and BAHULAYAN N (1997) Storm surges in the Bay of Bengal and Arabian Sea the problem and its prediction Mausam v 48 pp 283 304

EMERY K 0 and AUBREY D G (1989) Tide gauges of India J Costal Res v 5 pp 489 501

GORNITZ V (1995) Sea Level Rise a review or recent past and future trends Earth Surf Process Land Forms v 20(1) pp 720

HOUGHTON J J JENKINS G J and EPHRAUMS J J (fid) (1990) Climate Change The Science of Climate Change Cambridge University Press Cambridge pp 363

HOUGHTON J J MERIA FELHO L G CAJLLENDER B A HARRIS N KATTERNBERG

A and MASKbLL, K (Eds) (1996) Climate Change, The Science of Climate Change Catnbudge Univeisity Press, Cambndge pp 572

HUGHES 1 , FASTOOK, J L and DEN1ON, G H (1979) Climate Wanning and the Collapse ot the West Antaictic Ice Sheet Oiono Maune, Univeisity of Marine

IPCt (1990) Policymakers Summary, In Climate Change, The IPCC Scienhfic Assessment J T Houghton G J Jenkins and J J Ephtaums (Eds), Cambridge University Press, UK

IPCC (1992) Climate Change The Supplementary Repoit to the IPCC Scientific Assessment, Houghton J I\ Callandei, B A and Varney S K (Eds), Cambridge University, U K

IPCC (2001) Thud Assessment Repoit Climate Change The scientific basis, Houghton, J T Ding, Y, Gngg, D J Nogucr, M, Van dei Lmdei, P J and Xiaosu, D (Eds) Cambridge Univusity Piess U K

M1IIR, M I (1981) Snow and ice in a changing hydrological world, Hydrological Sciences Journal v 28 (1), pp 3 - 2 2

SIlLIYr, S R.GOUVEIA, A D and PATIIAK, M C (1990) Vulnerability of the Indian coastal icgion to damage fiom sea level rise, Cuir Sci, v 59, 3, pp 152 - 156

SINGH O P (1999) Multiple variability of summer sea surlaee tempeiature and evaporation over the Indian Sets Mausam, v 50, pp 335 342

SINGH, O P (2000) Recent trends in summer temperature over the north Indian Ocean I J Mar Sci, v 29, pp 7 - 11

SINGH O P (2001) Cause I licet relationship between sea suriaee temperature precipitation and sea level along the Bangladesh coast Iheo & Appl Ch v 68, pp 233 - 243

SINGH, O P.KIIAN T M A RAHMAN, M S and SALAHUDDIN (2000) Summer monsoon rainlall over Bangladesh in relation to multivariate ENSO Index Mausam, v 51, 3, pp 255 260

SINGH O P, KHAN, T M A and RAHMAN, M S (2001) Sea Level changes along Bangladesh coast in relation to the Southern Oscillation Phenomenon Marine Geodesy, v 24, pp 65 - 72

SINGH, O P and SARKAR M A (2000) Recent sea surface temperature variability in the coastal region of north Indian Ocean, Indian, J Mar Sciences

TITUS J G and BATH, M C (1984) An overvrew of the causes and effects of the sea level rise Giccnhouse Effect and Sea Level Rise, Bath, M C and Titus, J G (Eds), Van Nostrand Remhlod Company, New York

WIGLEY T M C and RAPER, S C B (1992) Implication for the climate and sea levels of revised IPCC emissions scenarios, Nature, v 357, pp 293 - 300