Climate Change and its Impact on Coastal Systems

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THE CLIMATE SYSTEM: GENERAL OVERVIEW

Climate is generally defined as the average state of the atmosphere for a given time scale (hour, day, month, season, year, decade and so forth) and generally for a specified geographical region. The average-state statistics for a given time scale including all deviations from the mean are obtained from the ensemble of conditions recorded for many occurrences for the specified period of time. Thus the mean temperature for the month of April in New Delhi, India, is obtained from measurements considered representative for New Delhi averaged over the month of April from a record of many years. Climate descriptors also include conditions at the Earth's surface such as ocean temperatures and snow cover. The average-state description involves a wide range of variables depending on what is of interest. Temperature and precipitation are the most commonly used; however the list may include wind, cloudiness and sunshine, pressure, visibility, humidity and elements with noteworthy impacts on humans such as severe storms, excessively high and low temperatures, fog, snow and hail. The method of description focuses on statistical parameters, the mean and measures of variability in time such as the range, standard deviation, and autocorrelations.

It is important to identify the difference between weather and climate. Weather involves the description of the atmospheric condition at a single instant of time for a single occurrence. In general, climate may be thought of as an average of weather conditions over a period of time including the probability for distributions from this average. The climate system is defined as the five components in the geophysical system, the atmosphere and four others which directly interact with the atmosphere and which jointly determine the climate of the atmosphere. These five components are:

(*a*) Atmosphere; (*b*) Ocean; (*c*) Land surface; (*d*) Ice and snow surfaces (both land and ocean areas); and, (*e*) Biosphere (both terrestrial and marine).

Figure 1 shows the scope of the climate system, in which the two-way arrows in the diagram identify explicit interactions between the atmosphere and other components. At this point it is appropriate to recognize that there are other factors, also variable in nature, which contribute to determining the climate. These are considered 'external' forcing factors and include the sun, Earth orbital parameters, land-ocean distribution, Earth topography (land and ocean), and basic composition of the atmosphere and ocean. These are important determiners of the climate which, except for the basic composition of the atmosphere and oceans, are not affected in return by the climate conditions (Houghton, 2002)

The definition for the climate system makes it clear that one has to have an understanding of all of that system's components (atmosphere, ocean, land surface processes, cryosphere, and biosphere) in order to understand it. In reality one needs to know a limited amount, dependent on the time scales considered, about the non-atmospheric components to understand the interactions of those components with the atmosphere. In general, these interactions occur primarily at physical interfaces so that, for example, for ocean interactions, it is necessary to know only the conditions at the oceanic upper boundary and for cryosphere interactions only at the surface of the ice. To know such conditions, of course, it is necessary to understand how they vary in relationship to conditions within the ocean and ice. Unlike the other interactive components, the ocean is an easily movable fluid, as is the atmosphere, so that understanding the ocean for climate system applications requires dealing with geophysical fluid dynamic and thermodynamic relationships as complex as those for the atmosphere. Hence, it becomes necessary to use numerical model representation for the ocean comparable to that used for the atmosphere. Current climate system research depends strongly on coupled atmosphere-ocean numerical models.

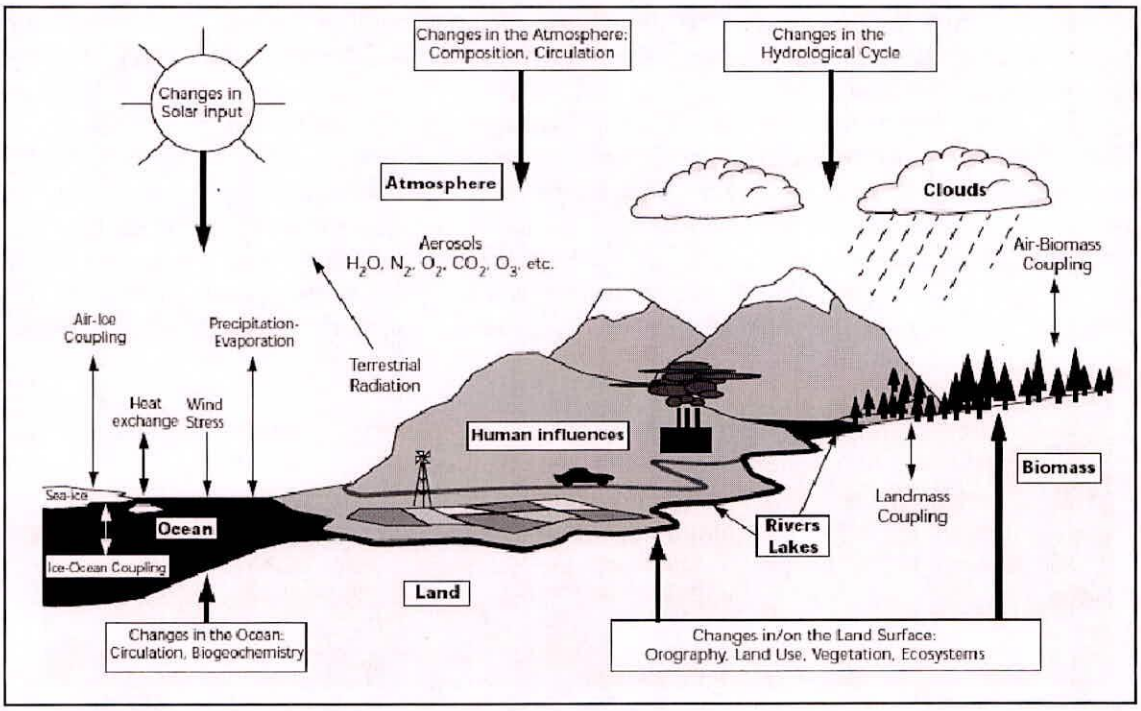

Fig. 1 Schematic view of the components of global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows) (Source: Houghton, 2002)

Radiation Processes

Electromagnetic wave energy transfer (radiation) accounts for nearly all energy transfer from the sun, and is the primary source of energy for the atmosphere and the entire climate system. Such transfer is also the only way in which significant amounts of energy can leave the climate system. The energy of the global climate system is nearly in balance with incoming and outgoing radiation transfers. A change in one component will produce a different balanced state. The primary human impact on the energy balance is to alter the radiative properties of the atmosphere with respect to these two energy streams. This effect far out shadows other anthropogenic energy sources and sinks effects such as the heating due to combustion and nuclear processes. Understanding the impacts of human environmental change on radiation transfer processes in the atmosphere and on the Earth's surface is crucial to understanding climate change.

The production (emission) of radiation energy depends upon internal energy (temperature) as well as other properties of the emitting material substance. The destruction (absorption) of radiation depends on the amount of incident radiation energy and properties of the absorbing material substance except for its temperature. The properties of radiation depend on its wavelength. Radiation can exist for a wide and continuous range of wavelengths referred to as the radiation spectrum.

There are two primary forms of radiation relevant to the energy balance properties of the climate system. The first is the 'solar' or 'short-wave' form predominant in the radiation from the sun. This is primarily in the wavelength range from 0.2 to 4.0 microns which encompasses the visible part of the spectrum. This short-wave radiation provides a source of energy for the climate system as it is absorbed in the atmosphere, clouds, ocean, land surface, and by living matter. The second form is the 'terrestrial' or 'long-wave' type predominant in the radiation emitted by matter in the climate system. The primary wavelength range for this form is from 4 to 60 microns which is entirely in the invisible infrared part of the spectrum. Sometimes the solar and terrestrial radiation forms are called 'visible' and 'invisible,' respectively.

The overall differences in predominant wavelengths are due to the differences in temperature of the emission sources for the radiation, about 6000 K for the sun and in the range of 190-330 K for the climate system components emitting terrestrial radiation. The relative roles of the two primary forms of radiation in the energy balance are complicated by the fact that the components of the climate system absorb as, well as emit, long-wave infrared radiation. Large-scale radiation effect variations in the climate system are most pronounced with respect to height and latitude. Horizontal variations in radiation transfer do exist at the small scale as demonstrated by the difference in solar heating at the Earth's surface on the two sides of a hill, one facing the sun and the other facing away from the sun. For general applications to the climate system, only the vertical component of radiation is considered.

Radiative Energy Budget

Solar radiation incident upon the Earth system coming into the atmosphere from above leads to heating as it is absorbed by gases, aerosols and clouds in the atmosphere, and by the ocean, land, ice and biosphere elements at the Earth's surface. The absorption is proportional to the intensity of the incident solar radiation and depends on the properties of these substances.

The solar radiation absorption (heating) within the atmosphere and at the Earth's surface depend strongly on the properties of the absorbing substance. The albedo (reflectivity) of sunlight from the Earth's surface is indicative of (inversely related to) the absorption of radiation by that surface. A surface with a high albedo (high visible brightness) is heated much less than one with a low albedo (low visible brightness). At the Earth's surface, the albedo ranges from about five per cent for ocean surfaces (with the sun high in the sky) and the top surface of dark thick coniferous forests to 90 per cent for fresh snow. Thick clouds in the atmosphere can also have an albedo nearly as high as fresh snow. Since much of the reflected and back-scattered solar radiation travels back out to space, it is never converted to heat in the climate system. The atmosphere (gases, aerosols, and clouds) absorbs less of the incident radiation than the Earth surface, so that solar heating effects are greater at the Earth surface than in the atmosphere.

Terrestrial (long-wave) radiation is both emitted and absorbed by material substances in the climate system. The absorption depends on the incident radiation intensity and physical properties of the substances (except for temperature) whereas the emission depends on the temperature and other physical properties of the substances. The Earth's surface and clouds have radiative properties that tend to produce the maximum amount of terrestrial radiation given by 'black body' values and to absorb incident terrestrial radiation completely. On the other hand, the radiation emission and absorption characteristics of atmospheric gases have a large variability depending on wavelength. The strongest effects are exhibited by minor constituents in the atmosphere: water vapour, carbon dioxide, ozone, nitrous oxide, and methane. These gases occur naturally and are known as 'greenhouse gases.'

The 'greenhouse gas' radiative properties are much more pronounced for terrestrial radiation than for solar radiation. The large absorptivity of the atmospheric gases for the terrestrial radiation together with atmospheric temperatures in the 210-310K range leads to emission of significant amounts of terrestrial radiation in all directions even where clouds are not present. It is the downward component which retains energy in the climate system and keeps equilibrium temperatures at the Earth's surface and in the lower atmosphere higher than would otherwise be the case. This enhanced temperature is said to result from the 'greenhouse effect.'

Role of Radiation in Overall Energy Balance

When considering only the vertical transfers of energy, radiation energy transfers have a dominant role in the overall energy balance of the globally-averaged atmosphere and the Earth's surface. Figure 2 summarizes these energy transfers. The solar radiation components are shown on the left side. The terrestrial radiation components are on the right side, and the sensible and latent heat transfers are shown in the center. About 30 per cent of the incoming solar radiation is returned to space without being converted to heat (an albedo of about 30 per cent for the Earth–atmosphere system); about half is absorbed at the Earth surface, and only about 20 per cent is absorbed in the atmosphere. For the terrestrial radiation emitted from the Earth only about 10 per cent is transmitted directly to space; the remaining part is absorbed in the atmosphere.

The energy component labeled 'back radiation' is a key indicator of the greenhouse effect. Note also that the magnitude of terrestrial radiation emitted downward from the atmosphere to Earth and absorbed at the Earth's surface is nearly equal to the total solar radiation incident at the top of the atmosphere and is about double the amount of solar radiation absorbed at the Earth's surface. In general, the magnitudes of radiation energy transfer are considerably larger than those associated with the sensible and latent heat transfers (see Fig. 2).

A basic aspect of radiation forcing is the systematic variation with latitude. There is generally an overall reduction with distance from the equator in the daily total solar radiation coming into the Earth–atmosphere system, being more extreme in the winter season and nearly absent at the time of the summer solstice. The net radiative forcing depends on both the input from solar radiation and losses due to terrestrial radiation emission to space. Latitude variations of terrestrial radiation emission are much less than for solar.

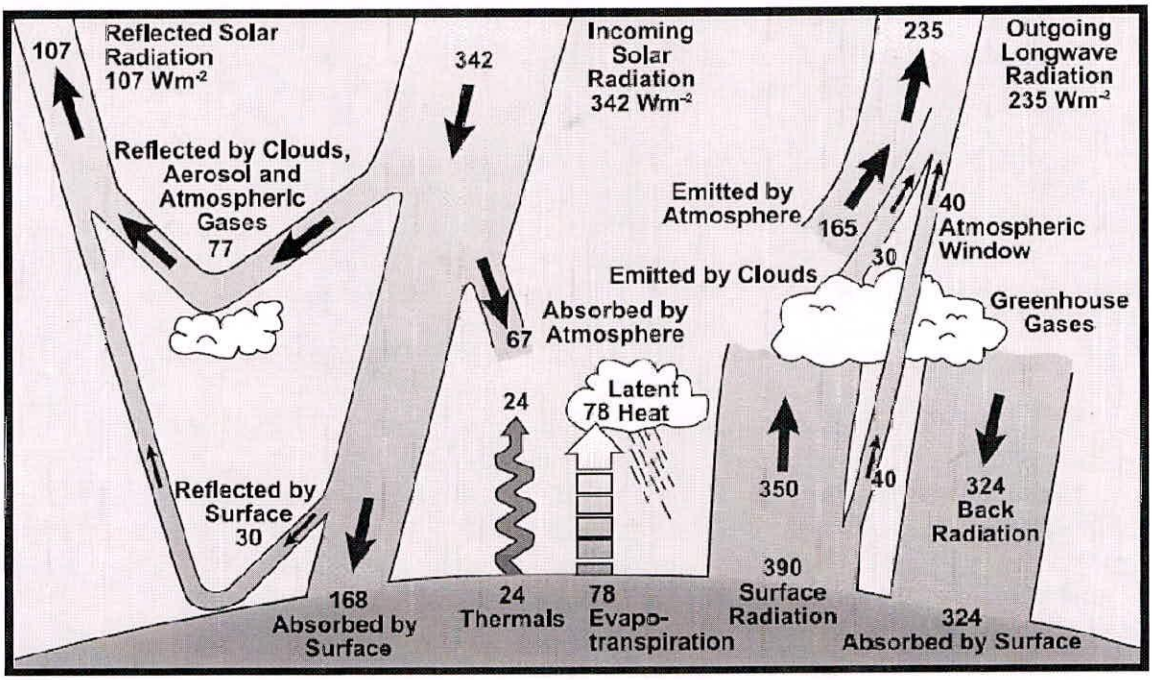

Fig. 2 The Earth's radiation and energy balance. The net average incoming solar radiation of 342 Wm^{-2} is partially reflected by clouds and atmosphere, or at the surface, but 49 per cent is absorbed by the surface. Some of that heat is returned to atmosphere as sensible heating and most as evapotranspiration that is realized as latent heat in precipitation. The rest is radiated as thermal infrared radiation and most of that is absorbed by the atmosphere which in turn emits radiation both up and down, producing a greenhouse effect, as most of the thermal radiation lost to space comes from cloud tops and parts of the atmosphere much colder than the surface (Source: Treut, 2007).

The resulting net radiation forcing for the Earth–atmosphere system has a net excess in the tropical latitudes and a deficit in the polar latitudes. If radiation transfer were the only process occuring, the equatorial regions would be hotter than observed and the polar regions colder than observed. However, the transport of heat from the equatorial to polar regions by atmospheric and oceanic circulations offsets this radiation imbalance and provides an overall energy balance at each latitude. Thus, the primary connection between human activity and climate change is the alteration of the radiation transfer characteristics of the atmosphere. The change in greenhouse gas concentration and the addition of other gases with similar characteristics will change the terrestrial radiation transfer. In addition, a change in aerosol concentration and perhaps related change in cloud cover will change the solar radiation transfer. Except on a very local scale, the energy transferred by radiation is far greater than any production rate of energy due to human activity.

Biosphere

The biosphere is a component of the climate system that has a distinct role in the interactions of both the oceans and land surface with the atmosphere. Vegetation on the land surface and both plant and animal life in the oceans are all relevant elements of the biosphere component that interact with the atmosphere. Climate conditions of the atmosphere have a direct effect on the type of terrestrial plant growth at the Earth's surface. The nature of the plant cover in turn feeds back on the atmospheric condition by influencing the sensible and latent energy transfers from a land surface, as well as surface layer turbulence in the atmosphere.

Furthermore, land vegetation is a significant reservoir for carbon with a total carbon content nearly equal to that in the atmosphere. Changes in the amount of land vegetation due, for instance, to forest cutting and burning or simply seasonal changes have a direct impact on the carbon dioxide concentration in the atmosphere. Along with dissolved inorganic carbon and calcium carbonate solids, plant and animal life have key roles in the ocean, in the carbon cycle which influences the concentration of the greenhouse gas, and carbon dioxide in the atmosphere and results in a loss of carbon due to sedimentation of carbonates at the ocean bottom.

The interactions between the biosphere and atmospheric climate have produced a record of past climate conditions. Tree rings, fossil patterns, pollen counts in ocean and lake bottom sediments, and coal and oil deposits are records which give us information on past climates. Humans, themselves, are members of the biosphere. Humans alter the biosphere directly by agricultural and forestry activities and indirectly by altering the climate system in which the biosphere exists. Biosphere is a component that interacts with other climate system components, and is the component where the effects of climate change will be clearly evident to people.

FEEDBACKS IN THE CLIMATE SYSTEM

There are numerous significant physical interactions among the components of the climate system that are relevant to climate change. A brief overview of these components is presented below, they include: radiation energy transfer, heat energy transfer, and biosphere interactions.

Radiation Energy Transfer

Radiation is a primary mechanism for energy transfer in the climate system. At the same time characteristics of the climate system itself have a great impact on the magnitudes of radiative energy transfer. There are two key feedbacks as described below.

Temperature feedback: The interrelationship between temperature and radiation provides a negative feedback whereby radiation transfer tends to reduce variations in temperature and to stabilize temperature conditions.

Albedo feedback: A primary energy source for the climate system is the absorption of solar (visible) radiation. The amount absorbed is dependent on the reflectivity (albedo) properties of the substance. Since there is a large variation of albedo for substances in the climate system, significant feedbacks exist based on variations in amounts of specific substances

Heat Energy Transfer

Sensible and latent heat energy transfers provide for important energy-related transfers between the components of the climate system and involve important feedbacks. Vertical energy transfers between the ocean and atmosphere have already been mentioned. To this must be added the energy transfers between land and atmosphere and between ice and ocean water. The latent heat component arises from the phase change of water between its vapour, liquid, and solid forms. Because of their fluid nature, both the atmosphere and ocean transfer significant amounts of heat energy by horizontal motions.

Biosphere Interactions

On one hand, the biosphere, as a central component in the carbon cycle, is a key determiner of greenhouse gas concentration in the atmosphere. On the other hand, the atmosphere, in particular its temperature and precipitation, has a major influence on the biosphere. The biosphere in both the atmosphere and oceans plays a significant role in the carbon cycle which includes the atmospheric carbon dioxide.

GLOBAL NATURE OF THE CLIMATE SYSTEM

The circulations in the atmosphere and ocean transmit changes in one region of the climate system to broad sectors of the world. This means that many aspects of both natural climate variability and climate change are global in nature. This makes the climate change issue a global one which will require the understanding of people everywhere and the participation of all countries in dealing with its impacts.

REGIONAL NATURE OF THE CLIMATE SYSTEM

Climate has a global nature, but it also has local-scale variability which is very important for having its impacts on life. Local variations are caused by topography, differences in ground cover at the Earth's surface and organization of weather systems resulting from the atmospheric general circulation in tropical regions, such as the Inter-Tropical Convergence Zone (ITCZ). Mean temperature and rainfall conditions change markedly with elevation of the land. Variations also exist upstream and downstream of topography with effects such as 'rain forests' or 'rain shadows' where the mean rainfall is greater or less, respectively, than in surrounding areas. At the very small scale, farmers know that the slope of the surface and small valleys in fields can noticeably alter growing conditions. Even the areas of shade and sun around one's home provide for very small-scale climate variations (microclimates) which affect plant growth.

NATURAL TEMPORAL VARIABILITY IN THE CLIMATE SYSTEM

Earth's climate exhibits natural variability on all time scales. For any time scale there are variations in the climate variables such as temperature, precipitation, and severe storms and in related climate system parameters such as sea-surface temperature and sea level. The variations in variables can be in terms of magnitude, range, periodicity, and extremes. The variability can be of systematic and irregular types. It is a continuing challenge to demonstrate variations that are due to anthropogenic causes rather than natural causes. Some of the variability, for instance, that has occurred in surface temperature is much larger than anything envisioned due to human impacts. This lecture does not focus on natural temporal variability in climate system.

HUMAN IMPACTS ON THE CLIMATE SYSTEM

The primary human activities which cause climate change are those which influence radiative transfer in the atmosphere and radiation absorption on the Earth's surface. Other human activities, such as heating the atmosphere through combustion and changing surface wind flow by deforestation and building construction, are of secondary importance. There are four specific impacts to be considered: increasing greenhouse gas concentrations in the atmosphere, adding aerosols to the atmosphere, changing cloudiness and changing surface conditions. The first two clearly have global effects. There is incomplete understanding for climate impacts from changes in cloudiness due to human activity. The effect could be large and global, particularly if the cloud changes are related to the aerosols added by human activity. Land surface changes may have large impacts on local climate; but have less impact globally as land covers only 29 per cent of the earth's surface.

There are several measures of the magnitude of human impact. An overall measure is accomplished by comparison of current conditions of the atmosphere and the Earth's surface with those that existed before the industrial revolution (considered to be before 1750). A measure used for gases and aerosols is the current rate of increase in atmospheric concentration. This is expected to relate directly to level of possible impact in the future. A convenient way to describe and compare the overall impact of human-caused changes in greenhouse gases or aerosols on radiation exchanges is by their 'radiative forcing.'

Radiative forcing here is defined as the change in average net total radiation in the planetary radiation budget at the top of the troposphere due to changes in solar and infrared radiation with fixed vertical structure for temperature. Radiative forcing can be used to describe the impacts of both anthropogenic and natural changes in the physical system. A positive radiative forcing (increase in net downward radiation) tends to cause average warming of the Earth's surface and a negative radiative forcing, average cooling. This definition was made by the Intergovernmental Panel on Climate Change (IPCC) in 1995.

Atmospheric Greenhouse Gas Enhancement

The natural atmosphere contains greenhouse gases (primarily water vapour, carbon dioxide, ozone, nitrous oxide, and methane) which have a major impact on determining temperatures in the atmosphere and at the Earth's surface. Human activity has provided additional sources for these and other gases that have greenhouse-gas characteristics. The result is an enhanced greenhouse effect which is expected to force increased temperature at the Earth's surface and in the lower atmosphere. All greenhouse gases have sources and sinks which may include chemical conversions in the atmosphere. The effect of human activity on concentration levels in the atmosphere depends on the cumulative amounts added by human activity and the strength of the sinks.

Natural Greenhouse Gas Constituents

Three of the five natural greenhouse gas constituents are exhibiting well-documented increases in concentration due to human activity: carbon dioxide, methane, and nitrous oxide. The other two naturally occurring greenhouse gases, water vapour and ozone, are less directly linked to human activity. The role of ozone is small. The relevant concentration for ozone includes both tropospheric and stratospheric components and not just the stratospheric concentration values for which there has been an observed decrease in polar regions. Water vapour is the dominant greenhouse gas and accounts for about 75 per cent of the overall greenhouse effect. However, its modification results primarily from changes in evaporation rates from the oceans due to temperature and surface wind variability and not from human activity.

The carbon cycle: CO_2 has been recognized for its importance as a greenhouse gas for almost a century. Carbon moves continually from the atmosphere into the food chain during photosynthesis and returns to the atmospheric during respiration.

- From the atmosphere it can be assimilated by plants on the land or in the oceans, or it can dissolve into the sea water.
- Respiration by living things, including decomposers that are feeding on dead organic matter, return CO_2 either to the oceans or to the atmosphere.
- A very small portion of the dead organic matter each year ends up being buried in sediments. The slow, historical accumulation of buried organic matter is the source of our fossil fuels – oil, gas and coal.
- When these are burned, C in the form of CO_2 is returned to the atmosphere. The rapid accumulation of CO_2 in the atmosphere is attributed mainly to fossil fuel burning and deforestation.

Carbon dioxide enhancement is the most important human impact on the greenhouse gases. This enhancement accounts for more than half of the total enhanced greenhouse effects due to human activity. A continuous observational record for atmospheric carbon dioxide has been obtained since 1958 at Mauna Loa, Hawaii and since 1957 at the South Pole. Concentrations prior to that time have been measured from air trapped in ice in Antarctica. Both of these measurements are considered to be representative of global mean concentration. Carbon dioxide concentration is rather uniform in the atmosphere. The change in concentration values from the pre-industrial period to about 1989 reveals that the rate of increase itself is increasing with time as shown in Fig. 3.

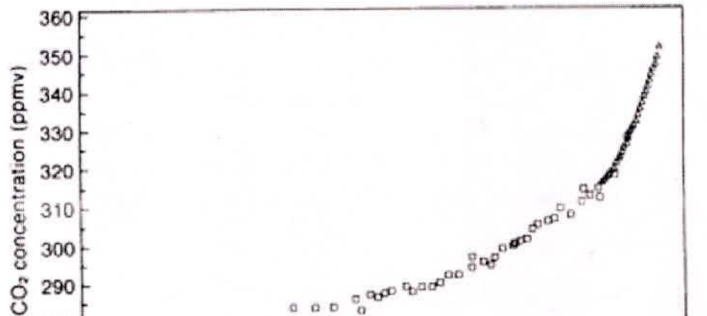

Fig. 3 Atmospheric CO_2 concentration for the past 250 years as indicated by measurements in air trapped in ice from Siple Station, Antarctica, and by direct atmospheric measurements at Mauna Loa, Hawaii. Note: ppmv means part per million by volume (Source: Houghton, 2002)

The overall human impact on carbon dioxide concentration has been to increase it from roughly 278 ppmv to 365 ppmv (the value in 1998), an increase of 87 ppmv or almost 31 per cent. The current level is estimated to be higher than at any time since the last interglacial warming about 120,000 years ago. At the current rate of increase, the carbon dioxide concentration will double in less than 100 years. Fossil fuel combustion and cement manufacturing account for more than 75 per cent of the total carbon dioxide input. The remainder (less than 25 per cent) is due to net effects of deforestation and other land-clearing operations mainly in tropical areas. Of the total carbon dioxide input into the atmosphere, almost half remains in the atmosphere, an estimated 30 per cent goes into the ocean, seven per cent into Northern Hemisphere forest re-growth, and the remainder is assumed to go into other parts of the terrestrial biosphere.

Two other 'natural' greenhouse gases that are increasing due to human activity are methane and nitrous oxide. Their relative increases between pre-industrial times and 1990 are significant especially for methane which has more than doubled in concentration since preindustrial times. Even though the absolute values of the concentration of both these gases are less than one per cent of that of carbon dioxide, the radiative effects of the human-caused increases in these two gases together amount to nearly 40 per cent of that of carbon dioxide.

New Greenhouse Gases

The introduction of new greenhouse gases by human activity has had a noticeable impact on the greenhouse effect, accounting for over 10 per cent of the total human impact on the greenhouse effect. Many different gases have been introduced. They are mainly halocarbons (compounds containing carbon together with halogens such as chlorine, fluorine, bromine, and iodine) such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). These compounds were manufactured for use in refrigeration units, foaming agents and solvents. The halocarbons are strong greenhouse gases and their lifetimes are possibly longer than those of the long-lived natural greenhouse gases.

Atmospheric Aerosol Enhancement

Fossil fuel combustion and biomass burning are the primary sources of aerosols due to human activity. These sources produce both soot (particulate black carbon aerosols), gaseous sulphur dioxide and nitrogen oxides. The latter two are partially transformed by chemical processes into sulphate and nitrate aerosols. Additional sources for human-produced aerosols include dust from changes in land use. All of these aerosol products remain primarily in the troposphere (unlike those produced by major volcanic eruptions) and thus are subject to rapid removal by precipitation and settling processes.

Change of Radiative Properties of the Land Surface

It is recognized that humans have greatly altered the Earth's land surface by settlements, deforestation and agriculture. These changes have resulted in both increases and decreases in local albedo values. Replacing forests with crops that are present only part of the year would likely increase albedo effects. Urbanization could either increase or decrease the albedo depending on the reduction in trees and on the materials used for roofs and streets. These albedo changes clearly have a role in the local energy balance and contribute to microscale climate changes such as the heat 'islands' over urban regions. However, other factors such as evaporation, precipitation and wind flow changes could have large impacts on local or even regional climate change. On a global basis the change in the radiative properties of land surfaces is not considered to be a major factor in the energy balance

Summary of Human Impacts

Figure 4 provides an overall summary of the relative importance of the many ways in which human activity can alter radiative energy transfers in the atmosphere. Confidence in the quantitative values is indicated at the bottom. The depiction includes ozone effects and, for comparison, solar variability effects due to the sun spot cycle. Increases in tropospheric ozone are estimated to give a radiative forcing value of +0.4 Wm^{-2} which is equal and opposite to the forcing due to tropospheric sulphate increases. The cloud change impacts due to aerosols are shown in terms of the range of estimated values of radiative forcing.

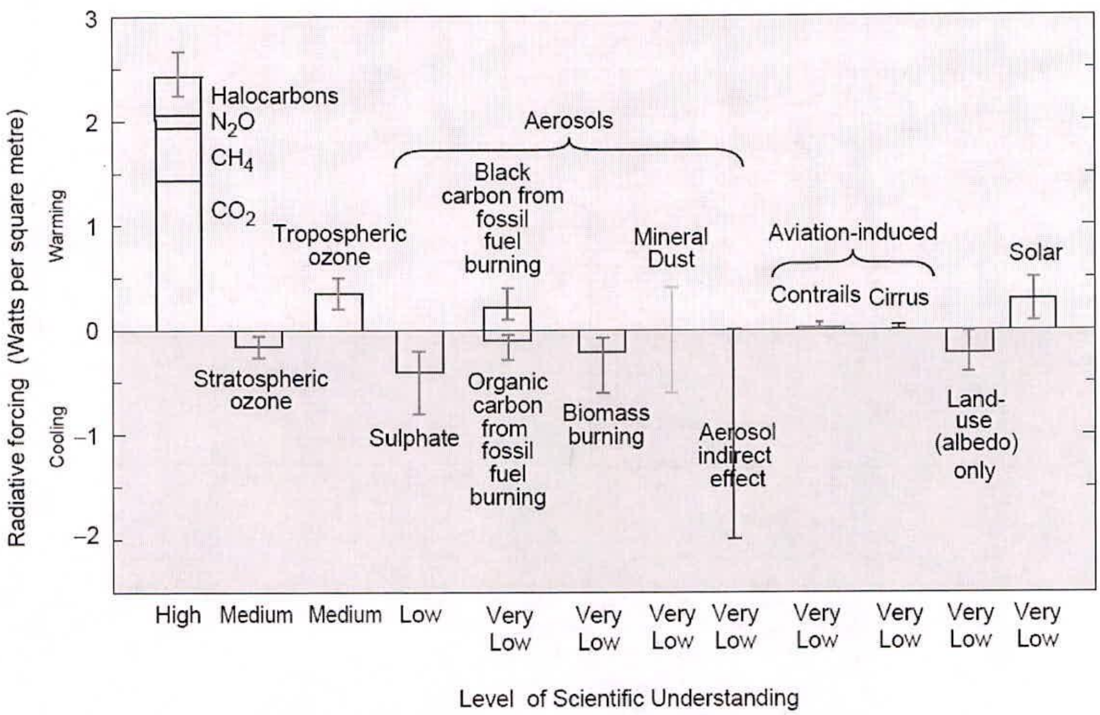

Fig. 4 Global, annual mean radiative forcings (Wm^{-2}) due to a number of agents for the period from pre-industrial(1750) to present (late 1990s; ~2000). The height of the rectangular bar denotes a central or best-estimate value while its absence denotes no best estimate is possible. The vertical lines capped with horizontal lines indicate an estimate of the uncertainty range, for the most part guided by the spread in the published values of the forcing. At the bottom a 'level of scientific understanding' index is accorded to each forcing. This represents a subjective judgement about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual mean contributions due to CO_2, CH_4, N_2O and halocarbons (Source: IPCC, 2001)

Further understanding is needed to establish a mid-range estimate as is done for all the other radiative forcing components. No entry is made for volcanic effects, which are quite variable in time, or for the impacts of changes in surface albedo as these effects are considered important primarily on a regional scale. Much research is needed to reduce these uncertainties especially with respect to the indirect aerosol effect on clouds.

OBSERVED CHANGES IN THE CLIMATE SYSTEM

Observations of the climate system are based on direct measurements and remote sensing from satellites and other platforms. Global-scale observations from the instrumental era began in the mid-19th century for temperature and other variables, with more comprehensive and diverse sets of observations available for the period 1950 onwards. Paleoclimate reconstructions extend some records back hundreds to millions of years. Together, they provide a comprehensive view of the variability and long-term changes in the atmosphere, the ocean, the cryosphere, and the land surface.

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased (refer Fig. 5).

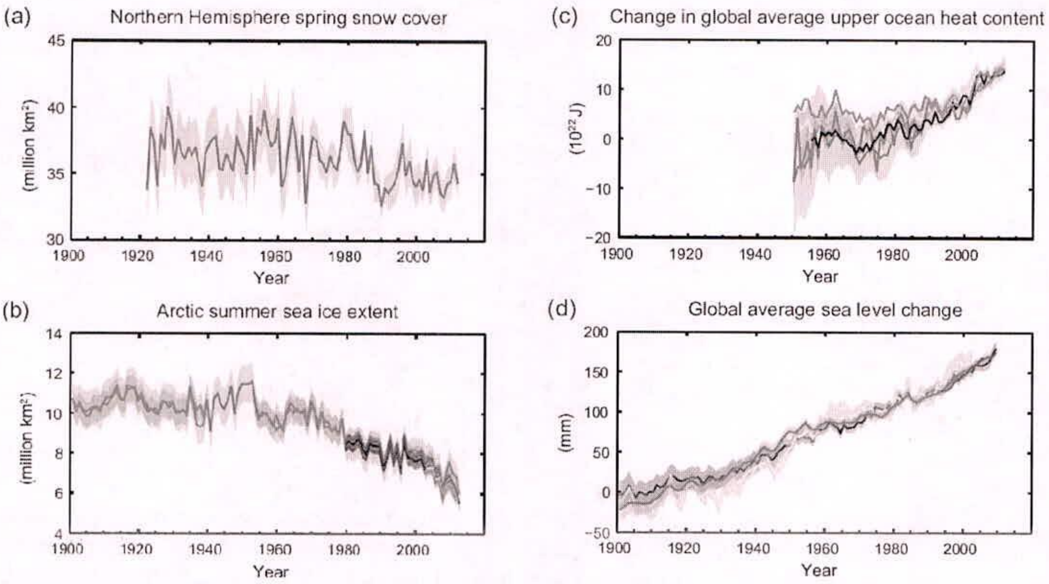

Fig. 5 Multiple observed indicators of a changing global climate: (a) Extent of Northern Hemisphere March-April (spring) average snow cover; (b) extent of Arctic July-August-September (summer) average sea ice; (c) change in global mean upper ocean (0–700 m) heat content aligned to 2006–2010, and relative to the mean of all datasets for 1970; (d) global mean sea level relative to the 1900–1905 mean of the longest running dataset, and with all datasets aligned to have the same value in 1993, the first year of satellite altimetry data (IPCC, 2013)

Climate change is expected to have an impact on a wide range of ecological and socio-economic areas including human health. The overall impact on a system depends on both sensitivity to the climate-condition changes and the adaptability and compensating factors that the system itself possesses. In many cases actual impacts will depend on regional climates for which the estimates of change are far more uncertain than for global-mean conditions.

EMISSION SCENARIOS

Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modeling and the assessment of impacts, adaptation, and mitigation. The possibility that any single emissions path will occur as described in scenarios is highly uncertain. In subsequent paragraphs, following terminology is used:

Storyline - a narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces.
Scenario - projections of a potential future, based on a clear logic and a quantified storyline.
Scenario family - one or more scenarios that have the same demographic, politico-societal, economic and technological storyline.

IPCC developed long-term emissions scenarios in 1990 and 1992 (six alterative IS92 scenarios a-f). These scenarios have been widely used in the analysis of possible climate change, its impacts, and options to mitigate climate change. In 1995, the IPCC 1992 scenarios were evaluated. The evaluation recommended that significant changes (since 1992) in the understanding of driving forces of emissions and methodologies should be addressed. These changes in understanding relate to, e.g., the carbon intensity of energy supply, the income gap between developed and developing countries, and to sulfur emissions. This led to a decision by the IPCC Plenary in 1996 to develop a new set of scenarios.

The IPCC Special Report on Emissions Scenarios (SRES; Nakićenović and Swart, 2000) SRES presented four narrative storylines, labeled A1, A2, B1, and B2, describing the relationships between the forces driving GHG and aerosol emissions and their evolution during the 21st century for large world regions and globally (Fig. 6). Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways and result in different levels of GHG emissions. The storylines assume that no specific climate policies are implemented, and thus form a baseline against which narratives with specific mitigation and adaptation measures can be compared. In simple terms, the four storylines combine two sets of divergent tendencies: one set varying between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization . The storylines are summarized as follows (Nakicenovic et al., 2000):

- A1 storyline and scenario family: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.

- A2 storyline and scenario family: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
- B1 storyline and scenario family: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
- B2 storyline and scenario family: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

After determining the basic features of each of the four storylines, including quantitative projections of major driving variables such as population and economic development taken from reputable international sources (e.g. United Nations, World Bank and IIASA), the storylines were then fully quantified using integrated assessment models, resulting in families of scenarios for each storyline. In all 40 scenarios were developed by six modelling teams. All are equally valid, with no assigned probabilities of occurrence. Six groups of scenarios were drawn from the four families: one group each in the A2, B1 and B2 families, and three groups in the A1 family, characterising alternative developments of energy technologies: A1FI (fossil intensive), A1T(predominantly non-fossil) and A1B (balanced across energy sources).

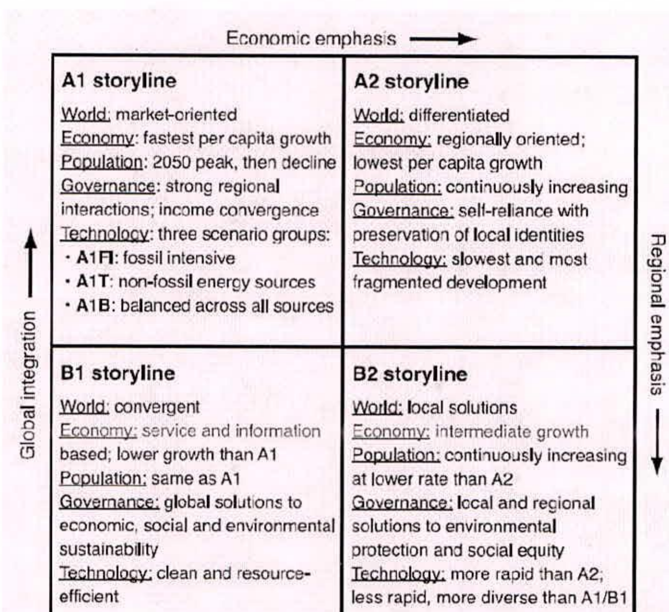

Fig. 6 Summary characteristics of the four SRES storylines (Source: Nakićenović and Swart, 2000)

Projections in the recent Fifth Assessment Report (AR5) are based on "Representative Concentration Pathways" (RCPs). The RCPs are consistent with a wide range of possible changes in future anthropogenic greenhouse gas emissions. RCP 2.6 assumes that global annual GHG emissions (measured in CO_2-equivalents) peak between 2010-2020, with emissions declining substantially thereafter. Emissions in RCP 4.5 peak around 2040, then decline. In RCP 6, emissions peak around 2080, then decline. In RCP 8.5, emissions continue to rise throughout the 21st century.

IMPLICATIONS OF CLIMATE CHANGE FOR COASTAL SYSTEMS AND LOW-LYING AREAS

Natural Coastal Systems

Coasts are dynamic systems, undergoing adjustments of form and process (termed morphodynamics) at different time and space scales in response to geomorphological and oceanographical factors. Human activity exerts additional pressures that may dominate over natural processes. Often models of coastal behaviour are based on palaeoenvironmental reconstructions at millennial scales and/or process studies at sub-annual scales. Adapting to global climate change, however, requires insight into processes at decadal to century scales, at which understanding is least developed.

Coastal landforms, affected by short-term perturbations such as storms, generally return to their pre-disturbance morphology, implying a simple, morphodynamic equilibrium. Many coasts undergo continual adjustment towards a dynamic equilibrium, often adopting different 'states' in response to varying wave energy and sediment supply. Coasts respond to altered conditions external to the system, such as storm events, or changes triggered by internal thresholds that cannot be predicted on the basis of external stimuli. This natural variability of coasts can make it difficult to identify the impacts of climate change. For example, most beaches worldwide show evidence of recent erosion but sea-level rise is not necessarily the primary driver. Erosion can result from other factors, such as altered wind patterns, offshore bathymetric changes, or reduced fluvial sediment input. A major challenge is determining whether observed changes have resulted from alteration in external factors (such as climate change), exceeding an internal threshold (such as a delta distributary switching to a new location), or short-term disturbance within natural climate variability (such as a storm).

Increasing Human Utilisation of the Coastal Zone

Utilisation of the coast increased dramatically during the 20th century, a trend that seems certain to continue through the 21st century. Coastal population growth in many of the world's deltas, barrier islands and estuaries has led to widespread conversion of natural coastal landscapes to agriculture, aquaculture, silviculture, as well as industrial and residential uses. It has been estimated that 23% of the world's population lives both within 100 km distance of the coast and <100 m above sea level, and population densities in coastal regions are about three times higher than the global average. The attractiveness of the coast has resulted in disproportionately rapid expansion of economic activity, settlements, urban centres and tourist resorts. Migration of people to coastal regions is common in both developed and developing nations. Rapid urbanisation has many consequences, e.g. enlargement of natural coastal inlets and dredging of waterways for navigation, and port facilities exacerbate saltwater intrusion into surface and ground waters. Coastal and ocean activities, such as marine transportation of goods, offshore energy drilling, resource extraction, fish cultivation, recreation, and tourism are integral to a nation's economy. Coastal areas are also home to species and habitats that provide many benefits to society and natural ecosystems.

Impacts of Climate Change and Sea-Level Rise on Coastal and Adjoining Low-Lying Areas

A global perspective on the impacts of climate change and sea-level rise on coastal and adjoining low-lying areas is provided in subsequent paragraphs, with an emphasis on post-2000 insights. Here, coastal systems are considered as the interacting low-lying areas and shallow coastal waters, including their human components. In addition to local drivers and interactions, coasts are subject to external events that pose a hazard to human activities and may compromise the natural functioning of coastal systems (Fig. 7). Terrestrial-sourced hazards include river floods and inputs of sediment or pollutants; marine-sourced hazards include storm surges and tsunamis.

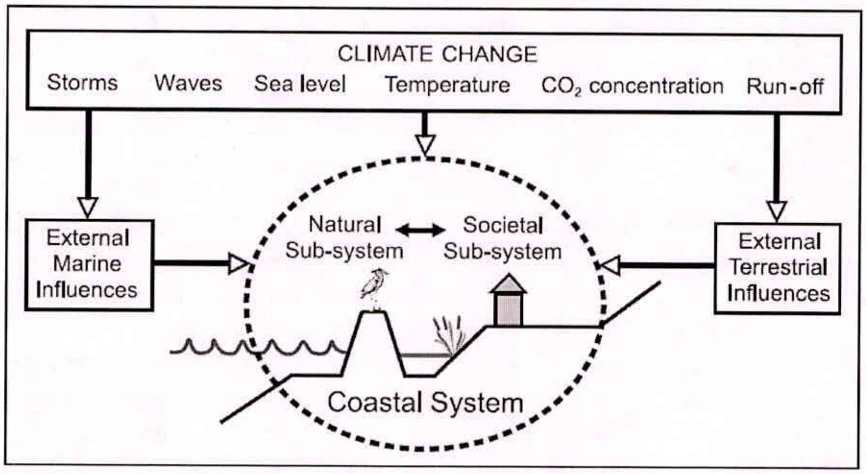

Fig. 7 Climate change and the coastal system showing the major climate change factors, including external marine and terrestrial influences (Source: Nicholls, 2007)

Coasts are experiencing the adverse consequences of hazards related to climate and sea level (very high confidence).

Coasts are highly vulnerable to extreme events, such as storms, which impose substantial costs on coastal societies. Annually, about 120 million people are exposed to tropical cyclone hazards, which killed 250,000 people from 1980 to 2000. Through the 20th century, global rise of sea level contributed to increased coastal inundation, erosion and ecosystem losses, but with considerable local and regional variation due to other factors. Late 20th century effects of rising temperature include loss of sea ice, thawing of permafrost and associated coastal retreat, and more frequent coral bleaching and mortality (refer Figs. 8-10)

Under all RCP scenarios, rate of sea level rise will *very likely* exceed that observed during 1971-2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets.

Coasts will be exposed to increasing risks, including coastal erosion, over coming decades due to climate change and sea-level rise (very high confidence).

Anticipated climate-related changes include: an accelerated rise in sea level of up to 0.6 m or more by 2100; a further rise in sea surface temperatures by up to 3°C; an intensification of tropical and extra-tropical cyclones; larger extreme waves and storm surges; altered precipitation/run-off; and ocean acidification. These phenomena will vary considerably at regional and local scales, but the impacts are virtually certain to be overwhelmingly negative. Storm surges already flood low-lying areas, damage property, disrupt transportation systems, destroy habitat, and threaten human health and safety. Sea level rise could magnify the impacts of storms by raising the water level that storm surges affect.

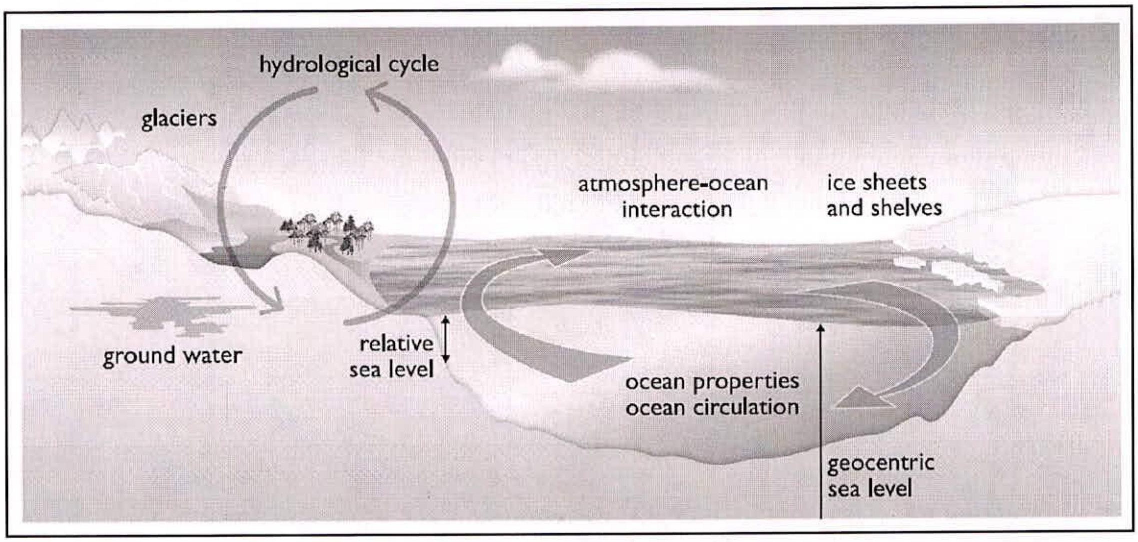

Fig. 8 Climate-sensitive processes and components that can influence global and regional sea level. Changes in any of the components or processes will result in a sea level change. The term 'ocean properties' refers to ocean temperature, salinity and density, which influence and are dependent on ocean circulation. Both relative and geocentric sea level vary with position.

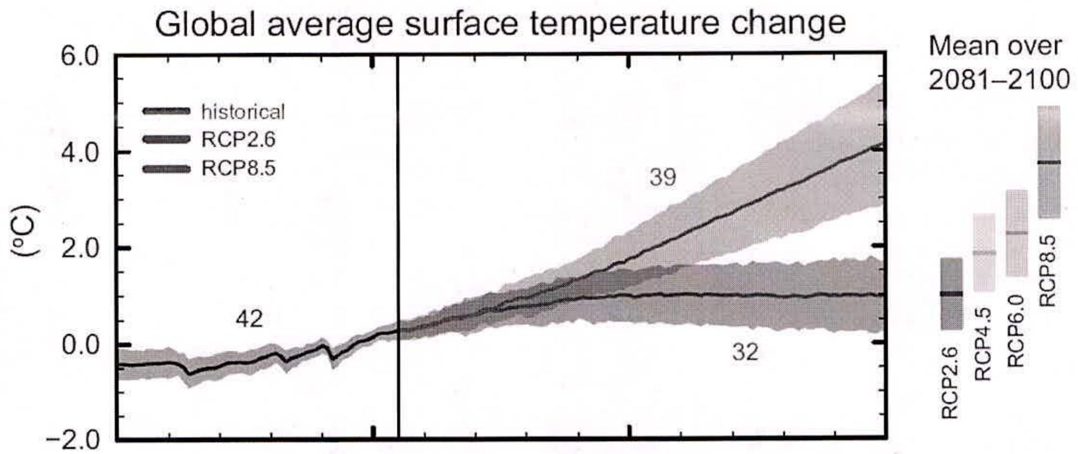

Fig. 9 Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed 2°C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2°C for RCP4.5 (Source: IPCC, 2013)

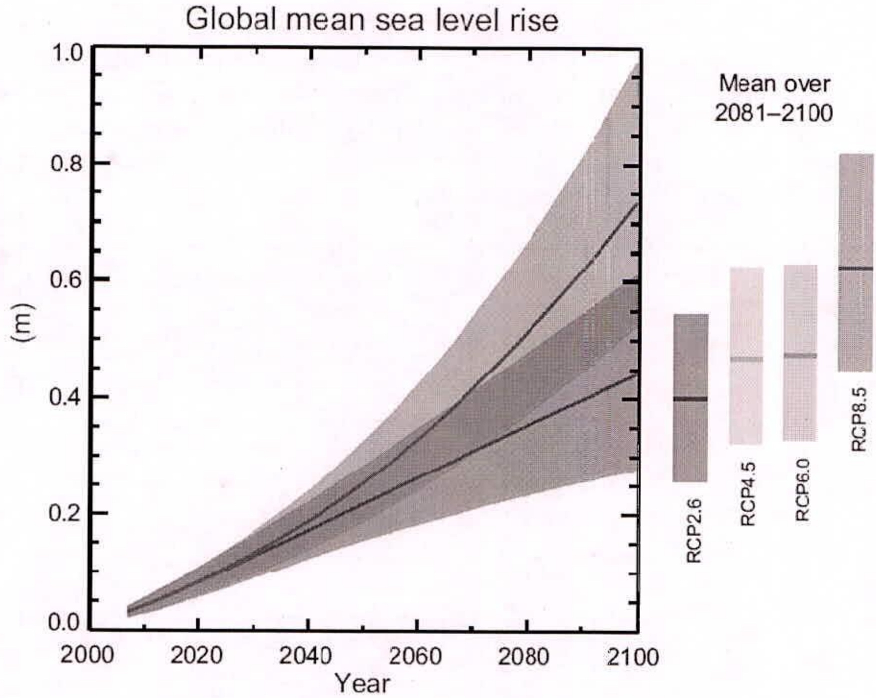

Fig. 10 Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 (Coupled Model Intercomparison Project Phase 5) ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean over the period 2081–2100 for all RCP scenarios are given as vertical bars, with the corresponding median value given as a horizontal line (Source: IPCC, 2013)

Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1 to 3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatisation by corals. Higher sea surface temperatures and ocean acidification would increase the risks of coral bleaching events that can lead to loss of critical habitat. The rising concentration of carbon dioxide (CO_2) in the atmosphere has increased the absorption of CO_2 in the ocean, where a chemical reaction that reduces the pH and makes the oceans more acidic occurs. This trend will likely continue in the coming decades. A more acidic ocean would adversely affect the health of many marine species, including plankton, mollusks, and other shellfish. Warming coastal waters may cause suitable habitats of temperature-sensitive species to shift northward. Some areas have already seen range shifts in both warm- and cold-water fish and other marine species. Pollock, halibut, rock sole, and snow crab in Alaska and mangrove trees in Florida are a few of the species whose habitats have already begun to shift. Suitable habitats of other species may also shift because they cannot compete for limited resources with the southern species that are moving northward. Invasive species that had not been able to establish populations in colder environments may now be able to survive and start competing with native species.

Coastal wetland ecosystems, such as salt marshes and mangroves, are especially threatened where they are sediment starved or constrained on their landward margin. Degradation of coastal ecosystems, especially wetlands and coral reefs, has serious implications for the well-being of societies dependent on the coastal ecosystems for goods and services. Increased flooding and the degradation of freshwater, fisheries and other resources could impact hundreds of millions of people, and socio-economic costs on coasts will escalate as a result of climate change.

Climate change will likely bring heavier rainfall and more precipitation to some coastal areas. This could lead to increases in runoff and flooding. In addition, warmer temperatures in mountain areas could lead to more spring runoff due to melting of snow. In turn, increases in spring runoff may also threaten the health and quality of coastal waters. As increases in spring runoff bring more nitrogen, phosphorus, and other pollutants into coastal waters, many aquatic species could be threatened. Decreases in precipitation could also affect the salinity of coastal waters. Droughts reduce fresh water input into tidal rivers and bays, which raises salinity in estuaries, and enables salt water to mix farther upstream.

The impact of climate change on coasts is exacerbated by increasing human-induced pressures (very high confidence).

Utilisation of the coast increased dramatically during the 20th century and this trend is virtually certain to continue through the 21st century. Under the SRES scenarios, the coastal population could grow from 1.2 billion people (in 1990) to 1.8 to 5.2 billion people by the 2080s, depending on assumptions about migration. Increasing numbers of people and assets at risk at the coast are subject to additional stresses due to land-use and hydrological changes in catchments, including dams that reduce sediment supply to the coast. Populated deltas (especially Asian mega deltas), low-lying coastal urban areas and atolls are key societal hotspots of coastal vulnerability, occurring where the stresses on natural systems coincide with low human adaptive capacity and high exposure. Regionally, South, South-east and East Asia, Africa and small islands are most vulnerable (Fig. 11). Climate change therefore reinforces the desirability of managing coasts in an integrated manner.

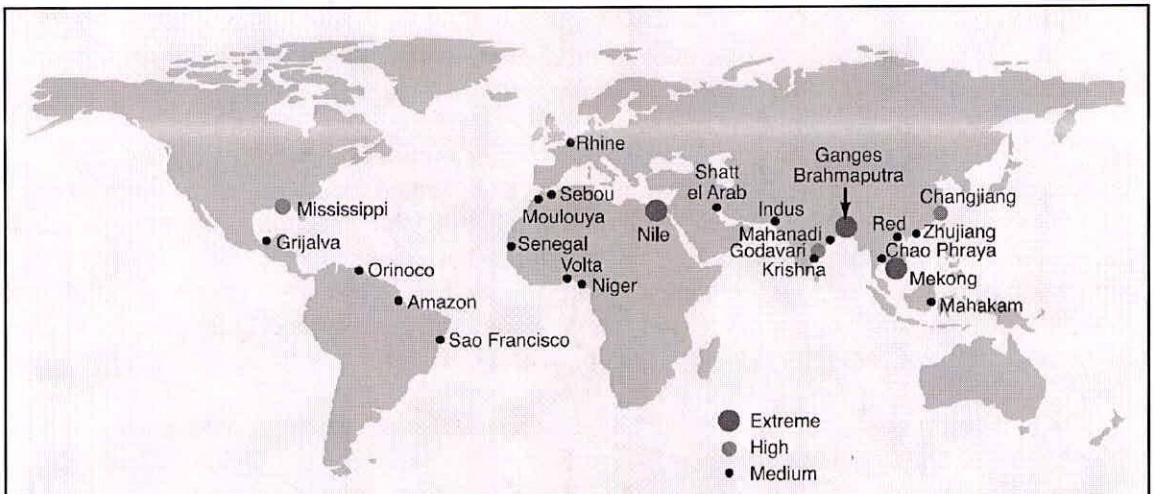

Fig. 11 Relative vulnerability of coastal deltas as shown by the indicative population potentially displaced by current sea level trends to 2050 [Extreme = > 1 million; High = 1 million to 50,000; Medium = 50,000 to 5,000] (Source: Nicholls et al., 2007).

Adaptation for the coasts of developing countries will be more challenging than for coasts of developed countries, due to constraints on adaptive capacity (high confidence).

Adaptive capacity is the ability of a system to evolve in order to accommodate climate changes or to expand the range of variability with which it can cope. The adaptive capacity of coastal communities to cope with the effects of severe climate impacts declines if there is a lack of physical, economic and institutional capacities to reduce climate-related risks and hence the vulnerability of high risk communities and groups. But even a high adaptive capacity may not translate into effective adaptation if there is no commitment to sustained action.

While physical exposure can significantly influence vulnerability for both human populations and natural systems, a lack of adaptive capacity is often the most important factor that creates a hotspot of human vulnerability. Adaptive capacity is largely dependent upon development status. Developing nations may have the political or societal will to protect or relocate people who live in low-lying coastal zones, but without the necessary financial and other resources/capacities, their vulnerability is much greater than that of a developed nation in an identical coastal setting. Vulnerability will also vary between developing countries, while developed countries are not insulated from the adverse consequences of extreme events.

Adaptation costs for vulnerable coasts are much less than the costs of inaction (high confidence).

Adaptation costs for climate change are much lower than damage costs without adaptation for most developed coasts, even considering only property losses and human deaths. As post-event impacts on coastal businesses, people, housing, public and private social institutions, natural resources, and the environment generally go unrecognised in disaster cost accounting, the full benefits of adaptation are even larger. Without adaptation, the high-end sea-level rise scenarios, combined with other climate changes (e.g., increased storm intensity), are as likely as not to render some islands and low-lying areas unviable by 2100, so effective adaptation is urgently required.

The unavoidability of sea-level rise, even in the longer-term, frequently conflicts with present-day human development patterns and trends (high confidence).

Sea-level rise has substantial inertia and will continue beyond 2100 for many centuries. Irreversible breakdown of the West Antarctica and/or Greenland ice sheets, if triggered by rising temperatures, would make this long-term rise significantly larger, ultimately questioning the viability of many coastal settlements across the globe. The issue is reinforced by the increasing human use of the coastal zone. Settlement patterns also have substantial inertia, and this issue presents a challenge for long-term coastal spatial planning. Stabilisation of climate could reduce the risks of ice sheet breakdown, and reduce but not stop sea-level rise due to thermal expansion.

In the absence of an improvement to protection, coastal flooding could grow tenfold or more by the 2080s, to affect more than 100 million people/yr, due to sea-level rise alone. Figure 12 shows the consequences and total costs of a rise in sea level for developing and developed countries, and globally. This analysis assumes protection is implemented based on benefit-cost analysis, so the impacts are more consistent with enhanced protection, and investment is required for the protection. The consequences of sea-level rise will be far greater for developing countries, and protection costs will be higher, relative to those for developed countries. Hence, it is apparent that the most appropriate response to sea-level rise for coastal areas is a combination of *adaptation* to deal with the inevitable rise, and *mitigation* to limit the long-term rise to a manageable level

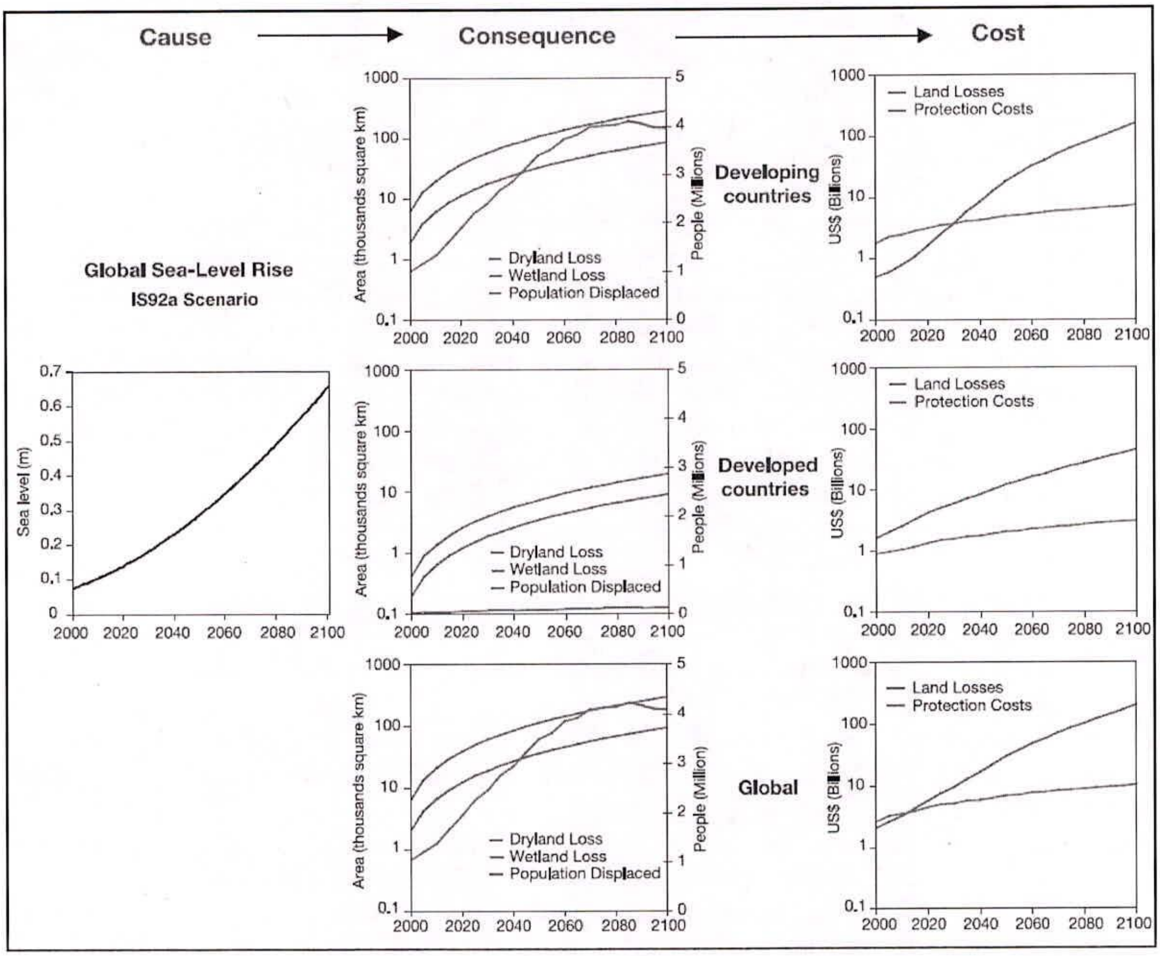

Fig. 12 Causes, selected consequences (dryland and wetland loss, people displaced) and the total costs of an assumed sea-level rise, for developing and developed countries, and as a global total (Source: Tol, 2007)

Impact of Climate Change on Coastal Groundwater

Seawater intrusion is a global issue, exacerbated by increasing demands for freshwater in coastal zones and predisposed to the influences of rising sea-levels and changing climate. Worldwide, seawater ingress has emerged as a major challenge for state/ local government bodies. Coastal areas around the world have been forced to address the issue of seawater intrusion, and they will likely continue to address it in the context of the growing need for freshwater and a changing climate.

Anthropogenic Factors: Demands on groundwater resources are particularly high in coastal areas, resulting in unmanaged indiscriminate pumping of groundwater resources and, exposing coastal aquifers to increased risk of seawater intrusion. Fresh groundwater resources in low-lying delta areas are used intensively for domestic, agricultural and industrial purposes, while the availability of huge quantity and good quality of fresh groundwater relative to the surface water makes it a popular resource. In the future, the exploitation of fresh groundwater resources will increase due to population and economic growth, intensified agricultural development, and the loss of surface water resources due to contamination. In addition, more-densely populated urbanized coastal areas usually have more-developed infrastructure with large paved surfaces that inhibit natural recharge of the aquifer; and large industries spewing out industrial effluents that are prone to contaminating underlying groundwater sources.

Climate Change: Sea-level rise contributing to saline intrusion or inundation of coastal freshwater resources is probably the most direct impact of climate change, particularly for shallow sandy aquifers along low-lying coasts. The natural groundwater dynamic equilibrium existing in a coastal system is also susceptible to changes in recharge and discharge associated with climate change. In addition, the anticipated sea-level rise and changes in recharge and evapotranspiration patterns will aggravate the pressures on the coastal groundwater system. It is not clear how far the coastal zones will be threatened by these future stresses from the point of view of groundwater. Conceptually, it is obvious that coastal aquifers will become more saline at an accelerating rate and that this could lead to a loss in fresh groundwater resources. Sea-level rise and climate change may potentially impact groundwater resources in the following ways:

- Seawater intrusion (progressive encroachment through the subsurface) and inland migration of the saltwater-freshwater interface.
- Seawater inundation (surface flow into low-lying areas) and flooding of unconfined aquifers.
- Contamination and damage of wells by storm surges particularly in low-lying areas.
- Changing recharge due to variable rainfall and evapotranspiration resulting in an altered distribution of freshwater in the aquifer.
- Changing discharge patterns due to extreme rainfall events can generate waterlogged conditions and may have an impact on aquatic and wetland ecosystems.
- High water table to have an impact on infrastructure, industries, residential properties, heritage properties, and commercial properties
- Sea-level rise and more-frequent extreme weather events will in turn lead to increased coastal erosion putting island communities, in particular, at risk (IPCC 2007). Similar to the effects of overpumping, decreased recharge, and sea-level rise, coastal erosion causes the shoreline to recede and the saltwater-freshwater interface to move further inland. Once again, this shift will allow saltwater to infiltrate more of the aquifer, increasing the likelihood of well contamination.

The occurrence of these impacts can vary substantially between different localities due to site-specific factors. Some impacts, such as changes to recharge and discharge patterns may also be naturally influenced by climatic variability. In some areas, groundwater extraction and subsidence of the land surface can heighten the potential impacts of climate change and sea-level rise. Long-term hydrologic monitoring is essential for understanding the effects of sea-level rise, climate change, and urbanization on the hydrologic system of the coastal zone and on the aquatic and estuarine ecosystems that depend upon that hydrologic system (Fig. 13). These 'agents of change' affect the hydrologic system in different ways and on different time scales.

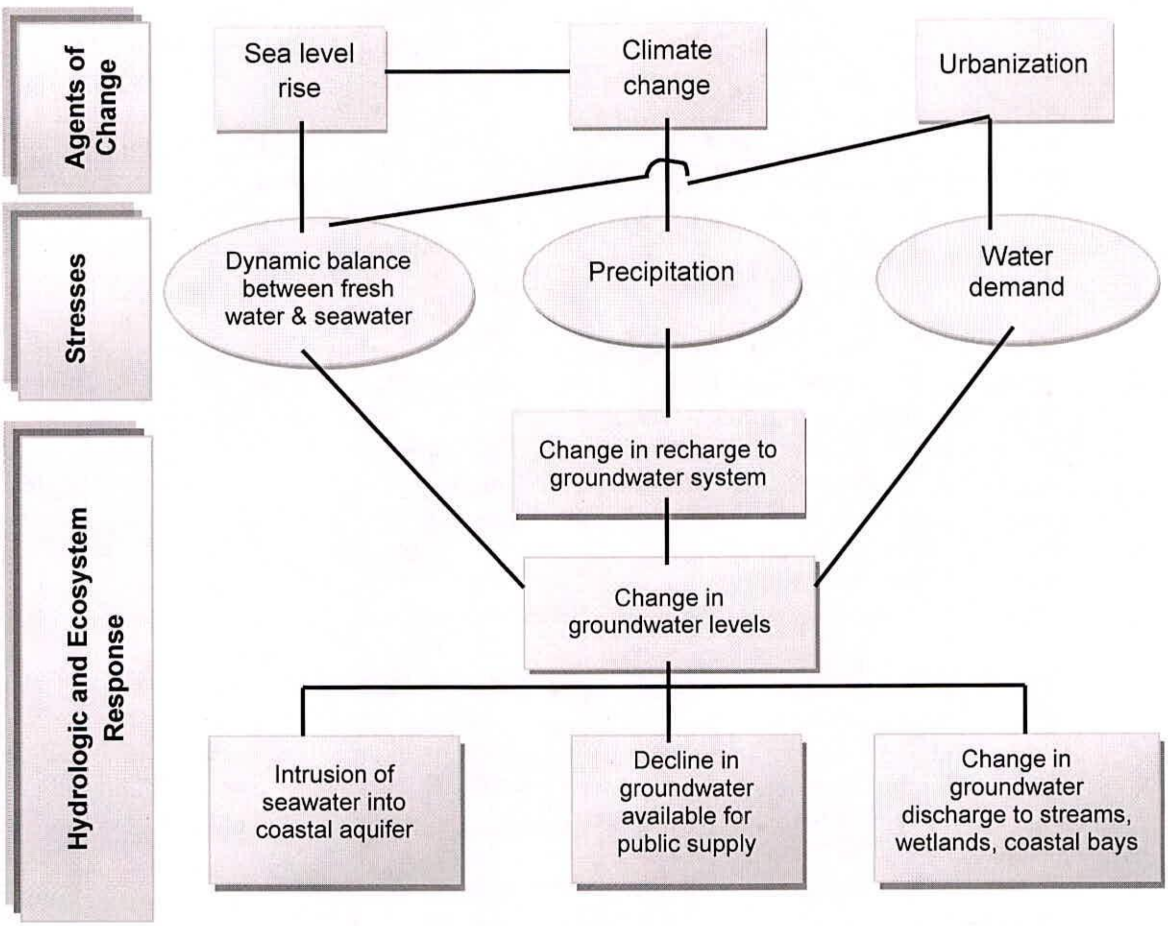

Fig. 13 Illustration of how 'agents of hydrologic change' can stress the coastal hydrologic system and cause a variety of ecosystem responses (Modified from McCobb and Weiskel, 2003).

EPILOGUE

Recent studies have indicated that direct impacts of sea-level rise on coastal inundation and extent of storm surges is of greater concern for groundwater conditions than classical lateral seawater intrusion. In coastal regions of India, there is still a great deal to be learned about the hydrogeologic conditions and hydrogeochemical processes that currently influence the prevalence and severity of seawater intrusion. By and large, the narrow coastal regions sandwiched between the Western Ghats and the Arabian Sea on the western side of the lengthy Indian coastline, have steep surface topography and mixed geological formations comprising of fractured hard rock, limestone and alluvium. The climatic conditions which affect groundwater replenishment vary considerably with Saurashtra region in Gujarat on the northern side having arid to semi-arid climate and Malabar coast towards the southern side of the west coast having tropical humid climate. On the other hand, the Eastern Coastal Plain is a wide stretch of gently sloping land lying between the Eastern Ghats and the Bay of Bengal. The Mahanadi, Godavari, Kaveri, and Krishna rivers drain these fertile alluvial plains.

The continued impacts of climate change contribute an additional element of uncertainty to the sustainability of fresh groundwater resource in these coastal zones. As sea-level rises and coastal erosion and demand for groundwater increase, the threat of seawater intrusion is also likely to increase. Deltas of the Ganga, Krishna, Godavari, Cauvery and Mahanadi on the east coast may be threatened along with irrigated land and adjoining settlements. Most vulnerable is the fragile ecosystem of Sundarbans, an archipelago of several hundred islands and world's largest mangrove ecosystem, located on the southern fringes of the state of West Bengal, where the Gangetic plain meets the Bay of Bengal. Vulnerable stretches along the western Indian coast include Khambat and Kutch in Gujarat, Mumbai and parts of the Konkan coast and south Kerala.

The specific effects of climate change impacts are not certain, however, and are likely to be highly variable from location to location. Coastal erosion rates, for example, can be different within very short distances. Similarly, because soil characteristics vary from place to place, changing precipitation regimes may not affect recharge rates uniformly across the region. Such uncertainty highlights three notable voids currently inhibiting progress in our attempt to address vulnerability of coastal zones in India to climate change and seal-level rise: the need for better data, the need for better collaboration, and the need for better planning.

Better data and better collaboration form the foundation for better planning. The inevitability of climate change and its impacts on natural coastal systems prompts the need for long-term decision making. Data of increased quality and quantity help to paint a more complete picture of existing coastal conditions, providing accurate and up-to-date information regarding coastal erosion rates, sea-level rise, temperature and precipitation trends, and the position and the subsurface movement of the saltwater-freshwater interface. These data can assist in land use regulation and policy development, particularly regarding sustainable groundwater development in coastal zones.

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About NIH and GWRDC

The **National Institute of Hydrology (NIH)** is a premier research Institute in the area of hydrology and water resources in India. The Institute has its headquarters at Roorkee (Uttarakhand), two Centres for Flood Management Studies at Guwahati and Patna, and four Regional Centres at Belgaum, Jammu, Kakinada and Sagar. The Institute was established in 1978 as a research organization at Roorkee. Since inception, the Institute has carried out research studies covering almost all areas of hydrology, and has established contacts with national and international organizations of repute.

The Institute is well equipped to carry out computer, laboratory and field oriented studies with a team of 80 well qualified and trained scientists with excellent academic background. The Institute has state-of-the-art laboratories with latest instruments and facilities. NIH has actively participated in technology transfer activities. With these activities, the Institute has positioned itself as a centre of excellence for research and development in the area of hydrology in the country.

The **Gujarat Water Resources Development Corporation Ltd. (GWRDC)** was created in 1975 with a view to concentrate on groundwater investigation, exploration, management and recharge works in the State of Gujarat. GWRDC is functioning under the Narmada Water Supply & Water Resources Department of Govt. of Gujarat. GWRDC has total 72 offices all over the state of Gujarat with Head Office at Gandhinagar and 4 Circle Offices at Gandhinagar, Ahmedabad and Kherva.

GWRDC has three technical wings, namely (a) Geological Wing (1 Circle), which deals with groundwater investigation and monitoring, (b) Mechanical Wing (1 Circle) which deals with drilling operation and maintenance of rigs vehicles and pumps, and (c) Civil Wing (2 Circles) which deals with maintenance and management of irrigation tubewells, and construction and maintenance of civil works like building, pipeline, construction of recharge works (check dam, deepening of ponds etc.), and lift irrigation schemes. There are four laboratories for chemical and biological analysis of water and soil samples with highly sophisticated instruments. Modern facilities exist for remote sensing data analysis and GIS for groundwater investigations.

Coastal Groundwater Development, Modeling & Management

Training Course under HP-II, Ahmedabad (March 3-7, 2014)
Organized by NIH Roorkee & GWRDC Gandhinagar

Field experiments in Odedar Village near sea coast, Porbandar District