Imminent Climate Change and Response of Ecosystems and Natural hazards: Challenges Ahead

A.C. Narayana
Centre for Earth, Ocean and Atmospheric Sciences
University of Hyderabad, Hyderabad – 500046
E-mail: acnes@uohyd.ac.in

P. Yunus Ali
National Institute of Environmental Studies, Tsukuba, Japan

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Why to understand past climate?

1. Past variability can show climatic extremes that have not been experienced during recorded history.

2. In order to understand the effects of human activity on climate, we must establish what the planet, the atmosphere, and climate change was like before human perturbations.

3. Constructing and interpreting long-term records of climate are the only means to determine how periodic climate change is (All in all, we are just a blip).

4. Past is prologue.

“The farther backward you can look, the farther forward you are likely to see.” - Winston Churchill
Orbital-Scale Changes in CO$_2$

**Vostok Ice in Antarctica**
- Four 100,000-year cycles
- 23,000-year cycle not prominent
- Maxima: 280-300 ppm
- Minima: 180-190 ppm

**Major CO$_2$ cycles match marine $\delta^{18}$O (ice volume) cycles in an overall sense**

**Which is driving which?**

**Difficulties:**
- Low accuracy in dating in Antarctica
- Dust reacts with CO$_2$ bubbles in Greenland
Causes of Climate Change Since Deglaciation

<table>
<thead>
<tr>
<th>Period</th>
<th>Climate controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>21k yrs ago</td>
<td>Large ice sheets</td>
</tr>
<tr>
<td>21-6k yrs ago</td>
<td>Increasing summer insolation</td>
</tr>
<tr>
<td>6-0k yrs ago</td>
<td>Decreasing summer insolation</td>
</tr>
</tbody>
</table>

Climate controls:
- Low CO₂
- Increasing CO₂
- High CO₂
Stronger, Then Weaker Monsoons

High lake levels in the north tropics 9000 years ago
Yearly Temperature Change for the Last 2000 Years

Data from tree rings, corals, ice cores, and historical records are shown in various colors. Thermometers data in black.

About 1000 y.a., Medieval Warm Period. Certain regions were warmer than others. Warm and dry summers in England (1000-1300): vineyards flourished and wine was produced. Vikings colonized Iceland and Greenland.
Yearly Temperature Change Since 1850

Global Temperatures

- Annual Average
- Five Year Average

Data from thermometers

Yearly Temperature Change Since 1850

http://commons.wikimedia.org/wiki/Image:Instrumental_Temperature_Record.png
Comparison of two sea level reconstructions during the last 500 Myr: Exxon curve and Hallam curve. The scale of change during the last glacial/interglacial transition is indicated with a black bar.
Does sea-level rise have an impact on saltwater intrusion?

Sun Woo Chang a, T. Prabhakar Clement a,*, Matthew J. Simpson b, Kang-Kun Lee c

a Department of Civil Engineering, 212 Harbert Engineering Center, Auburn University, Auburn, AL 36849-5337, USA
b Discipline of Mathematical Sciences, Queensland University of Technology, G.P.O. Box 2434, Brisbane, Queensland 4001, Australia
c School of Earth and Environmental Science, Seoul National University, Seoul 151-742, Republic of Korea

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ABSTRACT

Climate change effects are expected to substantially raise the average sea level. It is widely assumed that this raise will have a severe adverse impact on saltwater intrusion processes in coastal aquifers. In this study we hypothesize that a natural mechanism, identified here as the “lifting process,” has the potential to mitigate, or in some cases completely reverse, the adverse intrusion effects induced by sea-level rise. A detailed numerical study using the MODFLOW-family computer code SEAWAT was completed to test this hypothesis and to understand the effects of this lifting process in both confined and unconfined systems. Our conceptual simulation results show that if the ambient recharge remains constant, the sea-level rise will have no long-term impact (i.e., it will not affect the steady-state salt wedge) on confined aquifiers. Our transient confined-flow simulations show a self-reversal mechanism where the wedge which will initially intrude into the formation due to the sea-level rise would be naturally driven back to the original position. In unconfined systems, the lifting process would have a lesser influence due to changes in the value of effective transmissivity. A detailed sensitivity analysis was also completed to understand the sensitivity of this self-reversal effect to various aquifer parameters.

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Climate Change and Antarctica Ice

2. Evidence from past climate for CO$_2$ link to climate

C. The ice ages
Climate Change and Antarctic Glaciers

- Climate change is strongly affecting Antarctica.
- Around the Antarctic Peninsula, temperatures are warming at a rate that is approximately six times the global average.
- Air temperatures increased by ~2.5°C from 1950-2000.
- Regional rapid warming began in the 1930s.
- The annual mean air temperature -9°C isotherm has moved southwards, resulting in ice-shelf collapse and glacier recession.
- A recent ice core from James Ross Island shows that warming in this region began around 600 years ago and then accelerated over the last century.
- This rate of warming is unusual, but not unprecedented.
Collapsing Ice Shelves

Ice shelves are the floating extensions of a grounded ice sheet. Ice shelves disintegrating very rapidly over the last few decades, which has destabilised on-shore glaciers, which rapidly thinned and receded following removal of a buttressing ice shelf.

Each summer, a significant amount of meltwater is produced as Climate in the Antarctic Peninsula has warmed by 3°C, which causes the retreat of stable ice shelves. Since the 1950s there is a loss of 25,000 km2 of ice shelf.
Average calving rate (Gt/yr) of Antarctic ice shelves for 2005-2019.

Relationship between annual iceberg calving distribution for 2005 to 2019 and (a) oceanic Niño index data from https://ggweather.com/enso/oni.htm and (b) maximum daily ice sheet surface melting area data (http://pp.ige-grenoble.fr/pageperso/picardgh/melting/)

Qi et al., 2021
Annual distribution of cumulative iceberg calving frequency, area, and mass for August 2005 to August 2019.

<table>
<thead>
<tr>
<th>Year</th>
<th>Calving frequency</th>
<th>Calving area/ km²</th>
<th>Calving mass/ Gt</th>
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</thead>
<tbody>
<tr>
<td>2005/06</td>
<td>127</td>
<td>3372.5</td>
<td>755.9</td>
</tr>
<tr>
<td>2006/07</td>
<td>98</td>
<td>1702.5</td>
<td>402.0</td>
</tr>
<tr>
<td>2007/08</td>
<td>69</td>
<td>2775.3</td>
<td>570.8</td>
</tr>
<tr>
<td>2008/09</td>
<td>113</td>
<td>4341.3</td>
<td>704.4</td>
</tr>
<tr>
<td>2009/10</td>
<td>87</td>
<td>4261.5</td>
<td>1001.7</td>
</tr>
<tr>
<td>2010/11</td>
<td>83</td>
<td>1707.6</td>
<td>332.0</td>
</tr>
<tr>
<td>2011/12</td>
<td>95</td>
<td>3218.3</td>
<td>847.4</td>
</tr>
<tr>
<td>2012/13</td>
<td>119</td>
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<td>762.7</td>
</tr>
<tr>
<td>2013/14</td>
<td>99</td>
<td>2148.0</td>
<td>562.3</td>
</tr>
<tr>
<td>2014/15</td>
<td>73</td>
<td>2262.4</td>
<td>552.5</td>
</tr>
<tr>
<td>2015/16</td>
<td>206</td>
<td>5584.5</td>
<td>1398.8</td>
</tr>
<tr>
<td>2016/17</td>
<td>224</td>
<td>9260.2</td>
<td>1832.6</td>
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<tr>
<td>2017/18</td>
<td>168</td>
<td>1386.3</td>
<td>338.9</td>
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<tr>
<td>2018/19</td>
<td>225</td>
<td>2806.4</td>
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</tr>
<tr>
<td>Average</td>
<td>127.6</td>
<td>47759.0</td>
<td>10795.0</td>
</tr>
<tr>
<td>Total</td>
<td>1786</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spatial distribution of annual calving events for different scales and types of Antarctic ice shelves for August 2005 to August 2019.
Antarctic ice-shelf ice-thickness change rate $\Delta T/\Delta t$, 2003–2008.

Pritchard et al., 2012
Larsen Ice Shelf

Landsat images showing the collapse of the Larsen Ice Shelf. Note the blue mottled appearance in 2002, resulting from the exposure of deep blue ice.

The Larsen Ice Shelf collapsed dramatically and very rapidly in 2002, and glaciers that previously fed into the Larsen Ice Shelf have since accelerated, thinned and receded. The ice shelf disintegrated very rapidly, main event just happening one warm summer.

The Larsen B Ice Shelf, shown in Figure, has been stable throughout the Holocene and this is the first time it has collapsed in the last 10,000 years.
Impacts on wildlife: penguins
There are about 20 million breeding pairs of penguins in the Antarctic. Some species of penguins in Antarctica are declining in numbers. Adélie penguins, a species well adapted to sea ice conditions, have declined in numbers in some areas and have been replaced at some sites by open-water species such as chinstrap penguins. Further south, emperor penguins, which breed on sea ice surrounding continental Antarctica, have also experienced a decline in numbers by up to 50% in places.
Climate change over the past few decades has already caused significant shifts in marine and terrestrial ecosystems (Hughes 2000; Walther et al. 2002; Thomas et al. 2004).

Marine species are affected by physical and biochemical alterations of our oceans because of increasing emissions and rising temperatures.

Antarctic ecosystems, particularly those around the Antarctic Peninsula, a region which is experiencing one of the fastest rates of regional climate change on Earth (Turner et al. 2009), are particularly vulnerable and sensitive.

Continued warming together with increasing CO$_2$ concentrations in the SO is causing a cascade of environmental effects with far-reaching consequences for the benthic fauna (Fig. 2, flow chart).
Flow chart of the main effects climate change caused in the marine environment, indicating a cascade of effects that will ultimately have an effect on the benthic biology. Red-framed boxes indicate interacting physico-chemical variables that change the environmental settings and can have an effect on the benthic biota or communities. Blue, brown, green colored boxes are factors that are affected by the physico-chemical variables, which may interact with each other and cause a type of disturbance to the benthic biota/communities (Jeroen Ingels et al. 2012).
Since 2000, global anthropogenic CO$_2$ emissions have been rising at alarming rates and exceed worst-case scenarios projected by the IPCC (IPCC’s Fourth Assessment Report) (Raupach et al. 2007b).

As atmospheric CO$_2$ concentrations rise, ocean CO$_2$ uptake increases and the chemical balance of seawater is disturbed; causes the pH to decrease which has wide range of consequences for marine pelagic and benthic life and ecosystems (Gattuso and Hansson 2011).

Consequently, the production of biogenic calcium carbonate becomes difficult for certain marine organisms (Kroeker et al. 2010).
Climate Change Impacts on Marine Ecosystems

Conceptual diagram of human and climate interactions on nutrient-enhanced productivity, harmful and noxious algal blooms, and formation of hypoxia. Positive (+) interactions designate a worsening of conditions related to algal blooms and hypoxia, and negative (−) interactions designate fewer algal blooms and lessening of hypoxia symptoms. Dashed lines indicate negative feedback processes to nutrient-enhanced production and subsequent hypoxia. Dotted line between anthropogenic activities and climate variability/climate change indicates that current climate change is driven largely by humans, but that climate change can certainly affect human activities (Rabalais et al. 2010; Doney et al. 2012).
Climate change puts at risk many of nature’s benefits, or ecosystem services, that humans derive from the sea. For example, climate-induced sea-level rise could put added pressure on coastal infrastructure.

Natural habitats such as wetlands, mangroves, coral and oyster reefs, and seagrasses buffer coastlines from erosion and inundation, providing important protective services.

**Coral Reef Systems**

One-quarter of all marine species associate with coral reefs, and the ecological impacts of changing climates and chemistry on overall marine biodiversity are potentially severe and widespread. The ability of the coral animal to create massive and complex reef structures, on which the rest of the ecosystem depends, is sensitive to relatively small changes in temperature and pH (Kleypas et al. 2006, Hoegh-Guldberg et al. 2007).

Ocean acidification makes it more difficult for corals to secrete and maintain their skeletons (Salvat & Allemand 2009).
Ocean acidification in the coastal ocean

The oceans play a crucial role in the global carbon cycle and store about one third of the anthropogenic carbon dioxide (CO$_2$) emissions since 1800. When CO$_2$ dissolves in seawater, it generates a decrease in pH and in the concentration of carbonate (CO$_3^{2-}$) ions.

Since pre-industrial time, surface ocean pH has declined by 0.1 unit and, according to model projections, a further decrease of 0.2-0.4 unit is anticipated for the end of the century.

In the coastal ocean, more complicated pH trends than in the open ocean due to various biogeochemical and hydrological processes.

Although the coastal ocean only represents a small portion of the oceanic surface area, it exhibits high biological activities and primary production that may be affected in the coming decades.
Seawater pH has already declined by 0.1 unit and the concentration of CO$_3^{2-}$ by about 30% compared with pre-industrial values (Gattuso & Hansson 2011; Orr 2011). By the end of this century, pH is projected to decrease by another 0.2 to 0.4 unit (Orr 2011; see Fig.).

Figure: Changes in atmospheric pCO$_2$ and surface-ocean pH over time. Modern surface pH data are from the GLODAP 1994 dataset for upper ten meters (Key et al. 2004); the historical values of atmospheric CO$_2$ are from the analysis of the air bubbles trapped in the ice (Enting et al., 1994) until 1957, after which they come from the annual average of atmospheric CO$_2$ measurements at the Mauna Loa Observatory (Keeling et al. 2009). Also shown are atmospheric CO$_2$ values for glacial and preindustrial periods as well as that for year 2100 (under the IS92a scenario; IPCC 2007). Modified from Körtzinger (in IMBER 2005) by Gazeau et al 2011.
Figure: Upper plot: Variation of pH along a transect toward a CO$_2$ vent south of Castello d’Aragone (Ischia, Italy). Lower plot: along the same transect, the abundances of key species of this ecosystem are presented. The percentage cover (left axis) of calcareous (blue solid line) and non-calcareous algae (green dotted line) as well as the abundance (right axis) of sea urchins (red dotted line) are shown. Data are from Hall-Spencer et al. (2008).
Fig. Climate change and non-climate stressors interact and affect ecological systems at multiple scales. These combined stressors affect individuals, populations, and species, as well as ecosystem processes and properties. The relative impact of climate change versus other stressors varies depending on the species or ecosystem. Diverse biological communities and functioning ecosystems are critical to maintaining the ecosystem services (Millennium Ecosystem Assessment, 2005) that support human well-being (Díaz et al., 2019).

Natural resource management affects biodiversity, ecosystems and their services and can moderate or exacerbate climate change and non-climate stressors.
Greenhouse gases and Hydrological cycle

**Conceptual model:**

Effect of greenhouse gases and global warming on the **hydrologic cycle** and phenomena associated with many climate extremes (source: Trenberth)
Hydrological changes associated with greenhouse warming

- Regional patterns of precipitation will change.
- A rise in global mean temperature of about 1.5 to 4.5\degree C would increase global mean precipitation about 3 to 15%.
- Increased precipitation rates leads to reduced runoff.
- The frequency and severity of droughts could increase in some areas as a result of decreased total rainfall.
- Flood frequencies increase in many areas and may become less frequent in some areas.

The hydrology of arid and semiarid areas is particularly sensitive to climate variations.
Map of reported historic and newly detected GLOFs in five major drainage basins in the Himalayas
Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya

Cook et al, 2018

Nie et al 2021
Hydrological risks and water stress in the Himalaya and Karakoram basins. 

- **a** | Riverine flood risk in terms of average annual impact, where a higher risk indicates a greater proportion of population to be impacted.
- **b** | Drought risk.
- **c** | Baseline water stress.
- **d** | Future water stress in 2040 under the representative concentration pathway (RCP) 8.5 scenario.

Nie et al. 2021
Imminent threat of climate warming in High Mountains: Considerations from Chamoli landslide and other recent cases
On the morning of February 07, 2021, a catastrophic flood occurred in Dhauli Ganga River, destroyed Tapovan-Rishigad and Rishi-Ganga Hydropower plants. Killed more than 100 people.

Initially several print media and online sources reported this event as a ‘glacial’ burst or glacial lake outburst flood disaster, because a catastrophic flood was first noticed in the middle of the day in the Rishi Ganga river, a tributary of the Ganges.
Fan, Yunus and others (communicated)
Satellite image interpretation confirmed that the source area consists largely of bedrock covered with some amount of ice, and no lake or lake burst involved, hence we termed the event as **ice-rock avalanche**.
Fig. a and b are the longitudinal and transverse slope profile of the source area of 2021 ice-rock avalanche event from pre- and post-event DEM. c is the slope profile of the source area of 2016 landslide event (cf. section ‘unrecorded 2016 event’), d-f are the transverse cross section profile or river valley shown in g. The pre-event DEM is from ALOS PALSAR (12.5 m), and post event DEM is from Pleiades (2 m) of February 10, 2021, both resampled to 10 m (the red color area in g is zone of maximum difference between two DEMs). Fan, Yunus and others (communicated)
The landslide scar was located nearly 125 m from the summit of Ronti glacier at an elevation of approximately 5500 m a.s.l. The maximum width and length of the block that removed from the source is 602 m and 700 m respectively. The estimated area is 0.30 km²
Identifying the Causes

2016/09/19

Fan, Yunus and others
(communicated)

2016/10/09
Sources of flood

Satellite imagery prior to February 07, 2021 shows that the river valley was covered with some amount of ice/snow before the ice-rock avalanche failure. Additionally, there was thick pile of sediments and water (or ice possibly) deposited below the present-day cover, originated from the 2016 event. These materials supplied the medium for the catastrophic flood together with the ice-rock block that failed on February 7, 2021.

Fan, Yunus and others (communicated)
Are there any earthquakes?

The region also has been the site of moderate earthquakes. Between 2000 and 2021, there were 13 earthquakes (>\(M_w 4\)) occurred within 50 km, and 124 earthquakes within 200 km of the landslide source. The largest being \(M_w 5.6\) (June 2002 and October 2004), and latest being in October 2020 with \(M_w 4.6\), all three of them at >150 km from the source. Nonetheless, no particular seismic event was reported during the two event periods in 2016 and 2021.
Climatic data suggest that there were no unusual weather events recorded during the 2016 landslide event or during the 2021 event except for the fact that both years recorded higher than average land surface temperature (LST) and lower than average snowfall in the winter months. (Fan, Yunus and others)
Inference

- It is evident from satellite images after the 2016 landslide event that a linear fracture was well developed at the scar region of 2021 event.

- This fracture is formed because of debuttressing and removal of rock mass along two set of weak joint planes that is visible throughout the slope.

- Over the time, this fracture is widened, most plausibly by a multitude of factors including freeze-thaw action and thermo-mechanical behavior in rocks that is strongly prevalent in the glaciated regions nowadays owing to climate warming.
Future Challenges

- Assessing glacier retreat and links between increasing landslides and channel erosion in High Mountain Areas such as Himalayas.
- Glacial Lakes outburst and fluvial dynamics.
- Estimating sediment budget following the disasters (Mass balance problem).
GLOBAL WARMING AND REGIONAL CLIMATE SHIFT IN THE ARABIAN SEA

Arabian Sea is a site of tropical cyclones that occur during spring–summer (May–June) and fall–winter (October–November) transition periods.

However, the ratio of occurrence of tropical cyclones in the AS is 4 times lesser (Dube et al., 1997) than that in the Bay of Bengal.

Though the number of the tropical cyclone is less, its impact on the AS biogeochemistry is huge (Byju & Prasanna Kumar, 2011).
In recent years, Arabian Sea is experiencing more cyclones. One of the most compelling reasons for this appears to be the warming of the Arabian Sea.

Indian Ocean is warming at much faster rate than the rest of the world ocean and the warming of the Indian Ocean is concentrated in its western (Arabian Sea) region. **Arabian Sea is warming at overall rate of** 9.8 millidegrees per year (0.0098°C per year) from 1960 to present (Joshua D’Melo & Prasanna Kumar, 2018).

**Rate of warming has increased since mid-nineties**, from 7.2 millidegrees per year from pre-mid-nineties (1960 to mid-nineties) to 11 millidegrees per year post mid-nineties.

Cyclones used to be very rare in the Arabian Sea compared to Bay of Bengal (pre-mid-nineties).

Increased cyclones would lead to increase mixing of the upper ocean, which will bring more nutrients from subsurface to surface ocean and finally its utilisation by phytoplankton leading to increased primary production (Byju & Prasanna Kumar, 2011, Chowdhury et al., 2020a,b, Chowdhury et al., 2021).
Fig. Track of the cyclone Phyan (black line) over the Arabian Sea during 09th to 11th November 2009. Shading and the filled contours are SST averaged during the above period. Box ABCD denotes the area influenced by the cyclone while box EFGH indicates the location of the cold pool. Blue patches are waters colder than 27.5 °C, seen during cyclone period to the right of the cyclone track.
Cyclone *Tauktae* began to parallel the coast of the Indian states of Kerala, Karnataka and Maharashtra, before rapidly intensifying into a very severe *cyclonic* storm, early

Extremely Severe Cyclonic Storm Tauktae was a powerful tropical cyclone in the Arabian Sea that became the strongest tropical cyclone to make landfall in Gujarat. Since 1998 Gujarat cyclone is one of the strongest tropical cyclones to ever affect the west coast of India.
Thanks to:

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