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A Review on Storm Surge Studies along the Indian Coasts

Invited Article

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Area of Interest - Wind-Wave Modeling, Marine Acoustics, and Ocean Wave Climate Projections

Storm surge is a phenomena related with an abnormal rise of water level over and above the regular astronomical tide near the coast caused mainly by a landfalling tropical cyclone. The combined effect resulting from storm surge and astronomical tide is termed as 'storm-tide' coined by Cline (1920). According to Cline, the storm-tide is probably not more than 5 feet in open-ocean, however, the obstruction due to coastline acts as a barrier and water gradually banks up as it does against a dam across a stream. The concepts on storm surge were further modified by Tanehill (1927), Harris (1957) etc. Later, Harris (1957) defined storm surge as the difference between the actual tide as influenced by the meteorological disturbance, and the astronomical tide that would have occurred in the absence of any meteorological disturbance. Heaps (1967) defined storm-surge as the raising or lowering of sea level produced by wind caused by changes in atmospheric pressure over the sea associated with a storm. Very intense storms can generate large and devastating surge. Various forcing mechanisms such as strong winds, waves, and reduced atmospheric pressure within a cyclone generate storm surge. The magnitude of storm surge at any given location has a direct bearing on the intensity of cyclone that makes landfall. They are extremely dangerous as they cause extensive damage to infrastructure and flooding along the coastal areas. The total water level near the coasts that cause flooding, is therefore a combined effect resulting from storm surge, astronomical tide during the surge event, wave induced setup, rivers, and other additional factors. One can expect the worst possible scenario of flooding when storm surge coincides with high astronomical tides. For any location, the maximum storm surge depends on a number of factors. These include the cyclone intensity (higher central pressure drop increases the intensity, and vice-versa), forward motion of the cyclone (fast- and slow-moving cyclones), cyclone size (radius of maximum winds), angle of attack with respect to the coastline, geometry and characteristics of the coastline (coastline shape and presence of barriers, bays, lagoons etc), and beach geometry (offshore slope of the beach).

Looking in a global perspective, the western part of North Pacific Ocean reported the maximum number of tropical cyclones (average of 26 per year), followed by the eastern North Pacific (average of 17 per year). The North Atlantic and South Indian Ocean experience an average of about 10 cyclones per year, while the regions in North Indian Ocean (NIO) have an average of 5 cyclones per year (Niyas et al, 2009). Interestingly, the NIO accounts for about 7% of the global tropical cyclone activity and the frequency in the Bay of Bengal are about 5 times higher than Arabian Sea. The months during mid April-June and October-December are the peak periods of tropical cyclone activity in the NIO. Hence, in the Indian context, the states bordering the Bay of Bengal are at a higher risk from tropical cyclones compared to those bordering the Arabian Sea. In a broader perspective during the past 200 years, storm surges have killed as many as 2.6 million people around the world (Nicholls, 2004), that brings an average of about 13,000 people annually. As per the report of Intergovernmental Panel on Climate Change (IPCC, 1994) as many as 250 million people who live lower than the maximum storm surge level are highly vulnerable to coastal inundation from storm surge every year (Needham et al, 2015).

In the context to Indian sub-continent, storm surge studies started during the early 1970s. These studies focused mainly on the Bay of Bengal region, as it was well-known as a potential region for cyclogenesis. Das (1972) initiated the pioneering work on storm surge modeling leading to development of the first numerical model to predict storm surges in the Bay of Bengal for India and Bangladesh regions. This model simulated a devastating storm that struck the northeastern Bay of Bengal coast near Chittagong on November 12-13, 1970, providing a maximum storm surge of about 3.2 m southwest of Chittagong. Thereafter, storm surge prediction models were developed and implemented for the coastal plains of Bangladesh, being a high risk low lying

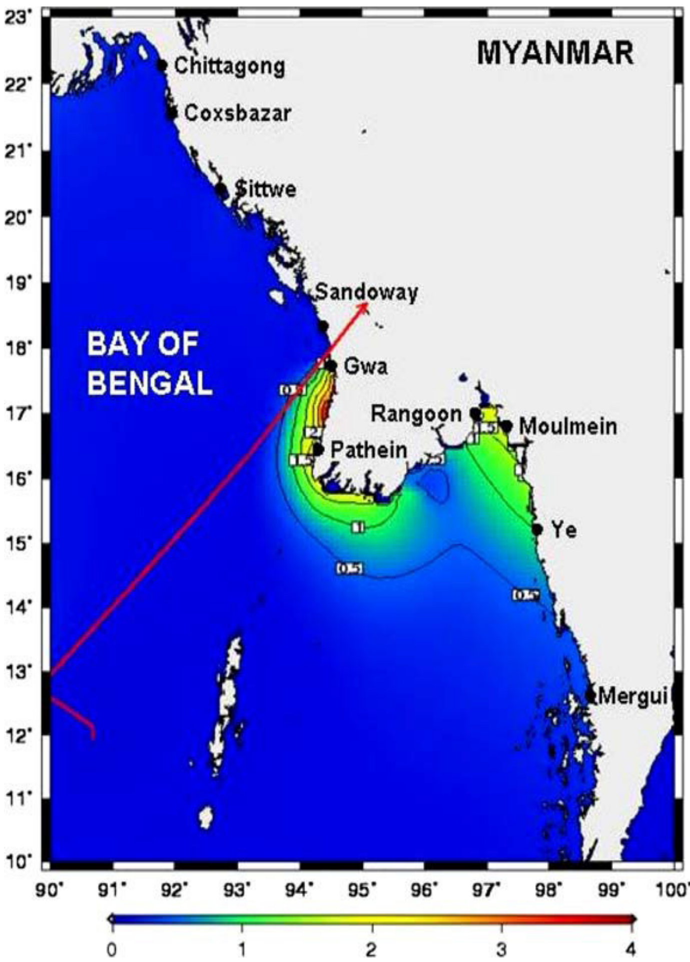


Fig. 1 Simulation of storm surge for 2006 MALA cyclone, the color bar with contours shows the magnitude of storm surge near the coast.

delta. The conical (funnel) shape of the water body in the Bay of Bengal intensify an approaching cyclone with their forward motion slowing down due to interaction with the wide and shallow deltaic continental shelf in the head Bay region (Dube et al, 1997). It was quite recently (from 2010 onwards) that the India Meteorological Department (IMD) began posting on the annual reviews of tropical cyclones including storm surge on its website. Thereafter, several works on storm surge prediction in the Bay of Bengal were reported by Das et al, (1974). Thereafter, Dube et al, (1997), reported an elaborate study on storm surges for the Indian coast using a finite difference model (popularly called as IIT-D storm surge model).

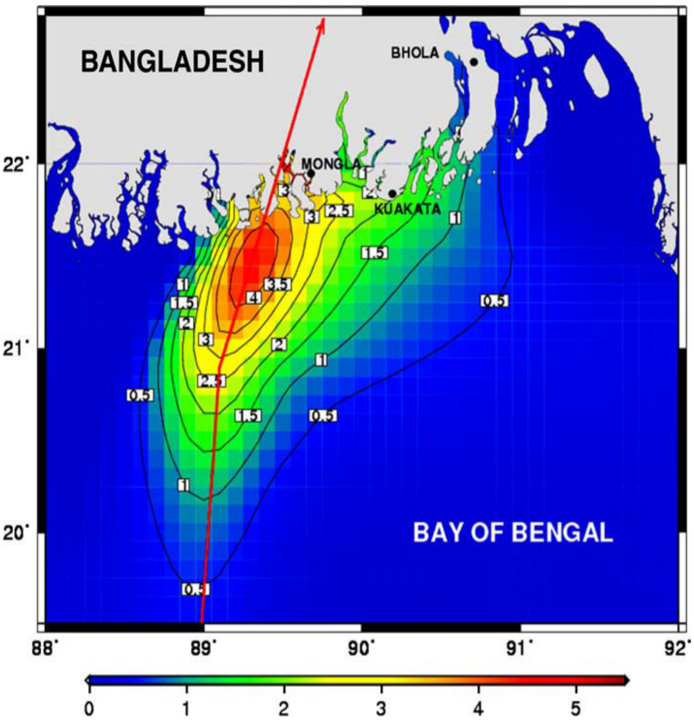


Fig. 2 Storm surge simulation for 2007 SIDR Cyclone.

A detailed review on the storm surge problem in Bay of Bengal is available in the published works of Ali (1979), Shaji et al. (2014) and references therin. Developments on real-time storm-surge prediction system for coastal regions of India were reported (e.g. Dube et al. 1994). Storm surge prediction system in real-time were developed for Bangladesh, Myanmar, Pakistan, Sri Lanka and Oman (e.g. Dube et al., 2004).

The National Meteorological and Hydrological Services of many countries surrounding the Indian Ocean rim achieved success providing storm surge warnings under the overall guidance and support of Tropical Cyclone Programme (TCP) of the World Meteorological Organization (WMO). Through the technology transfer from Indian Institute of Technology Delhi and Kharagpur, operational storm surge models were implemented for Bangladesh, Myanmar, Pakistan, Sri Lanka and Oman. Figure-1 shows the numerical simulation of storm surge using the IIT-D model for the severe cyclonic storm 'Mala' that occurred during 2006 and had landfall over the Myanmar region (Dube et al., 2009). The reported peak storm surge by the Department of Meteorology and Hydrology, Yangon was about 4 m in the Myanmar deltaic coast at Gwa. The model-simulated surge was 3.6 m to the right of the landfall location near Gwa, whereas the peak surge at Pathein was 2m (Dube et al., 2009). In another case, storm surge prediction using IIT-D model for November 2007 very severe cyclonic storm Sidr that had landfall over Bangladesh is shown in Figure-2. The computed maximum storm surge was 5.8 m near Mongla Port that was in close agreement with the highest surge estimates provided by Unisys (Dube et al., 2009). Figure-3 shows the simulated storm surge for the 1999 Odisha super cyclone. A maximum storm surge of 7.8 m occurred close to the landfall point, and post-storm survey reported surge in excess of 7 m near Paradip coast (Dube et al., 2009).

There have been many developments on storm surge prediction since the inception of IIT-D model attributing to the multifold increase in the computational resources and parallel computing. The High Performance Computing (HPC) systems have made it possible for rapid computation of very high resolution grids warranted for the coastal and nearshore regions. The grid structure comprising of finite element mesh has a definite advantage over the finite difference grids used in IIT-D storm surge model. The finite element grids can very well capture the complex coastline geometries, and especially in the head Bay of Bengal region there are numerous riverine drainage systems, mud flats, and shoals. In addition to this added advantage, a very high-resolution finite element grid over the nearshore regions precisely captures the correct location of peak surge. The recent pioneering works on storm surge modeling have led to the development of ADCIRC (Advanced Circulation Model) model. The depth-averaged version of ADCIRC (2DDI) can be used to study the phenomena of storm surge during extreme events like tropical cyclones. The development of ADCIRC model is a joint collaborative effort between the U.S. Army Corps of Engineers (USACE) Engineering Research and Development Centre, University of Notre Dame, and the University of North Carolina, U.S.A. The ADCIRC is a continuous Galerkin finite element shallow water model that solves the water level and currents at different range of scales (Luettich and Westerink, 2004). The model provides solution for the equation of motion in a rotating coordinate system. The governing equations are formulated using Boussinesq

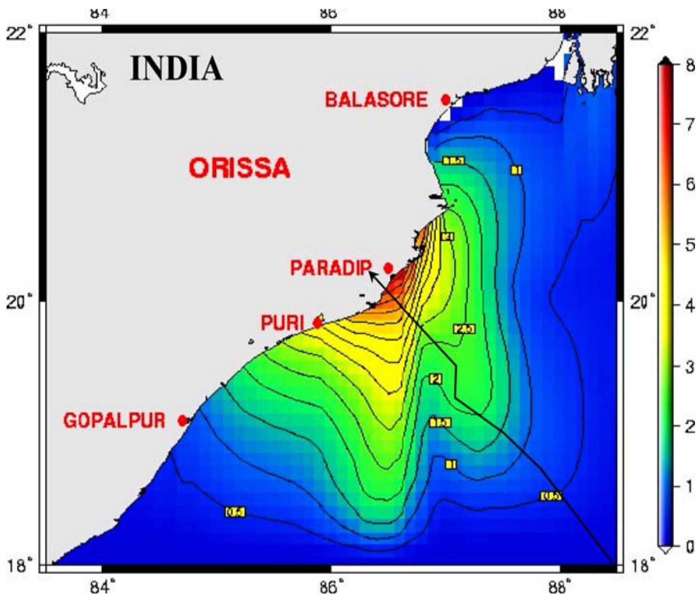


Fig. 3 Storm surge simulation for 1999 Odisha Super Cyclone.

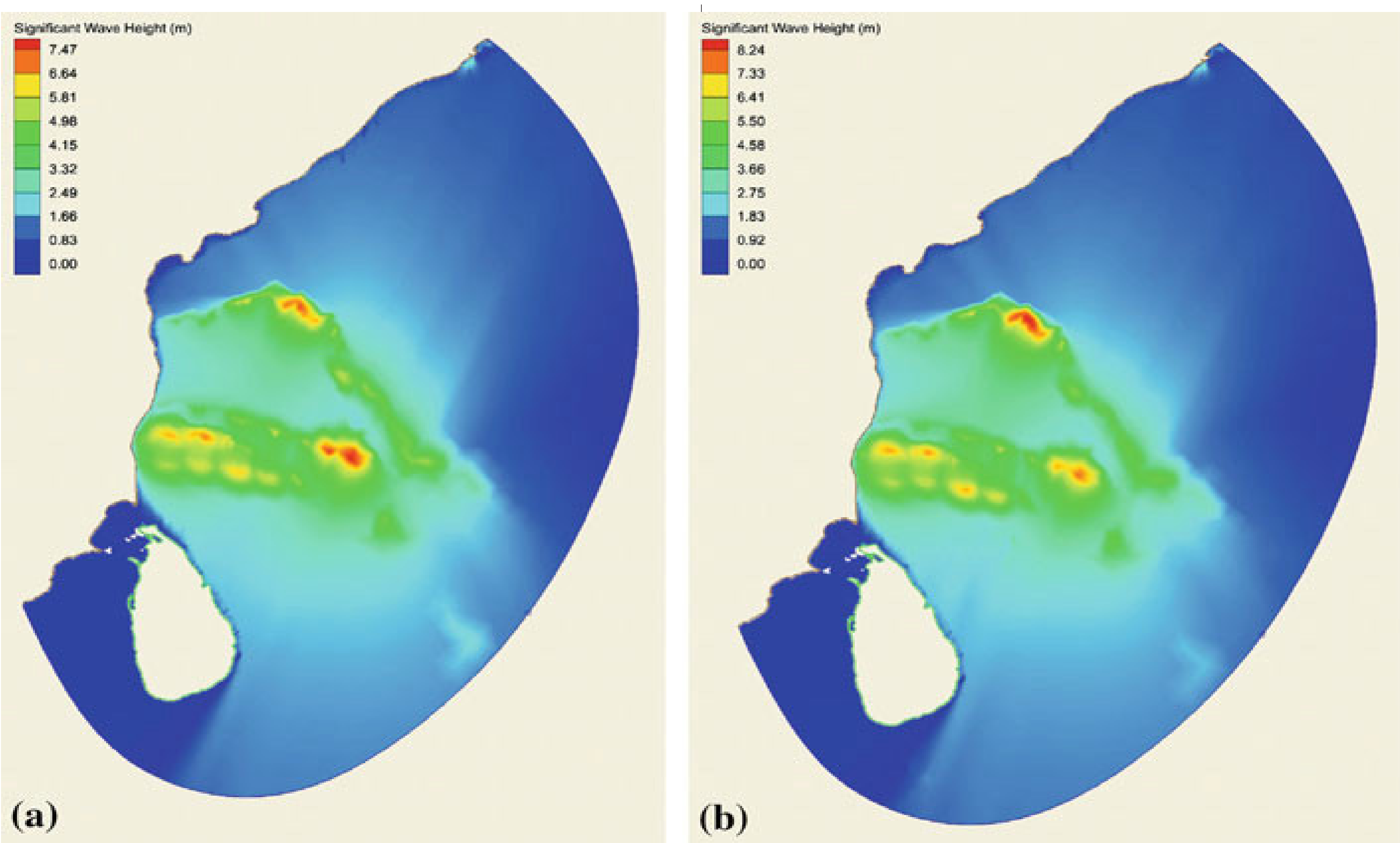


Fig. 4 Comparison of significant wave heights using ADCIRC in (a) standalone mode, and (b) two-way coupling (ADCIRC+SWAN).

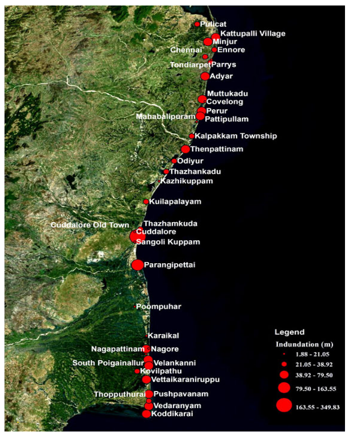
approximation and discretized in space using finite element method, and in time using finite difference method. It requires wind and pressure fields, and tidal forcing along open ocean boundary as essential inputs. The model uses a sophisticated algorithm for wetting and drying that activates and de-activates the grid points along nearshore areas during inundation and recession of coastal topography. In addition to storm surge computation, ADCIRC also provides information of coastal flooding during tropical cyclones. Rao et al. (2010) implemented ADCIRC model for the east coast of India to evaluate extreme storm-surge scenarios along Kalpakkam coast, known for its nuclear power plant. Authors identified eleven very severe cyclonic storms that made landfall in coastal Tamil Nadu from 1971-2007. Using these actual and theoretical tracks, seven synthesized generated tracks provided a comprehensive geographical coverage for the coastal areas of Tamil Nadu.

The advanced version of ADCIRC couples both the hydrodynamics and waves. The waves are simulated using SWAN (Simulating Waves Nearshore) model. In this context, the coupled model (ADCIRC+SWAN) is a powerful tool that takes into account the non-linear interaction process between waves and currents. For the first time, Bhaskaran et al., (2013), attempted the modeling effort for Indian seas using the coupled model. This study evaluated the performance and validation of the coupled parallel model for Thane cyclone event. The coupled model provides a realistic description of the net water level at the coast due to the combined wave-current interaction process. The model simulations with no-coupling (Figure-4a), and with a two-way coupling (Figure-4b) show the importance of a coupled modeling system for operational use.

There have been several other studies conducted using coupled ADCIRC+SWAN model for the Indian seas such as simulation of Phailin event (Murty et al., 2014) and inundation studies for Thane cyclone (Bhaskaran et al., 2014) and Aila cyclone (Gayathri et al., 2015).

The cover image shows the horizontal extent of coastal flooding associated with the Thane cyclone event. The future scope of work and direction should aim in development of robust operational modeling system that provides reliable predictions of water level and extent of coastal inundation that has wide socio-economic impacts. In addition, the impact of climate change and possible sea-level rise along with changes in the frequency and intensity of tropical cyclones is a challenging task. These factors are required to assess the flooding risks from storm surges in low-lying regions that encompass the north Indian Ocean. The results need integration on a GIS (Geographical Information System) framework to provide information on vulnerable areas and evacuation planning for coastal zone management authorities.

The cover image shows the computed coastal inundation scenario associated with THANE cyclone



Eddies in the Ocean

Review

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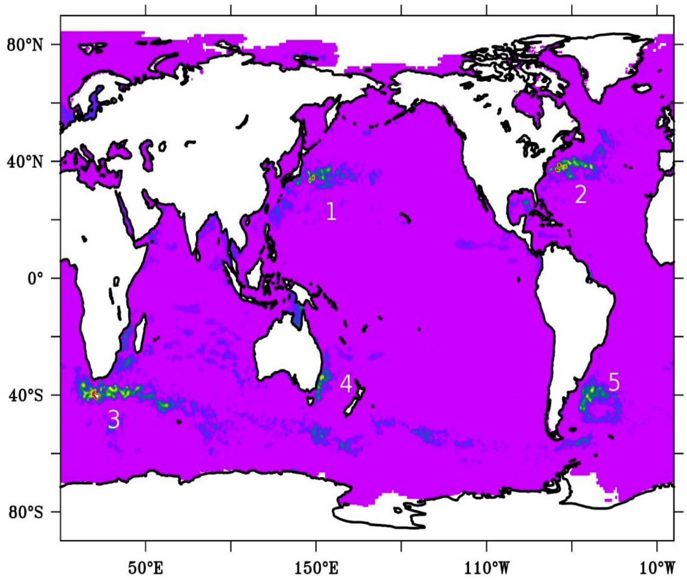
A 'traditional' picture of oceanic fields of temperature, salinity, density and current shows that the changes occurring in time and space are slow and smooth. This notion of a slow and smooth ocean was rendered illusory with the advent of high resolution observation techniques. They revealed that the oceanic motions vary abruptly in time and in space and are highly energetic. This variability mostly arises from circulating water columns commonly referred to as eddies and received great attention during the recent years.



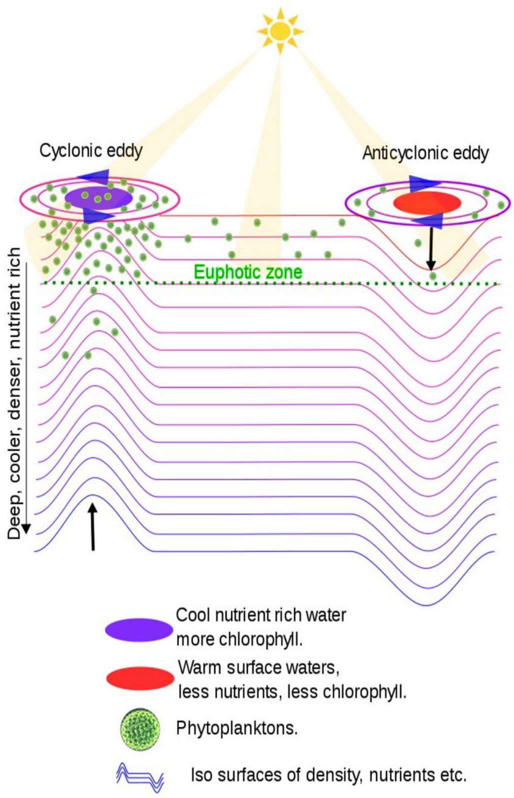


Figure. (Top) variance of sea - level anomaly for world oceans derived from satellite Altimetry (www.aviso.altimetry.fr). Higher variance indicates strong eddy activity. Regions of strong eddy activity are 1) Gulf stream 2) Kuroshio extension 3) Agulhas retroflection 4) East Australian current 5) Brazil – Malvinas confluence. In the North Indian Ocean strong eddy activity are found in Somali region in the western Arabian Sea and in the Bay of Bengal. (Bottom) Schematics of a cyclonic and anticyclonic eddy in the Northern Hemisphere. In a cyclonic eddy density surfaces are elevated w.r.t the surroundings, bringing cold nutrient rich subsurface waters to the euphotic zone, often triggering boliogical productivity, where as in an anticyclonic eddy density surfaces are pushed down resulting in warm nutrient depleted surface waters, often associated with low biological productivity.

At planetary scales, (spatial and temporal scales in which a motion "feels" earth's rotation) in the northern hemisphere, a northward/southward moving parcel of water would deflect right under the influence of Coriolis force. Consequently, water converges in a clockwise (anticyclonic) rotating eddy and diverges in an anticlockwise (cyclonic) eddy, leading to downwelling (upwelling) at their centres. This will result in dense cold nutrient rich (warm light and nutrient depleted) waters in a cyclonic (anticyclonic) eddy. Hence, cyclonic eddies, under the right circumstances would turn in to biologically active locations.

Eddies are formed from the instabilities within the ocean. Majority of eddies are found in western boundary regimes where the ocean currents may become unstable and generate eddies. Eddies generated from the Gulf Stream, in the North Atlantic, were the first to be studied experimentally, way back in 1793 [Robinson, 1983]. These eddies contribute to the salt transport and biological productivity in the region [The Ring Group, 1981]. Another eddy dominated region of World Ocean is the Northwest Pacific, which is known for the poleward flowing Kuroshio current. In the Indian Ocean, the best studied regions for eddies are the Somali and Agulhas current. Eddies in the Agulhas region play a vital role in inter-basin exchange of water across Indian and Atlantic oceans [Lutjeharms, 2006]. Eddies are abundant in the Bay of Bengal also. Situated in the North eastern corner of the Indian Ocean, the basin is marked by low biological productivity. Cyclonic eddies, however, makes the Bay of Bengal occasionally productive [Nuncio, 2007]. It has also been noted that anticyclonic eddies fuel cyclonic storms when they pass over it [Ali etal., 2007] and cyclonic eddies weaken them [Sreenivas and Gnanaseelan, 2014]. Thus in oceans, eddies are hotspots, where intense physical, chemical and biological processes are found.

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On the possible cause of distinct El Niño types in the recent decades

Student Article

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Introduction

The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual variability in the tropical Pacific having global socioeconomic impacts. Different El Niño types have been observed in the recent decades with warm anomalies in the eastern Pacific, known as canonical El Niño (EL) and warming in the central equatorial Pacific, El Niño Modoki (EM). A basinwide warming pattern (TP) is seen during 2009 and 2014. In this study, we carry out a detailed analysis of the observed and reanalyzed datasets along with numerical simulation experiments to understand the possible cause for different El Niño flavours.

Results

Composites of equatorial sea surface temperature anomalies (SSTA) and thermocline depth (D20) anomalies (Fig. 1) during EL, EM and TP years show appreciable differences in the spatial pattern and seasonality during the evolution. The amplitude of SSTA during the EM events is weaker as compared to EL. The warm SSTA are confined to the central equatorial Pacific, flanked by colder SSTA on both sides, in late boreal spring (MAM) of the EM events. For the EL events (Fig. 1a), the warm SSTA are seen in the central and eastern equatorial Pacific by late boreal spring and amplify during the consequent seasons, through boreal winter. The SSTA for 2014 shaded in Fig. 1c, shows the warm SSTA in the western and central equatorial Pacific by boreal spring with extension of warm anomalies since late boreal spring, without cooling the western Pacific unlike an EL or an EM event. Thus a basinwide warming pattern persists in the tropical Pacific from late boreal spring till the decay of the TP event.

The distinct SST pattern during different El Niño types is corroborated by distinct thermocline response as shown by the D20 anomalies (contour in Fig. 1). The thermocline in the eastern tropical Pacific starts deepening by boreal summer along with a shoaling in the western equatorial Pacific during an EL (Fig. 1a), and is anomalously deeper by about 30m in the east during the mature phase (boreal winter (DJF)). A sharp east-west gradient is generated in the equatorial thermocline anomaly, which amplifies the Bjerknes feedback and warms the SST in the eastern Pacific (Fig. 1a) during EL. On the other hand, during an EM, the eastern thermocline is comparatively shallow, with a maximum deepening of only about 10m is seen in the east and a weak shoaling in the west (Fig. 1b) during its peak phase. However, during a TP event (Fig. 1c), the thermocline deepened in the east during boreal summer, and was comparable to EL (Fig. 1a). Similarly the shoaling in the west is also weaker. Thus, a very weak east-west gradient is generated across the equatorial Pacific even during the mature phase of a TP event.

The difference in the evolution of thermocline and

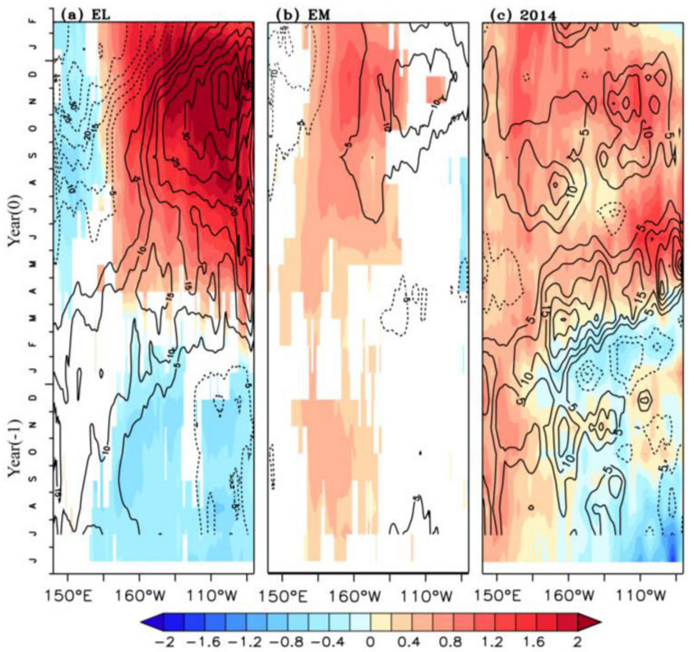

Fig. 1. Time-longitude plot showing composite anomalies of sea surface temperature (°C, shaded) and 20 °C isotherm depth (m, contour) averaged between 5°S-5°N for (a) canonical El Niño (b) El Niño Modoki. Significance values above 90% confidence level from a two-tailed student's t-test are shaded in (a) and (b) and (c) 2014 anomalies of sea surface temperature (°C, shaded) and 20 °C isotherm depth (m, con-tour) averaged between 5°S-5°N.

SSTA can be explained by distinct pattern of westerly wind anomalies (U') and warm water anomalies (T') in the Pacific. Strong U' is seen from boreal spring to fall of an EL over the western to central equatorial Pacific, while U' are weaker and confined to western Pacific during EM and U' were absent, during boreal summer of 2014 and boreal spring of 2009. Similarly stronger T' develop during boreal spring of an EL and TP, while it is weaker during EM. Thus the co-evolution of ocean and atmosphere is different between different El Niño's. Stronger boreal spring (Mar-May) through summer (June-September) U', with relatively stronger ocean pre-conditioning can lead to EL, weaker ocean preconditioning and weaker U' can generate EM, while stronger ocean preconditioning and weaker U'can lead to basinwide warming pattern. Thus this study has important implications for understanding the nature of El Niño in advance.

Acknowledgements: I express my sincere thanks to Director IITM and head CCCR for encouragement and support. I am also thankful to Dr. Swapna Panickal for her constant encouragement and guidance.

The myth regarding the "Great Bombay Cyclone" of 6 June 1882

History Article


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In a recent debate, a so called "Great Bombay cyclone of 6 June 1882" became the point of discussion. The question that may naturally arise in reader's mind is why such a discussion is needed after almost 133 years of the event. It is possibly due to the inquisitive mind of researchers that like to revisit already documented history and check its authenticity. The "Great Bombay Cyclone" of 6 June 1882 was reported to kill around 100,000 people which was one eighth of the total population of Bombay at that time and also reported to cause storm surge of 6 meter. This cyclone is mentioned in the list of deadliest cyclone by many authors. The book 'Divine wind' published by Oxford University Press in the year 2005 and written by Kerry Emanuel gives an account of history and science of Hurricanes. The "Great Bombay cyclone" of 1882 is listed in this book with the similar figures of loss of life and storm surge. Another recent book "Disastrous History of the World: Chronicles of War, Earthquake, Plague and Flood" written by John Withington and published in 2010 also mentioned about the "Great Bombay Cyclone" and its calamities. Another two prominent books namely the "Encyclopedia of Hurricanes, Typhoons, and Cyclones" By David Longshore and "the Oceans and Climate" by Grant R. Brigg have mentioned the "great Bombay Cyclone of 1882" and its associated devastations. Although all these books have listed the Bombay Cyclone of 1882, there is no reference available in the books, which ensures the source of information.

An independent search about the reports of the cyclone in the newspaper archive only brings out that it was reported in an article published in Telegraph of 17 September 1947 and also in another article published in the news paper "The Evening Independent" of 31 March 1964 from St. Petersburg. Besides these reports of newspapers and the above mentioned books, the "Great Bombay Cyclone" appears promptly in wikepedia by any www search engine. The question that recently perturbed a large number of researchers mind from US, India and other countries and engage them in an email based discussions is whether the event really occurred. The final conclusion that has come out is no such cyclone hit Bombay on 6 June 1882 and the conclusion could only be reached due to availability of the authentic maps of cyclone track and the daily weather summary from India Meteorlogical Department (IMD), Pune archive.

The article on "Tracks of Storms and Depressions in the Bay of Bengal and Arabian Sea during 1877-1970" does provide the tracks of cyclones during the month of June 1882 (Figure 1) where it is clear that no cyclone or depression passed over Bombay (now Mumbai) in the month of June. IMD also has a precious collection of a report "Cyclone Memoirs" written by J. Eliot and published in 1891. This article provides the brief account of all recorded cyclones over Arabian Sea during 1648-1889. This report mentions a 44th storm during 27 May – 2 June of 1881 and next it mentions 45th storm over Arabian Sea during 3-4 July 1883. Interestingly, it did not mention about any storm over Arabian Sea during 1882.

Further search in the archive of IMD brings out the most interesting document published by IMD as daily weather report prepared for Revenue and Agricultural Department during those periods. The weather summary was written by Mr. H. F. Blanford. Blanford's summary of 5th, 6th and 7th June 1882 did not mention about any storm near the Bombay coast, neither it mentioned about any flooding. The Bombay station's meteorological report printed in the daily weather report also did not show any presence of cyclonic storm. However, on 6 June 1882, Tuesday, Bombay station reported thunderstorm. Those days, the report used to get prepared by 10 AM everyday and the weather reported in the table was said to be realised over the station during the past 24 hour. So the thunderstorm reported on Tuesday, 6th June 1882 over Bombay would mean that the Bombay station observed thunderstorm sometime during 10 AM of 5th June and 10AM of 6th June. This thunderstorm report by the Bombay station got some coincidence with another news paper report published by The Times (available from Time archive) which mentioned about a severe thunderstorm on Friday 2 June 1882. Blanford's weather summary for all the days during the first week of June, 1882 indicated onset of southwest monsoon over Bombay region and overcast skies associated with heavy rains from many surrounding stations. The occurrence of thunderstorms over west coast during the onset of south-west monsoon is a well known phenomenon and a thunderstorm can't cause devastation as mentioned for the Bombay Cyclone of 1882.

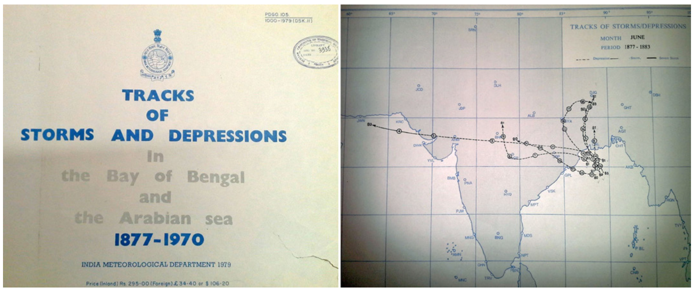

Fig. 1. Photo of tracks of cyclones and depressions for the month of June during 1877-1883. (Courtesy: IMD Library archive)

After all the searches and researches, it is conclusively established that there is nothing great about the so called "Great Bombay Cyclone" of 6 June 1882 which did not ever happen. So it was a myth rather than a reality which could be proved only due to precious IMD archives.

Acknowledgements: We are grateful to Prof. R. R. Kelkar, Former Director General of Meteorology, IMD for his advice, guidance and suggestions for this endeavour. We thank Shri B. Mukhopadhyay, Additional Director General of Meteorology, IMD, Pune. We also thank Dr. S. Balachandran of IMD, Chennai for helping in the endeavour. We sincerely thank all of them who are associated with IMD Library and archive. We also acknowledge all the scientists but particularly Prof. Adam Sobel of Columbia University who participated in the discussions and provided various links of books, articles, news papers etc.

Dinitrogen (N_2) Fixation in the northern Indian Ocean

Contributed Article

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Nitrogen is an essential nutrient for life and its availability determine the strength of oceanic biological pump, i.e., carbon sequestration from the sunlit ocean layers to the deep. Diazotrophic dinitrogen (N_2) fixation provides major input of bio-available nitrogen to the marine phytoplankton in the warm and oligotrophic oceans[1]. The Arabian Sea has traditionally been recognized as a "hot-spot" for N2 fixers but no direct measurements for N_2 fixation rates were done until 2009. During a spring Trichodesmium bloom cruise in 2009, we have measured higher (up to 34 mmol N m^{-2} d^{-1}) than ever reported N_2 fixation rates using $15N_2$ bubble method in the eastern Arabian Sea[2] (Fig. 1). Despite of these higher rates, there exist an imbalance between nitrogen gain and loss as the Arabian Sea losses about 20–40% of global oceanic bio-available nitrogen through denitrification[3]. The loss of nitrogen from denitrification (33 $TgNyr^{-1}$) is around double than that it gains (15.4 $TgNyr^{-1}$) through N_2 fixation. This nitrogen imbalance exists in the global ocean[4]. Many hypotheses have been proposed to resolve the imbalance: (i) there could be heterotrophic N_2 fixation in the deeper parts of the ocean, (ii) we may have ignored some regions and focused on traditionally N_2 fixation regions, (iii) there could indeed be imbalance on a shorter time scale.

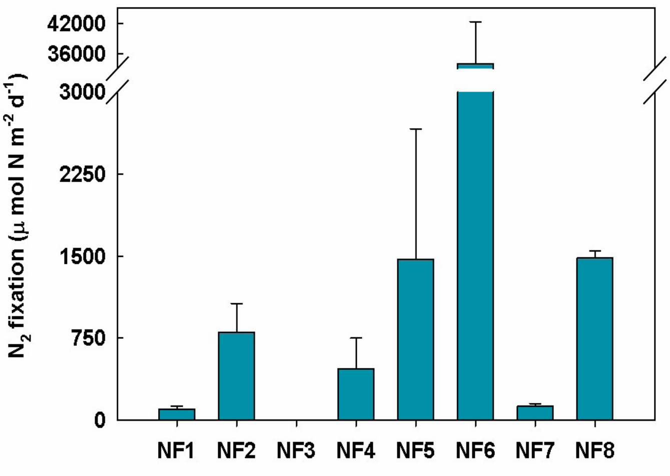

Fig. 1. N_2 fixation measurements using "bubble" method in the Arabian Sea. Figure modified from Gandhi et al (2009).

In a recent synthesis of the primary production data, we have found that export production in the Bay of Bengal is as high as in the Arabian Sea (Fig. 2). We hypothesized that the high export production could be sustained by nitrogen inputs via N_2 fixation in the Bay. The Bay of Bengal is warm and stratified, hence should be a perfect niche for N_2 fixation. Our future biogeochemical studies should focus on the Bay of Bengal.

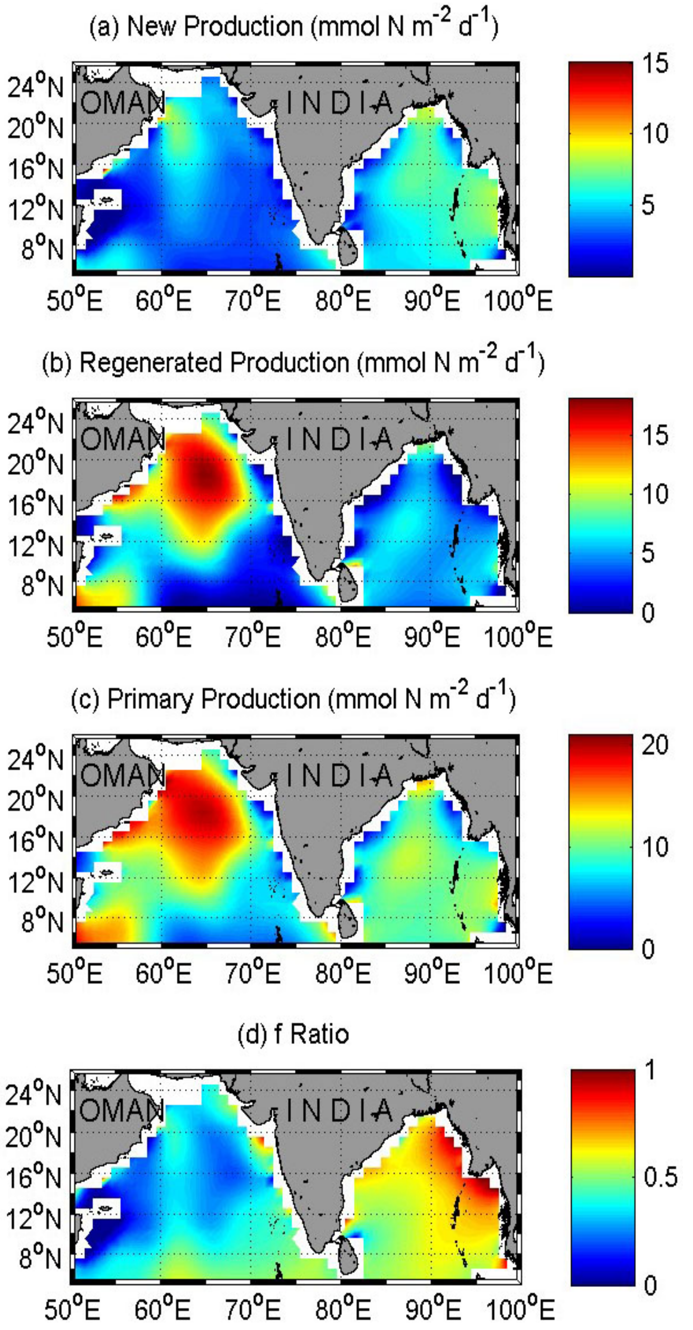

Fig. 2. (A) new (B) regenerated (C) primary production and (D) f ratio in the northern Indian Ocean. Figure modified from Singh and Ramesh (2015).

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The Global Carbon Budget updated for the year 2015

Contributed Article

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The atmospheric concentrations of carbon dioxide (CO_2) was 277 parts per million (ppm) during the pre-industrial era which we refer to the year 1750. Since then the large scale human re-settlement, search for new land areas, deliberate deforestations and land use change (LUC) caused the atmospheric CO_2 to increase. While emissions from fossil fuels started before the industrial era, they only became the dominant source of anthropogenic emissions to the atmosphere from around 1920, and their relative share has continued to increase until present (Le Quere et al., 2015). The dominant sources of anthropogenic carbon to the atmosphere are from fossil fuel burning and cement production. Other sources of carbon are primarily from methane (CH_4), carbon monoxide (CO), and volatile organic compounds such as isoprene and terpene.

The Global Carbon Project (GCP) was formed to assist the international science community to establish a common, mutually agreed knowledge base supporting policy debate and action to slow the rate of increase of greenhouse gases in the atmosphere. GCP updates the carbon budget every year based on most reliable data sources of emission

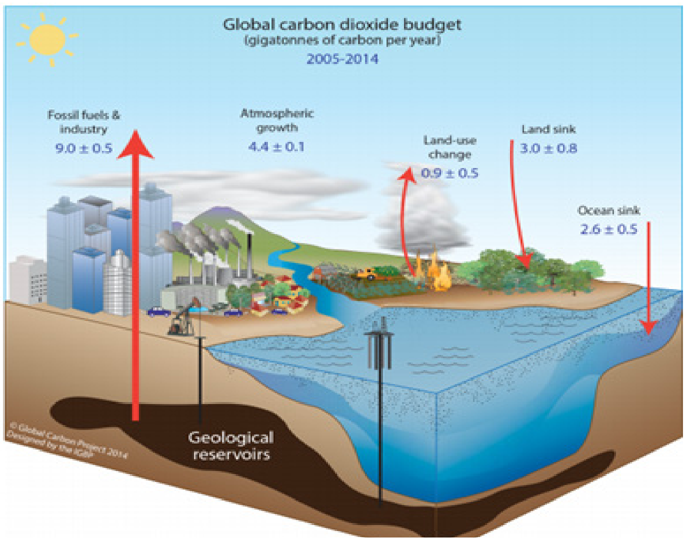

Fig. 1. Partitioning of total carbon emitted into various pools of earth system.

inventories and state-of-the-art model simulations and estimates of uncertainties. The recent carbon budget updated for the year 2015 is just published by Le Quere et al., (2015). This article highlights the summary of latest GCP carbon budget report.

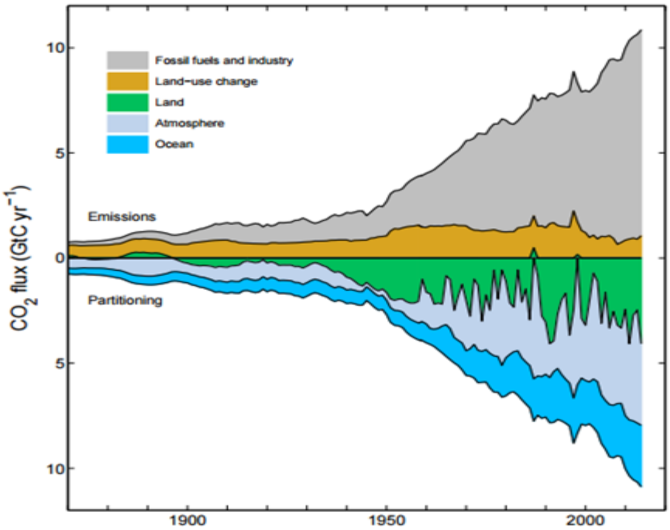

Fig. 2. Combined components of the global carbon budget illustrated in Fig.1 as a function of time. Partitioning of carbon into various pools is shown from pre-industrial to today. The bottom panel shows the units in GtC CO2 emission, to get carbon emission one has to divide this by 3.664.

The only longest direct measurements of atmospheric CO_2 from a ground-based station are the one available from Mauna Loa in the Hawaii Islands. This data showed that by March 2014 the atmospheric mean concentration of CO_2 has crossed over 400 ppm, which is highest in the history of the human! A curious question one may ask is 'how much amount of CO_2 is required to raise the atmospheric CO_2 over 1 ppm?' The units of carbon mass suggests that a rise of 1 ppm requires an addition of 2.12 Giga tonne (GtC) of carbon to the atmosphere (1 Giga tonne = 10^{15}). However the estimated total anthropogenic emission of carbon by the fossil fuel burning and land use changes alone (since the industrial era) is approximately 555±55 GtC from 1870-2015, out of which about 75% is from fossil fuel combustion and 25% is from land use change. The above conversion suggests that this would result today's atmospheric CO_2 to be over 540 ppm compared to the observed value of 400 ppm. So a part of the emitted anthropogenic carbon has been assimilated into the terrestrial biosphere and another part has been dissolved into the ocean. By this balance today's atmospheric CO_2 is regulated to 400 ppm, although a rise from 277 ppm of pre-industrial value to 400 ppm of today's value is quite alarming. The partitioning of man-made carbon into various pool of earth system such as terrestrial biosphere (land), ocean and atmosphere are keys to understand the potential role of carbonaceous greenhouse gases in the global warming.

The carbon balance in various pool is represented as follows: EFF + ELUC = GATM + SOCEAN + SLAND where EFF = fossil fuel emission, ELUC is the emission due to land use change, GATM is the atmospheric growth rate of carbon, SOCEAN and SLAND mean the sinking of carbon into ocean and land, respectively. All units are given in GtC per year in this article.

How do we estimate the net emission of carbon just by fossil fuels? The calculation of global and national CO_2 emissions from fossil fuels, including gas flaring and cement production (EFF) relies primarily on energy consumption data, specifically data on hydrocarbon fuels, collated and archived by several organisations. To name a few of these organizations are Carbon Dioxide Information Analysis Center (CDIAC), the British Petroleum (BP), the International Energy Agency (IEA), the United Nations (UN), the United States Department of Energy (DoE), Energy Information Administration Netherlands (EIA) and United Nations Framework Convention on Climate Change UNFCCC. For the last decade available (2005–2014), EFF was 9.0 ± 0.5 GtC yr^{-1} according to the recent budget update of Le Quere et al., (2015).

How do we estimate the net CO_2 emission from land use change (ELUC)? Land-use-change emissions reported here (ELUC) include CO_2 fluxes from deforestation, afforestation, logging (forest degradation and harvest activity), shifting cultivation (cycle of cutting forest for agriculture and then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture. The annual estimate for 1959–2010 is from a book-keeping method that keeps track of the carbon stored in vegetation and soils before deforestation or other land-use change, and the changes in forest age classes, or cohorts, of disturbed lands after land-use change, including possible forest regrowth after deforestation primarily based on net forest area change and biomass data from the Forest Resource Assessment (FRA) of the Food and Agriculture Organization (FAO). This data is only available at intervals of 5 years. The ELUC are also estimated by dynamical global vegetation models (DGVM). The estimated ELUC for the period by all these methods for 2005-2014 was 0.9 ± 0.5 GtC yr^{-1}.

How do we estimate the net CO_2 growth rate in the atmosphere? The global growth rate is based on measurements of atmospheric CO_2 concentration averaged from the Mauna Loa and South Pole stations, as observed by the CO_2 Program at Scripps Institution of Oceanography. The observations are used to calculate the net rate of change of mean atmospheric ppm and they are converted to equivalent emission rate by a relation 1 ppm = 2.12 GtC per year. For the last decade available (2005–2014), GATM was 4.4 ± 0.1 GtC yr^{-1}.

How do we estimate the net oceanic sink of CO_2? The observations of surface ocean partial pressure of CO_2 (pCO_2) is available from 1990s and extensively available by the ship based underway sampling from the 2000s. These pCO_2 data are compiled into a mean year representing 2000 or 2010, the monthly mean cycle of pCO_2 is constructed. With the standard gas-exchange formula for the air-sea fluxes and the wind-speeds the oceanic sink of CO_2 can be calculated. Inverse methods also made use of in this case. In the inverse method the history of anthropogenic CO_2 in the ocean is traced from given sinks at different regions of the ocean to generate the 'response-functions'. Since CO_2 in the ocean slowly varies over the time a conservative C^* method is used to separate the anthropogenic CO_2 from the natural CO_2 observed in the ocean (Sabine et al., 2004). The misfit between the model transported anthropogenic CO_2 and the observations are assumed to be due to the errors in the assumed fluxes and the Bayesian inversions are utilized to correct the fluxes in order to minimise the observation-model misfit. In a third method general circulation models with various biogeochemical processes included are utilized to simulate the air-sae CO_2 fluxes for several decades. In fourth method the machine learning techniques such as neural network, multi-linear regression etc. are used to infer the relation between various oceanic parameters and available pCO_2 observations. The data-gap in observed pCO_2 is filled with such methods and the air-sea fluxes are diagnosed. In this article the estimates of the global ocean CO2 sink are based on a combination of a mean CO_2 sink estimate for the 1990s from the available ocean observations, and a trend and variability in the ocean CO_2 sink for 1959–2014 from eight global ocean biogeochemistry models. The summary of CO_2 flux estimates of the ocean by all these methods for the last decade available (2005–2014) turns out to be a net sink of SOCEAN = 2.6 ± 0.5 GtC yr^{-1}.

How do we estimate the land sink of CO_2? There are multiple methods available for this. A simple method is to find the land sink of CO_2 (SLAND) as simple residual term, i.e. SLAND = EFF + ELUC – (GATM + SOCEAN). In addition to this the dynamic vegetation models with biospheric processes can also be used to find the land sink of CO_2. The atmospheric inversion methods (top-down approach) using Bayesian methods also used to infer the land and ocean sink of CO_2. By all these methods the net SLAND for 2005-2014 periods is estimated to be 3.0 ± 0.8 GtC yr^{-1}. The above two pictures summarize the carbon emission and sinks between various pools of the earth systems as per the 2015 GCP estimates (adopted from Le Quere et al., 2015). The partioning of carbon between various pools as a function of time is also shown in the picture.

References:

1. Le Quere et al. (2015): Global Carbon Budget 2015, Earth Syst. Sci. Data, 7, 349-396, doi:10.5194/essd-7-349-2015.

Cloud Computing and Higher Education

Contributed Article

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Education is an important component of human life and no human beings are able to survive properly without education. With the growing population and ever growing demand for education, the scientists and researchers across the globe are trying to find innovative ways to meet this ever surging demand of education. The massive proliferation of affordable computers, internet broadband connectivity and rich education content has created a global phenomenon in which information and communication technology (ICT) is being used to transform education. The evolution of ICT has changed all sections of society and these changes have been creating an irreversible impact on the online delivery of education. The role of ICT has always been extremely crucial for education sector owing to the highly unpredictable nature of evolution of education. The fast technological evolution of 'Web 2.0' has enabled new ways to create, develop and deliver educational content. This innovative pace of change has led to the progressive development of online distance learning and education. There is a need to redesign the educational system and paradigm to meet the ever growing educational needs better. Cloud is a metaphor for the internet. The term 'cloud' describes the virtual, server based world that is controlled by the Web or by mobile networks. Delivery of storage and computing capacity through the internet to the end users is called 'Cloud Computing'. Cloud computing has recently emerged as a compelling paradigm for managing and delivering services, including education, over the internet. The rise of cloud computing is rapidly changing the landscape of information technology. Cloud computing can effectively transform higher education. Cloud computing is highly scalable and creates virtualized resources that can be made available to the end users. Cloud computing will have a significant impact on the educational environment in future. Every higher education institute was an isolated silo before the advent of internet. It is cloud that has made an interconnected world possible. With cloud, higher education institutes can solve their problems of infrastructure and lack of resources, including faculty and finance. This is possible as cloud providers can make infrastructure (server), platform (operating system) and software (application software and databases) available as paid services. These services can be rented as per the specific requirements of higher education institutes, obliterating the need to buy and store them thus saving money, space and manpower. The servers and the system software are also remotely managed by the cloud providers thus doing away the need of a system manager and administrator. Cloud technology, with its obvious advantages, is the future of higher education. It is the best platform for education delivery, available anywhere anytime. Cloud enables higher education institutes to outsource most of their administrative work thus enabling them to focus primarily on their core activity of education delivery. Those who jump to the cloud bandwagon fast will be the prime movers and can leapfrog into higher levels of learning. The rest will be left behind as luddites.

Educational institutions throughout the World are increasingly becoming dependent on information and communication technology to service their ever increasing educational needs and requirements. These educational services are increasingly provided online by internet technologies and accessed from web browsers. These e-services are offered cheaply and sometimes even freely with much higher availability than can be provided by the educational institutions themselves. Educational institutions are now facing a future where the majority of their education related services will be hosted in the cloud and educational institutions shall no longer need to store their education related data with expensive hardware and computing services which are rarely fully utilized. A key feature of cloud computing is its rapid elasticity allowing for sudden peaks in demand and giving an impression that online educational services are infinitely scalable. There are lots of paradigms for getting education, but cloud computing has emerged as a new most promising paradigm for education. Cloud computing represents the most significant change to the way we use information and communication technology since the introduction of World Wide Web. Cloud is rapidly changing the way people communicate and learn and as a consequence it is changing the way people pursue their education in the cloud era and how the educational institutions are meeting people's ever increasing online educational demands. Cloud computing has emerged as one of the most talked about solution on the educational scene and it shows the agility of 21st century education.

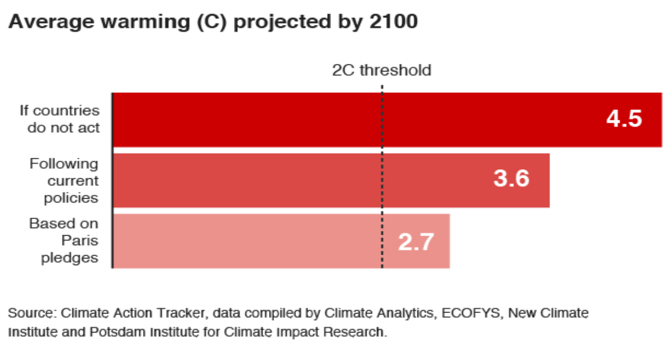
With the evolution of cloud computing and its subsequent popularity, the service providers are coming up with the very innovative and affordable education related solutions for the end users. The upcoming technology of cloud computing is predicted to bring revolutionary changes to the education sector. Cloud computing is regarded as a technology which makes available 'Information Technology' allied services in a very simple and user friendly manner at an affordable cost. The term 'Cloud Computing' refers to the fact that end users do not really need to know who is providing those services and cloud hid all the technicalities from the end users. Cloud can offer a centralized "Education Bank" which can be used to store all education related information. This education bank can be made available to users from education sector at anyplace and anytime at a very affordable cost. Higher education institutions can use cloud depending on their own innovative ideas and as per their specific needs. Universities like MIT and Harvard are using cloud for delivering massive open online courses. Universities are being created in the cloud without any physical building. If two higher education institutes have an expert faculty each, they can offer a blend of courses using webinars and video conferencing without the faculty ever getting together. Cloud can bring down the human resource used and the time taken for administration to a fraction by doing everything online i.e. from processing of applications to collection of fees and from admission to exams. With cloud higher education institutes can deliver personalized educational experience. Faculty can connect with students through email groups, social networking sites like 'Facebook', 'Twitter', 'Blogs', 'Skype', 'Youtube', 'Slideshare' etc.. Learning of management systems like 'Moodle' can be used by educators to create effective online learning sites. Higher education institutions can get students to explore Wikipedia and e-books. Besides these, students can take their e-lessons at their own pace and convenience in these virtual classrooms and also practice what they learn via simulation. Even research can be organized and research collaborations can take place online through academic social networks like 'Mendeley'. Recruitment of faculty and staff and placement of students can also be done through social networking sites. Cloud can also be used to issue digital certificates to students in a demat format. Higher education institutes shall need somebody who is either internal or outsourced and knowledgeable enough about web and cloud applications. Organizations like 'Educause' and 'School 2.0' handhold higher education institutes who need help with such applications.

The biggest change in the era of cloud enabled education is the transformation of educational experience. Earlier if students faced any trouble in understanding something, they either used to go to faculty or the library. Today in such situations students generally go online. Students learn through video lectures on Youtube, which they can attend any time as per their convenience and ease and also submit their assignments and take exams online. In the era of internet, students are becoming smarter than the faculty as they are more internet savvy. This has changed faculty's role from an information provider to information facilitator and a mentor. The economics of computing has significantly changed as it is available on tap and you pay for it as you pay for other utilities such as electricity. Cloud enables students, faculty and higher education institutes to share knowledge among them. However, online education may not be a perfect replica of what we get in a traditional classroom. So, blended learning which is a combination of traditional classroom teaching as well as online learning is a good, feasible and implementable proposition. IT strategy of higher education institutes will rely on cloud as a platform to deliver their all education related services with added flexibility of providing them 'Anytime, Anywhere'. Access to the internet, which is still very limited in our country, is a major challenge in effectively implementing cloud enabled higher education in our country. Educators need to be educated on cloud technology for harnessing cloud enabled higher education. Cloud enabled education shall herald the migration from the traditional 'Gurukul' to the online 'e-kul' and from the traditional campus to the 'Digital Campus'.

News and Views

Recent Updates

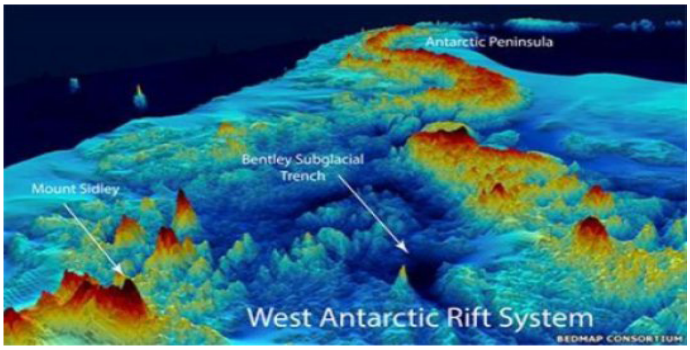
Why the Earth's climate is changing – the problem – the cause – the effects – the future - [Read More]



Climate Change Summit 2015 at Paris
The goal of the 2015 Paris Climate Conference, COP21, is to achieve a legally binding, international agreement to keep average global temperatures no more than 2°C above pre-industrial temperatures. [Read More]

By 2100, global temperatures may rise by 8°C
Researchers found that if emissions continue to grow at current rates, with no significant action taken by society, then by 2100 global land temperatures will have increased by 8°C. Such a rise would have a devastating impact on life on Earth. It would place billions of people at risk from extreme temperatures, flooding, drought and food shortages, researchers said. [Read More]

Hot rock and ice: Volcanic chain underlies Antarctica
Scientists were able to deploy ruggidized seismometers that could withstand intense cold in Antarctica only recently. A line of seismometers strung across the West Antarctic Rift Valley and the Marie Byrd Land have given geologists their first good look at the mantle beneath the ice and rocks, revealing areas of hot rock that might affect the behavior of the overlying ice sheet. [Read More]



Source: Bedrock Consortium

Our Deadened, Carbon-Soaked Seas
The increasing amounts of carbon dioxide absorbed by the sea from the atmosphere is likely to disturb the chemical balance of our oceans, which is indeed a disturbing story for the marine ecosystem and the world. Though not visible to naked eyes, this massive amount of carbon dioxide going into the ocean forms carbonic acid, changing the water's chemistry at a rate faster than seen for millions of years. Human health too can be affected due to this. [Read More]

3.2 Millimeters: A Troubling Rise in Sea Level
Sea levels are rising, and rising faster every year. According to the latest report of the Intergovernmental Panel on Climate Change, there was an average rise of sea levels by 1.7mm a year during the 20th century. By 2081, yearly increases are likely to be as high as 16 millimeters a year. By the end of this century, seas will have risen by as much as three feet. [Read More]

Arctic air temperatures highest since 1900
Rick Spinrad, chief scientist at NOAA said the rate of warming is two times faster in the Arctic compared to anywhere else in the world. This is due to climate change and its impacts are creating major challenges for Arctic communities. The annual sea ice maximum occurred this year two weeks earlier than the average and also the extent was the lowest since records began in 1979. [Read More]

Models overestimate rainfall increases due to climate change
Most climate models overestimate the increase in global precipitation due to climate change. The research team at Lawrence Livermore National Laboratory looked at 25 models and found they underestimate the increase in absorption of sunlight by water vapor as the atmosphere becomes moister, and therefore overestimate increases in global precipitation. [Read More]

Conferences

Upcoming Events

- IMS Pune - OSI Pune - National Monsoon Workshop 2016, Feb. 23-24, 2016 at IITM. For details kindly use the link http://www.tropmet.res.in/monsoon_workshop/
- National Workshop On Atmospheric Instrumentation and Meteorological Sciences: Theory & Challenges which will be held at Vishwakarma Institute of Technology, Pune from 19th-21st January, 2016. See More: http://www.vit.edu/
- 7th International Ice Charting Working Group Workshop on Sea Ice Data Assimilation and Verification from 5th -7th April 2016 at ESRIN in Frascati, Italy. See More: http://www.congrexprojects.com/2016-events/IICWG/home

Opportunities

Job/Fellowship Opportunities

- PhD studentship in Arctic storm risk at the University of Reading on Arctic Storm Risk, to start in September 2016. For more info: http://www.met.reading.ac.uk/nercdtp/home/available/desc/SC201615.pdf
- PhD Opportunity on Predictability of the Interdecadal Pacific Oscillation at the University of Tasmania, Hobart, Australia. https://www.climatescience.org.au/content/707-graduate-opportunities-expressions-interest
- Two PhD studentships based at the British Antarctic Survey, to start in October 2016. 1) Is ocean melting driving Larsen C Ice Shelf towards collapse? (with University of East Anglia) http://www.enveast.ac.uk/projects/display/-/asset_publisher/G2PAL8zto56C/content/holland_ubas16ee. 2) The effect of Amundsen Sea freshwater on melting of the West Antarctic Ice Sheet (with University of Southampton) http://noc.ac.uk/gsnocs/project/effect-amundsen-sea-freshwater-melting-west-antarctic-ice-sheet

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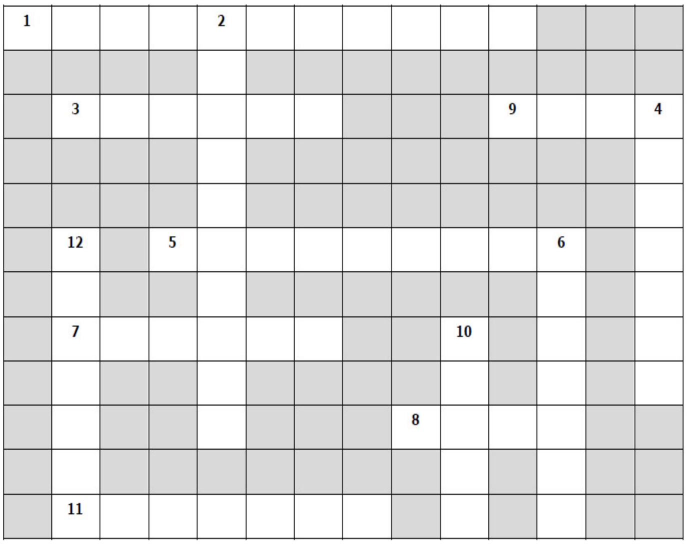
Crossword

The clues for the Earth Science Crossword can be traced to the present and previous issues of Ocean Digest. Enjoy.



ACROSS

1. The ozone layer in the upper part of the atmosphere protects us from these rays
3. This is the smallest ocean in the world
5. This wind is also known as "Doctor-Wind"
7. Sunda Trench is part of this ocean
8. This type of agricultural crops are sown in winter and harvested in the spring
9. This canal connects the Mediterranean Sea to the Red Sea
11. Imaginary great circle of latitude 0°, which is equidistant from the poles, that separates the Northern Hemisphere from the Southern Hemisphere

DOWN

2. The coal with highest calorific value, is
4. Victoria Falls is a waterfall in southern Africa on this river
6. This hill is found where the Eastern Ghats and the Western Ghats meet
10. This type of soil has the largest area covered in India
12. Composite weather conditions over a considerable period of time are termed as

Compiled by Bhupendra B. Singh, IITM