# Assessing Atmospheric Instability over the Bay of Bengal during October and November Months between 2007 – 2018

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**ABSTRACT:** An attempt has been made in this research to delineate a pattern for atmospheric instability during the months of October and November from 2007 to 2018. The results show an alarming trend of increasing instability throughout the study period. The average temperature at 2-meters height around the Bay of Bengal has changed significantly over time. Most notably, the gap between monthly average highest and monthly average lowest temperatures (at 2-meters height) is more or less increasing from 2007 to 2018 – ranging from 3.0 degrees to 11.0 degrees Celsius. Similar tendencies are observed for CAPE (Convective Available Potential Energy) as well – with the highest value of more than 3000 J/Kg. The findings of this research will help in understanding the prevailing conditions over the Bay, and also enable better preparedness for any potential severe convective activities.

**Keywords:** Atmospheric instability, Bay of Bengal, 2-m Air Temperature, CAPE

## INTRODUCTION

Bangladesh is a deltaic country, located in South Asia – with the Himalayas to her North and the Bay of Bengal to her South. The coastal region represents an area of 47, 201 square kilometers (km), which is about 32% of Bangladesh's total geographical coverage (Rasheed, 2008). Bangladesh is globally recognized as one of the most vulnerable countries due to natural disasters. In 2004, the United Nations Development Program (UNDP) ranked Bangladesh as the number one nation at risk for tropical cyclones and number six for floods (MoEF, 2009).

Bangladesh is regularly affected by devastating natural disasters because of its geographic location, unique natural settings, and characteristics of tropical monsoon (Paul, 2012; Haque, 1995; Elahi, 1991). The most common and catastrophic natural disasters that commonly occur include tropical cyclones, storm surges, tornados, floods, droughts, and nor-westers (Ali, 1999). The country is hit by at least one tropical cyclone each year (Haque, 1997; Mooley, 1980) that makes the coastal area more unsafe for the people living there (Murty and Neralla, 1992). The meteorological origin of tropical cyclones (TC) is owing to many complex interactions among land surface, ocean, planetary boundary layer, and convective processes (Zhang and Emanuel, 2016; Xie and Kubokawa, 1990). Several reasons; including – the re-curvature phenomena of a tropical cyclone in the Bay of Bengal, shallow continental shelf, funnel shape at the head of the Bay of Bengal, almost sea-level orography of the coastal land, and high density of population; are responsible for the large impacts of tropical cyclones in Bangladesh (Murty and El-Sabh, 1992). The climatic conditions of the country are modified and regulated by these unique settings, but ultimately make the country more vulnerable to tropical cyclones (Paul and Routray, 2010; Ali, 1996). Tropical Cyclones in the past have caused massive damage to the coastal region of Bangladesh (Ramsay, 2017). The post-monsoon months are always a threat to the country as some of the most destructive tropical cyclones have formed during this season – mostly during October and November (Singh, 2007). So far in this century – Cyclone *Sidr* has been the most destructive post-monsoonal TC (Islam et al., 2011), which made landfall on Bangladesh's coast at around 1600 UTC on 15th November 2007 (Paul, 2009). Although no such post-monsoon cyclones with that much intensity have not hit Bangladesh since, the probability of recurrence for such a catastrophe is not so low either (Bensi and Weaver, 2020); especially considering the situation of the Bay in October and November of recent years (Baaqeel et al., 2018).

Atmospheric Instability is always responsible for the intensification of convective activities (Chen et al., 2015; Caron et al., 2013; Craig and Gray, 1996).

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Again, an imbalance in temperature is vital for the increase in atmospheric instability (Gubenko and Rubinshtein, 2015; Marinaki et al., 2006). And, formation of tropical cyclones is closely related to an increase in atmospheric instability (Lahaye and Zeitlin, 2016; Williams and Renno, 1993). Apart from that, there is a positive correlation between the strength of tropical cyclones and the prevalence of atmospheric instability (Takemi and Yamasaki, 2020). Tropical cyclones in the Bay of Bengal, especially those formed in post-monsoon, are frequently becoming stronger (Balaguru et al., 2014; Krishna, 2009). Therefore, research on the situation regarding the recent condition of atmospheric instability over the Bay is highly necessary. Studying the evolution of atmospheric instability will provide a better understanding of the genesis of tropical cyclones, which in turn will assist in a more accurate prediction of tropical cyclones (Montgomery and Smith, 2017; Meng and Zhang, 2012). Therefore, the objective of this research is to determine the tendency of atmospheric instability over the Bay of Bengal during October and November.

## METHODOLOGY AND DATA USED IN THIS RESEARCH

The study was done by recreating past scenarios with the help of forcing data through the WRF (Weather Research and Forecasting) Model (version 4.0.1). The Weather Research and Forecasting (WRF) model (version 4.0.1) has been used to derive the temperature and CAPE values for the post-monsoon season in Bangladesh. In the present research, the ARW solver of the WRF model has been used. The ARW system consists of fully compressible non-hydrostatic equations and different prognostic variables. The model's vertical coordinate is terrain following hydrostatic pressure and the horizontal grid is Arakawa C-grid. Great detail on WRF Model can be found in the works of Skamarock et al. (2008). Table 1 has all the necessary information regarding the setup of the experimental design for this research.

For this study, NCEP FNL Operational Model Global Tropospheric Analyses data have been used from NCAR's Research Data Archive (NCEP, 2000) to simulate the surface temperature and convective available potential energy over the coastal region of Bangladesh during the post-monsoon season. Global Data Assimilation System (GDAS) continuously

collects observational data from the Global Telecommunications System (GTS) and other sources for analysis. Final Reanalysis (FNL) 1-degree by 1-degree data collected from National Center for Environmental Prediction (NCEP) is used as initial and Lateral Boundary Conditions (LBCs), which are updated at six hours intervals.

**Table 1:** An Overview of the Experimental Design for this Research

| Properties | Configuration for the Research |
|---|---|
| Dynamics | Non-hydrostatic |
| Microphysics | Ferrier (new Eta) scheme |
| Radiation scheme | Dudhia for short-wave radiation / RRTMG for long-wave |
| Surface layer | Noah-LSM scheme |
| Cumulus parameterization schemes | Kain-Fritsch scheme |
| PBL parameterization | Yonsei University scheme |
| Number of domains | 01 (one) |
| Central points of the domain | Central Latitude: 18°N; Central Longitude: 91°E |
| Horizontal grid distance | 18 kilometers |
| Integration time step | 90 seconds |
| Number of grid points | X-direction: 54 points; Y-direction: 108 points |
| Map projection | Mercator |
| Horizontal grid distribution | Arakawa C-grid |
| Vertical co-ordinate | Terrain-following hydrostatic-pressure co-ordinate (33 sigma levels up to 100 hPa) |
| Time integration | $3^{rd}$ order Runge-Kutta |
| Spatial differencing scheme | $6^{th}$ order centered differencing |
| Initial conditions | Three-dimensional real-data (FNL: $1° \times 1°$) |
| Lateral boundary condition | Specified options for real-data |
| Top boundary condition | Gravity wave absorbing (diffusion or Rayleigh damping) |
| Bottom boundary condition | Physical or free-slip |
| Diffusion and Damping | Simple Diffusion with No Damping |

The WRF model has been configured in a single-nested domain (Figure 1) of 18 km horizontal grid spacing with 54×108 grids in the east-west and north-south directions and 33 vertical levels. In this research, the Ferrier (new Eta) microphysics scheme coupling with the Kain-Fritsch cumulus parameterization scheme has been used.

The model has been integrated by using initial and LBCs from NCEP-FNL analyses data (Dutra et al., 2017) at six hourly intervals. The model has been simulated continuously for 31 days to get a long-range observational scenario starting with the initial conditions for 0000 UTC of 1st October and continuing up to 1800 UTC of 31st October; for the years of 2007 to 2018. With a similar mechanism and experimental setup, simulated values of November (for the aforementioned 12 years) have also been obtained. The instability conditions during October – November of 2007 have been given more importance in the analyses, due to the intensity and sheer destruction caused by Cyclone *Sidr* (Haque and Jahan, 2016; Nadiruzzaman and Wrathall, 2015; Paul, 2010) during November of 2007. The succeeding 11 years after 2007 (2008 to 2018) have been analyzed – to discern a trend of atmospheric instability over the Bay of Bengal – to fulfill the objectives of this research.
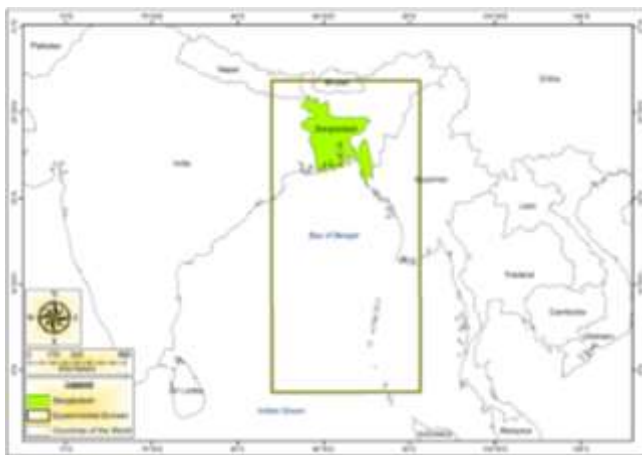


**Figure 1:** Experimental Domain for Simulations with WRF Model in this Research. The experimental domain has been drawn with WRF-Hydro GIS (Geographic Information System) pre-processing toolkit (downloaded from https://ral.ucar.edu/projects/wrf_hydro/pre-processing-tools) integrated with ArcGIS Software (version 10.6)

Two (02) parameters were chosen for analysis, which are – Air Temperature at 2-meters height and Convective Available Potential Energy (CAPE). The 2-m air temperature has been essential in understanding the near-surface temperature situations (Baker, 1975), and hence has been widely used by operational meteorologists (Rayner et al., 2003; Whitaker and Hamill, 2002). For avoiding redundancy, this parameter is cited as 'Surface Temperature' in the following sections. The highest average temperature and lowest average temperature values for 24 months (October and November for 12 consecutive years) have been calculated from simulated results. Again, CAPE is an essential atmospheric instability index for studying tropical cyclones (Molinari et al., 2012) and requires the temperature values for calculation (Moncrieff and Miller, 1976). Monthly averaged CAPE values have been calculated and used in this research. Also, it should be noted that – all the averages used in this research are temporal averages, not spatial averages (Moody et al., 2008). Monthly maximum and minimum CAPE values, which were also analyzed, were also identified from the simulations.

Records of tropical cyclones over the Bay of Bengal have been accessed from the portal of RSMC (https://rsmcnewdelhi.imd.gov.in/). RSMC or Regional Specialized Meteorological Centre has data available from the 19th century onwards (Mohapatra and Vijay Kumar, 2017). But for this research, data for 2007 to 2018 have been collected. Also, the data for Severe Cyclonic Storms – SCS (maximum sustained surface wind speed of 48 to 63 knots) and above are being used in this research.
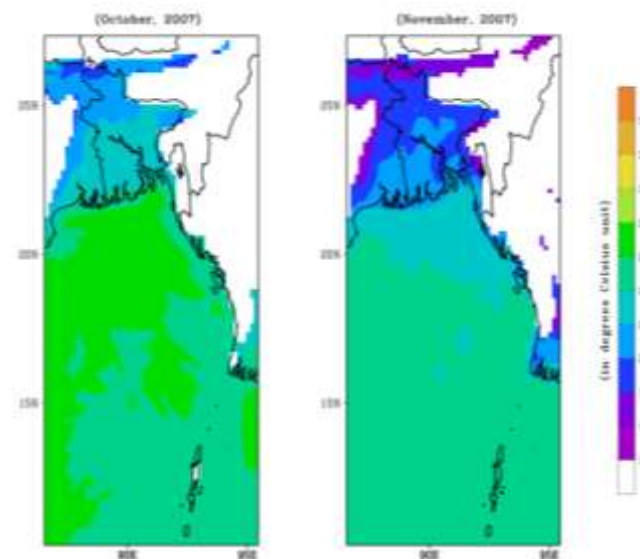


**Figure 2:** Distributions for Monthly Average Surface Temperature During October and November of 2007

## DISTRIBUTION OF SURFACE TEMPERATURE

The monthly average distribution of surface temperature for 2007 has been illustrated in Figure 2. The temperature in October ranged between 25 to 29 degrees Celsius, but a major portion of the Bay remained within 27 to 29 degrees Celsius. The Bay

became cooler during November of 2007. Most portions remained within 25 to 27 degrees Celsius. The temperature further decreased to the north, gaining a lowest value of 21 degrees near the coastal regions of Bangladesh.

The distributions for 2008 to 2018 are listed in Table 2a. From 2008 onwards, a rise in monthly highest average surface temperature value (from the value of 2007) was found. The average highest temperature in October remained between 31 to 33 degrees Celsius (°C) from 2008 to 2015; after which it went below 30°C. For the distributions of highest average temperature values in November, the range was from 30 to 33°C. Similar to the distributions of highest average maximum values in October, the values for November were also found to be less than 30°C from 2016 to 2018. So, 8 values of monthly average highest temperature for October were greater than the value for 2007; 1 was equal and the remaining 2 were lower.

The lowest average temperature for October values had multiple peaks of increasing and decreasing values within its distribution. A decrease in values (from the values for 2007) of the lowest average temperature was observed for 2008 and 2009. After that, from 2010 onwards, an increasing trend continued up to 2013. Again, the values showed a decrease in both 2014 and 2015. After an increase in 2016, the lowest average monthly temperature dipped to 21°C. So, only 4 values of monthly average lowest temperature for October were greater than that of 2007; 1 was equal and 6 values were lower.

The monthly highest average temperature values for November showed similar tendencies to the distributions of October. The values increased from 2008 onwards – ranging from 30 to 33°C. From 2016 onwards, there was a decrease. But to the contrary of the distribution for October, the values remained equal or more than the values for November of 2007. Therefore, no values of the highest average monthly temperature from 2008 to 2018 were less than that of November 2007; 10 were greater and only 1 was equal.

The monthly lowest average temperature value for November-2007 was 20°C. From 2008 onwards, it showed an increase that continued up to 2013. Then there was a slight decrease, followed by increased and decreased values in every alternate year (except for

November of 2015 and 2016). Therefore, 2 lower values (in comparison to the value for November 2007) were found for the lowest monthly temperature value for the distribution of November; 1 equal and 8 greater values were observed.

## DISTRIBUTION OF CAPE

The 2007 distributions of monthly average CAPE for October and November are given in Figure 3. During October, most parts of the Bay had CAPE values higher than 1700 J/Kg (Joules per Kilogram). Lower CAPE values (less than 500 J/Kg) were observed around the coastal regions. The monthly average CAPE during November ranged between 500 to 900 J/Kg within a major area of the Bay, while the remaining areas had an average CAPE of less than 500 J/Kg.

The monthly maximum and minimum CAPE values (Table 2b) have been picked out for gaining a much better insight into the conditions over the Bay. The maximum CAPE was 3000 J/Kg in October 2007. This value remained to the highest up to 2015. A maximum CAPE of 3200 J/Kg was found during October of 2016. In between 2007 and 2016, a value of 2900 J/Kg was also found during October of 2013. The final two years of the distribution had a maximum CAPE of equal and considerably less than 3000 J/Kg, which was the obtained value for October of 2007.
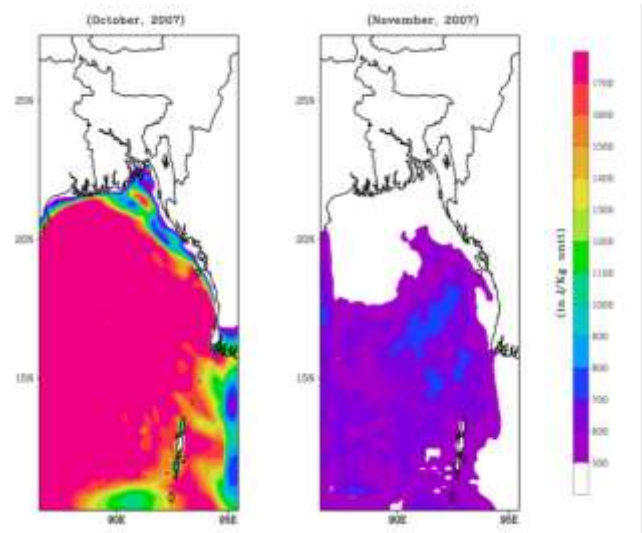


**Figure 3:** Distributions for Monthly Average CAPE during October and November of 2007

The monthly minimum CAPE values for October had a different distribution. This distribution showed

multiple peaks of increase and decrease. But the most notable values were found for Octobers of 2013 and 2017 – whereby the values were found to be 1400 J/Kg and 1700 J/Kg. Both values were greater than the monthly maximum CAPE value for October of 2009 (1300 J/Kg). Other values were lower or equal to 700 J/Kg.

The monthly maximum CAPE value for November also showed multiple increases and decreases when compared with the value for November of 2007 (1400 J/Kg). The values mostly remained within 1800 J/Kg. However, maximum CAPE values of more than 2000 J/Kg were found for the November months of 2010, 2013, and 2016. A longer increasing pattern for maximum CAPE values was observed from 2013 to 2017 (in comparison with 2007). But, the value for 2018 became much lower than the preceding values.

The lowest CAPE values for November showed an increasing trend from 2008 to 2015. The lowest minimum CAPE value for November-2013 (1200 J/Kg) was higher than the maximum CAPE values for November 2009 and 2018. But recent years found a slightly decreasing trend in minimum CAPE value for the distributions of November.

## DISCUSSING MAJOR FINDINGS

The distributions of both surface temperature and CAPE are being described in previous sections. From both distributions, it is obvious that there are increases and decreases in both parameters during recent years. But, interestingly the extent of this change – be it increasing or decreasing – is neither equal nor symmetric. Tables 2a and 2b have all the records from the simulations for this research. Also, the frequency data for tropical cyclones (SCS and above) formed at the Bay of Bengal during the study period have been listed in Table 2c.

**Table 2:** Distributions of Maximum and Minimum – (a) Surface Temperature; and (b) CAPE Values for the Experiments in this Research. (c) Frequency Data for Tropical Cyclones (SCS and above) Formed over the Bay of Bengal from October and November of 2007 to 2018

| Time | Highest Average Value | Lowest Average Value | Difference |
|---|---|---|---|
| (a) distribution of Surface Temperature (in degrees Celsius unit) | | | |
| October-2007 | 28 | 25 | 3 |
| October-2008 | 32 | 24 | 8 |
| October-2009 | 32 | 24 | 8 |
| October-2010 | 33 | 25 | 8 |
| October-2011 | 33 | 27 | 6 |
| October-2012 | 32 | 29 | 3 |
| October-2013 | 32 | 30 | 2 |
| October-2014 | 32 | 24 | 8 |
| October-2015 | 31 | 24 | 7 |
| October-2016 | 28 | 26 | 2 |
| October-2017 | 27 | 23 | 4 |
| October-2018 | 27 | 21 | 6 |
| November-2007 | 26 | 20 | 6 |
| November-2008 | 30 | 21 | 9 |
| November-2009 | 31 | 25 | 6 |
| November-2010 | 30 | 28 | 2 |
| November-2011 | 31 | 22 | 9 |
| November-2012 | 31 | 27 | 4 |
| November-2013 | 33 | 26 | 7 |
| November-2014 | 30 | 19 | 11 |
| November-2015 | 30 | 20 | 10 |
| November-2016 | 27 | 23 | 4 |
| November-2017 | 26 | 18 | 8 |
| November-2018 | 28 | 22 | 6 |

| (b) distribution of Convective Available Potential Energy (in J/Kg unit) | | | |
|---|---|---|---|
| Time | Maximum Value | Minimum Value | Difference |
| October-2007 | 3000 | 550 | 2450 |
| October-2008 | 1700 | 500 | 1200 |
| October-2009 | 1300 | 550 | 750 |
| October-2010 | 2200 | 650 | 1550 |
| October-2011 | 1900 | 550 | 1350 |
| October-2012 | 1800 | 450 | 1350 |
| October-2013 | 2900 | 1400 | 1500 |
| October-2014 | 2000 | 700 | 1300 |
| October-2015 | 1900 | 700 | 1200 |
| October-2016 | 3200 | 600 | 2600 |
| October-2017 | 3000 | 1700 | 1300 |
| October-2018 | 2100 | 300 | 1800 |
| November-2007 | 1400 | 850 | 550 |
| November-2008 | 1200 | 400 | 800 |
| November-2009 | 1100 | 450 | 650 |
| November-2010 | 2200 | 600 | 1600 |
| November-2011 | 1500 | 700 | 800 |
| November-2012 | 1350 | 650 | 700 |
| November-2013 | 2500 | 1200 | 1300 |
| November-2014 | 1800 | 850 | 950 |
| November-2015 | 1500 | 700 | 800 |
| November-2016 | 2200 | 300 | 1900 |
| November-2017 | 1600 | 400 | 1200 |
| November-2018 | 1050 | 300 | 750 |
| (c) number of tropical cyclones formed over the Bay of Bengal | | | |
| Year | Total Number of TCs during October | | Total Number of TCs during November |
| 2007 | 0 | | 1 |
| 2008 | 0 | | 0 |
| 2009 | 0 | | 0 |
| 2010 | 1 | | 1 |
| 2011 | 0 | | 0 |
| 2012 | 0 | | 0 |
| 2013 | 1 | | 2 |
| 2014 | 1 | | 0 |
| 2015 | 0 | | 0 |
| 2016 | 0 | | 0 |
| 2017 | 0 | | 1 |
| 2018 | 1 | | 1 |

The most notable thing is the difference in monthly highest average temperature and monthly lowest average temperature values. Since 2008, the gap has remained mostly above 6°C apart from the values for October-2012, 2013, 2016, 2017; and November-2010, 2012, 2016. The difference remained to be more than 10°C during two consecutive Novembers of 2014 and 2015. This gap is always increasing with time, and if this trend continues then it may cause a significant rise in atmospheric instability over the Bay (Chen et al., 2020; Holley et al., 2014; Gettelman et al., 2002).

A steady rise in atmospheric instability has been observed over the Bay throughout the study period. The change in CAPE did not maintain any pattern, similar to that of surface temperature. But a conspicuous change can be easily understood from the distributions of maximum and minimum CAPE values for October. The difference between the maximum and minimum CAPE values was found to be less than 1200 J/Kg only once – during October of 2009. And in recent years, the gap between monthly maximum and minimum CAPE values has shown a clear

increase. With these analyses, the frequency data for tropical cyclones over the Bay of Bengal provide a very clear scenario. Throughout the study period of 12 years (2007 to 2018), only 03 years have recorded tropical cyclones in consecutive months of October and November – 2010, 2013, and 2018. And during both years of 2017 and 2018, November has experienced tropical cyclones over the Bay. Also, 2013 has seen the highest number of tropical cyclones (3) among the years studied in this research. It should be noted that – 2013 saw considerably high values of both maximum and minimum CAPE. A subtle increase in the number of TCs since 2013 can be easily envisaged.

There are implications of an increasing atmospheric instability to the intensification of tropical cyclones (Lee and Frisius, 2018; Seeley and Romps, 2015). The analyses and data in this research can delineate a pattern of increasing atmospheric instability and rising numbers of TCs. This trend of an increasing number of TCs may continue in the future as well if the atmospheric instability is continuing to be augmented.

## CONCLUSIONS

In this research, the atmospheric instability over the Bay of Bengal during the October and November months has been assessed for a study period of 12 years – from 2007 to 2018. The objective was to seek a pattern of atmospheric instability – be it increasing or decreasing. The study reveals that there is a change in temperature activities over the Bay during these 12 years. The difference between the monthly average highest temperature and lowest temperatures is increasing over time. Along with that, the CAPE values are also increasing. And, there is a rise in the frequency of TCs also. So, all these comprehend a worrying scenario for Bangladesh – where the country may frequently experience more intense tropical cyclones in the future.

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