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Analysis of Ocean-Atmospheric features associated with extreme temperature variation over east coast of India-A special emphasis to Orissa heat waves of 1998 and 2005

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सार – 1998 से 2007 तक के दशक में भारत के पूर्वी तट पर स्थित उड़ीसा और आंध्रप्रदेश दोनों ही राज्य भीषण गर्म हवाओं (लू) के अक्सर चलने की वजह से बहुत ज्यादा प्रभावित रहे जिसके परिणामस्वरूप अनेक लोगों को अपनी जान से हाथ धोना पड़ा। पिछले कुछ वर्षों में इस क्षेत्र में उड़ीसा में वर्ष 1998 में और आंन्ध्र प्रदेश में वर्ष 2003 में गर्मी के मौसम में सबसे भीषण गर्म हवाएँ (लू) चलीं जिसकी वजह से क्रमशः 2042 और लगभग 3054 लोगों ने अपनी जान गँवाई। 2005 की गर्मियों में यद्यपि उड़ीसा और उसके समीपवर्ती पूर्वी तटों में कुछ अत्यधिक गर्मी वाले दिन थे तथापि उसकी वजह से पहले की तरह अधिक नुकसान नहीं हुआ। क्षेत्र में तापमान के बढ़ने की ऐसी घटनाओं के नियमित रूप से प्रभावित करने की सिथति में जब इस प्रकार के मौसम की आवृत्ति कम होती है तब उनके दीर्घ अवधि तापमान के आँकड़ों का विश्लेषण तथा उनका विभिन्न प्रादेशिक और भूमंडलीय महासागर वायुमंडलीय विशेषताओं के साथ संबंध का अध्ययन किया जाना बहुत आवश्यक हो जाता है ताकि इनके संभावित कारणों का पता लगाया जा सके और पूर्वानुमान में उनका उपयोग किया जा सके। इस अध्ययन में बड़े इलाके से छोटे इलाके, जैसे कि पूरे भारत का तापमान, भारत के पूर्वी तट का तापमान आदि, में उपलब्ध विभिन्न तापमान समय श्रृंखलाओं का विश्लेषण करने का प्रयास किया गया है ताकि यह समझा जा सके कि जिन वर्षों में बड़े इलाके में चरम तापमान रिकॉर्ड किया गया है उनका छोटे इलाके, जैसे उड़ीसा के स्टेशन से प्राप्त तापमान के आँकड़ों के साथ संबंध है या नहीं। उड़ीसा और आंध्रप्रदेश राज्यों में भीषण लू वाले वर्षों में गर्म हवाएँ (लू) चलने की संपूर्ण अवधि के दौरान ताप सूचकांक के परिणाम और उसके कारण हुई कुल जानों की हानि के बीच संबंध को समझने के लिए सामान्य, ताप सूचकांक जैसे विभिन्न ताप सूचकांक, थॉम डिस्कमफर्ट और वेब्स कंफर्ट सूचकांक का परिकलन किया गया। तत्पश्चात् इनकी तुलना बताए गए वर्षों में इन राज्यों में गर्म हवाओं की वजह से हुई जान की हानि के साथ की गई है। विभिन्न ताप सूचकांक के अलावा विभिन्न महासागर वायुमंडलीय विशेषताएँ जैसे – बंगाल की खाड़ी का मासिक समुद्र सतह तापमान, दिन प्रतिदिन के सिनॉप्टिक अपवाह पैटर्न, चक्रवात तूफान का प्रतिवक्र होना जो निम्न स्तरीय पश्चिमी हवाओं को सुदृढ़ करता है और क्षेत्र में तटीय स्थानों पर समुद्र समीर के आरंभ को रोकता है और इसके परिणामस्वरूप लू चलती है। इन विशेषताओं का स्थानिक और कालिक रूप से भी सूक्ष्म विश्लेषण किया गया है ताकि इस प्रकार की घटनाओं में इनकी भूमिका का पता लगाया जा सके। तापमान में बढ़ोतरी के साथ उनके सांख्यिकीय लैग सहसंबंध की जाँच की गई जिससे समय से काफी पहले इन घटनाओं के पूर्वानुमान करने की संभावनाओं का पता लगाया जा सके।

ABSTRACT. During the decade of 1998-2007, both Orissa and Andhra Pradesh at east Coast of India have been affected by heat waves more frequently and more severely causing very high damages to human lives. The most severe heat wave years for the region in the recent past are summer of 1998 over Orissa and 2003 over Andhra Pradesh when 2,042 and nearly 3054 people lost their lives respectively. In summer of 2005, though severe heat wave conditions were experienced for some days over Orissa and adjoining east coasts, the damages were not high as before. In view of such extreme temperature events have been regularly affected the region during the period where their normal frequency is low, analyses of their long period temperature data and study of their relationship with various regional and global ocean-atmospheric features are very much necessary, to find possible causes and then use them in forecasting. In the present study, an attempt has been made to analyze various temperature time series as available, varying from large domain to small domain, *e.g.*, all India temperature, east coast of India temperature etc., to understand whether years which had recorded extreme temperatures in these larger domains have any relationship with that occurred over its very smaller domain, *e.g.*, Orissa from station data, of which later is a part. To understand the relation between the magnitude of heat indices and loss to total human lives it caused during respective whole periods of heat waves, different heat indices, *viz*., general heat indices, Thom's discomfort and Webb's comfort indices have been computed during these extreme years over Orissa and Andhra Pradesh states and compared with total heat wave related human deaths over the respective states for the corresponding years. In addition to various heat indices, various Ocean-atmospheric characteristics, *e.g.*, monthly

SST over Bay of Bengal, day-to-day synoptic flow pattern, recurving Cyclonic Storms which strengthen low-level westerly and prohibit onset of Sea breeze over the coastal stations in the region causing persistent of heat waves, have also been critically analyzed both spatially and temporally to find role of these features in such occurrences. Their statistical lag correlations if any with ensuing temperature rise have been tested to explore the possibility of using them in forecasting these events much in advance.

Key words – Extreme temperature, Heat waves, Trend analysis, Heat comfort indices, Recurving cyclonic storms.

1. Introduction

Orissa is situated at the northern parts of the east coast of India with wide Ocean basin at its east, *i.e*., the Bay of Bengal. Its geographical area is approximately 4.74% of India and its population is 36.7 million as per census 2001 with 70% of them mainly depending on rain fed agriculture. Like other maritime states, it is highly vulnerable to severe Cyclonic storms. Monsoon disturbances also regularly affect the state causing flood and there are incidences of droughts over the state due to vagaries of monsoon causing unfavourable synoptic conditions. In summer, the state in some years experiences very severe heat waves while it is pleasant in other years. Being at the coast, Orissa experiences highly variable circulation pattern in summer because of onset of Sea breeze during evening and nights at its coastal stations. Climatologically in summer, either low level dry continental westerlies or low level south-easterly/easterly wind regimes blow across the state depending on the prevailing synoptic situations. When westerly winds dominate the region at lower levels, it brings severe heat wave from west as witnessed during May 1998 and June 2005 while easterly winds controls such temperature rise in the region as witnessed during recent summers of May of 2006, 2007 and 2008. In former case, state also suffers under scorching heat waves due to presence of high humidity level because of its proximity to the coast resulting severe damage to human lives. Environmental degradation is also very fast in the state. Being rich in Iron ores and other minerals, the fast depletion in the environment is mainly due to large scale mining, large increase in steel industries, change of land use pattern; increase in coal based thermal plants, large scale deforestation, etc.

In the decade of 1998-2007, Orissa has been reeling under contrasting extreme weather conditions. Occurrences of climate induced natural disasters like severe heat waves, droughts, floods, and cyclones are more frequent and very intense during the decade causing misery to the lives of the people. In Orissa, a total of 2,338 people lost their lives between 1998 and 2004 due to heat wave prevailed in summer during the period. While 2,042 people were killed in 1998, 91 died in 1999, 29 in 2000, 25 in 2001, 41 in 2002, 67 in 2003 and 43 in 2004. More than 75 people have died as a result of the heat wave in 2005. Its neighboring state of Andhra Pradesh is also affected by frequent severe heat waves. About 3054 people lost their lives in Andhra Pradesh during May-June 2003 due to severe heat waves. To confirm whether repeated occurrences of record breaking extreme Temperatures in many areas of Orissa during summer are an impact of climate change or effect of the warm SST from adjoining sea prevailed during those years or repeated occurrences of simultaneous Interlocking of highly supporting regional synoptic flow pattern for longer period, detail ocean-atmospheric data analysis are required to be accurately made.

An earlier study by De and Mukhopadhyay (1998) showed that the heat wave in 1998 was linked with El-Nino of 1997. They showed that numbers of casualties from severe heat waves were more during years succeeding an El-Nino. Chaudhury *et al*., (2000) also studied sub-divisional heat wave frequencies for 1978-1999 and loss lives in these sub-divisions. They also discussed role of synoptic flow pattern which favours heat waves over various parts of India and analysed impact of El-Nino in causing high heat waves cases over India. On the other hand Kalsi and Pareek (2001) have ranked April 1999 as the warmest April of the last century for the north-western India, while the earlier studies have focused their attention on the months of May and June. They concluded, the pronounced heating in April 1999 cannot be therefore linked with global warming and it is attributable to local anomalous circulation setting over India and its neighbourhood. In the present study, longer period temperature data has been critically analyzed, at different spatio-temporal scale using temperature data of both all India temperature and east coast of India temperature, to understand the years having most severity of heat waves and trend of warming in these regions if any have any relationship with that of Orissa. We have also critically analysed whether such extreme temperatures recorded in last few years are part of natural variations or regional impact of climate change. For isolating most extreme temperature years over Orissa from the two extreme years of 1998 and 2005 and finding why human losses in other extreme years of 2005 were not as high as in 1998 over Orissa, different daily heat discomfort indices have been computed from state's station data for corresponding years and compared. These values have also been compared with corresponding heat indices of

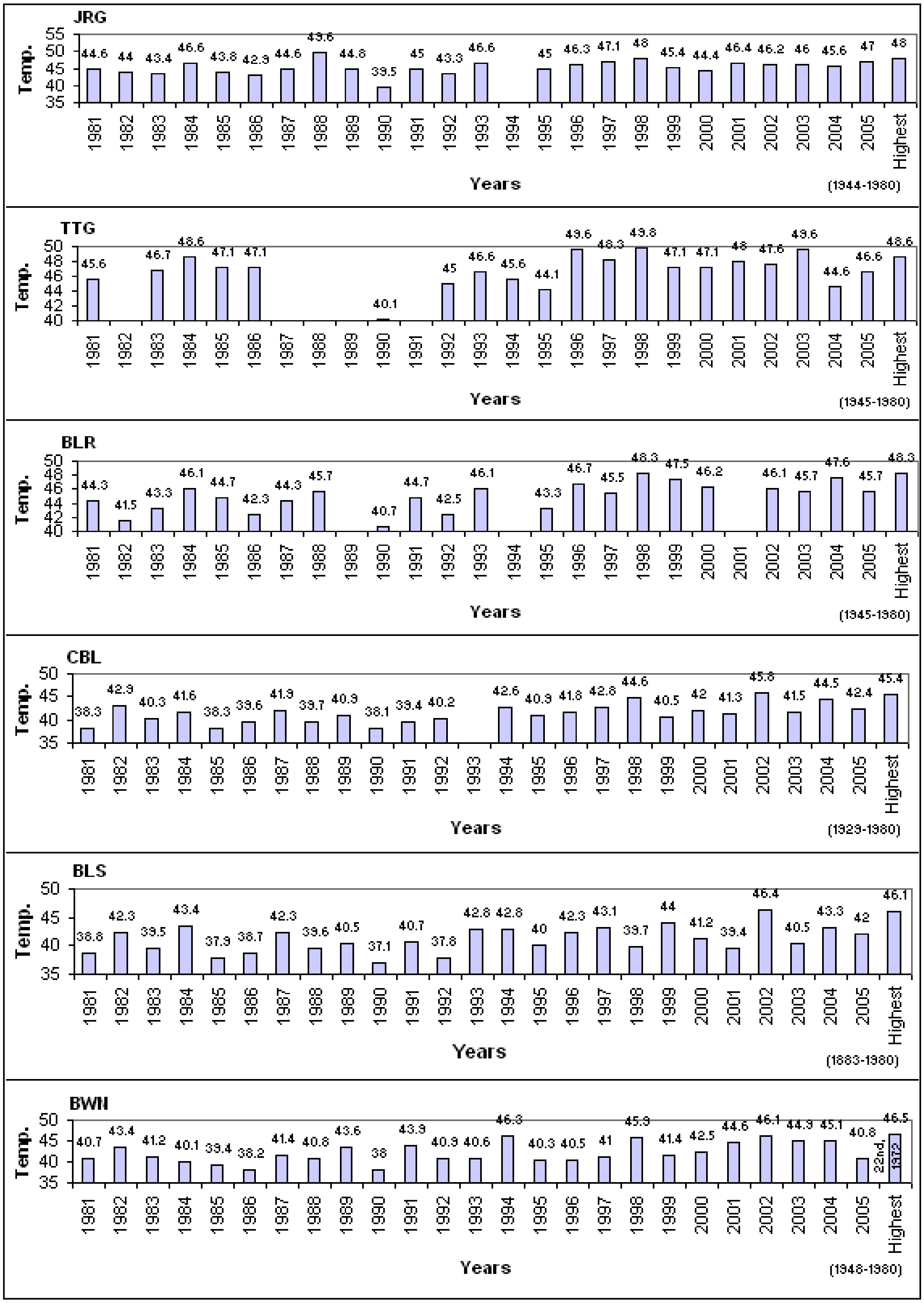


Fig. 1. Year wise extreme max. temp. values during May for the period 1981-2005 *vis-à-vis* earlier climatological extreme

2003 over Andhra Pradesh to find why the latter caused ever highest damage to human lives and properties. We have critically analyzed various Ocean-atmospheric characteristics, *e.g.*, monthly SST over Bay of Bengal which is the main heat source, daily synoptic flow pattern and recurving Cyclonic Storms responsible for strengthening of westerly, thus prohibiting onset of Sea breeze over the coastal stations of east coast and causing persistence of heat waves, both spatially and temporally to find role of these features in such occurrences. Their statistical lag correlations if any with ensuing temperature rise have been tested to explore the possibility of using them in forecasting these events much in advance. Apart from these meteorological aspects, there are many other factors which might be influencing Orissa's Summer Temperatures, *e.g.*,

- Deforestation particularly after super cyclone
- Change in crop pattern and land uses
- Decreasing of rural water Bodies
- Increase in Industrial-Vehicular pollutions
- Increase in Industrial Heating (Thermal plants and Iron ore smelting plants)
- Urbananization Effect-Heat Islands
- Changes in Housing Pattern, Life Style and availability of Road-side trees

Which need to be studied separately as their systematic data base is not available for longer period.

2. Data

Following data has been used for the present study:

(*i*) Daily Maximum temperature for main summer months of May-June over 16 different Stations of Orissa covering Bhubaneswar-BWN, Cuttack-CTK, Chandbali-CBL, Jarsugura-JRG, Titilagarh-TTG, Sambalpur-SBP, Keonjhargarha-KNJ, Baripada-BPD, Balesore-BLS, Paradeep-PRD, Gopalpur-GPL, Puri-PRI, Sundergarh-SNG, Angulu-ANG, Bolanagiri-BLG and Phulbani-PBN from IMD for 1981-2005.

(*ii*) Climate normal of above stations for the period 1951-1980 are referred from IMD (1991).

(*iii*) Monthly average Maximum/Minimum temperature and mean temperature data 1901-2003 for east coast of India from www.iitm.gov.in.

(*iv*) Daily wind composite charts and monthly SST data of north/south Bay of Bengal and Nino 3.4 region of Pacific for the period 1948-2003 from CDC, NOAA, USA (cdc.noaa.gov.in).

(*v*) Tracks of Cyclonic storms from IMD for the period 1970-2005 when Orissa and other parts of east coast have been affected by heat wave to severe heat waves.

3. Identification of extreme temperature years for Orissa and East coast

3.1. *Orissa using monthly station extremes*

For identification of years of extreme temperatures over Orissa, one can use monthly extremes, *i.e.*, the highest temperature recorded over the station in the month, from the daily maximum temperature data of various stations in the states to find if highest maximum temperature recorded during respective years in those months have exceeded earlier climatological highest. For this, the highest values up to which the maximum temperature has been raised in each season for main summer month of May and June are collected from IMD for recent 26 years of 1981-2005 for 16 stations distributed all over the state and compared with earlier highest records available in climate table book published by IMD (1991). Figs. (1&2) show highest maximum temperatures recorded for the month of May and June respectively for some stations of Orissa for the period 1981-2005. Details of ever highest maximum temperature recorded earlier before 1981 as per climate table in IMD (1991) is also shown in figures along with period of observation since when such data are available. In May, Jharsugura, an interior station of Orissa (Fig. 1) had recorded the ever highest maximum temperature till 1980 as 48 °C. Afterwards, in May, 1988, it recorded the highest as 49.6 °C, which has become the ever highest recoded maximum temperature at the station for the whole data period of 1944-2005. However, in the summer of 1998 when Orissa was affected most severely by heat waves for prolonged days, the highest maximum temperature of May reached upto 48 °C which was ever highest temperature record till 1980. Titlagarh in Fig. 1 shows breaking of earlier highest record of 48.6 °C observed in 1973 for the period 1945-1980 thrice afterwards in 1998, 1996 and 2003 by recording 49.8 °C, 49.6 °C and 49.6 °C respectively. It also shows that Bolangiri has equalized its erstwhile, before 1980, highest temperature record of 48.3 °C in 1998 followed by 2nd high values of 47.6 °C recently in 2004. Apart from these interior stations, the coastal stations Chandbali and Balesore (Fig. 1) of Orissa have recorded ever highest temperatures 45.8 °C and 46.4 °C in 2002 crossing their earlier records of 45.4 °C and 46.1 °C that recorded wayback in the years 1966 and 1895 respectively.

Bhubaneswar (Fig. 1), though did not break its earlier climatological record of ever highest temperature of 46.5 °C in the year 1972 for the month of May, it too

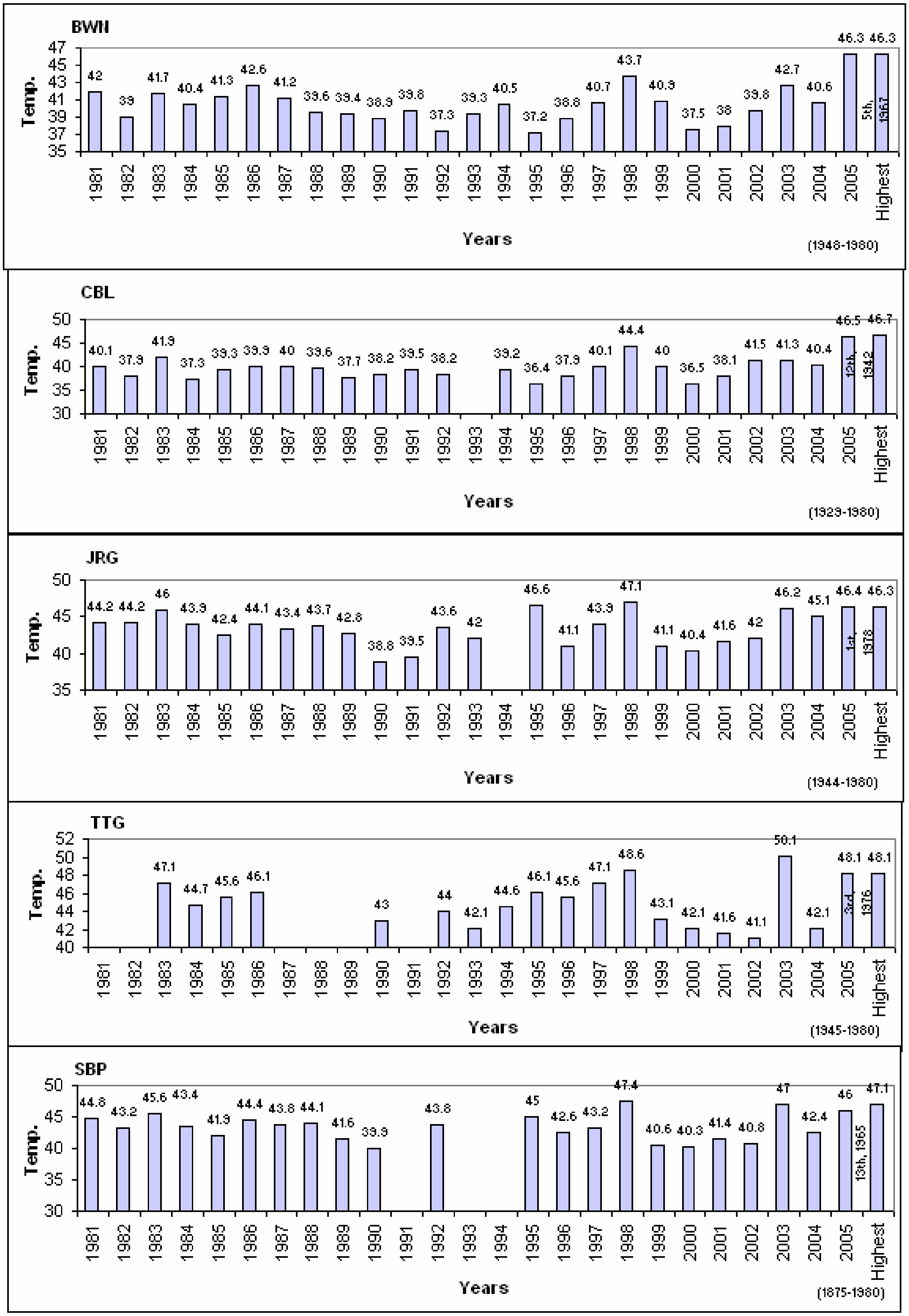


Fig. 2. Year wise extreme max. temp. values during June for the period 1981-2005 *vis-à-vis* earlier climatological extreme

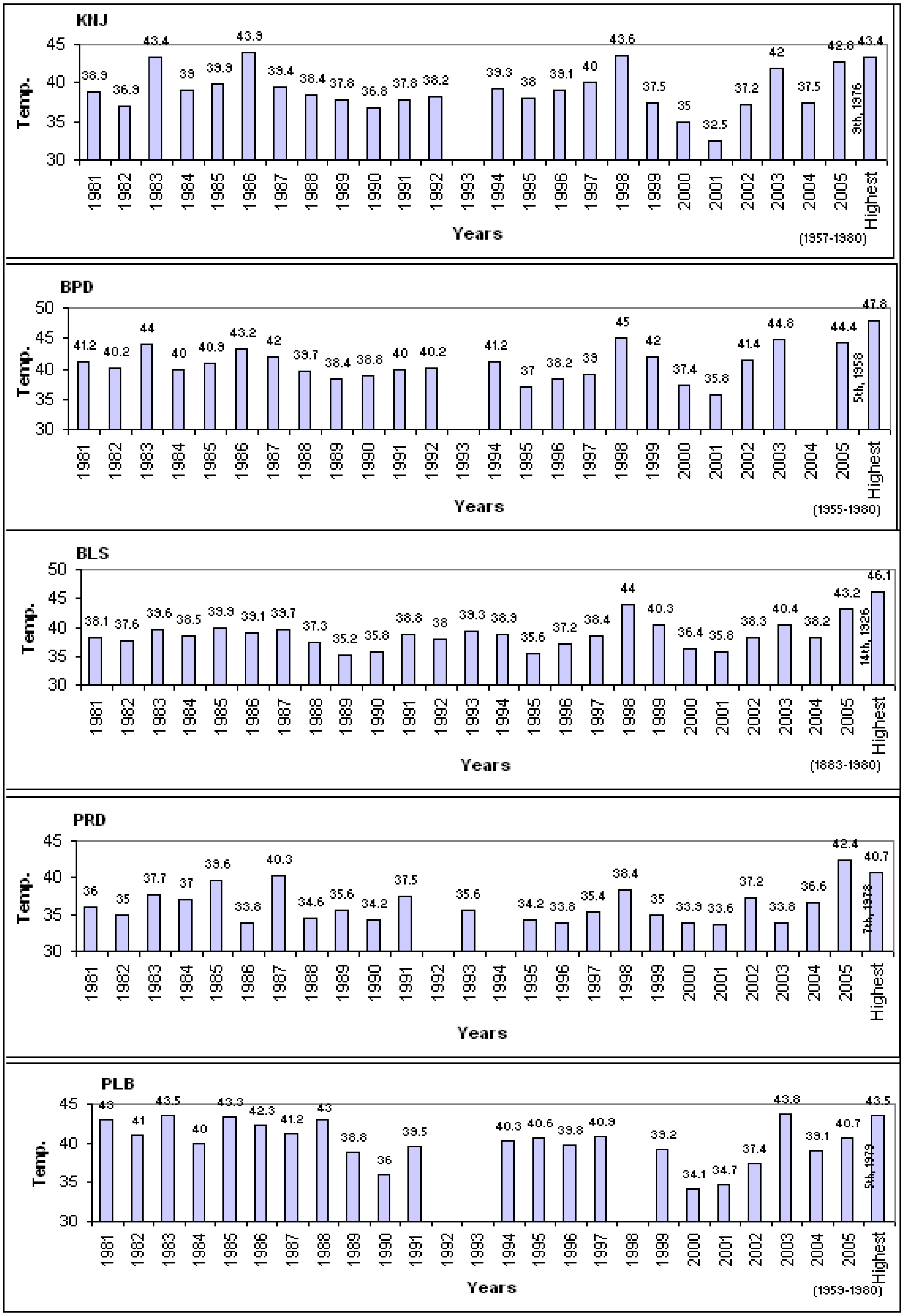
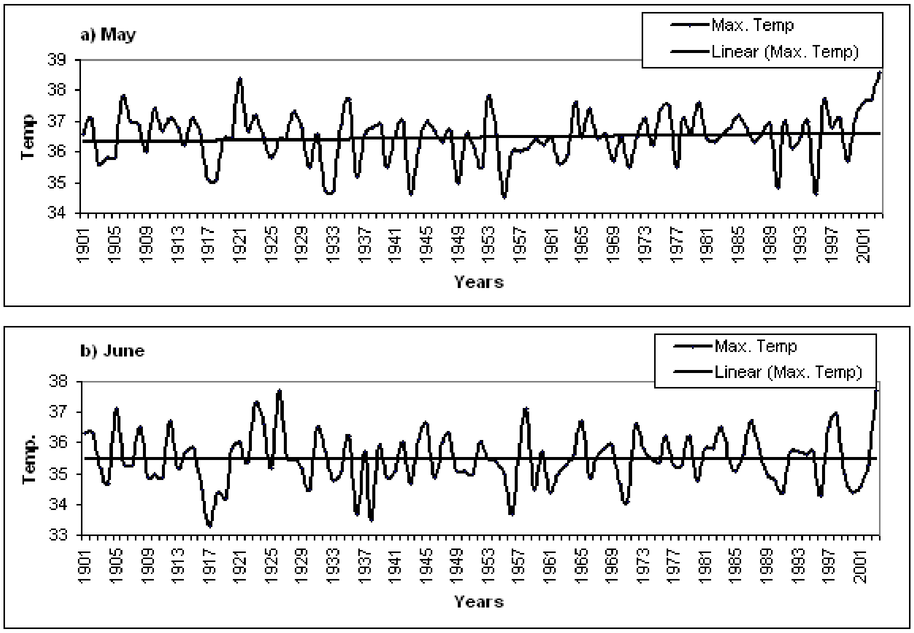


Fig. 2(*Contd.*). Year wise extreme max. temp. values during June for the period 1981-2005 *vis-à-vis* earlier climatological extreme

TABLE 1

Earlier climatological extremes of maximum temperature and recent extremes

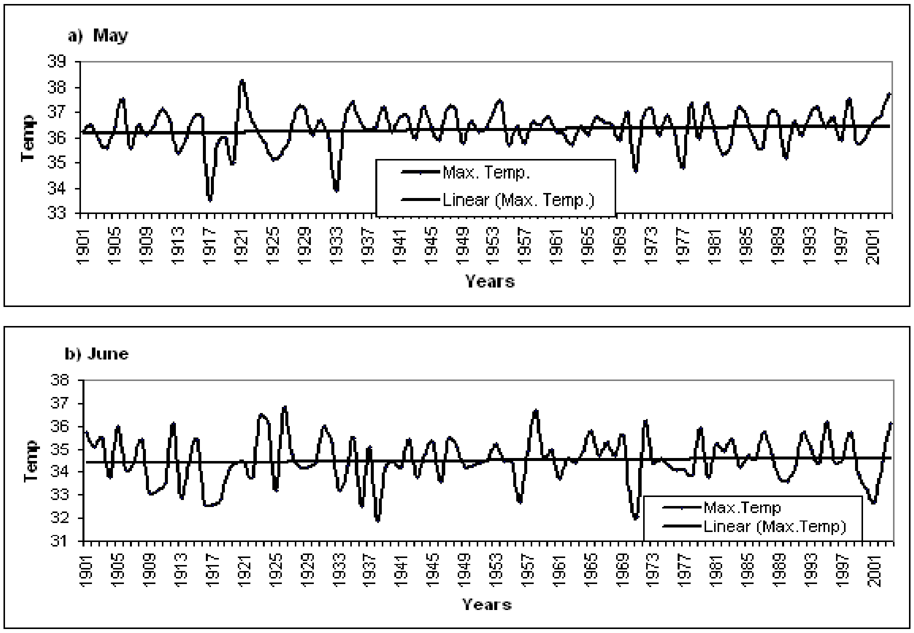
Station	Year of establishment	May: Data not available	May: Ever highest temp. from climate table	May: Highest values amongst yearly extreme temp. values 1st Value	May: 2nd Value	May: 3rd Value	May: 4th Value	June: Data not available	June: Ever highest temp. from climate table	June: Highest values amongst yearly extreme temp. values 1st Value	June: 2nd Value	June: 3rd Value	June: 4th Value
BWN	1948		46.5	46.3	46.1	45.9	45.1		46.3	46.3	43.7	42.7	42.6
				1994	2002	1998	2004			2005	1998	2003	1986
CTK	1867		47.7	45	44.4	44.1	44		47.2	45.2	43.1	42.9	42.8
				2002	2004	1998	1989			2005	1998	1983	2003
CBL	1929	1993	45.4	45.8	44.6	44.5	42.9	1993	46.7	46.5	44.4	41.9	41.5
				2002	1998	2004	1982			2005	1998	1983	2002
JRG	1944	1994	48	49.6	48	47.1	47	1994	46.3	47.1	46.6	46.4	46.2
				1988	1998	1997	2005			1998	1995	2005	2003
TTG	1945	1982, 87, 88, 89, 91	48.6	49.8	49.6	49.6	48.6	81, 82, 87, 88, 89,91	48.1	50.1	48.6	48.1	47.1
				1998	1996	2003	1984			2003	1998	2005	1983, 1997
SBP	1875	1991, 93, 94	47.7	47.5	47.2	46.9	46.7	1991, 93, 94	47.1	47.4	47	46	45.6
				1998	1981	1997	1999, 2003			1998	2003	2005	1983
KNJ	1957	1993	47.4	43.9	43.2	43.0	42.8	1993	43.4	43.9	43.6	43.4	42.8
				1984	1998	1996	1991			1986	1998	1983	2005
BPD	1955	1993, 2004	48.3	45.6	45.4	45.2	45.0	1993, 2004	47.8	45.0	44.8	44.4	44.0
				1984	1999	1994	1987			1998	2003	2005	1983
BLS	1883		46.1	46.4	44.0	43.4	43.3		46.1	44.0	43.2	40.4	40.3
				2002	1999	1984	2004			1998	2005	2003	1999
PRD	1962	1992, 1994	41.4	39.6	39.0	37.1	36.6	1992, 1994	40.7	42.4	40.3	39.6	38.4
				1983	2004	1997	2002, 2003			2005	1987	1985	1998
ANG	1905	1984-93, 1997	47.2	46.7	46.3	45.7	45.5	1984-1993	47.2	46.7	46.7	44.9	44.5
				1998	1996	1999	2001			1998	2005	1983	2003
PRI	1888		42.2	38.6	38.4	37.5	37.4		44.2	39.1	38.6	38.4	38.3
				1994	1992	1989	2001			1987	1988	1984	1985
GPL	1881	1991	43.3	42.6	40.3	37.8	36.7	1991	44	42.2	40.6	39.6	39
				2004	2000	1998	1997			2005	1987	1989	1999
PLB	1959	1992, 1993, 1998	44.6	44.2	43.6	43.5	43.5	1992, 93, 98	43.5	43.8	43.5	43.3	43.0
				1984	2005	1989	1999			2003	1983	1985	1981, 1988
BLR	1956	1989, 1994, 2001	48.3	48.3	47.6	47.5	46.7	1989, 94, 01, 03	46	47.7	45.7	45.6	45.1
				1998	2004	1999	1996			1998	2005	1983	1995
SNG		1981-94, 99, 2003, 2004	46.6	46.6	46.6	46.5	46	1981-94, 99, 04	45.8	46.6	46.6	44	43.2
				2002	2005	1997	2001			2003	2005	1997	1995



Figs. 3(a&b). Variation of mean max. temperature for the period 1901-2003 over east Coast

recorded very high temp. of 45.9 °C, 46.1 °C and 46.3 °C in 1998, 2002 and 1994 respectively. It is also interesting to note from Fig. 1 that neither of these station's year-wise highest in the month of May shows any systematic trends which confirms highest temperature observed over Orissa during May during each season have still not been affected by much discussed global warming trends. Table 1 documents the details of maximum temperature extremes over all 16 stations of Orissa since the year of establishment of the given station, past climatological highest maximum temperature using IMD (1991) climate table based on data till 1980, highest values recorded during recent 25-years of 1981-2005 including their 2nd, 3rd and 4th highest values. In case these high values recorded in 1998, 2003 and 2005 which are main season consider in the present study, we have marked them in various sheds in Table 1. It shows alone in 1998, 63% of these stations of Orissa during severe heat wave year of May 1998 which caused very high damage to human lives had recorded either ever highest or nearby values.

In case of June, it is revealed from Fig. 2 that most of the stations which are located both at coastal and interior Orissa, *e.g.*, Bhubaneswar, Chandbali, Jarsugura, Titilagarh, Sambalpur, Keonjhargarha, Baripada, Balesore, Paradeep and Phulbani, have recorded very high unusual temperature in 1998, 2003 and 2005 compared to other years in 1995-2005. Fig. 2 further indicates that the earlier record of highest maximum temperatures for June has been broken at Bhubaneswar in 2005, Jharsugura in 1998 and 2005, Titilagarh in all three years of 1998, 2003 and 2005, Sambalpur in 1998, Keonjhargarha in 1998, Paradeep in 2005 and Phulbani in 2003. Like May, we have also documented earlier climatological highest maximum temperature till 1980 and highest one recorded after 1980 for June in Table 1. In contrast to the months of May having only one year, *i.e.*, 1998 when most of the stations of Orissa have recorded very high temperatures whether it is 1st highest or 3rd highest in order, the month of June has these values in most of the stations of Orissa in 1998, 2003 and 2005. For the month of June Table 1 also reveals that in 9 out of total 16 stations that suppressed or reached to equal the earlier extreme temperature records, it was at 3 stations for each of 1998 (SBP, JRG and BLR) and 2003 (TTG, PLB, SNG) while it was at two stations in 2005 (BWN, PRD) and one station in 1986 (KNJ). Hence, out of various years when ever highest temperatures were recorded in May and June at various observatories of Orissa till 2005, there have been quite good number of extremes recorded during the period of May-June of 1998, June 2003 and June of 2005. However, it does not make us clear why damage wise, there were maximum of 2,042 people killed in 1998 with more than 75 people lost their lives in that of 2005. It may also be noted that the severe heat wave over Orissa in2003 was not much intense as it was in the neighboring state of Andhra Pradesh where it was unusually severe due to which nearly 3054 people lost their lives in Andhra Pradesh during May-June 2003. It will be very interesting if one will find why the human looses over Orissa was so high in summer of 1998 compared to other severe heat



Figs. 4(a&b). Variation of mean max. temperature for the period 1901-2003 over all India

TABLE 2

Long period temperature trend values for the period (1901-2003)

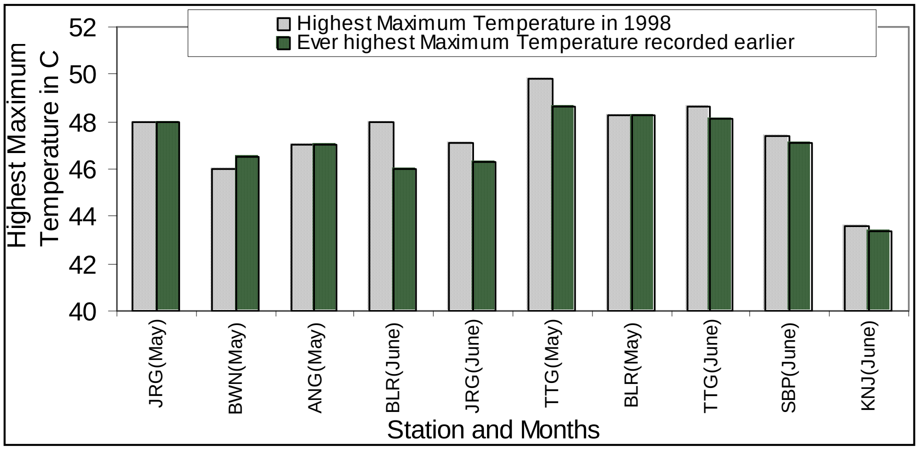
Time	All India	East Coast
Annual Averages	0.5	0.5
Annual Max. Temp.	0.8	0.7
Annual Min. Temp.	0.2	0.4
May Max. Temp.	0.3	0.4
June Max. Temp.	0.3	0.05

wave years of 2005 and 2003. Was it because of highly unbearable heat discomfort index related to prevailed unusual meteorological conditions or complete absence of awareness to take precautionary measures to avoid heat related deaths/sun strokes? If it is former one then how the losses of human lives over the sate have been significantly reduced by 2 order magnitude when it faced the intense summer of 2005? Is it because the special awareness campaigns initiated by Orissa Disaster Mitigation Agency(OSDMA)/State revenue Departments and various NGO which have been very active over the region after super cyclone of 1999. A study has already been conducted by Bhadram *et al*., (2005) to understand various aspects in case of severe heat waves of Andhra Pradesh in 2003 including prevailed discomfort index to understand the cause of such high unusual deaths which killed 3054 people. We have analyzed temperature data of 1998, 2003 and 2005 in Sec. 3.3 to find whether very high human losses in 1998 compared to 2003 and 2005 for Orissa was due to longer heat spells of very high temp. prevailed in 1998 compared to other years or such loss in later years were significantly reduced due to additional precautions taken by common public due to the lesson learnt from 1998 and massive awareness campaign as done by government afterwards.

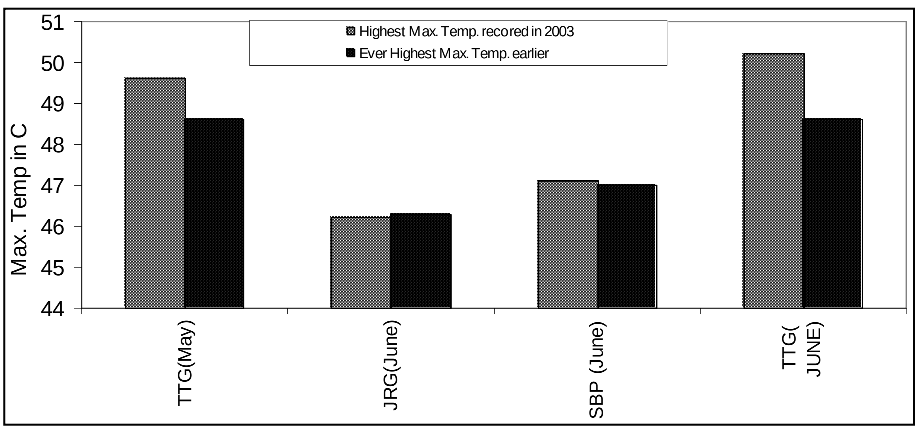
3.2. *East coast regional average temperature*

Figs. 3(a&b) shows regional maximum temperature averages over the whole east coast of India covering the states of Coastal Andhra Pradesh, Orissa etc. and their long term linear trend for the month of May and June respectively for the period 1901-2003. Both the figures indicate rising of maximum temperature over the

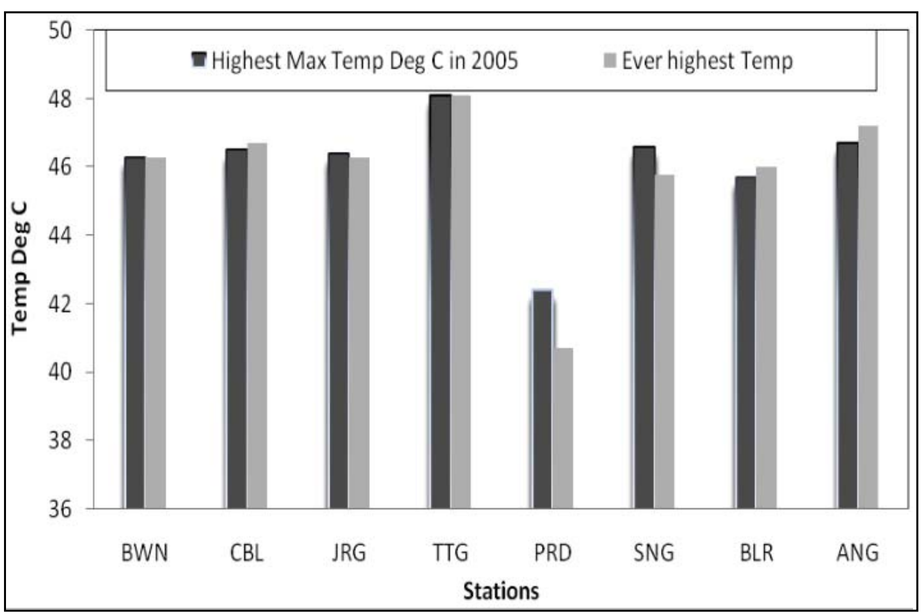
(a)



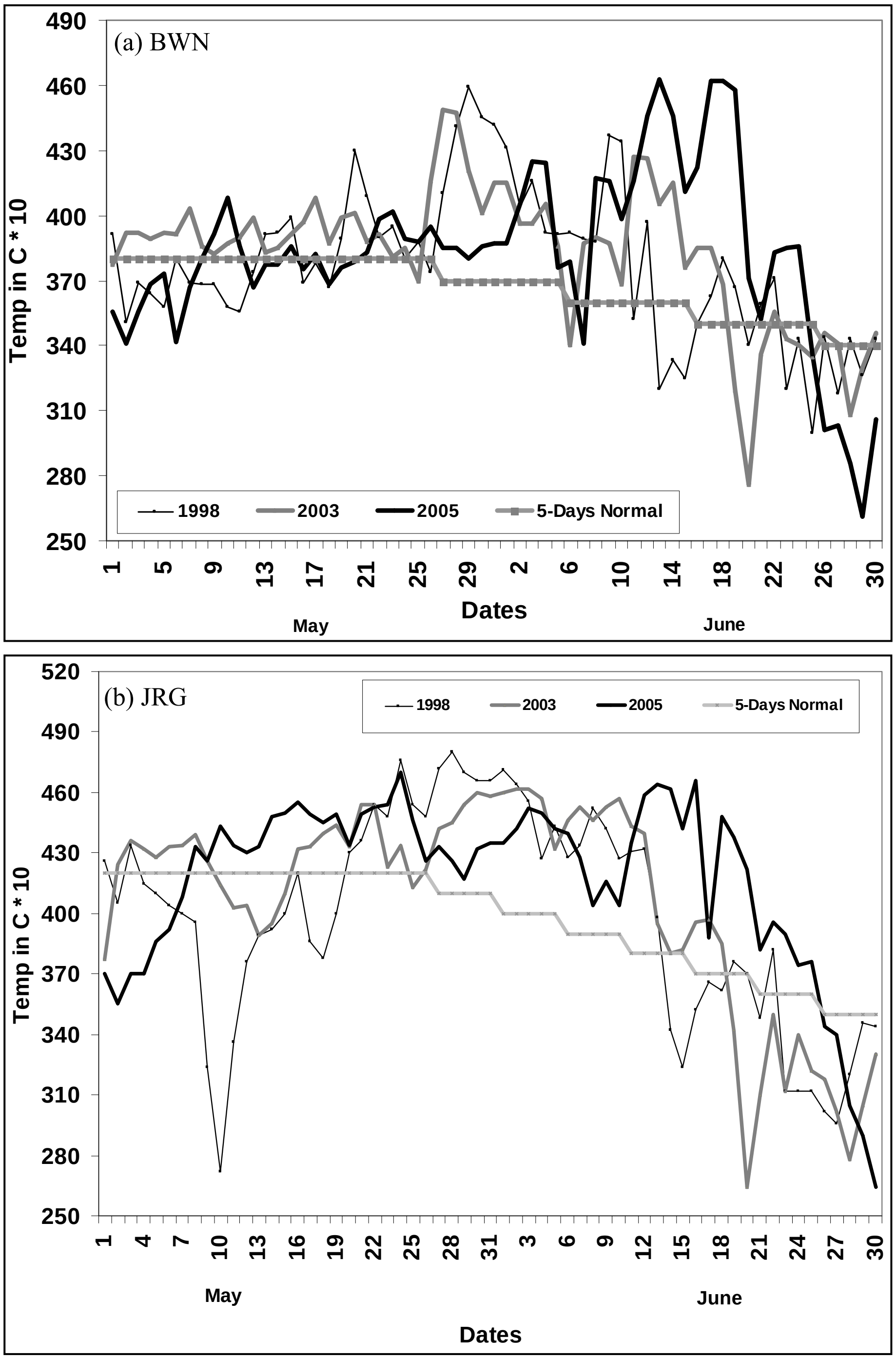
(b)



(c)



Figs. 5(a-c). Stations whose recent max. temp. has broken earlier records (a) 1998, (b) 2003 and (c) 2005



Figs. 6(a&b). Actual maximum temperatures reached in each date of the 61-days covering May-June of three extreme years of 1998, 2003 and 2005 for both stations (BWN and JRG) along with their normals

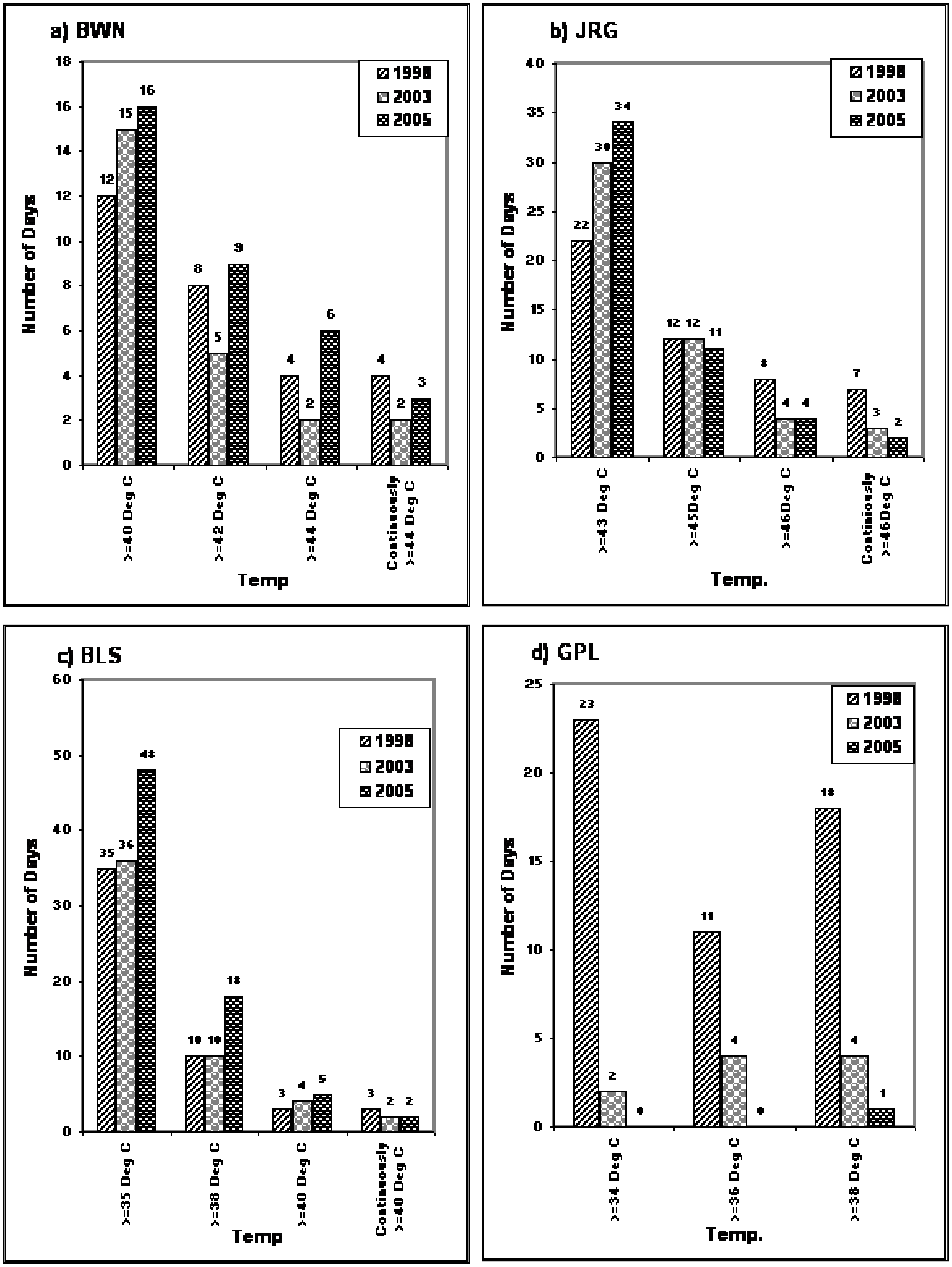
region to unusual high value in both the months in 2003 in the 103-year records. Though, average maximum temperature was not any significantly higher in 1998 for the region compared to other years for the month of May [Fig. 3(a)], it was the 2nd highest value during 1998 in June [Fig. 3(b)] for the recent period 1960-2005. Similarly we have plotted the maximum temperature averaged over all India for both months in Figs. 4 (a&b). Fig. 4(a) indicate the ever highest occurred in 1920 with 2nd highest in 2003 for May while Fig. 4(b) indicates the occurrence of ever highest in 1926 and 1958 for June with occurrences of some recent peak values in 1972, 1996 and 2003. Hence in the absence of data for 2005, both the figures also support the earlier findings that 1998 and 2003 are among various severe summers those affected the region in last 40-50-years. Table 2 shows trend values computed from Figs. (3&4) for annual / monthly averages for India and East Coast of India to understand the prevailing of such unusual present extreme temperature over Orissa in context of impact of climate change (all figures are not given because of space). It shows the trend values are alarmingly significant when annual averages are computed for the whole period as their values are 0.8 °C and 0.7 °C for India and east coast of India in case of annual maximum temperatures alone. But in case of Maximum temperature for both months of May and June over east coast of India, the trends are insignificant (.05 °C to .4 °C). Hence, unusual temperature raise during some dates of summer in 1998, 2003 and 2005 over Orissa and Andhra Pradesh are not because of impact of any ongoing significant linear warming trend prevailing either over whole of India or over east Coast during either month of May or June. Rather, it may be due to some other reasons discussed in following sections.

3.3. *Comparison of severity of heat waves of 1998, 2003 and 2005 over Orissa with 2003 over Andhra Pradesh*

Using daily threshold maximum temperature

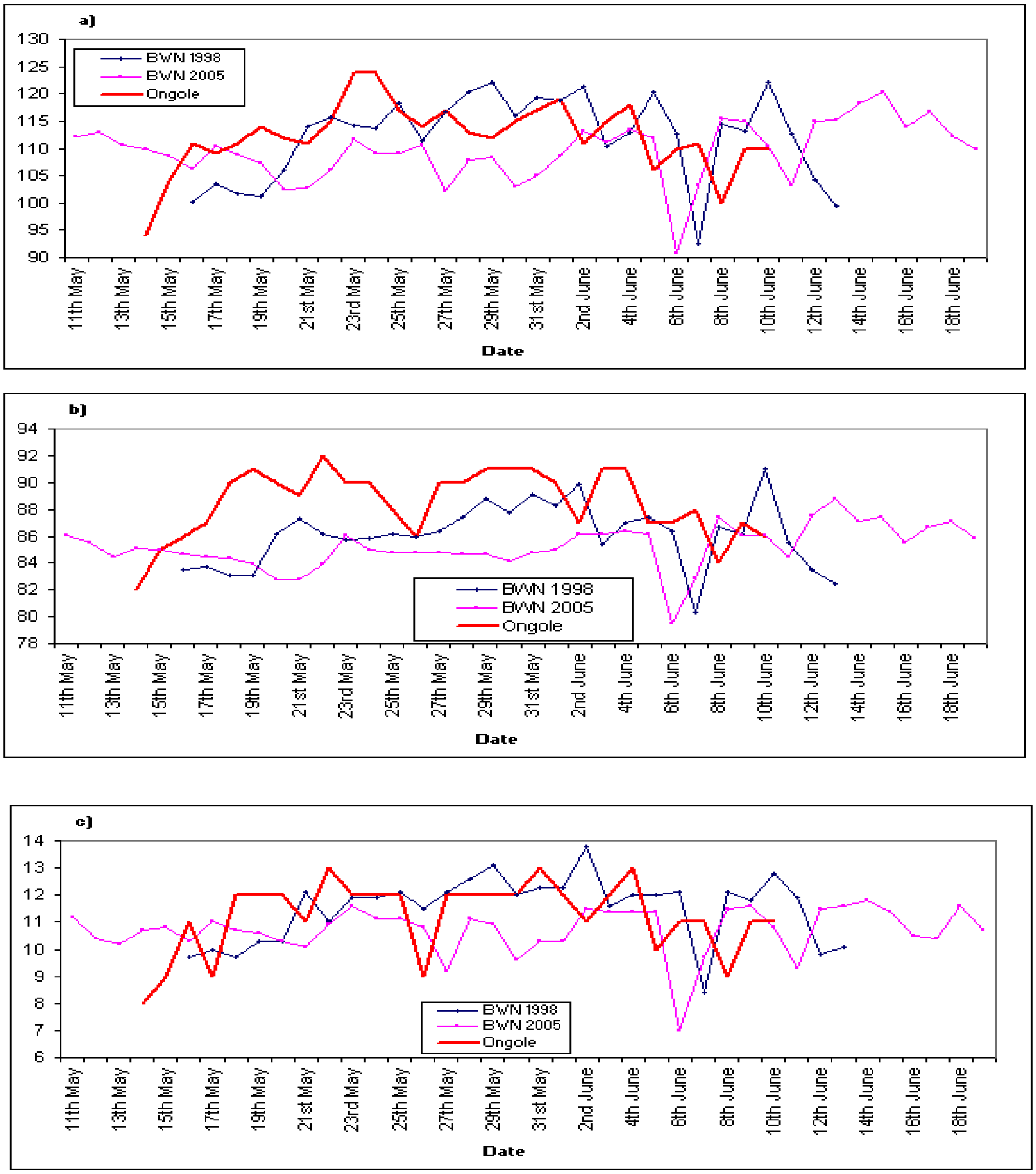
In order to further compare the severity of heat waves prevailed in the years 1998, 2003 and 2005, one has to find the exact period when positive maximum temperature anomalies were prevailed, intensity of such anomalies reached along with the values actual temperature reached and their days if any unusual high temperature were reported. We have plotted daily actual maximum temperature of few stations in Figs. 5(a-c) which have recorded very high temperatures during 1998, 2003 and 2005, thus suppressing or equalizing their earlier records. It indicates that most of the earlier highest temperature records which were made based upon data of more than 40-years since installation of different observatories are broken in May-June 1998 and June 2005 followed by few interior stations near Orissa-Andhra Pradesh border also recorded high temperatures in May-June 2003. We have plotted the actual maximum temperatures in each date for 61-days of May-June of three extreme years of 1998, 2003 and 2005 in Figs. 6 (a&b) for two stations with Bhubaneswar from coastal area and Jharsugura from interior Orissa along with their pentad normals to find how the temperatures was varying on day to day during these years and when above normal temperature and peak values were experienced. One may also find from these figures whether the peak temperature values reached and periods when prevailed in each of these three extreme summer months are comparable or significantly differ. It is revealed from Figs. 6(a) that above normal maximum temperatures were consistently prevailed during almost all days at BWN for a common period which was of longer duration covering 26 May-19 June during 61 days of May and June of 2003 and 2005 while such period during 1998 when the state of Orissa has highest lost of human lives, it was occurred earlier during 19 May-10 June. When these extreme summers are analyzed on the basis of departure from their pentad normals as shown in Fig. 6(a), it shows in the summer of 1998, the temperature departures of +3 °C to +9 °C prevailed at BWN during almost all days for the period 27 May-10 June with extreme phases occurred during 28-31 May and 9-10 June when it reached at its peak values of +7.1 °C to +8.9 °C. But in 2003, it was of +2 °C to +8 °C during almost all days for the period 26 May-18 June with extreme phases occurred during 27 May-1 June and 11-14 June excluding 30 May which had very high departures of +4.5 °C to +7.9 °C while in 2005, it was of +3 °C to +11 °C during almost all days for the period 8-24 June with extreme phases occurred during 3-4 and 8-19 June having very high departure of +5 °C to +11 °C. It may further be noted that during 17-19 June, 2005, the departure reached to 11 °C which is the ever highest at BWN during the season. The actual maximum temperatures recorded during various extreme periods of these summers at BWN are 45.8-46.2 °C for four dates on 13 June and 17-19 June in 2005 and 42-44 °C on 27-29 May and 11 June in 2003 while it was of 44.1-45.9 on 28-31 May in 1998. Hence amongst all three extreme summers, the ever actual highest maximum temperature for BWN was recorded in 2005 not in 1998.

In case of JRG [Fig. 6(b)], the above normal maximum temperature was prevailed during almost all days for the period of 8 May-25 June in 2005, for 16 May-18 June in 2003 and for 20 May-14 June in 1998 with their highest peak values reached to 45-47 °C on 23-25 May, 12-14 and 16 June in 2005 and 45-46 °C on 29 May-4 June and 6-10 June in 2003 while it was of 45-48 °C on 22 May-3 June and 8 June during 1998. Comparison with their pentad normal with actual temperature in Fig. 6(b) shows the temperature departures of +3 °C to +7.1 °C prevailed at JRG during 22 May-12 June with extreme phases occurred during 27 May-3 June when it reached at its peak values of 5.6 to +7.1 °C. But in 2003, it was of +3 °C to +6.7 °C during almost all days for the period 27 May-12 June with extreme phases occurred during 1-12 June excluding 5 June which had very high



Figs. 7(a-d). Number of days of extreme temperature of different intensity prevailed during 1998, 2003 & 2005 based on different threshold values

Figs. 8(a-f). Comparison of variation of different Heat Comfort Index for the year 1998 & 2005 (a) General Heat Index(HI) over BWN (b) General HI over JRG (c) Thom's Discomfort Index over BWN (d) Thom's Discomfort Index over JRG (e) Webb's Comfort Index over BWN and (f) Webb's Comfort Index over JRG



Figs. 9(a-c). Comparison of Heat Comfort Index between extreme temp. years of 1998 & 2005 over Orissa at coastal stations Bhubaneshwar against extreme temperature over AP in 2003 (a) General Heat Index (b) Thom's Discomfort Index and (c) Webb's Comfort Index

departures of +5 °C to +6.7 °C while in 2005, it was of +3 °C to +10 °C during almost all days for the period 1-7 June and 11-23 June with extreme phases occurred during 11-20 June having very high departure of +5.6 °C to +10 °C. Till now, it is still not clear why in 1998, 2042 people lost their lives while in 2005, only nearly 75 people lost their lives though the actual maximum temperature curve in Fig. 6 does not show a high difference for BWN in their temperature records except JRG recorded ever highest maximum temperature in 1998 compared to other years. To understand the reasons for higher number of deaths in 1998, compared to other two years under study, the duration of various high temperature spells are computed on the basis of various temperature ranges depending upon their normal in a month for four stations located at various places in Orissa along with BWN and JRG and shown Figs. 7 (a-d). In view of the interior stations generally have higher normal maximum temperatures compared to their corresponding coastal stations at same latitudes over Orissa, we have fixed

TABLE 3

Inter-Relationship (CC) among monthly temperatures of east coast of India (1951-2003)

Months(Period)	March	April	May	June
		Maximum temperature		
Jan (1951-2003)	0.4	0.4	0.3	
Feb (1951-2003)	0.4	0.3		
Mar (1951-2003)		0.4	0.4	
April (1951-2003)			0.3	
May (1951-2003)				
		Minimum temperature		
Jan (1951-2003)	0.4	0.4	0.6	0.3
Feb (1951-2003)	0.6	0.5	0.3	0.3
Mar (1951-2003)		0.5	0.4	0.3
Apr (1951-2003)			0.5	
May (1951-2003)				

higher or lower ranges depending upon it is an interior one or coastal one. It is well known that sun stroke related deaths will be more if both the intensity and spells of these extreme temperatures will be higher. In case, high temperature also prevailing uninterruptedly for longer durations, the damage will be much higher. It is revealed from Fig. 7(a) that BWN experienced higher number of days of higher temperature at ranges of $\geq$ 40° C $\geq$ 42° C and $\geq$ 44° C with 16, 9 and 6 days respectively in 2005 compared to other years while the number of days it reached to ever highest range of $\geq$ 44° C was of highest duration of 4 days in the summer of 1998. Similarly, Jharsugura [Fig. 7(b)] and Balasore [Fig. 7(c)] have the number of days persistently reaching to ever highest maximum temperatures ranges as 7 and 3 days in 1998 which are more longer duration than of 2005. Even at Gopalpur [Fig. 7(d)] where temperature hardly crossed 38° C, it crossed such limit a record times for 18 times in 1998 compared to 4 times and 2 times in 2003 and 2005 respectively. Hence apart from additional precautions taken by common public due to the lesson learnt from 1998 and massive awareness campaign as done by state Govt., this may be the one of the necessary reason why death reports are so high in 1998 compare to other extreme years, but not sufficient. However, one has to study and compared their human discomfort indices for these years using respective station data as has been analyzed by Bhadram *et al*., (2005) for Andhra heat wave of 2003 when more number of deaths were reported.

3.4. *By computing various heat indices (General Heat Indices (USA), Thom's discomfort indices and Webb's discomfort indices*

Using the available 1200 UTC meteorological parameters data from IDWR, General, Thom's discomfort and Webb's comfort daily heat indices (Bhadram *et al*, 2005) were computed for the two extreme temperature years of 1998 and 2005 for Bhubaneswar and Jharsuguda, coastal and far west interior stations of Orissa respectively and shown in Figs. 8(a-f). In respect of Bhubaneswar [Figs. 8 (a,c&e), all the three indices, *i.e*., general heat index, Thom's discomfort and Webb's comfort indices were found to be much higher in the year 1998 compared to 2005. The respective heat indices reached up to as high as 114-123, 87-91 and 12-14 during 24 May to 4 June in the summer of 1998 compared to 2005 when their respective values were 102-110, 83-85 and 9-12. However, in case of Jharsuguda [Figs. 8(b, d & f), all these respective heat comfort/discomfort indices are well comparable for the extreme temperature years of 1998 and 2005. Inter comparison of daily heat wave indices over Bhubaneswar for two most intense heat wave years of 1998 and 2005 that prevailed over Orissa with the daily heat wave index over Ongole, its counterpart in the neighbouring Andhra Pradesh state for the most intense heat wave year of 2003 that prevailed and caused record number of deaths over the state, is carried out and shown in Figs. 9 (a-c). An interesting observation from

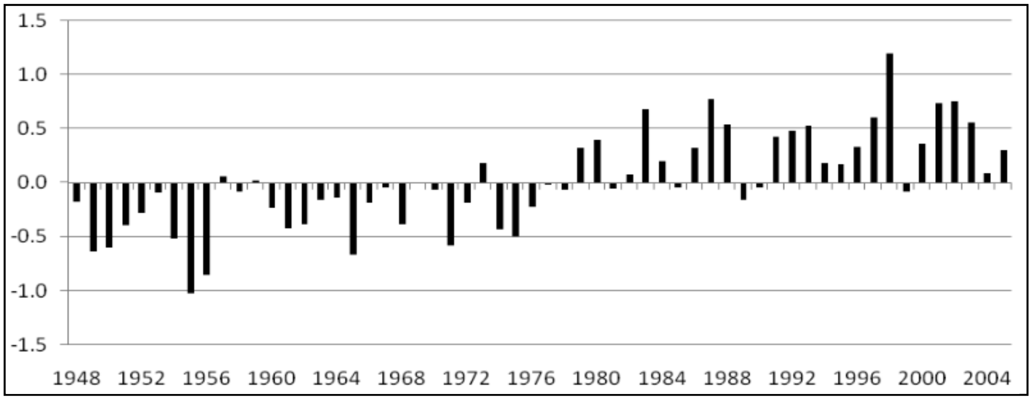


Fig. 10. Variation of SST anomalies of May-June over north Bay of Bengal

Figs. 9 (a-c) is that Thom's heat index [Fig. 9(b)] reached upto very higher values in the range of 88-92 were persisted for very long period covering 17 May-7 June in 2003 at Ongole in Andhra Pradesh during most of the days when the state experienced unusual higher temperatures compared to BWN at Orissa which have such high values of heat indices for very shorter period for 29 May-2 June 1998 while in summer of 2005, their values are less at BWN over Orissa. However, further Figs. 9(a&c) confirm that daily Webb's comfort and general heat indices over Orissa during its most severe heat wave year of 1998, when damage to lives over the state was ever highest, are well comparable with that of 2003 heat indices over Andhra Pradesh. Hence, discomfort levels were unusually higher during 1998 over Orissa particularly at its coast due to high moisture levels compared to other extreme years of 2003 and 2005, while it was further higher over Andhra Pradesh during 2003 which strongly support why damages to human lives were unusually high during respective years over respective states. Therefore, not only additional precautions taken by common public due to the lesson learnt from 1998 and massive awareness campaign of OSDMA and NGOs are the reasons for significant reduction in loss of human lives from 2043 in 1998 to below 100 in subsequent years, but also the most important factor is severity of heat waves causing human discomfort levels were not so much high in the other years of study as was in 1998 over Orissa and 2003 over Andhra Pradesh.

4. Role of various Ocean-Atmospheric features

4.1. *Inter-relationship among monthly temperature over the region*

Since atmosphere has got an unique memory for persistence of particular meteorological pattern whether warming or cooling with the start of the season much before, so we have prepared a correlation matrix by calculating correlations between different month's maximum and minimum temperature over the east coast at different lag period and listed their correlation coefficients (CC) values along with period of data used in Table 3. This may help us to estimate how the temperature of a succeeding month over a region will be affected based upon the condition of temperature of preceding month over the same region. It shows summer maximum temperature over east coast in March had highest but same CC of 0.4 with subsequent April and May followed by CC of that in April with May is 0.3 while June temperature had very weak CC for other months. But, minimum temperatures of all months of summer are strongly correlated compared to their maximum temperature with highest CC in case peak summer of 0.5 existing between April with following month of May minimum temperature.

4.2. *Influence of Oceanic features*

Several studies, *e.g.*, De and Mukhopadhyay, 1998, Choudhury *et al*., (2000), Nicholls *et al*., (2005), Revadkar *et al*., (2009), etc. have already linked occurrences of high temperature over various region of Asia due to anomalous high temperature of Pacific. An attempt has been made in the present study to find whether SST over various regions of Pacific and Bay of Bengal have been playing any role in controlling variation of monthly temperature over east coast of India. We have considered time series of SST over South Bay of Bengal (5º N - 14º N, 79º E - 96º E) and North Bay of Bengal (14º N - 22º N, 84.5º E - 92º E) and Nino 3.4 for Pacific ocean and maximum and minimum temperature of East coast for different months of the year for the period 1948-2003 to compute their CC as listed in Table 4. It indicates that the CC between maximum temperature of east coast

TABLE 4

Correlation coefficient between SST of various Ocean basin with maximum and minimum temperature of east coast of India for concurrent months

Ocean Basin/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Maximum temperature												
North Bay*	0.5	0.4		0.4	0.4	0.6	0.6	0.4	0.4	0.4	0.7	0.6
South Bay*	0.6	0.5	0.3	0.5	0.4	0.4	0.6	0.4	0.6	0.5	0.7	0.7
Nino 3.4	0.3						0.5	0.4	0.6			0.4
(b) Minimum temperature												
North Bay*	0.7	0.4	0.4	0.5	0.5	0.6	0.6	0.5	0.3	0.4	0.8	0.7
South Bay*	0.6	0.8	0.6	0.3	0.3	0.5	0.6	0.5	0.5	0.3	0.6	0.6
Nino 3.4	0.3	0.4	0.3				0.4		0.4		0.4	0.5

Areas considered* - SST over South Bay of Bengal (5° N - 14° N, 79° E - 96° E) SST over North Bay of Bengal (14° N - 22° N, 84.5° E - 92° E)

TABLE 5

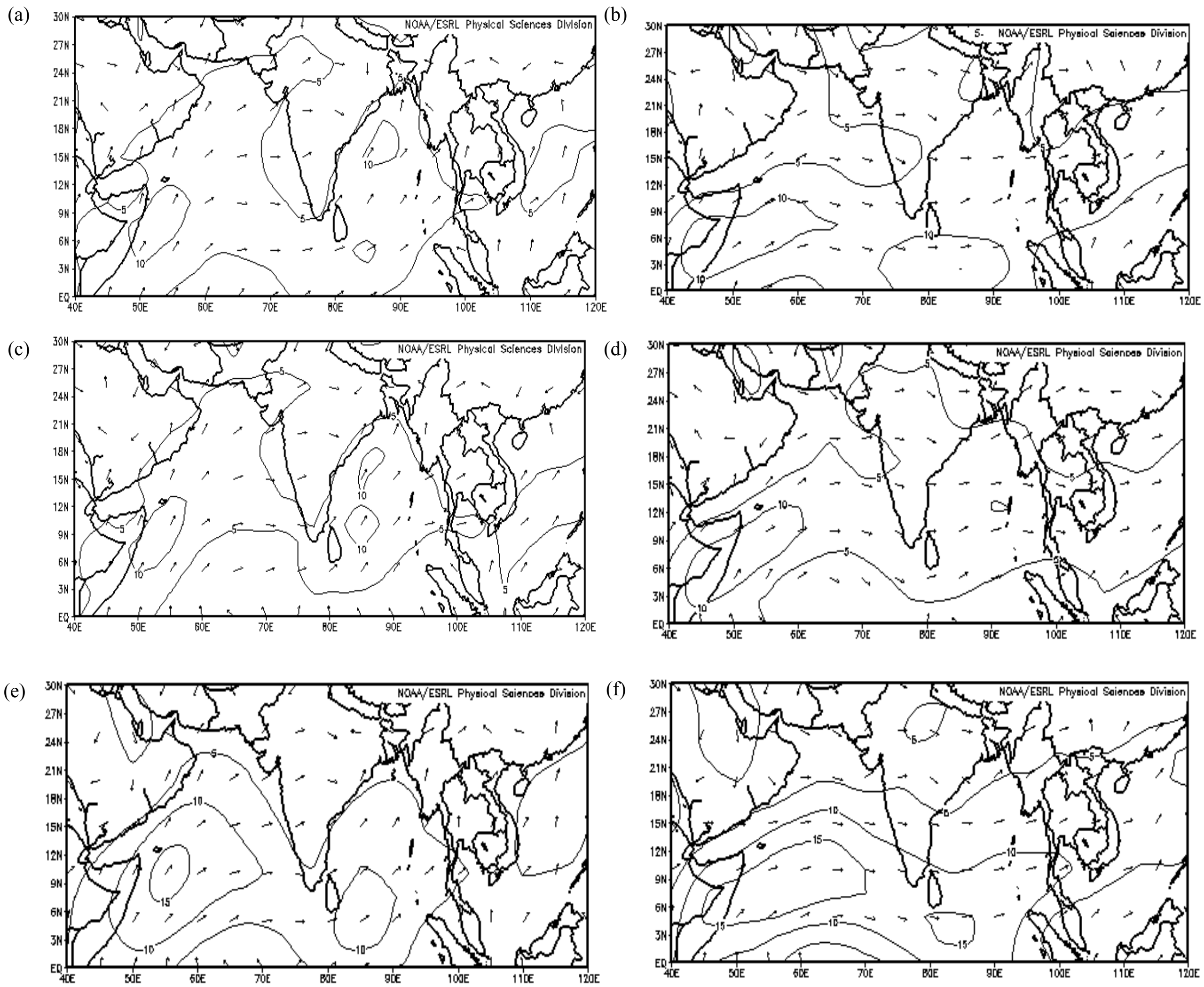
Possible Ocean predictors of maximum and minimum temperature for east coast of India (Lag CC are between SST of preceding month given as first months in first row of each column with maximum or minimum temperature of east coast for a following months given as 2nd month)

Ocean Basin	Maximum temperature				Minimum temperature			
	Feb-Mar	Mar-Apr	Apr-May	May-Jun	Feb-Mar	Mar-Apr	Apr-May	May-Jun
North Bay			0.3		0.4		0.4	0.4
South Bay	0.4	0.5			0.6	0.4		0.4
Nino 3.4				0.3	0.3			0.4

TABLE 6

Occurrence of severe heat wave cases over east coast of India due to sea breeze cut off as cyclonic storms recurved to northeastwards or wind discontinuity shifting eastwards to Bay (1970-2005)

Years	Period	Affected areas east coast	Dates of Cyclonic Storm(CS)/Wind Discontinuity(WDC)
1972	19-22 May	Gangetic West Bengal(GWB), Coastal Andhra Pradesh (CAP)	17-22 May (WDC)
1976	23-26 May	North CAP	17-27 May (WDC)
2005	8-22 June	Orissa, part of Andhra Pradesh	9-14 June (WDC) Late Onset of Monsoon by 13 Days
1970	13-16 May	GWB, CAP	2-6 May (CS)
1978	18-22 May	CAP	14-17 May (CS)
1980	20-27 May	South CAP, North Tamil Nadu	15-19 May (CS)
1994	6-13 May	West Bengal, Orissa, CAP, Costal Tamil Nadu	29 April – 2 May (CS)
1997	20-22 May	CAP, Orissa	12-20 May (CS)
1998	18 May – 6 Jun	Orissa	17-20 May (CS), Late onset of monsoon by 4 day to the normal date
2003	18 May- 6 Jun	Orissa, Andhra Pradesh	10-19 May (CS) Late onset of monsoon by 7-14 days to normal date of onset



Figs. 11. (a-f). Composite low level circulation pattern over east coast of India which highly favors the raise of the maximum temperature during the summer of 1998, 2003 and 2005 (a) 1000 hPa (27 May - 10 June 1998), (b) 850 hPa (27 May - 10 June 1998), (c) 1000 hPa (26 May - 18 June 2003), (d) 850 hPa (26 May - 18 June 2003), (e) 1000 hPa (8 - 24 June 2005) and (f) 850 hPa (8 - 24 June 2005)

and SST of North Bay of Bengal are higher during post monsoon months through winter and also during April to July. The CC is found to be least in the month of March. It is also seen from the CC Table 6 that even though equatorial Pacific ocean SST also influences both the minimum and maximum temperature of east coast of India, the CC is found to be of low values in almost all the months compared to CC with SST of north or south Bay of Bengal. In view of CC with north Bay are higher during main heat wave months of May and June (0.4 and 0.6) among the all months of summer compared to CC with other oceanic sectors, we have plotted anomalies of SST prevailed over North Bay for the period 1948-2005 in Fig. 10 for these months which also confirms warmest SST anomalies were prevailed in 1998 when Orissa was affected most by abnormal heat waves. Since SST affects concurrently both maximum and min. temperatures of East coast significantly, their lag CC is computed and given in Table 5 to find if SST over any of these region of the Globe have potential to act as precursor of the warm temperature anomalies over the region. It shows CC between SST of various regions and the east coast temperature fluctuates significantly with the progress of the month. SST of south Bay has higher lag CC with both maximum and minimum temperature of east Coast of India compared to any other Ocean Basin we have considered during most of the months with values between 0.4 to 0.6 except the lag CCs of 0.4 of SST of Pacific Ocean (Nino 3.4) for the month of May with that of June. The most dominant relationship among all CCs in the table are SST of February of same year over South Bay of Bengal with minimum temperature of the region in March with values as 0.6 followed by SST of same area in March with max temp of April.

4.3. *Influence of regional long time persistence of a particular synoptic flow pattern and Cyclonic Storm formation over Bay of Bengal*

As the summer temperature set in over Central and adjoining East coast of India, the main climatological low level flow pattern which develops over eastern Indian region in summer days is the development and persistence of a north-south wind discontinuity over the region which mostly runs from Bihar to southern tip of Peninsular parallel to the east coast of India with prevailing of continental dry westerly winds at its west and moist easterly/south-easterly at east from the Sea. During some days of the year in summer, low level dry continental westerly wind is so much stronger that it causes in shifting of this north-south trough or wind discontinuity temporarily to Far East well to the Sea. As a result, it lies parallel to the East coast at east over the Coast or Sea well outside of the East coast of India. Sea breezes over coastal stations are also totally cut off during such period as westerly are stronger. Thus, severe heat waves from far neighboring states at its west affect directly these parts of East coast. To find the evidence whether such peculiar synoptic circulation pattern was prevailed at very lower levels during severe heat wave spells of May-June 1998 over Orissa, May-June 2003 over Andhra Pradesh-Orissa and again in June 2005 over many parts of northeast coast of India including Orissa, we have analysed composite wind circulation pattern over the region in Figs. 11(a-f) using NCEP/NCAR daily re-analysed data for the same period. Fig. 11(a) shows presence of north-south trough/wind-discontinuity during unusual heat wave period of May-June 1998 at 1000 hPa, at nearest level of sea level at just over Orissa coast with prevailing westerlyto northwesterly winds at its east and north superimposed by the trough moving more towards sea side at 850 hPa in Fig. 11(b). Thus, confirming cut off of winds flowing from Sea but persistence winds from adjoining land and thus favouring onset and intensification heat waves over the region during the period. One may find almost similar dominant synoptic flow persisting over the coastal region in these levels in Figs. 11 (c-e) during latter two cases. While heat wave over Orissa and Andhra Pradesh during summer of 1998 and 2003 as discussed were severe due to cut off of winds flowing from Sea, the casue of in remaining parts of east coast, *e.g.*, West Bengal and Bihar, to get severe heat wave during other summers may be due to other meteorological reasons and land-Sea contrast and geographical reasons which have not been studied here. In June 2005, such peculiar synoptic circulation pattern together with late arrival of monsoon has been further worsened the temperature scenario over the region due to which severe heat wave conditions over the whole region continued till 21 June.

In Table 6, we have documented similar information about occurrence of various other severe heat wave cases in different years, approximate spell period over different states of east coast of India along with the relevant synoptic situation for the period 1970-2005. It shows besides north south wind-discontinuity associated with 3 cases of heat prevailed over part of the region, formation movement and intensification of cyclonic storms over Bay Bengal have been responsible for seven cases of prevailing of severe heat waves over some sub-divisions of east coast of India. In monthly time scale, highest number intense cyclonic storms form in November over Bay of Bengal followed by May. In fact, out of all intense cyclonic storms formed in May over Bay of Bengal, most re-curved to the east or northeast towards to Bangaldesh-Myanmar-Arakan coasts rather than crossing East coast of India. The formation of the intense system changes pressure distribution at lower levels causing the wind discontinuity/north-south (N-S) trough to move to the Sea to merge with such stronger system which even also were observed in the absence of strong continental westerly. As a result, Sea breeze over coastal station remains cut off continuously for days till the system recurved and moved to Bangladesh-Myanmar-Arakan coasts and temperature continues to rise resulting prevailing of severe heat waves over the region. The above features of prevalence of severe heat wave conditions over east coast of India due to recurving Cyclonic storms to northeastwards resulting in shifting of Wind discontinuity eastwards to Bay of Bengal were also observed by authors for the given period as in Table 6 for most of the cases using daily surface and low level weather charts as observed in the period 1970-2005. Observations shows period of prevailing of these severe heat waves are very much dependent upon respective temperature pattern at west and hence in case cyclonic storm formed and re-curved simultaneously at a time when already high temperature prevailing at west of the east coast then Orissa, some part of coastal region will be affected by persistent rise of temp and thus heat waves mainly because cyclone will be helping strengthening of westerly winds towards its locations. However in case the western region has low temperature, then development of heat wave may takes some time lag after the storm dissipated as westerly still persists after some days of dissipation of the storm over the Sea or its re-curvature. Tracks of all re-curving cyclonic storm which have been

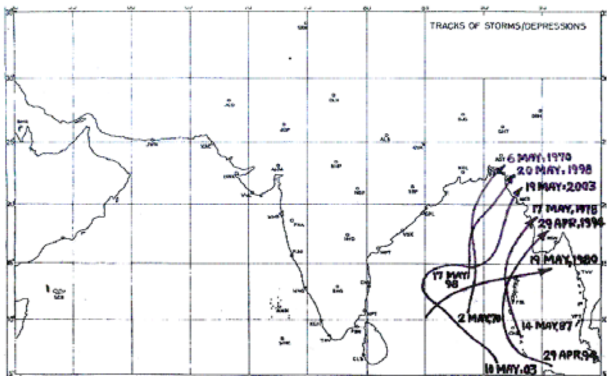


Fig. 12. Influence of Re-curving cyclonic storm of Bay which highly favors for raise of the max. temperature along east coast of India (1970-2005)

responsible for heat waves in Table 6 over east coast of India are shown in Fig. 12. Unusual severe heat waves which occurred recently in 18 May-6 June, 1998 and claimed 2042 lives over the state of Orissa are associated with the cyclonic storm of 17-20 May, 1998 followed by late arrival of monsoon by 4 days over the region. Also, another unusual severe heat wave spells which occurred during 18 May - 6 June, 2003 and claimed 3054 lives over the Andhra Pradesh is coincided with the another re-curved cyclonic storm of 10-19 May, 2003 followed by late arrival of monsoon by 7-14 days over the region. In another case of May 2007, Coastal Andhra Pradesh experienced heat waves when a cyclonic storm formed over Bay of Bengal and re-curved to Bangladesh. Therefore while tracking and issuing de-warnings to disaster managers along the east coast of India, in the event of storm in Bay of Bengal is expected to re-curve and move away from the coast, heat wave warnings may be issued to all concerned and general public to rescue and mitigate people against damage to life and health.

5. Conclusions

The present study brings following important conclusions:

(*i*) Many stations of Orissa have been repeatedly recording unusual high temperatures in recent years. Most of these unusual high temperatures over Orissa were observed in May - June of 1998, 2003 & 2005 with highest in 1998 followed by 2005. Daily discomfort indices, general heat index, Thom's discomfort and Webb's comfort indices for Bhubaneswar, Jharsuguda and Ongole stations revealed that discomfort levels were high during 1998 compared to other years in respect of Orissa, particularly for coastal stations, may be due to high moisture levels, while the indices were further high for the year 2003 in respect of Ongole of Andhra Pradesh state.

(*ii*) Year-wise analysis of global oceanic conditions indicates prevailing of unusual high SST over Bay of Bengal in 1998 and Equatorial Pacific Ocean in 1997-1998. Further analysis of the oceanic data shows strong CC between maximum and minimum temperature experienced in different summer months over the region of study with SST anomalies over various sectors of Bay of Bengal and Equatorial Pacific both at concurrent and lag time scale. Inter-monthly cross CC matrix between maximum temperature of east coast of India of a month of an year with various following months of that year shows presents of high CC between them for some months due to which one can use them for getting idea about likely temperature conditions during subsequent summer months over the same region.

(*iii*) Synoptic Study also shows onset/persistence/abating of severe heat wave cases (*e.g.*, as in 1998, 2003 and 2005) can be forecasted with monitoring the movement of North-South wind-discontinuity/trough or track of cyclonic storms over Bay of Bengal. Heat waves starts setting up when the former system moves eastwards from the land to the sea or the latter system persists or recurves to east or northeastwards away from the East coast. This is because both the synoptic conditions not only help in setting up the strong low-level westerly wind over the region resulting advection of very warm air/heat waves from west but also inhibit the setting of sea breezes for few days over coastal stations leading to rise of both maximum and minimum temperature over the coasts. Therefore while tracking and issuing de-warnings to disaster managers along the east coast of India, in the event of storm in Bay of Bengal is expected to recurve and move away from the coast, heat wave warnings may be issued to all concerned and general public to rescue and mitigate people against damage to life and health.

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