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ORIGINAL PAPER

Heat wave over India during summer 2015: an assessment of real time extended range forecast

D. R. Pattanaik[1] · M. Mohapatra[1] · A. K. Srivastava[2] · Arun Kumar[3]

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Abstract Hot winds are the marked feature of summer season in India during late spring preceding the climatological onset of the monsoon season in June. Some years the conditions becomes very vulnerable with the maximum temperature (T_{max}) exceeding 45 °C for many days over parts of north-western, eastern coastal states of India and Indo-Gangetic plain. During summer of 2015 (late May to early June) eastern coastal states, central and northwestern parts of India experienced severe heat wave conditions leading to loss of thousands of human life in extreme high temperature conditions. It is not only the loss of human life but also the animals and birds were very vulnerable to this extreme heat wave conditions. In this study, an attempt is made to assess the performance of real time extended range forecast (forecast up to 3 weeks) of this scorching T_{max} based on the NCEP's Climate Forecast System (CFS) latest version coupled model (CFSv2). The heat wave condition was very severe during the week from 22 to 28 May with subsequent week from 29 May to 4 June also witnessed high T_{max} over many parts of central India including eastern coastal states of India. The 8 ensemble members of operational CFSv2 model are used once in a week to prepare the weekly bias corrected deterministic (ensemble mean) T_{max} forecast for 3 weeks valid from Friday to Thursday coinciding with the heat wave periods of 2015. Using the 8 ensemble members separately and the CFSv2 corresponding hindcast climatology the probability of above and below normal T_{max} is also prepared for the same 3 weeks. The real time deterministic and probabilistic forecasts did indicate impending heat wave over many parts of India during late May and early June of 2015 associated with strong northwesterly wind over main land mass of India, delaying the sea breeze, leading to heat waves over eastern coastal regions of India. Thus, the capability of coupled model in providing early warning of such killer heat wave can be very useful to the disaster managers to take appropriate actions to minimize the loss of life and property due to such high T_{max}.

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✉ D. R. Pattanaik
pattanaik_dr@yahoo.co.in

[1] India Meteorological Department, New Delhi, India

[2] India Meteorological Department, Jaipur, India

[3] NOAA/NWS/NCEP, Climate Prediction Centre, College Park, MD, USA

1 Introduction

Hot winds known as "loo" are the marked feature of summer in northern India. Extremely hot weather is common in India during late spring preceding the climatological onset of the monsoon season in June. The climatology pattern (Pattanaik and Mukhopadhyay 2012) of maximum temperature (T_{max}) in April over India indicates a small pocket of T_{max} exceeding 40 °C over central India and by May, the T_{max} increases and exceeds 40 °C over large parts of India covering north-western parts of the country extending towards the Indo-Gangetic plain, whereas, in June, though the monsoon currents cool the southern parts of the country, the T_{max} remains more than 40 °C in north-western parts of the country. During summer, most areas of India experience episodes of heat waves almost during every year causing sunstroke, dehydration and death. As reported the death tolls that were recorded over an entire summer some 10 years ago over India now routinely occur

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in just 1 week (Larsen 2003). It is not only the loss of life associated with Heat Wave (HW) is important but also the continuous higher temperatures during critical growth stages of rabi crops reduces the crop yields considerably. Change in the characteristics of temperature extremes of different intensities and duration has significant impact on sectors like agriculture and health. Heat wave can kill birds in the poultry firm. It is estimated that about 20 lakhs birds died in May and June 2003 due to severe heat wave with an estimated loss of 27 crores in Andhra Pradesh (Rao 2012). Heat wave can reduce a milk yield by 10–30 % in first lactation and 5–20 % in second and third lactation periods in cattle and buffaloes it also effect the growth, puberty and maturity of crossbreed of cows and buffaloes. With respect to the fisheries, mortality of fish lings in shallow water ponds and during 'HW' conditions fish moves into the deeper layers thereby reduces fish catch in the water bodies.

A recent study (Perkins et al. 2012), based on the analysis of multiple indices derived from the latest HadGHCND daily T_{max}, minimum temperature (T_{min}) and average temperature for the period 1950–2011, found increasing global trends in the intensity, frequency and duration in the observed summer time heat waves and annually calculated warm spells. The changes in the frequency or intensity of these extreme events have profound impact on human society and the natural environment (Parker et al. 1994; Easterling et al. 2000; Meehl and Tebaldi 2004; Coumou and Rahmstorf 2012). A recent report by IPCC (2007) indicates increasing trend of the mean annual global (land + ocean) surface air temperature by about 0.74 °C during last 100 years (1906–2005) with land temperature increasing at much higher rate than this. This report also indicates significant increasing trend of 'HW' over different parts of the globe. Kothawale and Rupa Kumar (2005) indicate that mean maximum temperature (T_{max}) increased over India during 1901–1987 and there is a significant warming trend in annual mean temperature over India which appears to be mostly due to increasing T_{max} during the period 1901–2003. Dash and Mamgain (2011) using the gridded temperature data over India during the period from 1969 to 2005 also found warming trends in large parts of India associated with increasing number of warm days. Increasing trend of global surface air temperature is also reported over India with the linear trend per 100 years in the annual mean land surface air temperature anomalies averaged over India was 0.62 °C (IMD 2015a).

During the individual year the HW over India mainly depends on many factors viz., sudden end to the pre-monsoon rain, delay in the onset of monsoon over the southern and eastern parts of the country and its further progress northward, intensity of heating of vast Asian land mass due to incoming solar radiation, the snow cover during previous winter etc. Again during some years, the Tropical Cyclone (TC) in the month of May, which forms over the north Indian Ocean can also modulates the timing of heat wave over the different parts of the country as it can delay the formation of sea breeze over the eastern coastal region of India and the Bay of Bengal just before the onset of monsoon. There have been some earlier studies of climatological and other aspects of HW over India by Raghvan (1966) and Bedekar et al. (1974). Recently, many such studies highlighting different aspects of HW over India in recent times have been carried out (Kalsi and Pareek 2001; Mahapatra et al. 2001; De et al. 2005; Bhadram et al. 2005; Pai et al. 2013; Pattanaik et al. 2013a etc.). As shown by Pai et al. (2013) the spatial variation of seasonal climatology of 'HW' days experienced over the country expressed as average 'HW' days per season during last 50 years from 1961 to 2010 during March to July. They have shown that except over northeast India and large parts of Peninsula (South of $\sim$21°N and west of 80°E), most areas of the country have experienced on an average $\geq$2 HW days. The global climate anomalies have indicated that 1998 was the warmest year in last century (Jones and Briffa 1992) with more than 1000 people have died over India due to scorching temperatures over Odisha, Coastal Andhra Pradesh, Rajasthan and Tamil Nadu during May/June. Similarly, in May 2003 the heat wave claimed over 1600 lives throughout the country with some 1200 individuals died in the state of Andhra Pradesh alone. Like in 2003, during 2005 also India was under the grip of severe heat wave towards the third week of June and about 200 people died in the eastern parts of the country covering the state of Odisha and neighbourhood (Bhadram et al. 2005). As shown by Pattanaik and Hatwar (2006) the 'HW' during the middle of June in 2005 was due to such stagnation in monsoon progress over the region. In its detailed study of the deadly 2010 heat wave in Ahmedabad, the Indian Institute of Pubic Heath (IIPH) found that the number of deaths caused by heat strokes were highly under-reported and that the most vulnerable populations were construction workers and children, the elderly and women from slum settlements.

In May 2015, India was also severely impacted by a severe HW with casualties of more than 2500 people in many meteorological subdivisions over central, eastern coastal regions, north and northwestern parts of the country (Fig. 1). The Loo, a dry wind originating from Pakistan and northwest India, has contributed to increasing the temperature in many meteorological subdivisions of India as indicated in Fig. 1. The twenty met-subdivisions affected by HW are categorized into south-western region (Sector A), south-eastern region (Sector B), north-western region (Sector C) and north-eastern regions (Sector D) as

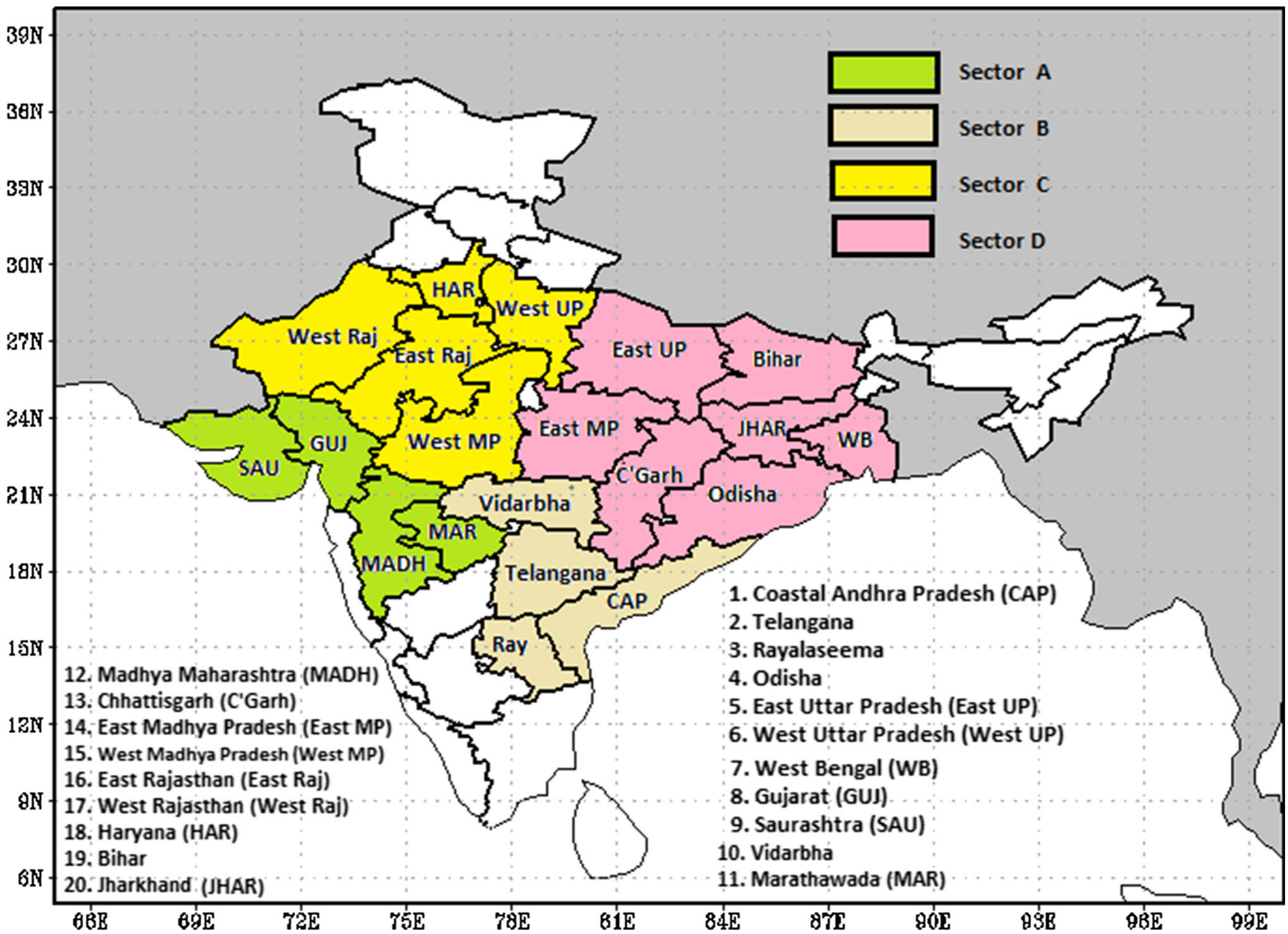


Fig. 1 Meteorological sub-divisions of India affected by heat wave during summer 2015

demarcated in Fig. 1. The South Indian states of Andhra Pradesh covering Coastal Andhra Pradesh (CAP) and the neighboring Telangana, where more than 1735 and 585 people died, respectively, were the areas most affected by the heat wave (Fig. 1). Other casualties were from the eastern states of West Bengal and Odisha, Maharashtra, Uttar Pradesh, Gujarat etc covering about twenty meteorological sub-divisions of India. The high demand for electricity to power air conditioning led to power outages in some cities. World Meteorological Organization has described 2015 as one of the warmest year on record with strong El-Nino. The sudden end of pre-monsoon rain showers in 2015, as indicated by 33 % less rainfall during the week from 20 to 27 May, 2015 over India has also contributed to the heat waves. Additionally, the monsoon onset over southern tip of India occurred on 5th June in 2015 (a delay of 4 days) against the normal onset of 1st June (http://www.imd.gov.in), which in conjunction with the El Niño effect, combined to create the record high temperatures.

India Meteorological Department (IMD) has been issuing experimental extended range forecast (ERF) since 2009 using available outputs from statistical as well as dynamical models from various centres in India and abroad (Pattanaik, 2014a). The ERF in the tropics are one of the most challenging tasks in atmospheric sciences. It fills the gap between medium-range weather forecasting and seasonal forecasting, is certainly a difficult time range for weather forecasting, since the timescale is sufficiently long so that much of the memory of the atmospheric initial conditions is lost. The latest generation coupled models are found to be very useful in providing skillful guidance on extended range forecast. As shown by Krishnan et al. (2010) a fully coupled model will be able to better capture the intra-seasonal and interannual variability of tropical weather and hence can be useful to predict the heat wave in the extended range time scale. The medium to extended range forecast (2–4 weeks) of such extreme high temperature has a wide range of applications in agriculture, energy, health, insurance, power, financial sector etc. The prediction of heat waves with significant accuracy can save lives and prevent damage to the property from these dangerous weather events. The recent operational coupled modeling system from NCEP (CFSv2) has shown improvement in the prediction of Madden Julian Oscillation (Saha et al. 2014). The model has also shown improved skill of prediction of active-break cycle of monsoon over the Indian region (Tyagi and Pattanaik 2012; Sahai et al. 2013; Pattanaik et al. 2013b; Pattanaik and Kumar 2014; Pattanaik 2014b). Now it is to be tested how this present generation coupled model can predict the HW, which is now considered to be a deadly disaster like cyclones and floods. In case of the natural disasters like cyclones or floods, India is improving its abilities to predict and prepare for them. With respect to heat waves, there has to be proper coordination between the IMD's forecasts and the state's disaster management authority affected by HW. Once the heat waves are given equal importance like the other hydro meteorological disasters, the coordination could be improved to prevent the loss of human lives. Thus, the objective of this study is to see whether the improvement in CFSv2 can provide improved extended range forecasting of HW condition over India like that of 2015 so that it can be used for operational guidance.

2 Observed maximum temperature (T_{max}) data and model forecasts used

2.1 A brief discussion on observed T_{max} data

The station level daily T_{max} data during the month of May and June 2015 is obtained from IMD observational network to study the observational feature of heat wave of 2015. The daily gridded ($0.5^0 \times 0.5^0$) T_{max} during the period from 1981 to 2010 is used for the preparation of observed climatology. These gridded data sets are obtained from the National Climate Center (NCC), India Meteorological Department, Pune (Srivastava et al. 2008). For the 2015 HW case the daily T_{max} at the same grid resolution is used to prepare the observed T_{max} anomaly.

2.2 A brief discussion on dynamical model (CFSv2) outputs used

The well known coupled models viz., the National Centre for Environmental Prediction's (NCEP's) Climate Forecast System version 2 (CFSv2) is used in this case of heat wave forecasting. The CFSv2 was made operational at NCEP in March 2011, which is upgraded version of nearly all aspects of the data assimilation and forecast model components of the previous version CFSv1 (Saha et al. 2014). The atmospheric model of CFSv2 has a spectral triangular truncation of 126 waves (T126) in the horizontal (equivalent to nearly a 100 km grid resolution) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. The oceanic component is the GFDL Modular Ocean Model V.4 (MOM4). The domain and resolution of MOM4 changed from a quasi-global domain (75°S to 65°N) to a fully global domain. Increasing resolution from 1° × 1° (1/3° within 10° of the equator) to ½° × ½° (1/4° within 10° of the equator). The vertical grid of 40 Z-levels with variable resolution (23 levels in the top 230 m) is retained. The sea-ice model in CFSv2 is an interactive three layer (two layers of sea-ice and one layer of snow) sea ice model with five categories of sea ice thickness representing different type of sea ice. The NOAH land surface model (Ek et al. 2003) used in CFSv2 was first implemented in the GFS for operational medium range weather forecast (Mitchell et al. 2005) and then in the CFSR (Saha et al. 2010). Within CFSv2, NOAH is employed in both the coupled land–atmosphere–ocean model to provide land-surface prediction of surface fluxes (surface boundary conditions), and in the Global Land Data Assimilation System (GLDAS) to provide the land surface analysis and evolving land states. NOAH has four soil layers (10, 30, 60, 100 cm) with frozen soil physics included. The CFSv2/NOAH vegetation parameters and rooting depths were refined to increase evapo-transpiration, which, along with a change to the radiation scheme (RRTM in GFS and CFSR, and now McICA in CFSv2), helped to improve the predicted 2 m air temperature over land. Also to accommodate a change in soil moisture climatology from GFS to CFSv2, NOAH land surface runoff parameters were nominally adjusted to favorably increase the predicted runoff. A recent study by Pattanaik and Kumar (2014) have also demonstrated better extended range forecast skill in CFSv2 model compared to that of CFSv1 model.

3 Methodology of deterministic and probability forecasts for heat wave

3.1 Real time bias corrected deterministic forecast

The CFSv2 model forecasts prepared based on the operational run has systematic bias (Saha et al. 2014). To prepare the bias free forecast there is a need to remove the bias from the model forecast. Bias correction methods are widely used to improve the prediction skill of forecasts ranging at different time scales. A simple mean correction method adopted by Richardson (2001) is being used frequently in reducing the biases in operational weather forecasts.

The quantity "Mean Bias" mainly explain how does the average forecast magnitude compare to the average observed magnitude and it does not measure the magnitude of the errors and also does not measure the correspondence between forecasts and observations. It is defined as:

$$\left(\sum_{i=1}^{n} F_i - \sum_{i=1}^{n} O_i\right)$$

Positive (negative) value of "mean bias" indicates the average tendency of the model to over (under) predict. To prepare the bias corrected T_{max} forecast for the HW of 2015 the mean bias is first calculated based on the hindcasts climatology of the CFSv2 model and the observed climatology of T_{max}. Thus, the real time CFSv2 forecasts for 4 weeks based on 8 ensembles members of every Wednesday and Thursday is prepared valid for the period from subsequent Friday to Thursday for 4 weeks. However, as the forecasts will have biases the bias free deterministic (ensemble mean) forecast is prepared and finally the bias corrected deterministic forecast is prepared as indicated in the schematic diagram shown in Fig. 2. The ensemble mean real time forecast for 4 weeks is corrected using the model bias and the bias corrected forecast is prepared for the 2015 heat wave with the weekly forecast valid from every Friday to Thursday coinciding with days 2–8, days 9–15, days 16–22, and days 23–29 (week-1, week-2, week-3 and week-4, hereafter, respectively), which is prepared on every Thursday.

3.2 Real time probability forecast

Taking advantage of a multi-ensemble member framework it will be useful to use the same in the probability formulation, where the each ensemble member may give information on the possible outcomes. Such information will be better as the spread increases. As emphasized by Palmer et al. (2000) the chaotic nature of forecasts associated with the spread of the ensembles requiring the need for a forecast in probabilistic sense. In view of the uncertainty of forecasts, there is also a need to see the probability forecast based on each member separately (Palmer 1994). The basic principle of probability forecast is the different ensemble members are associated with slightly different initial conditions. The ensemble members are having spread from one member to other. Thus, if the ensemble members have large standard deviation, which indicates it has large spread or the ensemble members deviates from one another (good for the probability forecast).

There are different methods of generating probability forecasts. Using the ensemble members separately the forecast probability of above normal and below normal T_{max} is calculated at each grid point using the climatological information of CFSv2 hindcast T_{max} over the region. The CFSv2 hindcast is 45 days retrospective forecasts for 12 years (1999–2010). In case of data of CFSv2 model, the 45 days hindcast runs from every 0000 UTC with 4 ensemble members per day over the 12 years period (1999–2010) is considered as hindcast climatology. Hence, by choosing 2 days of atmospheric initial conditions of Wednesday−Thursday, a total of 8 ensemble members on real time basis are used to generate the probability forecasts for subsequent 4 weeks (schematic diagram is shown in Fig. 2).

4 Observed Heat Wave of 2015

Every year India experiences severe heat waves in summer, but in the year 2015, casualties were abnormally high. Most of the deaths were concentrated in Andhra Pradesh,

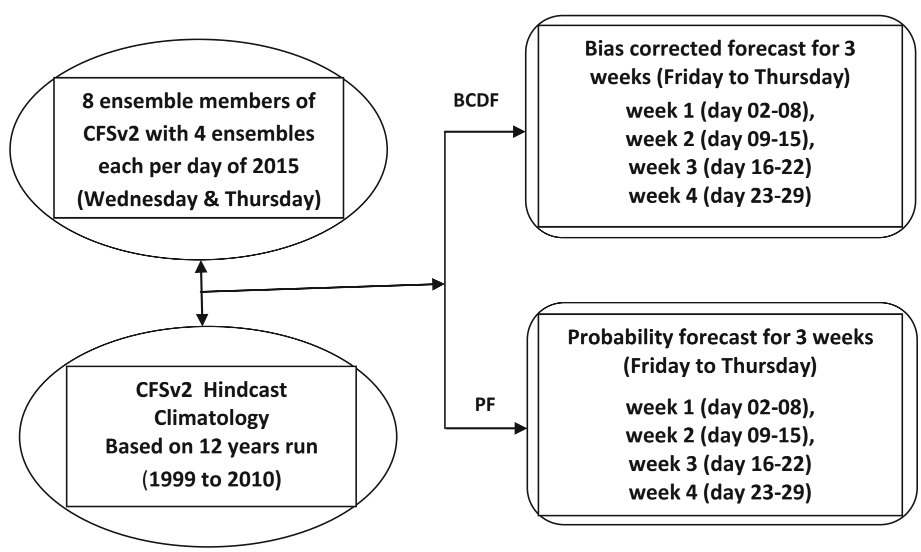


Fig. 2 Schematic diagram indicating how the real-time bias corrected deterministic forecasts (BCDF) and probability forecasts (PF) are prepared for the extreme temperature of 2015

Telangana, Odisha, West Bengal, Maharashtra, Haryana, Punjab, Uttar Pradesh, and many more regions of India (Fig. 1). In the recent past, many years like 1995, 1998, 2003, 2005, 2010, 2011, 2012, and 2013 have experienced heat wave with several hundreds of death. However, with over 2500 deaths, the heat wave has proven to be the most deadly since 1979. It is not only the loss of human life but also the animals and birds were very vulnerable to this extreme heat. It is reported that by 3 June, 50 lakh (5 million) chicken were killed by the heat wave across Telangana within a span of 2 weeks, causing the price of eggs and chickens to rise throughout the state as well as in the neighbouring Andhra Pradesh.

To analyse the observe T_{max} pattern for the month of May, 2015 it is found that the observed T_{max} was above normal over most parts of the country except for some parts of extreme south peninsula and parts of extreme north-eastern region (IMD 2015b). On weekly basis the actual weekly mean T_{max} from the first week of May to first week of June, 2015 is shown in Fig. 3a–f. As seen from Fig. 3a the T_{max} was above 40 °C over many parts of central India and northwest India during the first week of May with some parts of extreme northwest India and isolated pockets of central India reported T_{max} >42.5 °C. During subsequent week valid from 8 to 14 May (Fig. 3b) the T_{max} was just above the 40 °C over the parts of central India during the period, which gradually expanded both in southeast-northwest directions with T_{max} exceeding 42.5 °C reported over parts of central and northwest India during the subsequent week from 15 to 21 May, 2015 (Fig. 3c). The HW from northwest India further penetrated southeastward and during the week from 22 to 28 May, 2015 the maximum causality occurred over eastern coastal states of India with mean T_{max} exceeding 45 °C over many parts of eastern coastal states of India, central India and also the northwest India (Fig. 3d). Though the gridded T_{max} indicates temperature exceeding 45 °C over pockets of area, when plotted, the individual stations reported temperature exceeding 47 °C on many days during the period from 21 May to 31 May, 2015. With some showers occurring over eastern coastal regions during the first week of June the mean T_{max} falls below 40 °C during the week from 29 May to 04 June over the eastern coastal belts of India (Fig. 3e), however, the central parts of India stills indicate T_{max} exceeding 42.5 °C over many regions during the week. Although T_{max} over some coastal states of India was <40 °C during this week (29 May to 04 June, 2015) the shower towards end of the week caused the humidity to be much higher and the atmosphere was uncomfortable associated with compound effect of high temperature and high humidity. The high humidity along with high T_{max} leading to high heat index can cause more damages to human life (Pattanaik et al. 2013a). During the week from 5 to 11 June, 2015 (Fig. 3f), although the monsoon current could reduce the T_{max} at southern peninsula to <40 °C it remains more than 40 °C over parts of northwest and northern India. Thus, the highest temperature during the week from 22 to 28 May, 2015 happened to be the period when maximum death occurred followed by that of the subsequent week from 29 May to 04 June, 2015.

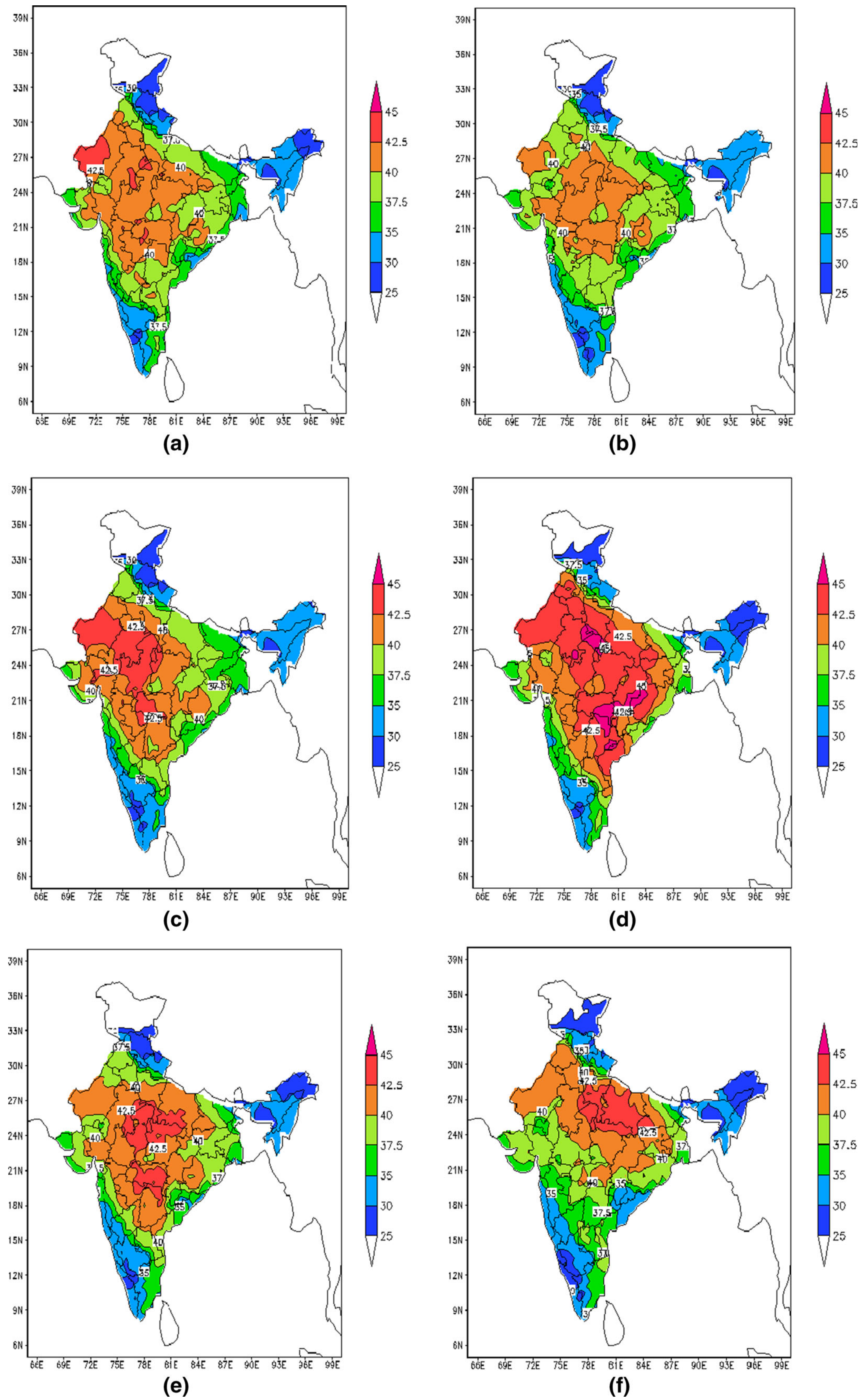
Fig. 3 Weekly mean observed maximum temperature (T_{max}) during ▶ May–June 2015. **a** 01–07 May, 2015 (Obs Tmax), **b** 08-14 May, 2015 (Obs Tmax), **c** 15–21 May, 2015 (Obs Tmax), **d** 22–28 May, 2015 (Obs Tmax), **e** 29 May to 04 Jun, 2015 (Obs Tmax) and **f** 05–11 Jun, 2015 (Obs Tmax)

The corresponding weekly T_{max} anomaly during the period from 22 to 28 May and 29 May to 04 June, 2015 is shown in Fig. 4a, b, respectively. As shown in Fig. 4a the T_{max} anomaly during the week from 22 to 28 May, 2015 indicates warming over most parts of India with meteorological subdivisions over sector-B and sector-D (as identified in Fig. 1) indicating warming exceeding 4 °C. On some individual days during the week, many stations reported T_{max} much higher than 45 °C with the anomaly of T_{max} exceeding 6 °C over a larger areas covering Coastal Andhra Pradesh, Odisha, Chhattisgarh, Telengana, Vidharbha, Chhattisgarh, Jharkhand, and east Madhya Pradesh meteorological sub-divisions (Fig. not shown). During the subsequent week from 29 May to 04 June, 2015 although the T_{max} cool downs over parts of southeastern coastal parts of India the T_{max} anomaly remained above normal over many met-subdivisions over sector-A and Sector-D with main heating belt is concentrated little northwestward of the region affected during the previous week (Fig. 4b). Although, the fall in temperature over some parts of eastern coastal region of India is reported during this period the T_{max} remained more than 40 °C over the coastal region. The high temperature exceeding 40 °C over the region of high humidity is very hazardous for the human health due to high heat index. On a representative day of 31st May, 2015 the T_{max} remained above 45 °C with anomaly exceeding 4 °C over many stations of central India (Fig. 4c, d).

5 CFSv2 model based heat wave forecast of 2015

5.1 Mean bias of the T_{max} in CFSv2 model during 22 May to 04 June, 2015

As discussed earlier the ensemble mean value based on the model forecast will have biases. This forecast bias occurs when there are consistent differences between actual outcomes and previously generated forecasts of those quantities; that is: forecasts may have a general tendency to be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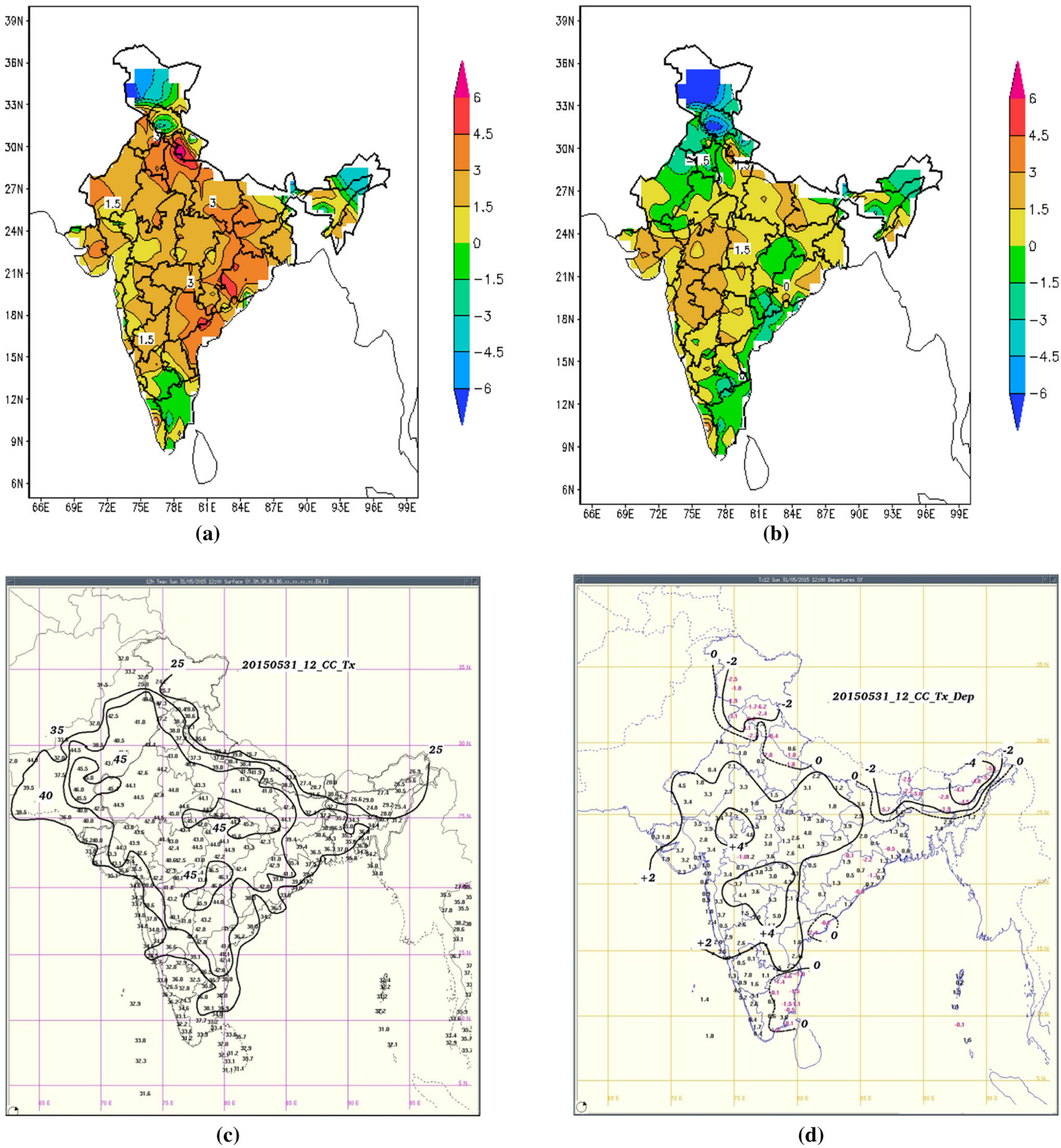


Fig. 4 **a**, **b** Observed maximum temperature ($T_{\max}$) anomaly for the week from 22 to 28 May, 2015 and 29 May to 04 June 2015 respectively. **c** and **d** Observed station level $T_{\max}$ and its anomaly in °C observed during 31 May, 2015.

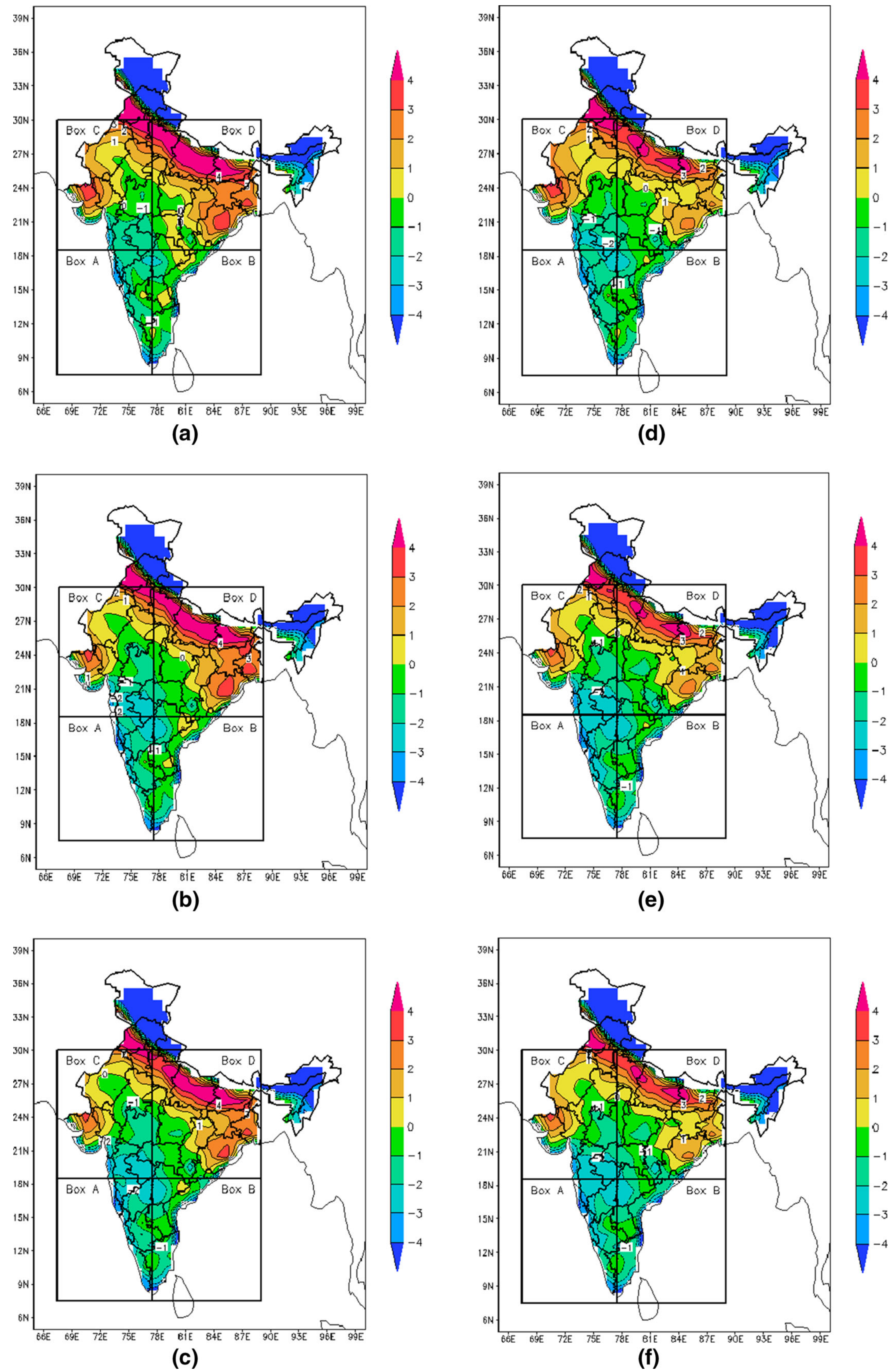
too high or too low. There is a need to remove the bias arises from the model forecast. The CFSv2 model climatology is represented here by retrospective forecasts (or ''hindcast''), made with 8-member ensemble, over the 12-year period from 1999 to 2010 as indicated in the schematic diagram (Fig. 2). To see the patterns of mean bias of the CFSv2 model with respect to the forecast of $T_{\max}$ the hindcast climatology (f_i) of the CFSv2 $T_{\max}$ is compared with the observed $T_{\max}$ climatology (o_i) values over the Indian region. The mean bias of $T_{\max}$ for the 2 weeks from 22 to 28 May and 29 May to 04 June with different lead time is calculated and is given in Fig. 5. The mean bias for the period from 22 to 28 May and 29 May to 04 June for week 1 (days 2–8), week 2 (days 9–15) and week 3 (days 16–22) forecasts show broadly identical patterns. As seen from Fig. 5 except the belts over Indo-Gangetic plain extending from northwest India to the state of Odisha the remaining regions of India (extreme north India, northeast India, central India and south peninsula) show mainly negative bias, thereby under predict the T_{max}. Thus, the only region which has positive bias or over predict is Gujarat and adjoining northwest India extending southeastwards along the Indo-Gangetic plain towards Odisha. It is also observed from Fig. 5 that the negative bias over southern peninsula, southern part of central India during week 1 forecast expanded to further north during week 2 and week 3 forecasts, thereby the area of negative bias gradually increases. It is not only the increase area of negative bias with decreasing lead time but also the magnitude of negative bias increases with decreasing lead time, where week 3 forecasts valid for the 2 weeks for 22–28 May and 29 May to 04 June have more cold bias compared to week 1 forecast valid for the same period over the central India and southern peninsula including southeastern coastal states of India (Fig. 5a). To quantify the mean bias over different regions of India the main land of India (except extreme north and north-east India) is divided into four regions (Fig. 5a–d) with south-west sector bounded by 67.5°E–77.5°E, 7.5°N–18.5°N represented as Box-A, south-east sector bounded by 77.5°E–89.0°E, 7.5°N–18.5°N represented as Box-B, north-west sector bounded by 67.5°E–77.5°E, 18.5°N–30.0°N represented as Box-C and north-east sector bounded by 77.5°E–89.0°E, 18.5°N–30.0°N represented as Box-D. The mean bias of T_{max} forecasts at different lead time for the weekly period from 22 to 28 May and 29 May to 04 June averaged over these boxes are shown in Fig. 6a, b, respectively. As seen from Figs. 6a, b the CFSv2 has cold bias by about 2–2.5 °C over the Box-A and box-B as indicated by negative mean bias of T_{max} in week 1, week 2 and week 3 forecasts. Over the northeastern sector (Box-D) the model indicates moderate warm bias of about 1 °C, particularly during the period from 22 to 28 May, which reduces to about 0–0.5 °C during the period from 29 May to 04 June. Over the northwestern sector (Box-C) it is very close to normal with slight warm bias in case of week 1 forecast and slight cold bias in case of week 2 and week 3 forecasts during both the weekly periods from 22 May to 04 June.

5.2 Bias corrected deterministic forecast of the heat wave event of 2015

As seen from Figs. 3, 4, many parts of eastern coastal states of India and some parts of central and northwest India experienced severe HW conditions on many days during the 2 weeks period from 22 May to 04 June. The performance of real time bias corrected T_{max} forecasts based on CFSv2 model is prepared for the 2 weeks periods from 22 May to 04 June, 2015 with different lead time and the results are discussed. As indicated the 8 members ensemble mean weekly T_{max} forecast based on the initial conditions of 6–7 May, 2015 (Wednesday and Thursday) valid for the period of 4 weeks from 08 to 14 May (week 1), 15–21 May (week 2), 22–28 May (week 3) and 29 May–04 June, 2015 (week4) are prepared (Fig. 2). Similarly with 8 ensemble members of 13–14 May, 20–21 May and 27–28 May each are also used to prepare the ensemble mean T_{max} forecast for the 2 weeks periods (22 May–04 June, 2015) to see the performance at different lead times.

In view of the mean bias in the CFSv2 model T_{max} forecast shown in Fig. 5 there is a need to remove this bias.Using the CFSv2 hindcast climatology the bias corrected forecast is prepared, which along with the forecast T_{max} anomaly valid for the 2 weeks period from 22 May to 04 June, 2015 at different lead times are shown in Figs. 7, 8, 9, 10 based on the ensembles of 06–07 May, 13–14 May, 20–21 May and 27–28 May, 2015, respectively. While analyzing the HW in CFSv2 model the real time forecasts up to week 3 is considered. The bias corrected CFSv2 week 3 forecast T_{max} based on the initial condition of 06–07 May, 2015 and valid for the most intense HW week of 22–28 May, 2015 is shown in Fig. 7a. This indicates large parts of India extending from northwest India to eastern coastal states indicating T_{max} >40 °C with eastern belts indicating more than 42.5 °C, which is almost matching with the observed T_{max} patterns valid for the same period as shown in Fig. 3d. The week 3 forecast T_{max} anomaly valid for the same period of 22–28 May, 2015 (Fig. 7b) also indicates a warming of about more than 4–5 °C over the most affected region of Andhra Pradesh, Telengana, Odisha, Chhattisgarh, Vidharbha and west Bengal. Thus, with a sufficient lead time of more than 2 weeks the forecast had indicated an impending high T_{max} during late May, 2015.

The bias corrected T_{max} forecast based on the initial condition of 13–14 May, 2015 and valid for week 2 forecast (22–28 May) and week 3 forecast (29 May–04 June) is shown in Fig. 8a, b, respectively. The corresponding T_{max} anomaly during this 2 weeks period is shown in Fig. 8c, d respectively. The bias corrected week 2 forecast of T_{max} valid for the period from 22 to 28 May, 2015 (Fig. 8a) clearly indicated high T_{max} >40 °C over most parts of India with some pockets exceeding 42.5 °C during the period valid for 22–28 May, 2015 like the observed T_{max} shown in Fig. 3d. Similarly, the week 3 forecasts valid for the period from 29 May–04 June, 2015 as shown in Fig. 8b also matches very closely with the observed T_{max} distribution during the week shown in Fig. 3e with observed higher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◀ **Fig. 5** Mean Bias of CFSv2 T_{max} forecast for 22–28 May and 29 May to 04 June with different lead times. **a** Mean Bias, week 1 forecast (22–28 May), **b** Mean Bias, week 2 forecast (22–28 May), **c** Mean Bias, week 3 forecast (22–28 May), **d** Mean Bias, week 1 forecast (29 May to 04 Jun), **e** Mean Bias, week 2 forecast (29 May to 04 Jun) and **f** Mean Bias, week 3 forecast (29 May to 04 Jun)

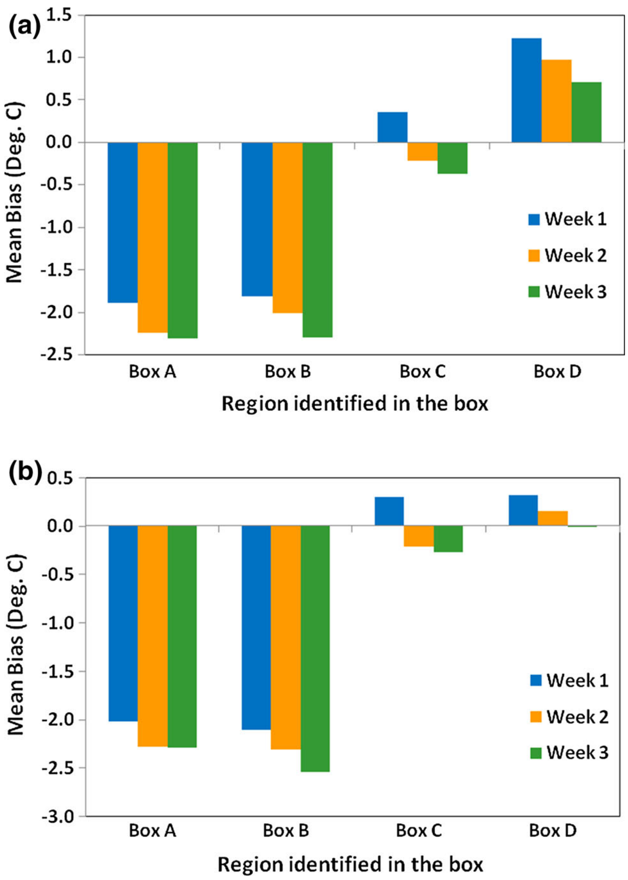


Fig. 6 **a** Mean Bias of CFSv2 T_{max} forecasts for 22–28 May at different lead time averaged over 4 boxes identified in Fig. 5. **b** Same as **a** but for the week 29 May to 04 June

T_{max} concentrated over central India and not over the eastern coastal India as during the period from 22 to 28 May 2015. The T_{max} anomaly during these 2 weeks periods indicate a warming of about 2–4 °C over eastern coastal region during the period from 22 to 28 May, 2015 (Fig. 8c) and over the region of central India during the period from 29 May–04 June, 2015 (Fig. 8d).

The bias corrected T_{max} forecast (week 1 and week 2) based on the initial condition of 20–21 May, 2015 and valid for the period from 22–28 May and 29 May–04 June, 2015 shown in Fig. 9a, b also indicated large scale warming with T_{max} exceeding 42.5 °C over many parts of northwest, central and eastern coastal belt of India. Similarly, the forecast T_{max} anomaly of more than 4 °C as indicated in Fig. 9c, d, respectively is sufficient to interpret the impending HW over the region during this period. Finally, the week 1 bias corrected T_{max} forecast based on the initial condition of 27–28 May, 2015 and valid for the period from 29 May to 04 June also indicated a large areas with T_{max} exceeding 42.5 °C with an anomaly of 4–5 °C (Fig. 10a, b). Hence, it is very clear that the bias corrected T_{max} forecast captured the impending high temperature over the coastal, central and northwest India with sufficient

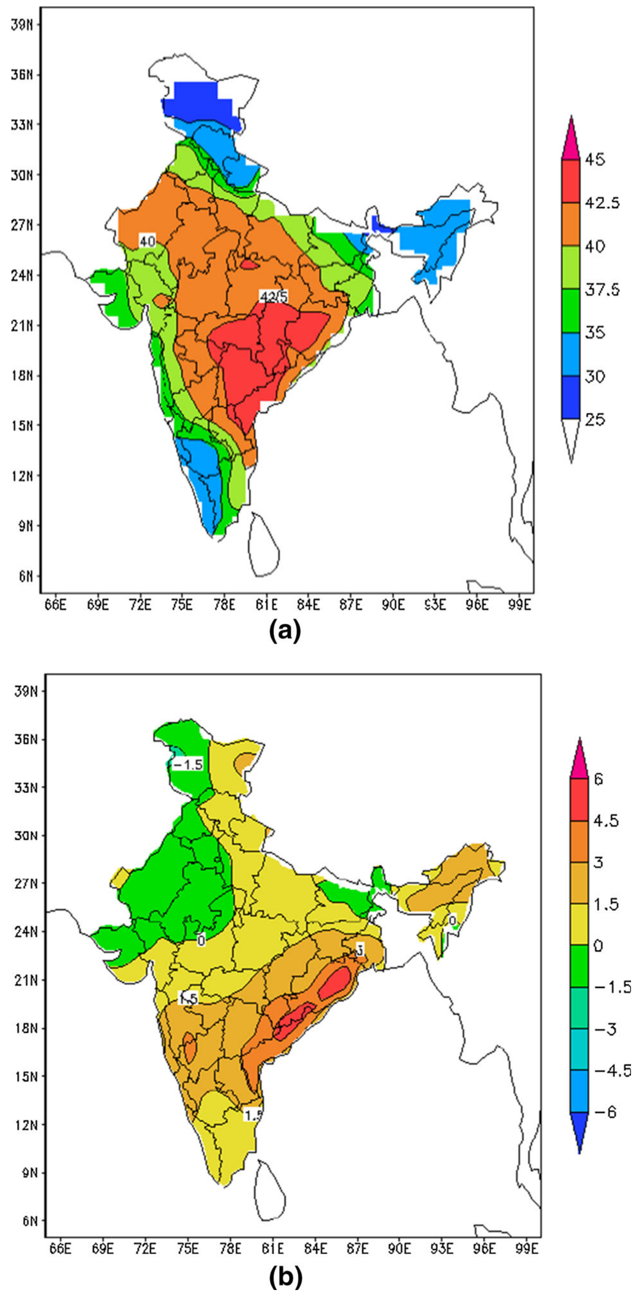


Fig. 7 **a** Bias corrected week 3 T_{max} (C^0) forecast based on the initial condition of 06–07 May, 2015 and valid for the period from 22 to 28 May, 2015. **b** Same as **a** but for T_{max} anomaly

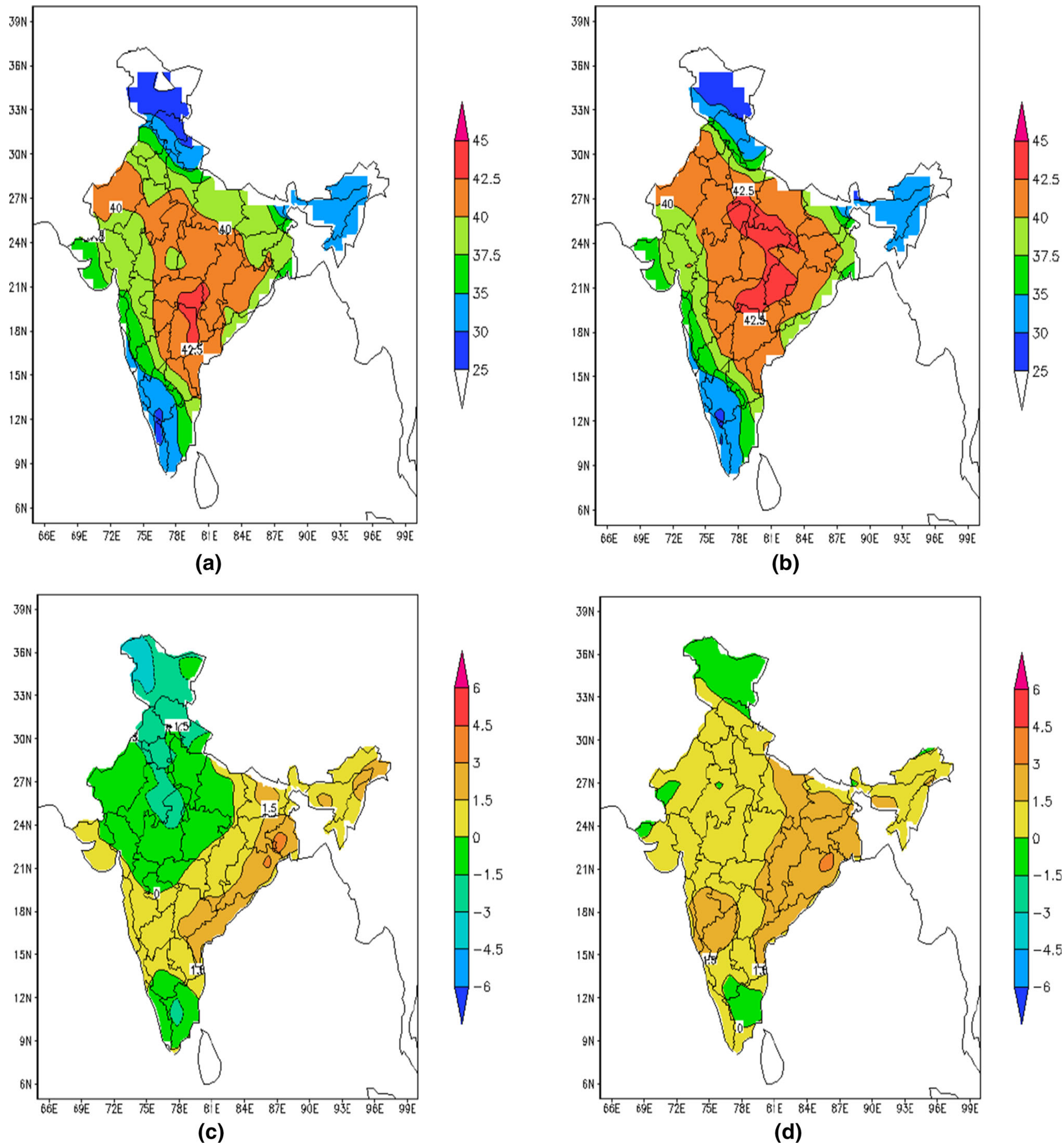


Fig. 8 **a**, **b** Bias corrected week 2 and week 3 mean $T_{\max}$ (C^0) forecasts based on the initial conditions of 13–14 May, 2015 and valid for the period from 22 to 28 May and 29 May to 04 June, 2015 respectively. **c**, **d** Same as **a**, **b** but for $T_{\max}$ anomaly

lead time, which can provide useful guidance to the public and disaster manager to formulate a proper action plan to reduce the loss of human life and properties.

As indicated above the forecast $T_{\max}$ during the period from 22 May to 04 June, 2015 is not only confined over the northwestern parts of the country but also extended much to the east like that is seen in the observed $T_{\max}$ patterns shown in Fig. 3d, e. This eastward extension of $T_{\max}$ during the HW period is normally associated with mass of hot dry air approaching from northwest India and adjoining Pakistan (Bedekar et al. 1974). This eastward shifting of $T_{\max}$ belt during the HW period of 22 May to 04 June, 2015 in

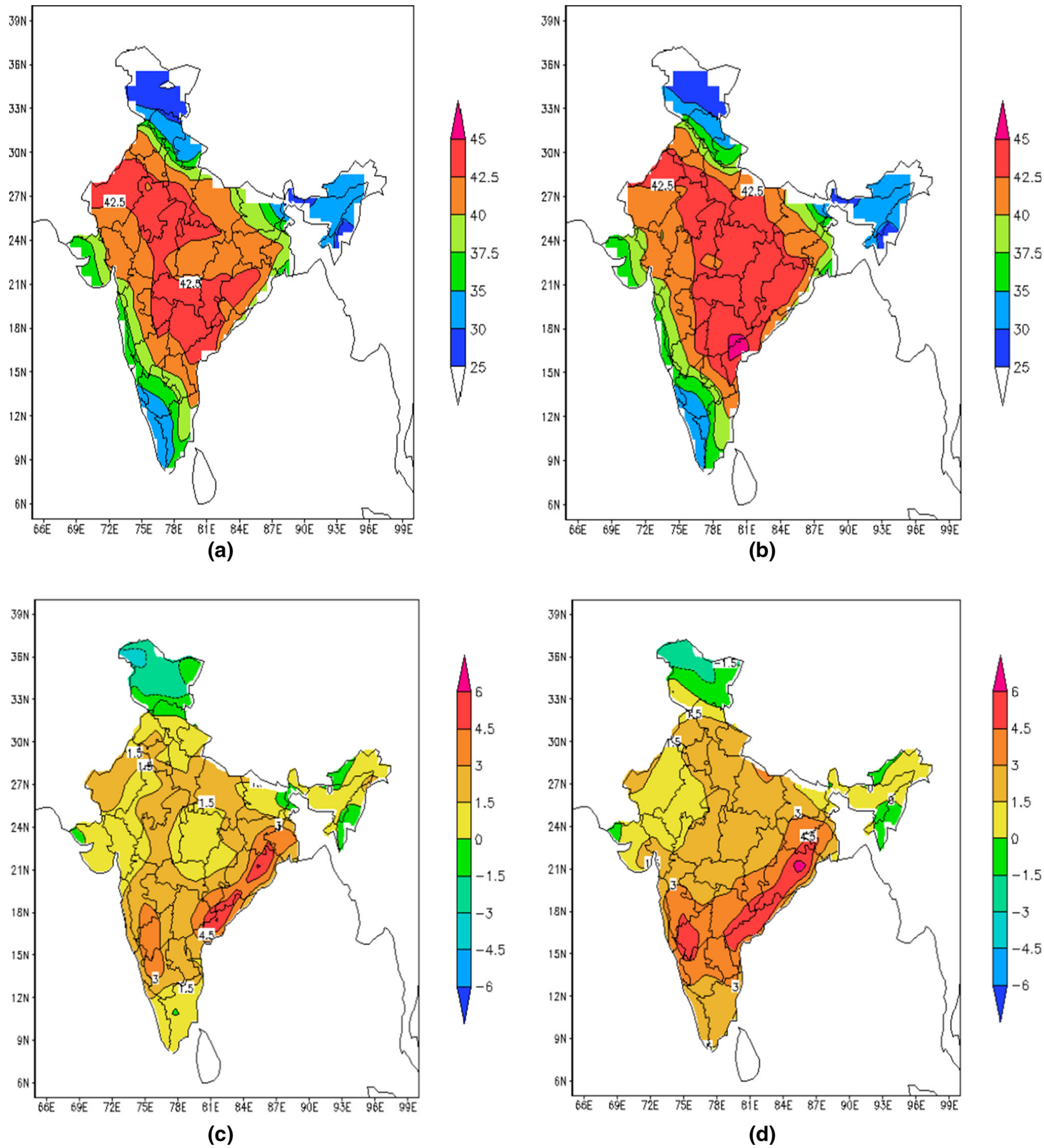


Fig. 9 **a**, **b** Bias corrected week 1 and week 2 $T_{\max}$ (C^0) forecasts based on the initial conditions of 20–21 May, 2015 and valid for the period from 22 to 28 May, and 29 May to 04 June, 2015 respectively. **c**, **d** Same as **a**, **b** but for $T_{\max}$ anomaly

the forecast plots shown in Fig. 9 based on the initial conditions of 20–21 May is also associated with winds pulling in warm air from Pakistan in northwesterly direction to central and eastern coastal states of India (Fig. 11a, b). As seen in Fig. 11a, b the week 1 and week 2 forecasts 850 hPa mean wind based on 20–21 May, 2015 initial condition indicated central and eastern states of India under the grip of northwesterly wind with northeast-southwest oriented trough appearing almost parallel to the eastern coastal boundary of India, a typical synoptic

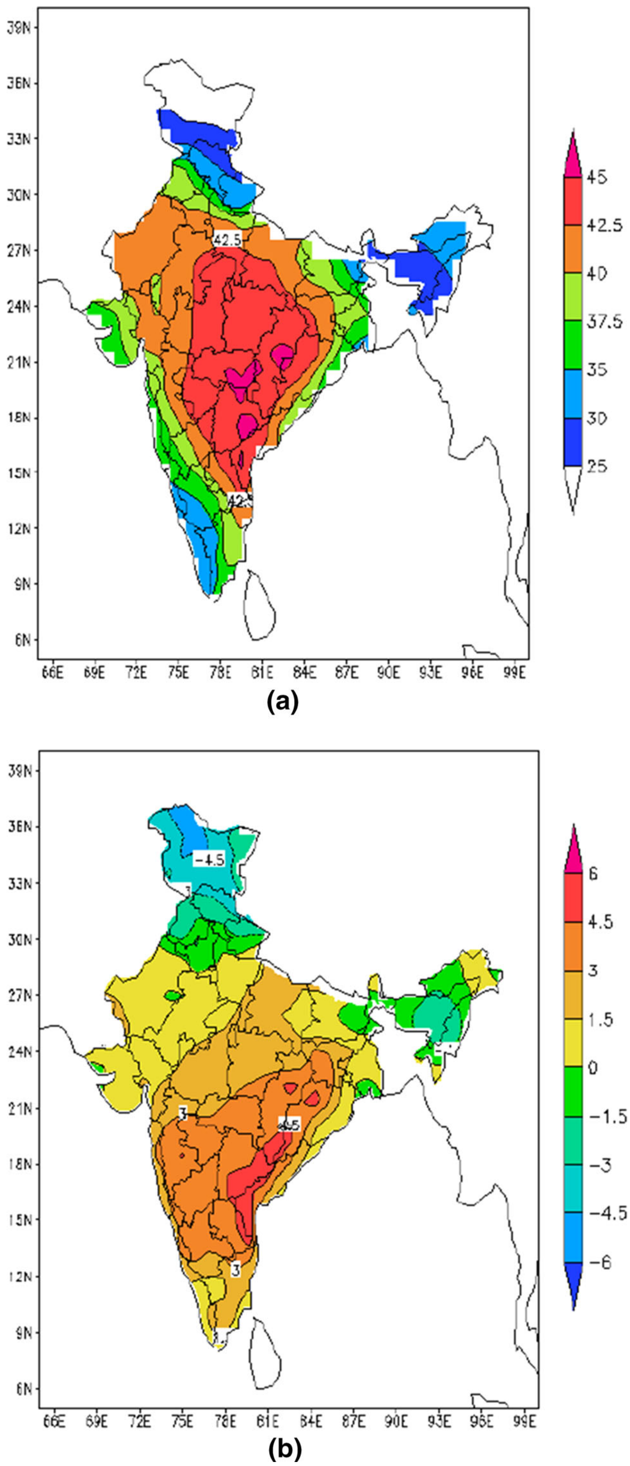


Fig. 10 Bias corrected week 1 T_{max} (C^0) forecast based on the initial condition of 27–28 May, 2015 and valid for the period from 29 May to 04 June, 2015. **b** Same as **a** but for T_{max} anomaly

condition generally observed during the strong HW period (Bedekar et al. 1974). A recent study by Ratnam et al. (2016) explained the two classes of HW over India associated with large scale forcing, where the first-type of HW

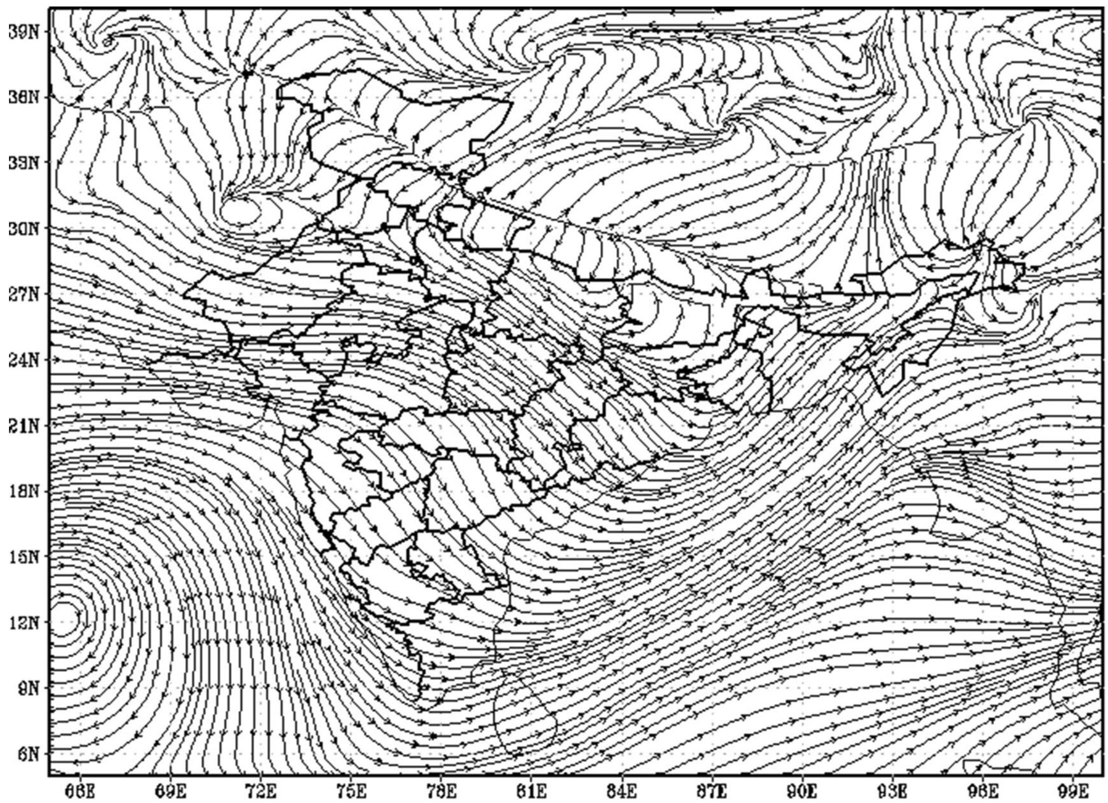
Fig. 11 **a**, **b** 850 hPa mean wind forecast for week 1 and week 2 ▶ based on the initial conditions of 20–21 May, 2015 and valid for the period from 22 to 28 May, and 29 May to 04 June, 2015 respectively

over the north-central India is found to be associated with blocking over the North Atlantic, which is associated with anomalous sinking motion and HW conditions over India. They have further shown that, the second-type of HW over the coastal eastern India is found to be due to the anomalous Matsuno-Gill response to the anomalous cooling in the Pacific associated with northwesterly winds over the main land mass of India, delaying the sea breeze, leading to heat waves over eastern coastal regions of India. The northwesterly forecast winds for 2 weeks as seen in Fig. 11a, b during late May and early June, 2015 is consistent with the second-type of heat wave described in Ratnam et al. (2016) over eastern-coastal regions of India.

5.3 Probability forecast of the heat wave event of 2015

In view of the uncertainty in the deterministic forecasts of forecasting the absolute values of T_{max} as well as the exact magnitude of T_{max} anomaly, there is also a need to see the performance of probability forecast. The basic principle of probability forecast is the different ensemble members are associated with slightly different initial conditions. The ensemble members are having spread from one member to other. There are different methods of generating probability forecasts. Based on the 8 ensemble members the probability of above normal and below normal T_{max} forecast for 4 weeks are calculated on weekly basis based on the hindcast climatology of 12 years from 1999 to 2010 as indicated in Fig. 2. The hindcast climatology at each grid point is used as the threshold and it is calculated how many of the total 8 members are found to be $\geq$ the hindcast mean and accordingly the above normal probability is calculated. Similarly the below normal probability is also calculated for the forecast period from 22 to 28 May, 2015 with different lead times. The above normal and below normal probability forecasts based on the initial conditions of 06–07 May, 13–14 May, and 20–21 May 2015 and valid for the period from 22 to 28 May, 2015 is shown in Fig. 12.

The probability of above normal week 3 T_{max} forecast based on the initial condition of 06–07 May, 2015 and valid for the period from 22–28 May, 2015 indicated high probability (>95 %) of above normal T_{max} over the eastern states of India (Fig. 12c), which is also most affected region of heat wave during this period. Similarly, based on the initial conditions of 13–14 May, 2015 the week 2 forecasts valid for the period from 22 to 28 May, 2015 indicated above normal probability of exceeding 75 % over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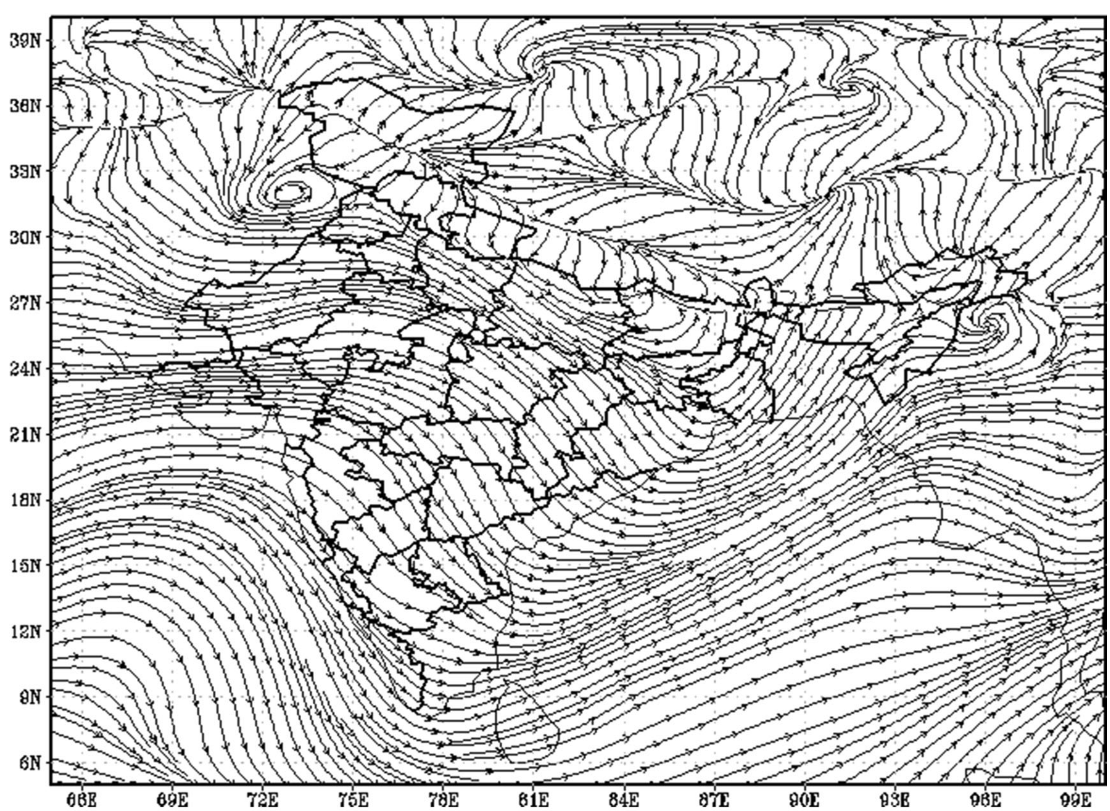
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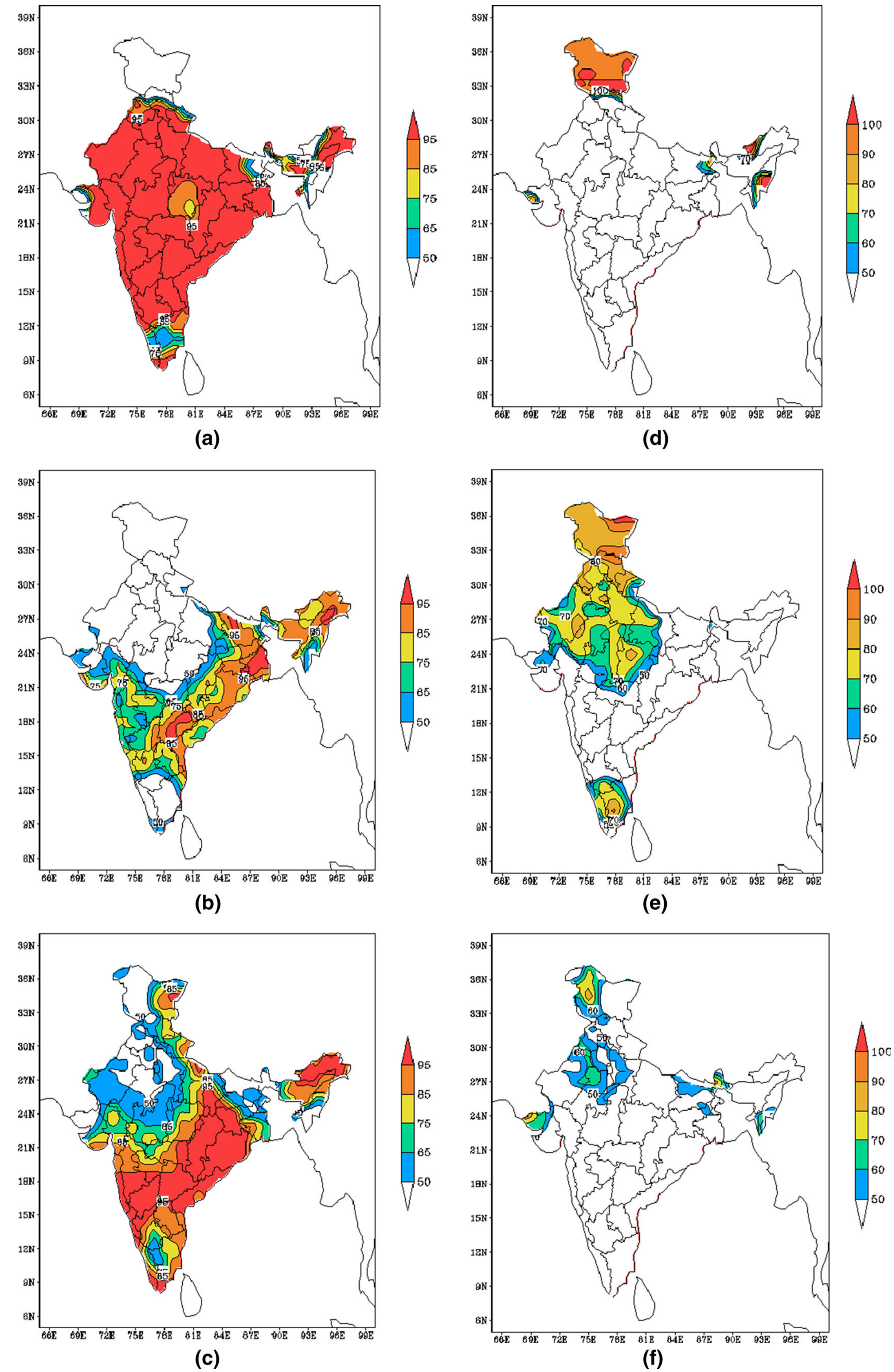
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◀**Fig. 12** **a–c** Probability of above normal (%) T_{max} forecast for week 1, week 2 and week 3 respectively and valid for 22–28 May, 2015. **d–f** Same as **a–c** but for probability of below normal (%) T_{max} valid for the same period. **a** Above normal (%), week 1 forecast, **b** above normal (%), week 2 forecast, **c** above normal (%), week 3 forecast, **d** below normal (%), week 1 forecast, **e** below normal (%), week 2 forecast and **f** below normal (%), week 3 forecast

the large portions of eastern coastal states of India with some pockets even indicating probability more than 95 % over Andhra Pradesh and Telengana region (Fig. 12b). Thus, the most of the ensemble members were indicating above normal T_{max} over the region. The initial condition based on 20–21 May and valid for week 1 forecasts shown in Fig. 12a indicated very high probability (≥95 %) of above normal T_{max} over almost entire India except some isolated parts of extreme northern India, northeast India and parts of south peninsula. The corresponding below normal probability forecasts for 22–28 May, 2015 at different lead time mainly indicates very low probability (<50 %) over most parts of India (Fig. 12d–f). For the subsequent week of 29 May to 04 June, 2015 the above normal probability forecasts at different lead time also indicates almost the similar probability as shown in Fig. 12a, c in case of the week from 22 to 28 May, 2015 (Fig. not shown). Thus, the bias corrected deterministic forecast and also the probability forecast captured the impending high temperature over many parts of India with at least a lead time of 2 weeks. For the quantification of forecast from week 1 to week 3, the above normal probability value of T_{max} forecast over the meteorological subdivisions in sector-A to sector-D identified in Fig. 1 and valid for the period from 22 to 28 May, 2015 at different lead time is shown in Fig. 13. As seen from Fig. 13 the probability forecast also indicates much higher values (>90 %) in case of week 1 forecast over all the 4 sectors. With respect to week 2 and week 3 forecasts the above normal probability of about 70–90 % is observed over the sector-B and sector-D. It may be mentioned here that the main HW belt was over the meteorological subdivisions in sector-B and sector-D, which is indicated by much higher probability. Similar probability map is also seen in case of weekly forecast valid for the period from 29 May to 04 June, 2015 at different lead time (Fig. not shown). Thus, both the deterministic and probabilistic forecasts did indicate impending HW over many parts of India at least with a lead time of 2 weeks. The timely warning based on skillful forecast of such extreme high temperature can be very useful to the planners and disaster managers to implement practices to prevent heat-related deaths and illnesses. The forecasts from meteorological communities can alert governmental agencies, health centre, health officials and hospitals, emergency responders, local community groups, and media outlets of forecasted extreme temperatures.

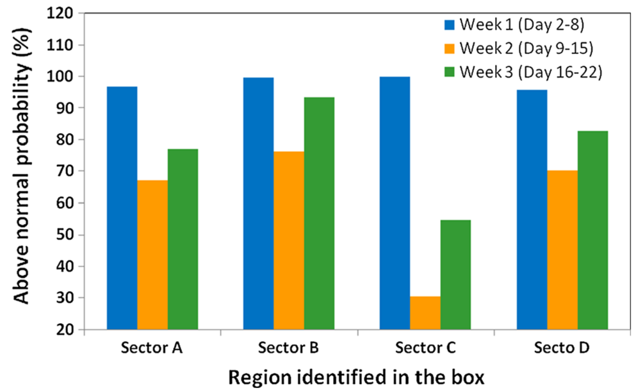

Fig. 13 Area averaged mean probability (%) of above normal T_{max} forecasts (*week 1*, *week 2*, and *week 3*) valid for the period 22–28 May, 2016 over the meteorological subdivisions under sector-A to sector-D identified in Fig. 1

6 Summary and conclusions

As the recent severe heat waves occurred over India during late May and early June 2015, the case study was performed for the same event to explore the possibility of using the bias corrected deterministic forecast and probability forecasts of maximum temperature over India on operational basis using the CFSv2 coupled model outputs. The heat wave condition was very severe during the week from 22 to 28 May, 2015 with subsequent week from 29 May to 4 June, 2015 also witnessed high maximum temperature over many eastern coastal states of India and neihghbourhood. While analyzing the CFSv2 model bias of maximum temperature forecast during the heat wave period of 22 May to 04 June it is found that the southern parts of India has a cold bias by about 2–2.5 °C, whereas, the meteorological subdivisions over the eastern parts of Indo-Gangetic Plain has a warm bias of about 1 °C. Over the northwestern parts of India the CFSv2 model shows very close to normal with slight warm bias in case of week 1 forecast and slight cold bias in case of week 2 and week 3 forecasts.

The 8 ensemble members of operational CFSv2 model are used to prepare the bias corrected deterministic forecast as well as the probability forecast using the hindcast climatology. The bias corrected T_{max} forecast with a lead time of 1 to 2 week indicated large scale warming with T_{max} exceeding 42.5 °C with a anomaly of about 4 °C over many parts of northwest, central and eastern coastal belt of India during the period from 22 to 28 May and 29 May to 04 June, 2015, which is associated with strong northwesterly forecast wind over the entire central and eastern coastal belt of India, delaying the sea breeze, leading to heat waves over eastern coastal regions of India. The probability forecast generated by CFSv2 outputs was also prepared during the heat wave period from 22 May to 04

June. The probability of above normal T_{max} forecast over the most affected meteorological subdivisions of eastern India during 22–28 May, 2015 is found to be ≥95 % for week 1 forecast and about 70–90 % for week 2 to week 3 forecasts. Thus, both the deterministic and probabilistic forecasts did indicate impending heat wave over many parts of India at least with a lead time of 2 weeks.

As the real time forecast could capture the bias corrected deterministic forecast and also the probability forecast captured the impending high temperature over many parts of India with at least a lead time of 2 weeks, the timely warning based on skillful forecast of such extreme high temperature can be very useful to the planners and disaster managers to implement practices to prevent heat-related deaths and illnesses. This is an evolving products and future work is suggested. The probabilities could be compared to observed frequencies and calibrated statistically, or, using more advance ensemble analysis techniques, other methods of computing the probabilities could be developed.

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