Chapter-1

Introduction

Anthropogenic activities such as industry, construction, transport and deforestation have caused concentrations of greenhouse gases such as carbon dioxide, methane and nitrous oxide to increase over the last 150 years, even faster than since the Industrial Revolution. The increase in greenhouse gas concentration in the atmosphere has ultimately led to global warming with a trend of about 1.1°C over the period from 1880 to 2022. Annual surface temperatures over India have also recorded a similar increase over the period 1901-2022. In recent years, minimum (night time) temperatures have increased more than day time temperatures, suggesting the possible role of moisture and greenhouse gases.

An increase in the mean or coefficient of variation (CV) of temperatures increases the probability of extreme temperature events, as shown in Fig. 1.1. This can lead to an increase in the frequency of heat waves as well as cold waves. Extreme weather events have become increasingly common globally in recent decades (IPCC 2012; IPCC 2014). India is also feeling the effects of climate change as extreme weather events such as heavy rainfall, heat waves and intense tropical cyclones are occurring more frequently every year. The increasing frequency and intensity of these extreme events causes great damage to crops and rural economies.

Heat waves are anomalous episodes with extremely high surface air temperatures, lasting for several days with serious consequences. Similarly, cold waves are anomalous episodes of extremely low surface air temperatures lasting several days. There is no universal definition of a heat wave or a cold wave. Heat waves are usually defined as events in which certain temperature thresholds are exceeded for a minimum number of consecutive days.

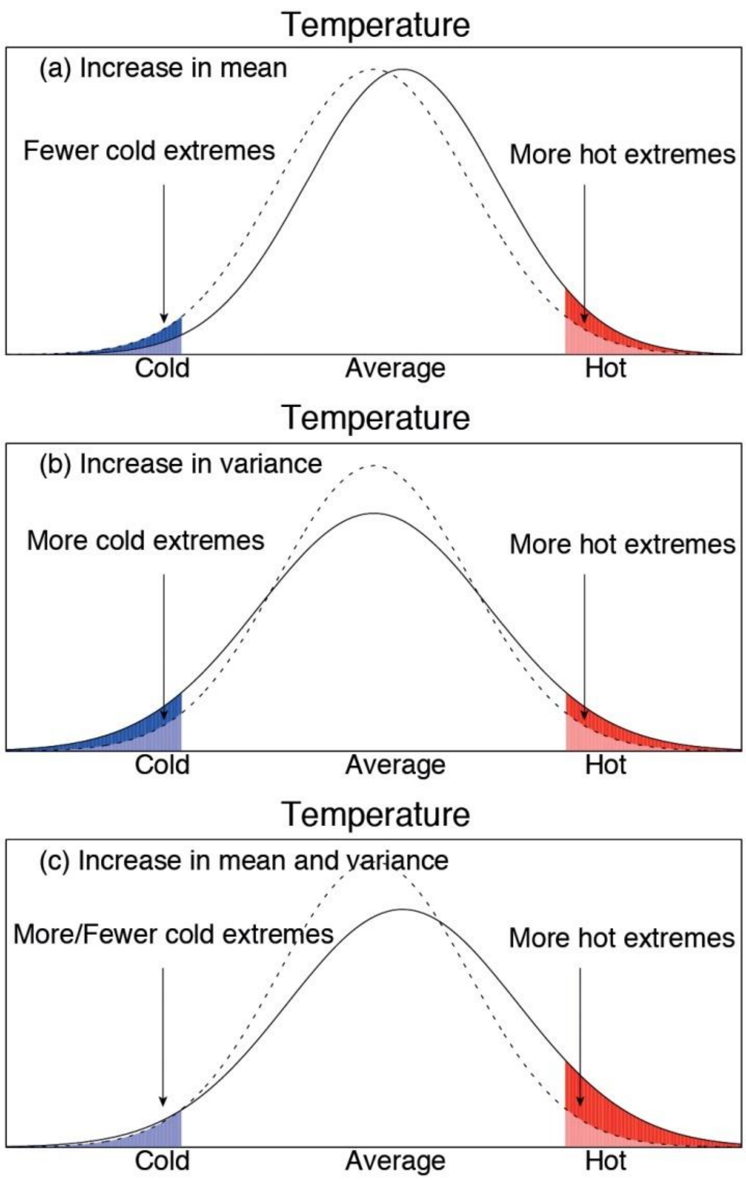

Fig. 1.1. Schematic representations of the probability density function of daily temperatures. Dashed lines represent a previous distribution and solid lines a changed distribution. The probability of occurrence, or frequency, of extremes, is denoted by the shaded areas. In the case of temperature, changes in the frequencies of extremes are affected by changes (a) in the mean, (b) in the variance or shape, and (c) in both the mean and the variance (Source: IPCC, 2014).

Heat waves are not uniform across the world and there is a lack of a common index to identify the heat extremes (Perkins et al. 2012). The thresholds used for defining heat wave are different for different regions. Thresholds may be absolute or statistical and the absolute thresholds depend on the region and its geography. World Meteorological Organization (WMO) defines heat wave as "when the daily maximum temperature exceeds the average maximum temperature by 5 °C for more than five consecutive days, the normal period being 1961-1990".

Heat waves are a major concern globally and regionally due to their catastrophic impact on society (Coumou and Rahmstorf 2012; Coumou et al. 2013; Cowan et al. 2014; Meehl and Tebaldi 2004; Perkins et al. 2012; Perkins 2015; Pai et al. 2013; Trenberth and Fasullo 2012; Rohini et al. 2016; Ratnam et al. 2016 a). The mortality rate due to heat waves is higher than any other natural hazard in different parts of the world (De et al. 2005). In 2003, an intense heat wave occurred over western Europe, causing about 70,000 deaths (Coumou and Rahmstorf 2012). On the other hand, the Russian heat wave in 2010 reportedly claimed 54,000 lives. The severe heat wave over the southeastern parts of India in May 2015 claimed the lives of more than 2500 people. This heat wave was triggered by the delayed onset of the southwest monsoon and persistent anomalous atmospheric conditions. The IPCC Fifth Assessment Report (IPCC 2014) states that the major climate risk for south Asian countries will be the rising mortality rate due to the impending heat waves. A moderate increase in average temperatures or a slight increase in the duration of heat waves will lead to a significant increase in the mortality rate in India.

Heat waves are considered silent killers because of their direct impact on human health (Patz et al. 2005; Hondula et al. 2014, Heo et al., 2019). Heat waves have immense impacts on human health, causing heat cramps, heat exhaustion, heat stress and heat stroke (Oldenborgh et al. 2018) and very severe heat waves even lead to death (Steffen et al. 2014). Children and the elderly are particularly affected, but also people who already suffer from illnesses such as heart and respiratory diseases, kidney diseases and psychiatric disorders (Nitschke et al. 2007; Hansen et al. 2008; Wilker et al. 2012; Steffen et al. 2014).

Another serious impact of heat waves is on agriculture (both crop and livestock). Extreme periods of high temperatures can lead to a significant reduction in crop yields and cause reproductive failure in many crops (Chaudhuri et al. 2000; Attri and Rathore 2003; Chakraborty et al., 2019, Dash and Mamgain 2011; Siebert et al. 2014; Steffen et al. 2014). Extreme temperatures increase water stress in plants, which can lead to plant death due to the cessation of photosynthesis (Schlenker and Roberts 2009; Steffen et al. 2014). In animals, heat stress leads to reduced appetite, lower productivity, adverse effects on the immune system and sometimes death (Lefcourt and Adams 1996; Steffen et al. 2014). A decline in agricultural productivity leads to lower food production, which in turn leads to an increase in food prices. Chakraborty et al. (2019) examined the impact of heat waves on wheat crop production over India and found a negative impact. Their study revealed the wheat crop yield decreased by 4.9 %. 4.1 % and 3.5% over Punjab, Haryana and Uttar Pradesh respectively.

Heat waves also cause damage to infrastructure such as the transport system, electricity supply, railways, etc. Heat waves affect the economy through lower labour productivity during extreme temperature periods (Kjellstrom and McMichael 2013; Steffen et al. 2014), agricultural failure, damage to infrastructure, etc. All these catastrophic impacts highlight the need for more studies on heat waves, their impacts and their predictive capabilities.

In India, heat waves (HW) usually occur in the pre-monsoon months from March to June. There are two areas in India where heat waves are prevalent. One is central and northwestern India, called the heat wave zone, and the other is on the east coast of India (Andhra and Odisha). The frequency of heat waves is higher in the heat wave zone than on the east coast of India. Different physical mechanisms are responsible for the heat waves in the heat wave zone and on the east coast of India.

In India, cold waves (CWs) usually occur during the period from November to March in association with the incursion of cold winds into north-western and central India when westerly disturbances (WDs) pass over the region (Bedekar et al. 1974). WDs are transient disturbances of mid-latitude westerly winds followed by the occurrence of cold waves, mostly over the areas north of 20^0 N and rarely in areas south of this latitude. There are many previous studies that have investigated various climatological features of CWs in India (Bedekar et al. 1974; Subbaramayya and Surya Rao, 1976; Chaudhury et al. 2000; De et al. 2005; Pai et al. 2004). Most of these studies have used threshold criteria based on minimum temperature anomalies to define CWs. Pai et al. (2004) studied the decadal changes in the various characteristics of CWs over India by using daily CW information over all meteorological sub-areas of India (the country was then divided into 35 meteorological sub-areas by the IMD) for the period 1971-2000 based on the minimum temperature deviation.

Bedekar et al. (1974) published the first India Meteorological Department (IMD) forecast manual on heat and cold waves, covering both climatological and forecasting aspects in detail. This publication is the first comprehensive documentation of the various aspects of heat and cold waves. Since then, many research papers have been published, especially in recent years when global warming has attracted the interest of researchers. However, a comprehensive compilation of the different aspects of heat and cold waves with updated information has not been produced. Since 1974, there has been tremendous progress in the understanding and predictive ability of heat and cold waves over India. The present monograph aims to compile and present the latest findings on various aspects of heat and cold waves over India. This monograph is intended as a reference book on heat and cold waves for researchers, students and forecasters.

In the next few paragraphs, a brief review of the recent studies on heat and cold waves in India is provided.

Most recent observational studies suggested an increasing trend in heat waves over India (Pai et al. 2013; Jaswal et al. 2015; Pai et al. 2017; Rohini et al. 2016). The recent study of Ratnam et al. (2016 a) identified the two prominent areas of heat waves over India which is maintained by two different physical processes. The trends of heat waves are significant both over the north western parts of India and southeastern coast of India (Ratnam et al. 2016 a; Rohini et al. 2016). Variability of heat waves over India is linked to El Nino/Southern Oscillation (ENSO) and the Indian Ocean SST anomalies (Ratnam et al. 2016 a; Rohini et al. 2016). These studies suggested that occurrence of heat waves over northwestern part of India is associated with anomalous persistent high along with depleted soil moisture and its variability is strongly influenced by tropical ocean SST anomalies. Frequency, duration and spatial extent of heat waves over India are found to be more in the succeeding year of El Nino (Pai et al. 2013; De and Mukhopadhyay 1998; Rohini et al. 2016).

In March and April 2022, large parts of South Asia including India and Pakistan experienced prolonged hot weather. The month of March was the hottest in India since 1901. Temperatures were consistently 3°C-8°C above average, breaking many records in several parts of the country (Zachariah et al., 2022). The states of Odisha, Madhya Pradesh, Gujarat, Chhattisgarh, Telangana and Jharkhand also experienced heatwaves. In Pakistan many individual weather stations recording monthly all-time highs in March. The heatwave conditions continued into April, reaching its preliminary peak towards the end of the month. Around 300 large forest fires occurred in the country on April 28, a third of these in Uttarakhand (Zachariah et al. 2022). In Pakistan, temperatures above 49°C were recorded in Jacobabad in Sindh. The 2022 heatwave is estimated to have led to at least 90 deaths across India and Pakistan, and to have triggered an extreme Glacial Lake Outburst Flood in northern Pakistan and forest fires in India. The heat reduced India's wheat crop yields, causing the government to reverse an earlier plan to supplement the global wheat supply that has been impacted by the war in Ukraine (Zachariah et al. 2022).

Pai et al. (2004) studied the decadal variations of cold and heat waves using the data of 1971-2000. A significant increase was noticed in the frequency, persistency and spatial coverage of both of these high frequency temperature extreme events (heat and cold waves) during the decade (1991-2000). These changes might be the manifestation of regional impact of highest ever decadal scale global warming recorded during the period (1991-2000). A part of these changes might also be caused by local factors such as deforestation, urbanization etc. The Cold Wave (CW)/Severe cold wave (SCW) activity over north India showed increase from the decade of seventies to eighties and then to nineties. Pai et al. (2013) examined the occurrence of heat waves over India in detail using the data of 1961-2010. It was observed that many areas of the country (north, northwest, central and northeast peninsula) have experienced HW days of more than 8 days on an average per season. The severe heat waves were mainly experienced over north, northwest and central parts of the country. Significant long-term increasing trends in HW days was also observed over India during the analysis period. In general, the frequency, persistency and area coverage of the HW/SHW days were found to be more than average during the years succeeding El Nino (El Nino +1) years.

Recently, Pai et al. (2017), have summarized the results related to heat and cold waves over India. During the hot weather season (AMJ), stations from the north, north-west, central, east India and north-east Peninsula (together called Core Heat wave Zone) are most prone for HW/SHW days with relatively highest frequency experienced during May. During the cold weather season (DJF), stations from CCZ that is nearly same as CHZ but includes Jammu and Kashmir and excludes coastal Andhra Pradesh are most prone for CW/SCW days with the highest frequency during January.

Satyanarayana and Bhaskara Rao (2020) studied the phenology of heat waves over India using the data from 1951-2015. Their study revealed three localized regions of heat wave vulnerability in the north, northeast and southeast parts of India, which are different from the three maximum temperature zones. Dodla et al. (2017) analyzed the 2015 catastrophic heat wave over the east coast of India, which claimed about 2500 lives. Analyses revealed that isolated region of Andhra Pradesh (AP) had experienced severe heat wave conditions during May 23–27, 2015, with temperatures above 42°C and the sudden escalation by 7–10°C within a short span of 2–3 days. Short-range weather predictions with Advanced Research Weather Research and Forecasting model at 3-km resolution, up to 72-h lead time, have been found accurate with statistical metrics of small mean absolute error and root-mean-square error and high index of agreement confirming the predictability of the heat wave evolution.

Kishore et al (2022) studied the human influence on the changing patterns of heat waves in India using the Heat Wave Magnitude Index daily (HWMId). Their study found that anthropogenic factors have increased the probability of occurrence of severe heat waves in central and central-southern India by two times during the twentieth century. The risk of heatwaves is projected to increase tenfold in the 21st century. More than 70% of the land area in India is expected to be affected by heat waves with a magnitude of more than 9. Mazdiyasni et al. (2017) suggested that future climate warming will lead to a significant increase in heat-related mortality, especially in lower-latitude developing countries like India, where heat waves will be more frequent and the population is particularly vulnerable to these extreme temperatures. The study also shows that even a moderate increase in average temperatures can lead to a sharp rise in heat-related mortality and supports the efforts of governments and international organizations.

The study by Murari et al. (2015) using CMIP data suggests that heat waves are projected to be more intense, have longer durations and occur at a higher frequency and earlier in the year. Southern India, currently not influenced by heat waves is expected to be severely affected by the end of the 21st century. Projections indicate that a sizable part of India will experience heat stress conditions in the future.

Vittal et al. (2020) examined the role of Atlantic Ocean SST anomalies on Indian heat waves. They used observations and climate model experiments to show that Indian heat waves during the period 1961-2010 period were only weakly driven by Indian Ocean SST, but were instead strongly tied to SST in the Atlantic Ocean. The conditions in the Atlantic that drove those heat waves were exacerbated by greenhouse emissions rather than natural forcing.

Pai and Smitha (2022) examined the impact of extreme phases (El Nino and La Nina) of El Nino-Southern Oscillation (ENSO) on the frequency, duration, magnitude and spatial coverage of heat waves (HWs). It was observed that there is an appreciable increase (decrease) in the number of HW days during El Nino (La Nina) events. Severe Heat waves were more prominent (longest and hottest) in El Nino years. Exactly opposite association was observed in case of CW days. El Nino event mostly inhibits cold wave activities over India. Nageswara Rao et al. (2020) examined the heat waves occurring over the east coast of India (Odisha, Andhra Pradesh and Telangana). The study revealed the continued increase in maximum temperature and its variability as the hot weather season progresses. In the recent period, a notable increase in the weekly Tmax and its variability has been observed.

Earlier studies (Bedekar et al. 1974) showed that cold waves occur mostly due to the intrusion of cold air from northern latitudes into the northwestern parts of India. The cold wave conditions over the northern parts of India are often associated with the passage of western disturbances, which manifest as an eastward moving well marked troughs in the upper tropospheric westerlies north of 20°N and often seen extending to the lower troposphere, transport cold air from northern latitudes into India. There are also few instances of occurrence of cold waves due to a low-pressure system over the

North Arabian Sea. In these cases, the easterlies to the north of the low-pressure system transport cold air from higher latitudes.

Jaswal et al (2017) studied increased trends in temperature and moisture induced heat index and its effect on human health in climate change scenario over the Indian sub-continent. Using dry bulb temperature and relative humidity records from 283 surface meteorological stations over India, they analyzed the heat index (HI) during summer and monsoon seasons. Averaged over the country, HI is increasing during summer and monsoon seasons at the rate of +0.56^0 C/decade and +0.32^0 C/decade respectively, which is statistically significant at 95% level. The increasing HI indicates high level of discomfort in both the seasons which is primarily due to increase in humidity in summer season and maximum temperature in monsoon season. Spatial distribution of HI indicates greater chances of heat related illness in India, more prominently in the southeast coastal regions (Andhra Pradesh, Orissa and Tamil Nadu) in summer and over northwest India (Rajasthan and Indo-Gangetic plains) in monsoon season.

Srivastava et al (2022) conducted a heat weather hazard analysis over India, attempting to quantify the impact of different meteorological parameters on heat waves in different regions of India for different summer months (March, April, May and June). The impact of different meteorological parameters is determined for different months and regions of the country. The cumulative values are calculated for different regions considering different meteorological parameters to make an initial analysis of the heat wave and zonation for the entire country.

Narkhede et al (2022) developed an empirical model-based framework for operational monitoring and forecasting of heat waves based on temperature data. In this study, they proposed an operationally applicable empirical model that uses a set of indices to monitor and forecast heat waves on the short-term time scale. The model consists of two main components: a) index-based monitoring over a spatial domain and

b) temporal prediction over different locations. Three heat wave indices are calculated, the heat stress index, the heat stress index and the heat stress factor. They have also considered the effects of meteorological parameters such as wind and humidity on the intensity and duration of heat waves. For the prediction component, they have used a simple machine learning based method for predicting the overheating factor index. The study shows that the heat wave indices can be predicted with this simple model up to a lead time of 2-3 days for most regions of India.

Sharma and Mujumdar (2017) studied the impacts of concurrent droughts and heat waves that could have more serious impacts. Meteorological drought condition, which is characterized by low rainfall can be amplified with simultaneous occurrence of heat waves. The study found significant changes in concurrent meteorological droughts and heat waves. There is substantial increase in the frequency of concurrent meteorological droughts and heat waves across whole India. Statistically significant trends in the spatial extent of droughts are observed in Central northeast India and west central India. However, the spatial extend affected by concurrent droughts and heatwaves is increasing across whole India.

Dubey et al. (2021) addressed the hot weather dynamics and variability. The seasonal composites for extreme temperature years show that hot season over North India (NI) occurs mainly due to blocking high in upper atmospheres. Similarly, daily temperature anomalies for the heatwave days during hot years exhibit stationarity of such blocks centered over the region. Two global teleconnections have been found to be responsible for the NI seasonal anomaly, (i) a continuous anomalous low over Europe cause anomalous high across the region, (ii) the subtropical jet stream and the polar jet stream help to maintain stationarity of anticyclonic blocks over the region. Sinking of air due to an upper atmospheric high over NI causes adiabatic warming near the surface.

The cold waves are known to increase mortality rate owing to the socio-economic conditions of people of the northern parts of India. For example, the cold wave that occurred in January 2003 resulted in death of about 900 people. During 1978–1999, a total number of 3264 deaths were reported due to cold waves in the northern parts of India (Ratnam et al. 2016 b). The cold waves also affect Rabi crops, crops that are sown in winter and harvested in the following spring, of the northern regions of India. A survey on the impact of cold wave on the Rabi crops showed that the economic losses were to the tune of 6230 million Indian rupees in the state of Rajasthan during 2005–2006 Rabi season alone.

Raghavan (1967) used 51 years of data (1911-1961) to prepare a detailed climatology of cold waves and severe cold waves over India and Pakistan. The study revealed that Jammu and Kashmir experiences maximum cold waves in a season. Subramayya and Surya Rao (1976) used 150 IMD stations for the period 1954-56 to examine heat and cold wave occurrence over India. They have found that for the country as whole, maximum heat wave and severe heat wave occur in the month of May. Maximum severe cold waves occur in the month of January.

In this monograph, the definitions of heat and cold waves are discussed in Chapter-2. In the chapter-3, long term climatology of cold waves and observed long term trends are discussed. For this purpose, a long- term, quality-controlled daily gridded temperature data set has been used. In the chapter-4, long term climatology of heat waves and observed long term trends are discussed. In the chapter-5, the physical mechanisms of heat waves and in the Chapter-6, physical mechanisms of cold waves are discussed in terms of large-scale dynamics and local factors. In the Chapter-7, the forecasting aspects (in all time scales, short range to seasonal) are discussed in terms of synoptic setting for such heat and cold waves. Skill of short to medium range forecasts, extended range forecasts and seasonal forecasts are also discussed using weather prediction models of Ministry of Earth Sciences (MoES)/ IMD as well as other TIGGE weather prediction models. In the last chapter-8, the main aspects of heat and cold waves are summarized and impacts and adaptation to heat waves are briefly discussed.