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Spatio-Temporal Changes in Cold Wave Characteristics Over the Diverse Meteorological Sub-Divisions of India

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Abstract—Cold wave (CW) and Severe Cold wave (SCW) prevail over India as a seasonal episode during winter season. The present study analyzes the changing spatio-temporal characteristics and trends of cold waves over India's meteorological subdivisions from 1951 to 2021 (Dec–Feb). It uses minimum temperature data obtained from the India Meteorological Department (IMD) at a spatial resolution of 0.5° × 0.5°. A declining trend in both CW and SCW days is found with a decrease of − 0.29 days/decade in CW days and 0.02 days/decade in SCW days. The study also explored the trend of spells of three, five and seven days of CW and SCW and found a significantly decreasing trend of − 0.02 days/decade and − 0.05 days/decade in 3 and 5-day SCW spell respectively. A consistent significant increase of 0.027 °C/decade in minimum temperature post 1980s is also reported in the study with a simultaneous decrease in cold wave. While the northwestern and northern meteorological subdivision record highest CW and SCW spells, a declining trend is reported in these regions, highest being in West Rajasthan (− 1.3 days/decade) and Punjab (− 1.3 days/decade). A significant increasing trend has been observed in CW, SCW days/spells in the eastern, eastern coastal and southern subdivisions such as Bihar (0.16 days/decade), Jharkhand (0.05 days/decade) and Odisha (0.2 days/decade). Overall, the study reports a decline in cold waves and identifies new cold wave-prone regions in the country. The study also highlights the emerging severe impact on agriculture sector in the scenario of declining cold extremes over major wheat producing belts.

Keywords: Cold wave, severe cold wave, India, agriculture, climate change, Mann Kendall.

1. Introduction

The unequivocal increase in global temperatures has led to changing climatic patterns and rising extremes worldwide (IPCC, 2021). As temperatures rise, minimum temperatures are increasing while cold extremes are decreasing (IPCC, 2021). Recent assessments indicate that as global warming continues, cold extremes will further decrease (Gaitán et al., 2019; IPCC, 2021). While rising global temperature thresholds have dire consequences over the health, agriculture, energy, economy, the decrease in cold extremes and rising minimum temperatures will impact crop yield severely threatening the food security of the countries (IPCC, 2021; Lobell et al., 2012; Ray et al., 2021; Revadekar et al., 2012; Singh et al., 2021a, 2021b; Singh et al., 2021a, 2021b; Zhao et al., 2017; Jaiswal et al., 2022). Cold waves are the manifestation of extremely low temperature observed over any region over a period of time (Pai et al., 2004). India observes cold wave as a common episode during the winter season during the months of Nov-Feb with most events being observed during Dec–Feb (Dec–Feb) where the criteria to declare cold wave is based on a threshold based departure of minimum temperature over any region (Bedekar et al., 1974; Pai et al., 2004; Ratnam et al., 2016). Although cold waves are a part of Indian climatology with severe impacts on health and agriculture, only a few studies have been conducted to understand the mechanism, characteristic features, trends and impacts of cold wave over India (Subbaramanya & Surya Rao 1976; De & Sinha, 2000; Pai et al., 2004; Nair et al., 2016; Bhatla et al., 2016; Ratnam et al., 2016; Pai 2017; Sandeep and Prasad 2020; Rajeevan et al., 2023; Athira et al., 2024).

Cold wave over India occur due to the cold air transported from the northern latitudes along with the eastward moving western disturbance affecting mostly the northern and northwestern part of the

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country (Pai et al., 2004; Bhatla et al., 2016; Nair et al., 2016; Pai et al., 2017; Sandeep and Prasad 2019; Athira et al., 2024; Mandal et al., 2023; Rajeevan et al., 2023). Ratnam et al., 2016 studied the mechanism of development of cold waves over India and found two types of cold wave days occur over the country. The first type is the dominant cold wave type occurring over all India and is attributed to the low-level cyclonic anomaly observed over the Indian region in response to the convective anomalies originating at the equator. The second type cold wave days are observed mainly over the northwestern region due to cold air brought in by a cyclonic anomaly originating over the western region. Pai et al. (2004) analyzed the decadal trend of cold wave and severe cold wave days over India and found an increasing occurrence of cold wave days over meteorological sub divisions of India in the recent decades. Nair et al. (2016) studies the trend of cold waves over India for 1971–2010 and found that northwest and central part of India experienced highest number of cold wave days with most of the cold waves observed during January and severe cold wave days during January and February. The study found a declining trend in time series of cold wave days over India since 1971–2010 indicating the influence of rising minimum temperature. Investigating the impact of El Niño Southern Oscillation (ENSO) studies have found cold wave events to be higher and of longer duration > 7 days during La Nina and vice versa during the El Niño (Nair et al., 2016; Pai et al., 2004). These temperature extremes have been found to be associated with increased risks of respiratory diseases, and different cardiovascular, morbidity, and mortality (Arbuthnott et al. 2018; Liu et al., 2015; Martinez et al., 2018; Malik et al., 2020; Singh et al., 2020; Singh et al., 2021a, 2021b).

Cold wave and severe cold wave days cause a number of deaths each year in India (De et al., 2005; Malik et al., 2020; Pai et al., 2004). Malik et al. (2020) reported cold wave to have caused on an average 230 deaths per year from 1974 to 2013 over India. The highest mortality due to cold waves occur during the month of December and January with Uttar Pradesh and Bihar being the two states with approximately 75% of mortality (Malik et al., 2020). January 2003 cold wave caused a death of 900 people alone in India (De et al., 2005). However, this seasonal phenomenon which cause health issues in the vulnerable sections of society, it is crucial for the rabi season crop production of the country as both cold stress as well as increase in temperature affects the crop production particularly wheat production in India and South Asia (Mall et al., 2006; Lobell et al., 2012; Mall et al. 2006; Kaur et al., 2018; Kumar et al., 2017; Zhao et al., 2017). Cold stress induced by low temperatures which affect the wheat production as they reduce the photosynthetic activity, grain filling, grain number per spike, leaf area reduction and freezing in case of extremely low temperatures (Allen & Ort, 2001; Thakur et al., 2010).

Ji et al. (2017) studied the impact of low temperature over wheat grain yield by analyzing low temperature stress at the jointing and booting stages. The study reported a negative impact on wheat yield where the booting stage was more affected by the low temperatures than the jointing stage. Rao (2010) reported an economic loss of around 6230 million rupee in rabi crop season during an extreme cold wave event of 2006 in the state of Rajasthan. Wheat crop is sensitive to temperature change and so an increase in global temprature can reduce the global wheat yield by $\sim$ 6% (Zhao et al., 2017). Gupta et al. (2016) reported that a 2 to 4% decline in wheat yield in response to 1 °C rise in daily minimum and maximum (Gupta et al., 2016) while a net reduction of 19–28Mt of wheat yield is projected for 3–5 °C rise in temperature (Aggarwal & Singh, 2010; Mall et al., 2006). Sonkar et al. (2019) studied the combined impact of rising temperature and aerosol loading on wheat crop and found a negative impact of on wheat yield across India where 1 °C rise in Tmean reduces the wheat yield by 7% which varied spatially. Madhukar et al., 2019 showed that yield stagnation has occurred over $\sim$ 48.3% of total wheat harvested area in India as the temperature has increased. Kumar (2019) reported an increase in minimum temperature trend over Bihar and projected a decline in wheat yield with increasing temperature.

While rising minimum temperature trends are being observed over India the decline in cold wave trends over some regions can adversely affect the wheat yield over India (Mall et al., 2006; Zhao et al., 2017; Mall et al., 2021). India has observed a consistent increase in minimum temperature with a rapid rise since 1991 with the rate of increase of minimum temperature being higher than the maximum temperature during the winter season in India (Attri & Tyagi, 2010; Kothawade et al., 2010; Mall et al., 2021). Sonali and Nagesh Kumar (2013) studied the temperature trends over the seven homogenous zones of the country for all seasons and reported a significant rising trend in minimum temperature trend over all the zones in all the seasons with highest in monsoon season. Vinnarasi et al. (2017) found a negative trend in diurnal temperature range over the climatic zones of the country in the recent decades of 1980–2010 and attributed this decline to rise in minimum temperature. Mall et al. (2021) also reported a significant increasing trend in minimum air temperature (0.21 °C/decade) and a subsequent decreasing trend in Diurnal Temperature Range (DTR) (− 0.02 °C/decade) was noted during 1991–2016 over the agroclimatic zones of India.

In the present scenario of rapidly rising temperature over India there is a need to assess the changes in cold wave days and identify the hotspots of increasing/decreasing cold wave trends over India particularly in the recent decades as it can severely affect both health and agriculture sector of the country. Since, very few studies have been done assessing the trends of cold wave over India it is necessary to carry out a comprehensive study of analyzing trend of cold wave and severe cold wave days at a high spatial resolution to provide an effective assessment of emerging cold wave hazard over the country. The study will also provide insights on the changing trends of prolonged spells of cold wave i.e. three, five and seven day long cold wave spell which have severe impact on health and agriculture. The objective of this present study is to characterize the changes in cold wave and severe cold wave days and prolonged spells of 3,5, and 7 days as well as trends of minimum temperature over India in cold wave season (Dec–Feb) during the last seven decades of 1951–2021.

2. *Data and Methodology*

2.1. *Study Area*

The study area lies over the meteorological subdivisions of India ranging over 8°4′–37°0.6′N latitude and 68°7′–97°25′E longitude (Fig. 1). The India Meteorological Department (IMD) has divided the country into 36 meteorological subdivisions based on homogenous climatic conditions (Attri & Tyagi, 2010) (Fig. 1). India is characterized by a diverse physiography including the mountains, deserts, plains, plateaus, and coastal region leading to varied climatic conditions across the country. The minimum temperature distribution varies significantly across these subdivisions, necessitating distinct and varied criteria for declaring cold wave conditions (Fig. 1). Coastal regions with higher mean minimum temperatures have higher temperature thresholds for observing a cold wave compared to hilly regions, which observe much lower mean minimum temperatures.

2.2. *Data*

Cold waves are commonly observed in India during the winter season (Dec–Feb). This study focuses on the cold wave season from December to February for the years 1951 to 2021 across the 36 meteorological subdivisions of India. Daily gridded minimum temperature data was obtained from the India Meteorological Department (IMD) for the study period (1951–2021) available at a resolution of 1° latitude × 1° longitude for dataset for 1951–1979 and a spatial resolution of 0.5° latitude × 0.5° longitude was available from 1980 to 2021, was This data was further interpolated to a resolution of 0.5° latitude by 0.5° longitude using the bilinear interpolation method for 1951–1979 to obtain a consistent resolution data for the entire study period (Srivastava et al., 2009).

2.3. *Criteria*

Cold wave (CW) and Severe cold wave (SCW) were defined according to the criteria given by the IMD. According to the criteria a cold wave is declared on the basis of daily temperature departure from the long-term normal (1980–2010) of the region equal or below a minimum threshold temperature of 0 °C for hilly, 10 °C for plain and 15 °C for coastal region as given in Table 1. (IMD, 2018). Cold wave spells and Severe Cold wave spells (SCW) have been

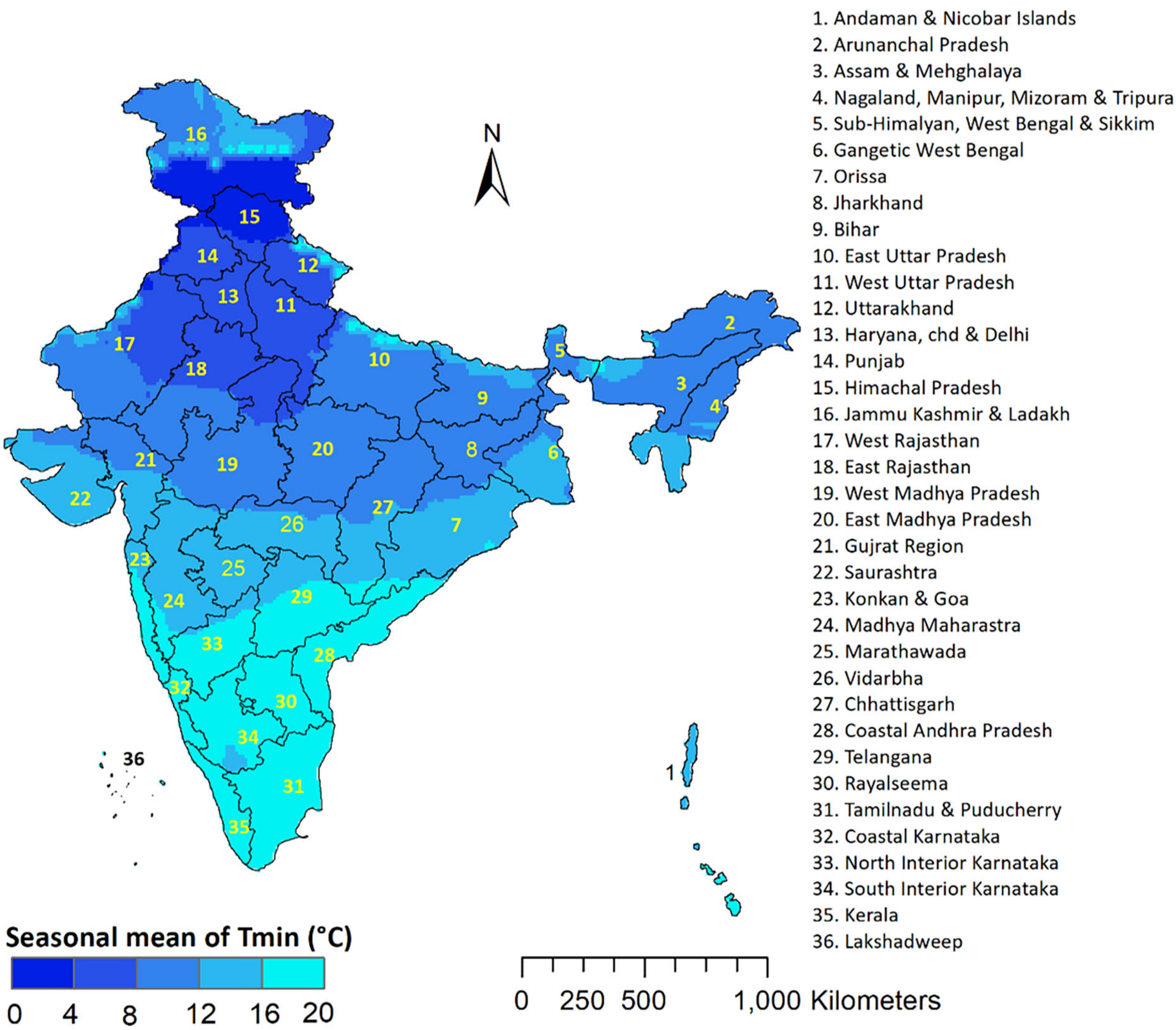

Figure 1
Seasonal mean minimum temperature over India for Dec-Feb during 1951–2021

estimated as a cold wave occurring for a consecutive three days (CW3/ SCW3), five days (CW5/ SCW5) and seven days (CW7/ SCW7) over any region. Trend analysis of the cold wave days and cold wave spells were carried out to understand the changing spatio-temporal pattern of cold wave over India during the past seven decades.

2.4. *Statistical Trend Analysis*

Mann–Kendall trend test is a non-parametric trend test, widely used in extreme weather trend analysis and climatological studies (Kumar et al., 2017; Singh et al., 2021a, 2021b). The present study used the Mann–kendall trend test at a 5% significance level to determine the presence of any monotonic decreasing or increasing trend in the cold wave occurrence for the long-term period Dec–Feb (1951–2021) over India.

3. *Results*

3.1. *Interannual Variation of Temperature Cold Wave Days and Cold Wave Spells*

The interannual variation of mean maximum and minimum temperature for the study period Dec–Feb

Table 1

IMD Criteria for CW and SCW days

(a) When minimum temperature of a station ≤ 10 °C for Plain, ≤ 0 °C for Hilly region and ≤ 15 °C for coastal region		
	Departure from normal	Actual Minimum temperature (only for plain)
CW	− 4.5 to − 6.4 °C	< 4 °C
SCW	< − 6.4 °C	< 2 °C

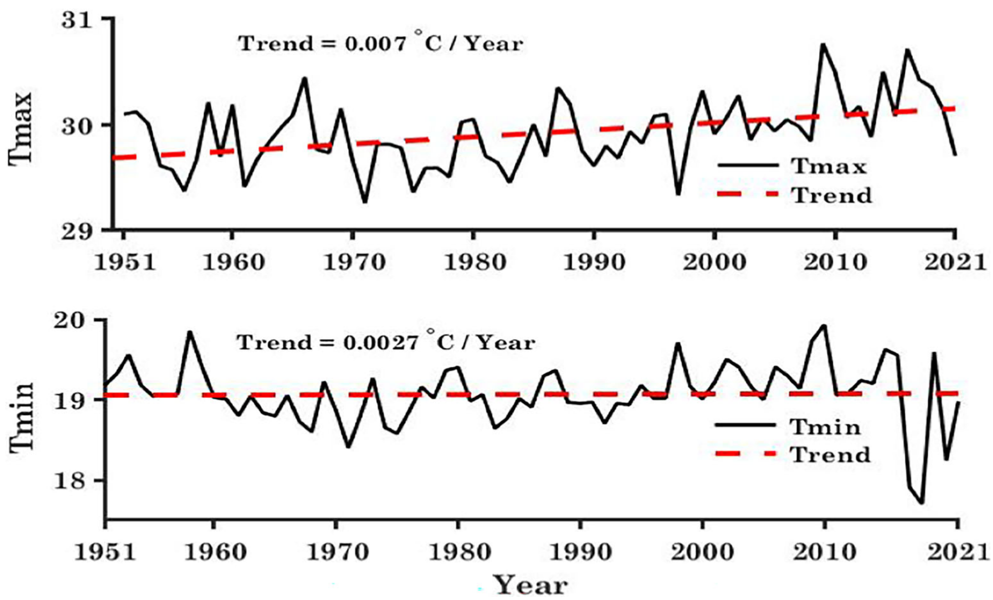

Figure 2
Temporal variation in the mean annual maximum and minimum temperature from 1951 to 2021

(1951–2021) shows an increasing trend in both the variables (Fig. 2). There has been an increase of 0.007 °C/yr in the maximum temperature while the minimum temperature showed an increase of 0.0027 °C/yr. It is observed that the trend of maximum temperature is greater than the minimum temperature over India with a higher increase in Tmax after 1980s which is also in line with the higher global warming (IPCC, 2021). While the temperature trends show an increasing trend, a continuous decrease in the frequency of cold wave and severe cold wave days is observed during the Dec-Feb (1951–2021). The spatial distribution of annual mean minimum temperature shows northern region observe the lowest minimum temperature reaching as low as 0 °C while the southern India witness a higher average temperature of ∼ 20 °C.

The interannual variation of the seasonal average cold wave and severe cold wave days per year observed during the cold wave season of Dec-Feb (1951–2021) has been analyzed (Fig. 3). Both the CW and SCW days show an increase from 1960 to 1980s with a decline after 1980s corresponding to the increase in minimum temperature from the same. Linear trends show a declining trend of -0.029 days/yr (-0.29 days/decade) in CW days which is higher than the trend observed in the SCW days of -0.002 days/decade. Apart from frequency, the trend in occurrence of cold wave and severe cold wave spells of short to long duration is also investigated (Fig. 4).

The area average frequency of 3 day CW days lies from 1 to 3 days/year over India which shows a declining trend of − 0.004 days/year for CW3.

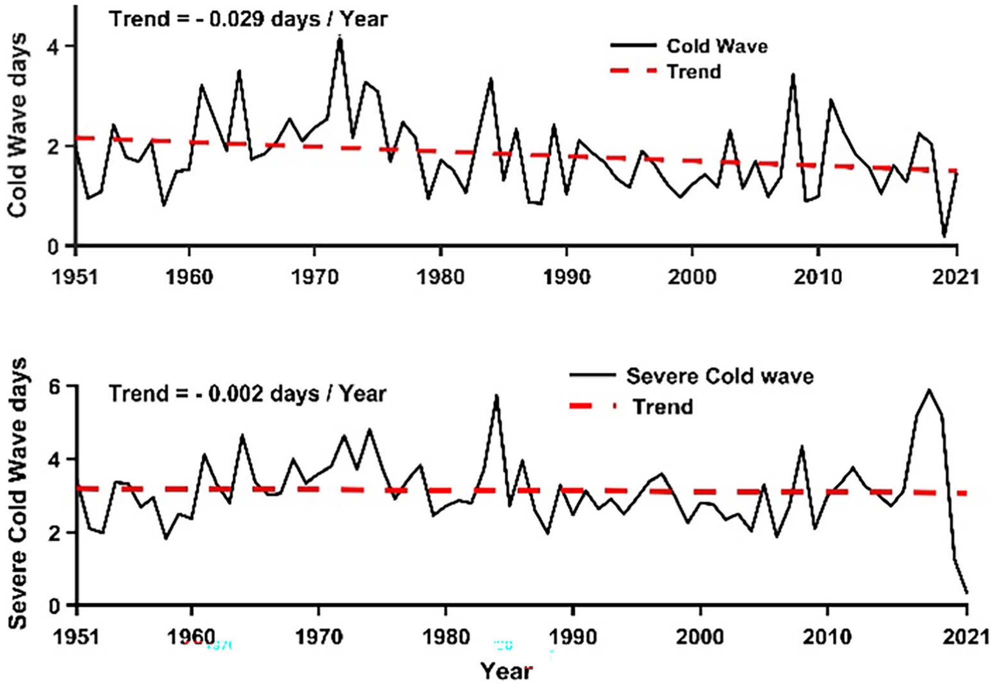

Figure 3
Linear trend of cold waves and severe cold waves from 1951 to 2021 over India

Similarly, the slightly higher 5 consecutive day spell observed a decline of − 0.0013 days/year and the area average range varies from 0 to 2 days/year over India. One of the rare episodes of continuous seven-day event with an average frequency of ~ 1.5 days/year, shows a consistent occurrence with a non-significant trend in either of the direction.

Similarly, trends have been observed for the severe cold wave spells (Fig. 5). The temporal variation of the average severe cold wave spells shows three-day SCW days to be more frequent and observed over a number of years as compared to 5 day which does have a higher frequency but a lower occurrence over the years and 7-day SCW spells which is lower in both frequency and yearly occurrence. A linear decreasing trend of − 0.002 days/year (− 0.02 days/decade) in 3-day SCW days have been observed. Similarly, 5-day SCW days saw a decreasing trend of − 0.005 days/year with no significant trend in 7-day SCW spell over the past seven decades.

3.2. *Spatio-Temporal Trends of Cold Wave and Severe Cold Wave*

The spatial distribution of decadal frequency of cold wave for the past half century 1951–2021 (Dec–Feb) has been studied (Fig. 6). The cold wave has been found to be most frequent in the northern and northwestern region of the country consisting of J&K, Punjab, Haryana, Uttarakhand, East and West Rajasthan meteorological subdivisions. While the north eastern region of the country did not observe cold wave in any of the decades, the southern region observed an increase in spatial occurrence in the recent decades except for the meteorological subdivisions of Kerala, Tamil Nadu and Rayalaseema. A gradual decrease in the frequency of cold wave has been observed from the 1951 to 2021 (Table S1). The northern region observed a decline in occurrence from 30 days/decade to 15–20 days/decade at the end of the century. The spatial distribution shows that the rest of the country experiences less than 10 days of cold wave every decade. During the 1961–1970 and 1971–1980 cold wave days were more frequent with higher frequency in the central region of the country.

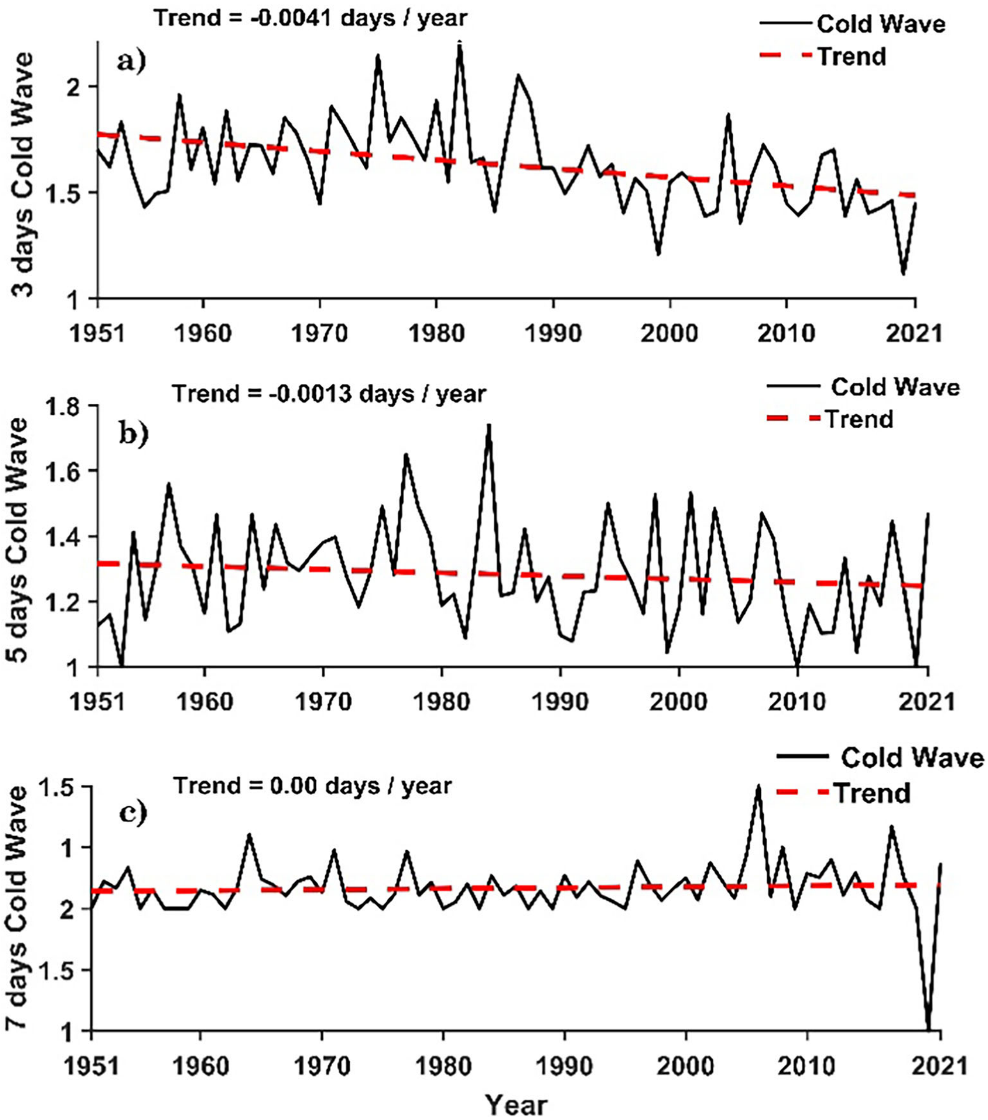

Figure 4
Linear trend of cold waves spell of 3 days, 5 days, and 7 days from (Dec–Feb) 1951–2021

However, post 1991 cold wave days showed a decline over most of the subdivisions, Odisha, North Interior Karnataka, South Interior Karnataka while Saurashtra & Kutch showed an increasing frequency of cold wave days (Table S1).

The decadal variation of severe cold wave event has been shown in Fig. 7. Severe cold wave days were found to occur over only few subdivisions of the country. It primarily occurs over the northern, northwestern, central region. An important observation obtained from the study shows that the SCW have receded post 1980s from most of central, eastern, south-central subdivisions indicating a declining trend from 1980s till 2010 (Table S2). However, an increase is observed in the decade of 2011–2021 where most part of the country is covered in the cold wave with highest frequency in the northern region. East Rajasthan, West Rajasthan and Punjab have recorded SCW in every decade with higher frequency than other subdivisions making them cold wave prone region of the country.

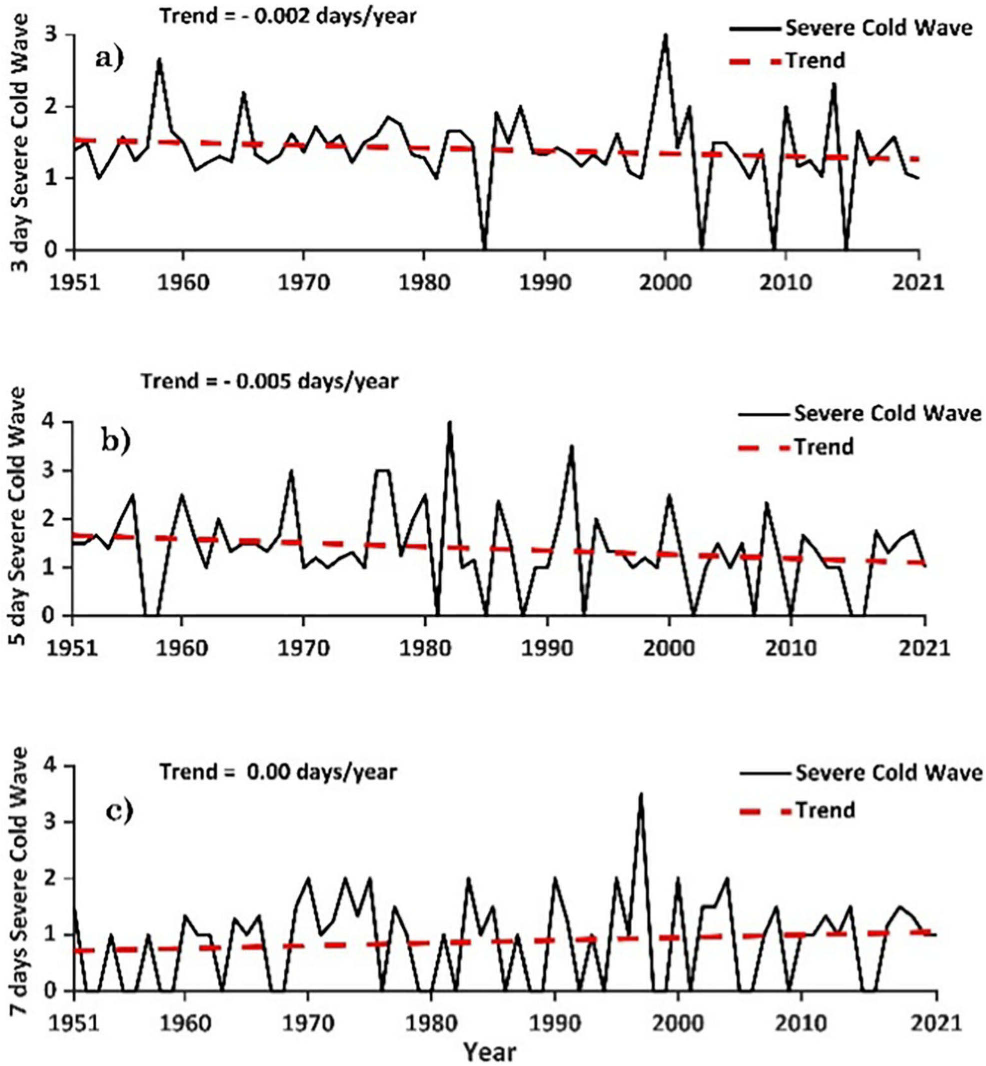

Figure 5
Linear trend of severe cold wave spell of 3 days, 5 days, and 7 days during (Dec–Feb) 1951–2021

Timeseries of cold wave days during Dec-Feb (1951–2021) and linear trend over each of the meteorological subdivision has been assessed (Fig. 8). A decreasing trend is observed in most of the subdivisions of the country with highest being in the West Rajasthan and Punjab (-1.3 days/decade). Geographically, the subdivisions located in the northern, north western, and western region of the country observed a declining linear trend of cold wave while an increasing trend in the eastern region such as Bihar (0.16 days/decade), Odisha (0.2 days/decade), Jharkhand (0.05 days/decade), along with Chhattisgarh (0.12 days/decade) and Marathwada (0.12 days/decade) in the central region of the country was observed. Similarly, the timeseries of severe cold wave days for Dec-Feb (1951–2021) show that only 14 of the 36 meteorological subdivisions observe cold wave days over India (Fig. 9). The time series of cold wave frequency also show that except J&K, Himachal Pradesh, Uttarakhand, East Uttar Pradesh all the meteorological sub divisions observing severe cold wave days showed a declining trend. These declining trends clearly indicate that

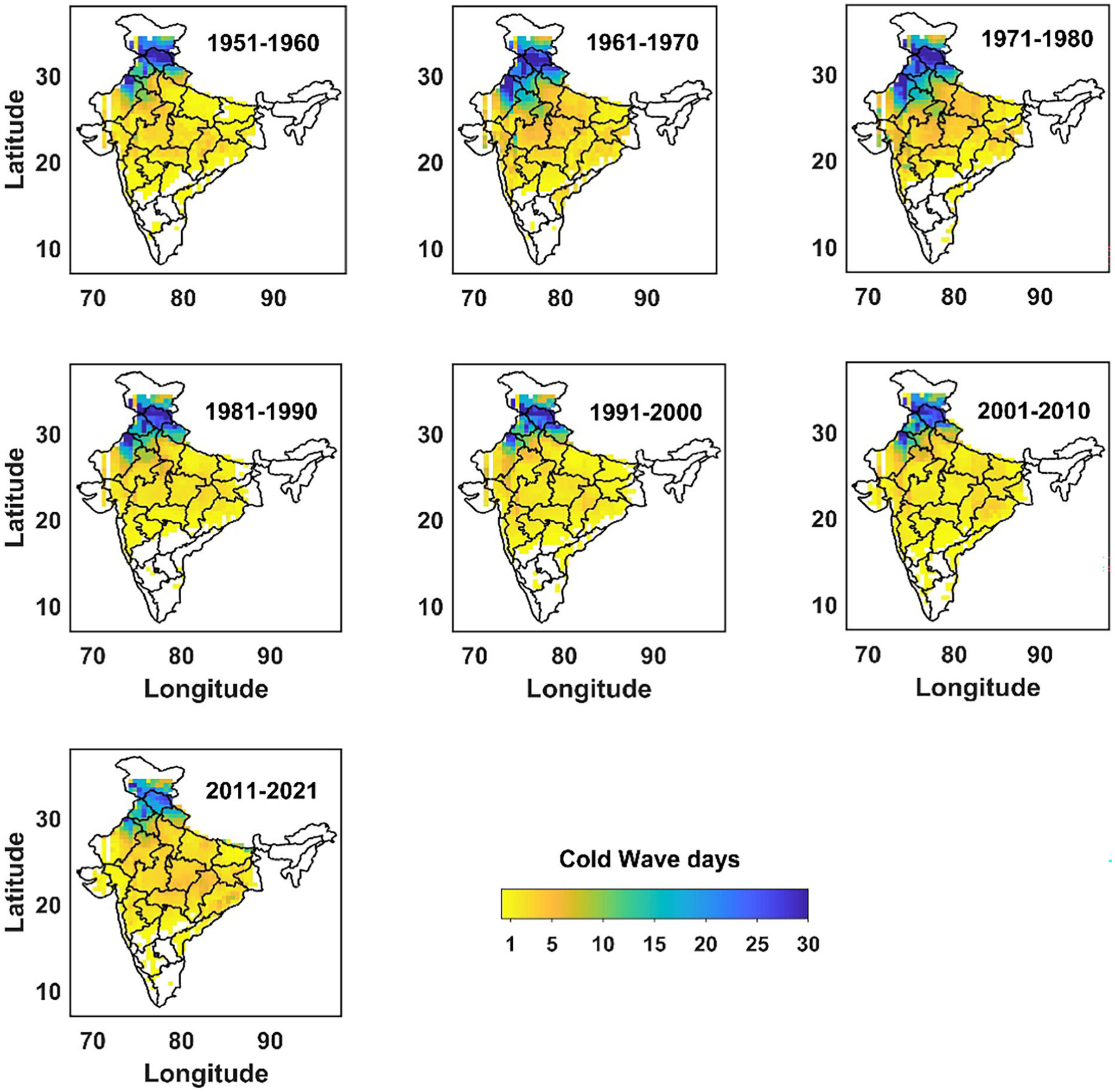

Figure 6
Spatial distribution of decadal cold wave days frequency over India during the 1951–2021(Dec–Feb)

increasing global temperature have reduced extreme cold temperature episodes over India.

3.3. *Spatio-Temporal Trends of Cold Wave and Severe Cold Wave Spells Over India*

Figure 10 shows the frequency of cold wave and severe cold wave spells CW3 (SCW3), CW5 (SCW5), and CW7 (SCW7) for Dec-Feb (1951–2021) over India. The spatial distribution shows that 3-day CW and SCW spells are most pronounced over the meteorological subdivisions of the country followed by 5 and 7-day spells of cold wave and severe cold wave over India. Region wise, the northern and north western subdivisions observe all of the three spells of both CW and SCW. The eastern coastal region consisting of Odisha and Rayalaseema have been found to observe both 5-day and 7-day cold wave

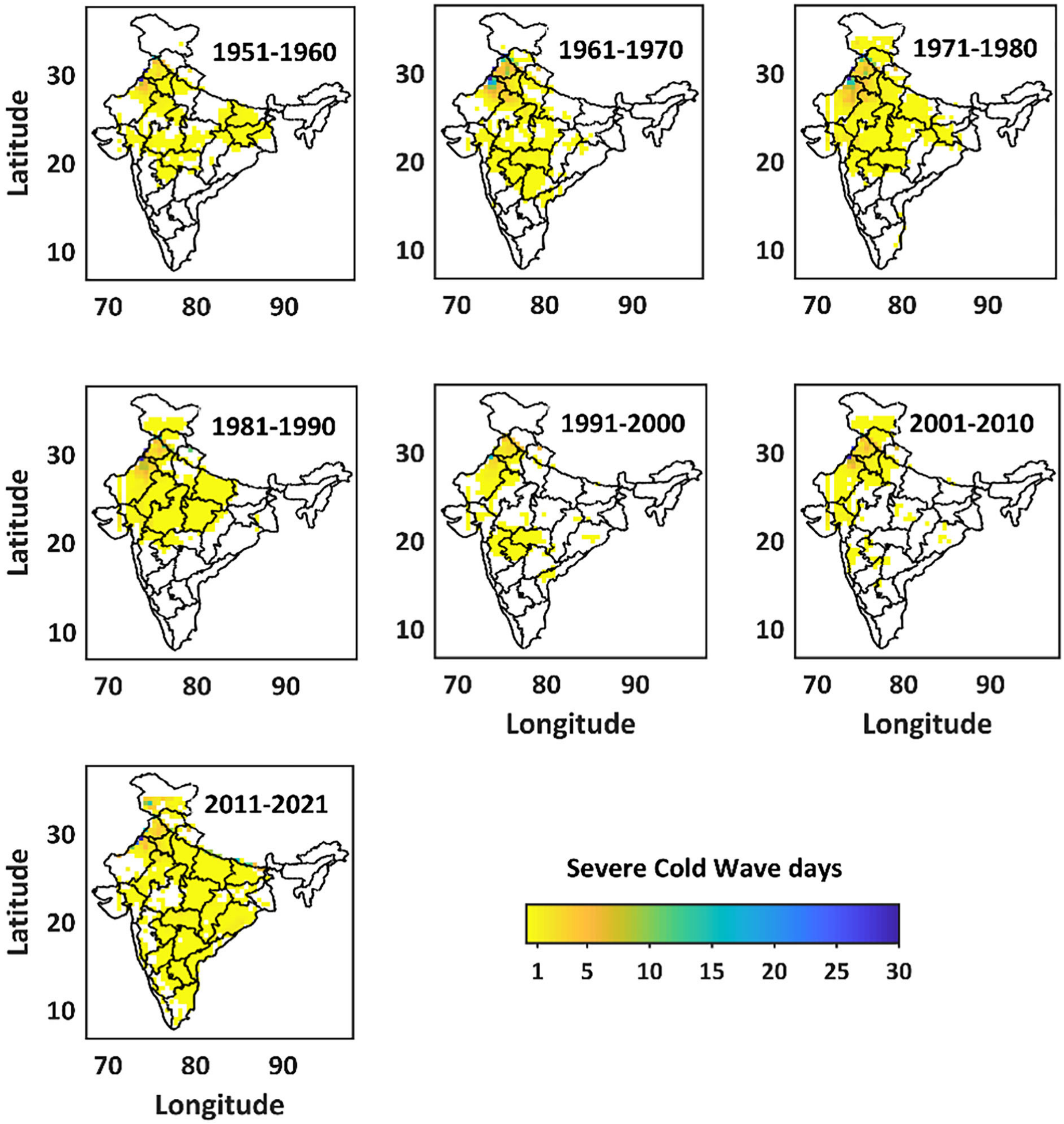

Figure 7
Spatial distribution of decadal severe cold wave days frequency over India during the 1951–2021(Dec–Feb)

spells indicating persistent cold days in these regions which have been devoid of long spells of cold in the earlier decades as shown in the decadal analysis. The seasonal frequency of SCW spells show that 7-day SCW spells have been found to be least frequent and limited to few grids of J & K, Punjab, West Rajasthan, Uttarakhand etc.

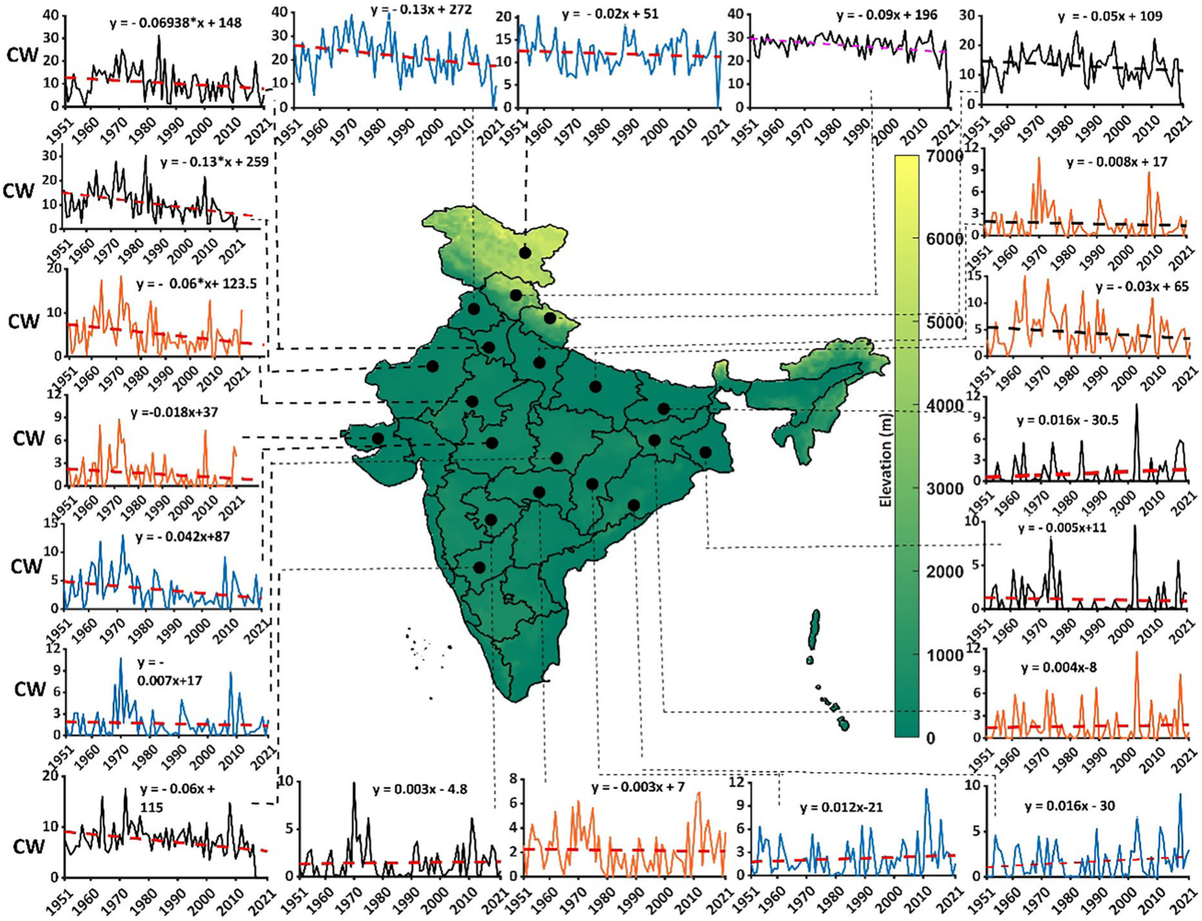

Figure 8
Time series of a seasonal cold wave days over each sub meteorological division for Dec–Feb (1951–2021)

3.4. Trend Analysis

Mann Kendall trend test at 5% significance level was used to determine the long-term trend of seasonal average cold wave and severe cold wave days over the meteorological subdivisions (Fig. 11). While the highest number of cold wave days have been found to occur in the northern and northwestern region of the country the seasonal trends show a decreasing trend over these regions. Eastern Uttar Pradesh experienced an increase in the trend while Punjab, Rajasthan, Haryana, Himachal Pradesh, Uttarakhand, Jharkhand, and Bihar showed a significant decrease. An increasing trend in the frequency and spatial coverage of SCW occurred over the area of southern coastal Odisha, northern J & K, and central Chhattisgarh. While a declining trend is observed in cold wave days over most of the sub-divisions, West Rajasthan (− 0.13 days/year), East Rajasthan (− 0.05 days/year), Haryana (− 0.07 days/year), Himachal Pradesh (− 0.05 days/year), Gujarat (− 0.01 days/year), Sub. Him. W. Bengal and Sikkim (− 0.02 days/year), Saurashtra, Kutch and Diu (− 0.02 days/year),and (− 0.04 days/year) reported a significant decline (Table 2).

West Rajasthan (− 0.02 days/year) and Punjab (− 0.04 days/year) reported a significant decline in severe cold wave days while other subdivisions reported a non-significant increase in the occurrence. Odisha and Chhattisgarh observed a non-significant increasing trend in cold wave and severe cold wave events. Similar trends have been reported by Bhattacharya et al. (2023) while analyzing the changing

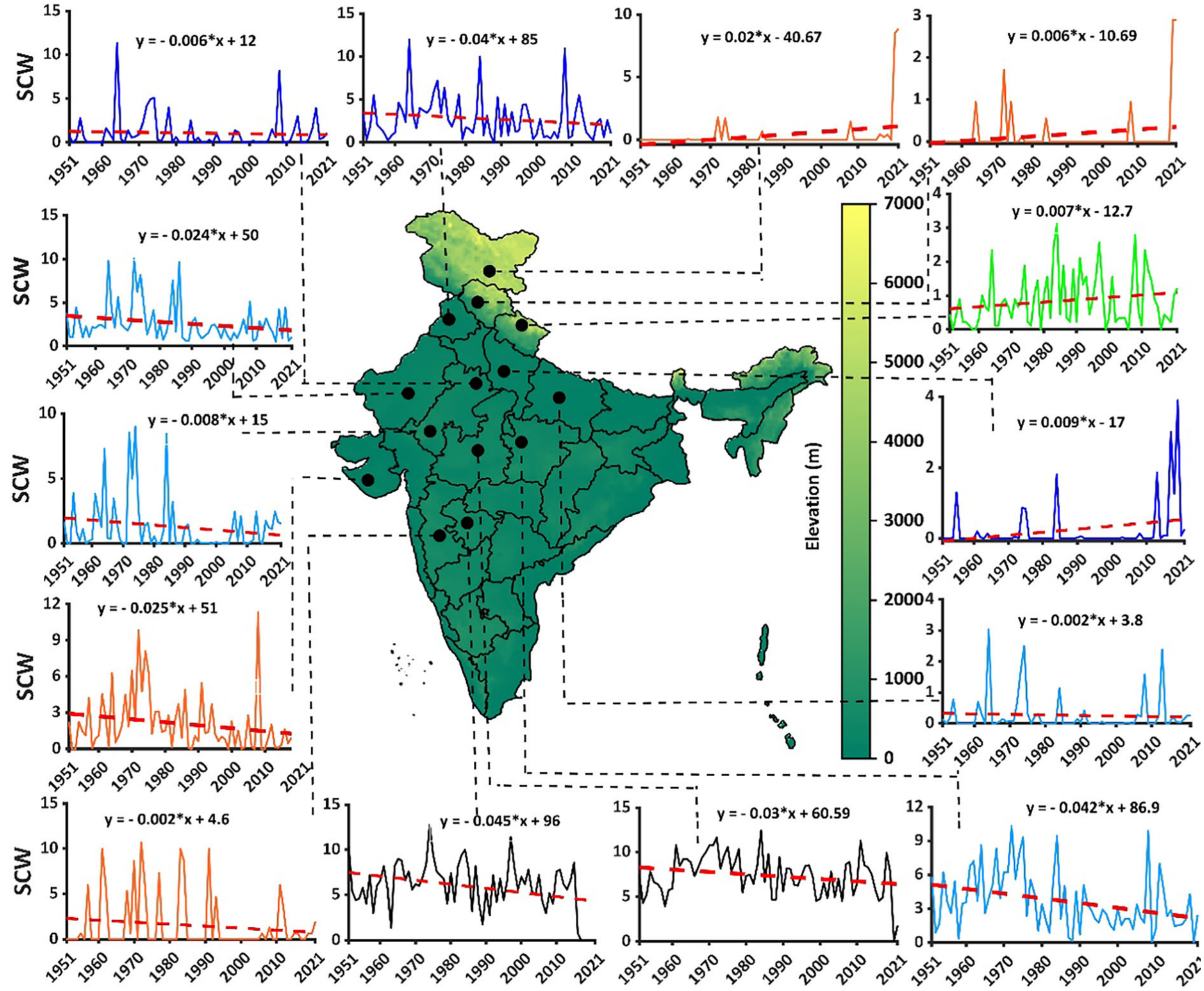

Figure 9
Time series of a seasonal severe cold wave days over each sub meteorological division

trends of heat wave and cold wave events over the climatic zones of India. This increase in cold wave days in Odisha and adjoining subdivisions corresponds to a decreasing trend in minimum temperature over the eastern region of the country extending to Indo-Gangetic Plain and meteorological sub divisions of Bihar, Jharkhand and Odisha as reported by Vinnarasi et al. (2017).

4. Discussion

The study reveals a declining trend in cold wave days and cold wave spells across the meteorological subdivisions of India over the past seven decades. This consistent decline in cold wave events, particularly in the northwest and central India, aligns with findings from previous studies (Nair et al., 2016; Pai et al., 2004). Nair et al. (2016) specifically noted a significant decline in severe cold wave trends from 1971 to 2010 over the 63 homogenously distributed stations in India. Our study corroborates these findings and highlights an increase in minimum temperatures in recent decades, especially post-1980s (Mall et al., 2021; Vinnarasi et al., 2017). The observed decrease in CW/SCW frequency and spatial coverage is largely attributed to the increasing trends

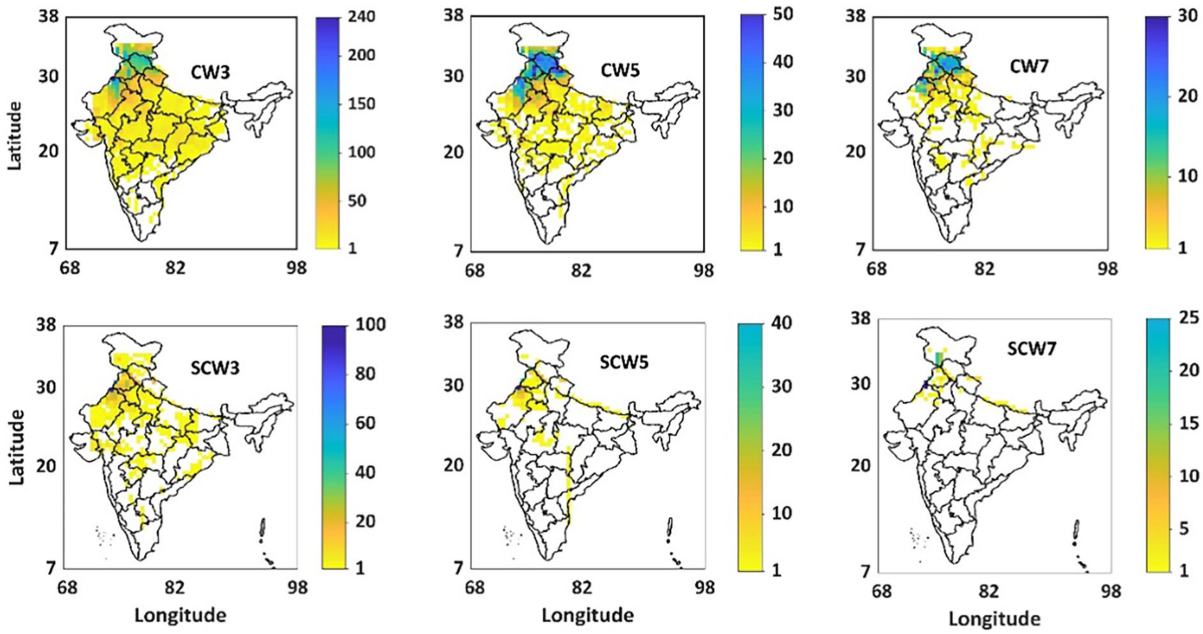

Figure 10
Spatial distribution of total number of 3-day (CW3/SCW3), 5-day (CW5/SCW5), and 7-day (CW7/SCW7) spells of CW and SCW days over India during 1951–2021 (Dec–Feb)

minimum temperature trends across India (Nair et al., 2016).

During the post-monsoon and winter seasons, the increase in minimum temperatures is particularly pronounced, which may explain the decline in cold wave occurrences (Mall et al., 2021; Nair et al., 2016). The rising trend of cold wave days in regions such as Odisha, Chattisgarh, and Coastal Andhra Pradesh corresponds with the declining minimum temperature trends in these areas over recent decades (Ross et al. 2018). This cooling anomaly is attributed to increasing aerosol concentration that absorb solar radiation over the Indo-Gangetic plains and the eastern regions of the country (Ross et al., 2018; Zhou et al., 2017). This increase in cold wave occurrences in the eastern coastal region, previously unaffected by such extremes poses significant health risks, particularly to the elderly, and negatively impacts crop yield. Despite the decreasing trend in cold wave events in regions such as Bihar, Odisha, and Chhattisgarh, the highest cold wave events are still reported in the northwestern and northern subdivisions, posing a significant threat to human health (Malik et al., 2020**).** These regions including northern (Chandigarh, Delhi, J and K), northwest (Rajasthan) central northeast region (Uttar Pradesh, Bihar, Jharkhand) record the highest mortality rates due to cold wave and frequent 3-to-7-day cold wave spells. Investigating the underlying physical mechanism of cold waves Athira et al. (2024) found that cold wave in these regions occur due to cold air advection from high latitudes. The northwesterly winds drive this advection over the northern India as baroclinic disturbances provide favorable condition for cold air intrusion. These conditions have also been reported for prolonged spells of cold wave events of duration $\sim$ 26 days over the northwestern India (Sandeep and Prasad, 2020). Along with the western disturbance, long spells of cold wave events are also observed in the presence of La-Nina condition hence long spells prevail more during La-Nina years (Mandal et al., 2023).

5. *Conclusion*

The present study shows a paradigm shift in the trend of cold wave days and spells over India during

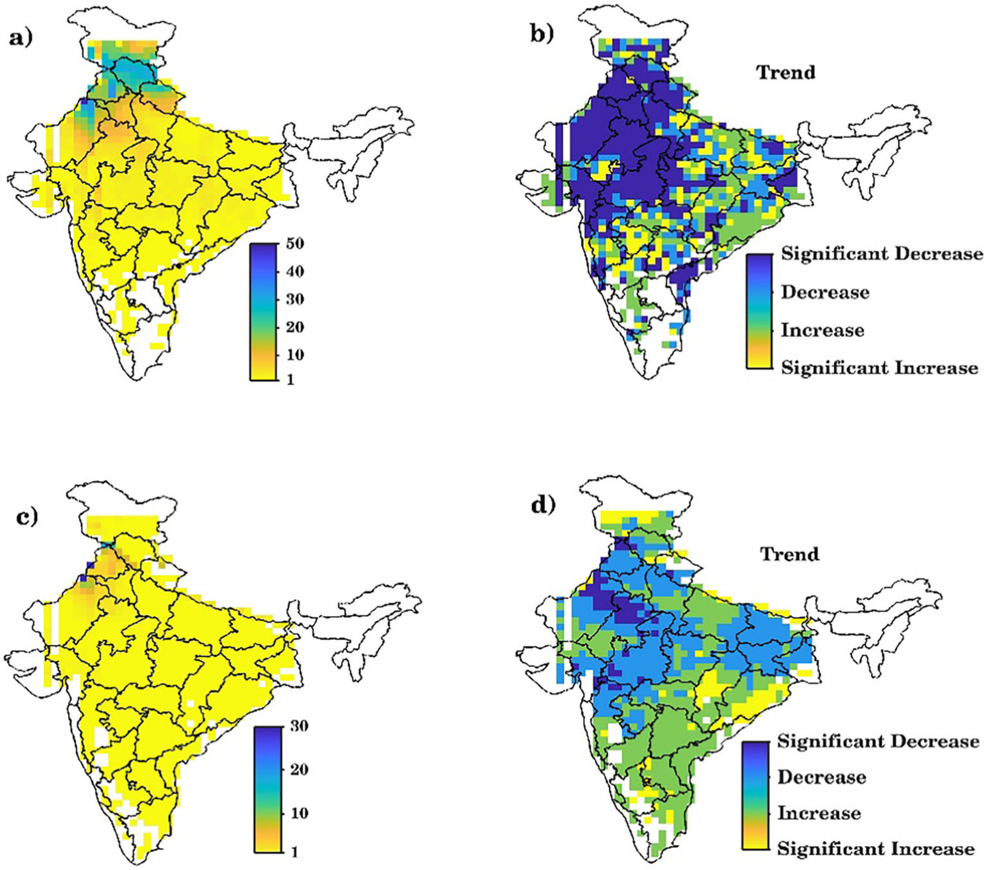

Figure 11
Seasonal average and Long-term trend in Seasonal Cold wave **a** and **b** and Severe cold wave **c** and **d** for Dec-Feb during 1951–2021

the last seven decades, with both declining and increasing trends reported in the different parts of the country. The northwestern India reported a significant declining trend where most cold waves are reported whereas an increase was observed in the Odisha and Andhra Pradesh. These new emerging trends of cold wave indicate towards the changing trends of mini mum temperature trends over India. While the increasing minimum temperature can be attribute to the increasing global temperature, the declining trend may have anthropogenic influence adding another dimension to cold wave research in future. Although the cold wave prone regions of the country are showing a declining trend, the highest mortality due to cold waves is reported in these regions, making them vulnerable to cold waves. As most of the meteorological subdivisions observe 3–5 days of cold wave spells, changing trends and occurrences may have severe impacts on both health and agriculture. The varied trend in cold waves and increasing minimum temperatures are altering the critical temperature needed for wheat production, making loss in wheat yield an inevitable impact of cold wave occurrences over India. As India records increasing and earlier occurrences of heat waves, which have negatively impacted wheat production, the consistent decline in cold extremes in recent decades will profoundly impact wheat yield, threatening the country's food security. While much research is be ing done on different climate extremes, there is still a lack of research on understanding the changing dynamics of cold extremes under warming scenarios and their impact on health and agriculture sectors. Therefore, this study emphasizes the need for in-depth analysis

Table 2

Cold wave and severe cold wave trend for the sub-meteorological division of India

Meteorological subdivision	Cold wave days		Severe cold wave days	
	Sen's slope	Kendall's Tau	Sen's slope	Kendall's Tau
Bihar	0.00	0.02	0.00	0.16
Chhattisgarh	0.00	0.02	0.00	0.14
Coastal Andhra Pradesh	0.00	− 0.07	0.00	0.09
East Madhya Pradesh	0.00	− 0.02	0.00	0.08
East Rajasthan	− 0.05*	− 0.18	0.00	− 0.06
Gangetic West Bengal	0.00	− 0.04	0.00	0.03
Gujarat	− 0.01*	− 0.18	–	–
Haryana	− 0.07*	− 0.15	0.00	0.00
Himachal Pradesh	− 0.05*	− 0.18	0.00	0.03
Jammu Kashmir and Ladakh	−0.01*	− 0.03	0.00	0.05
Jharkhand	0.00	− 0.04	0.00	0.08
Madhya Maharashtra	0.00	− 0.02	0.00	0.02
Marathawada	0.00	0.08	0.00	0.00
North Interior Karnataka	− 0.04*	− 0.18	00	0.02
Odisha	0.00	0.08	0.00	0.16
Punjab	− 0.13*	− 0.20	− 0.04*	− 0.16
Rayalaseema	0.00	0.02	0.00	0.07
Saurashtra, Kutch and Diu	− 0.02*	− 0.18	0.00	− 0.06
South Interior Karnataka	0.00	0.04	0.00	0.06
Sub Himalayan West Bengal and Sikkim	− 0.02*	− 0.24	0.00	− 0.19
East Uttar Pradesh	0.00	− 0.02	0.00	0.14
West Uttar Pradesh	− 0.02	− 0.10	0.00	0.00
Uttarakhand	− 0.05	− 0.11	0.01	0.13
Vidarbha	− 0.01	− 0.05	0.00	0.06
West Madhya Pradesh	− 0.04	− 0.20	0.00	− 0.03
West Rajasthan	− 0.13*	− 0.30	− 0.02*	− 0.18
Telangana	–	–	0.02	0.14

*Significant Increase/decrease at a 95% confidence level

of changing trends of cold extremes over India in future scenarios to prevent its impending impact on the agricultural production and health of the population residing in both cold-wave prone and newly emerging cold wave zones.

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Author Contribution RKM overall supervised and provided the resources for this study. RKM and SS contributed to the study conception and design. Material preparation, data collection and analysis were performed by SS and PKG. The first draft of the manuscript was prepared by SS & RKM reviewed and edited the manuscript at different stages. All authors read and approved the final manuscript.

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Data Availability

The IMD data can be accessed on request from https://cdsp.imdpune.gov.in/. Authors declare that all data and materials support their published claims and comply with field standards.

Declarations

Conflict of Interest The authors declare no competing interests.

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