Chapter 6

Physical Mechanisms of Cold Waves

This chapter discusses the physical mechanisms of cold waves over India. There are not enough studies dealing with the physical mechanisms of cold waves over India. Cold waves usually occur due to the transport of cold air from higher latitudes in conjunction with the eastward moving westerly disturbances (Bedekar et al. 1974). As the subtropical westerly jet stream moves south towards India, these weather systems affect the northern parts of India during the winter season. Cold waves are often observed after the passage of westerly disturbances. The occurrence of cold waves due to the prevailing low pressure systems over the northern Arabian Sea is also observed (Bedekar et al., 1974). The easterly winds north of these systems bring cold air from higher latitudes.

The study by Bedekar et al. (1974) found that cold waves are caused by the inflow of very cold air from northern latitudes, i.e. from the extreme northwestern parts of the Indian subcontinent or even beyond. When this unusually cold air spreads over other parts of the country, it manifests itself as a cold wave in those parts. Therefore, any pressure system or synoptic situation that can cause an influx of cold air from these northern latitudes into India creates favourable conditions for the occurrence of a cold wave. A pronounced trough in the upper westerly wind zone is more or less a common feature of the western disturbance systems. Near the axis of these troughs, a pool of cold air can often be discerned in the upper layers. This pool of cold air always moves along with the troughs, and sometimes it can also be seen to spread to deeper layers to reach the ground and manifest itself as cold surface waves.

The cold air that accompanies these troughs has a fairly pronounced tilt to the east in the vertical with respect to the axis of the trough. Due to this characteristic of cold air troughs, it can be observed that cold waves generally develop much earlier (about 12-36 hours) in the upper layers of stations located far east of the trough axis than in the surface layers of these stations. This characteristic feature is observed in most (about 80 %) of the severe cold-core depressions.

The recent study by Ratnam et al (2016 b) made a comprehensive analysis of the cold waves occurring over the Indian region and the associated physical mechanisms. They found that there are two types of cold waves over India, called type-1 and type-2 cold waves. This section discusses the detailed findings of Ratnam et al. (2016 b) in the context of cold waves over India.

Ratnam et al. (2016 b) identified cold waves using an index by taking an area average of minimum temperature (Tmin) anomalies over the region 71°E-80°E; 21°N-30°N (shown as a box in Fig. 6.1 a). A cold wave event is identified if the defined index on a selected day is less than one standard deviation and the anomalies persist for at least 4 days. Twenty-nine events were identified based on the criteria they adopted (which are similar to the IMD criteria). The cold waves occurring during the La Nina years are called TYPE1 events and the cold waves occurring during the El Nino years are called TYPE2 events. The TYPE1 and TYPE2 events thus identified are listed in Table 6.1 and Table 6.2 below. In general, TYPE1 events are more frequent compared to TYPE2 events.

Table 6.1

TYPE1 Cold Wave Events

(Taken from Ratnam et al. 2016 b)

1) 8–17 Nov 1983	8) 9–14 Jan 1989	15) 21–25 Jan 2008
2) 27–30 Jan 1984	9) 19–23 Feb 1989	16) 30 Jan-2 Feb 2008
3) 5–9 Feb 1984	10) 9–12 Feb 1989	17) 7–15 Feb 2008
4) 20–28 Feb 1984	11) 8–13 Dec 1996	18) 4–12 Jan 2011
5) 19–23 Dec 1984	12) 9–12 Jan 1999	19) 10–14 Jan 2012
6) 11–18 Feb 1985	13) 11–15 Dec 2005	20) 8–11 Feb 2012
7) 4–8 Jan 1986	14) 6–10 Jan 2006	21) 4–9 Jan 2013

Table 6.2

TYPE2 Cold Wave Events

(Taken from Ratnam et al. 2016 b)

1) 11–15 Jan 1983	4) 19–25 Dec 1986	7) 14–19 Jan 2003
2) 3–8 Feb 1983	5) 6–9 Dec 1987	8) 19–23 Feb 2005
3) 14–17 Dec 1986	6) 31 Dec 1990	

From these tables, it can be seen that most cold spells occur in the months of January (12) and February (10). Ratnam et al (2016 b) found that out of 29 events, 21 (8) occurred in La Nina (El Nino) years, suggesting that both phases of ENSO (El Nino and La Nina) favour the occurrence of cold waves over India. However, there is a tendency for more cold waves during the La Nina years.

The composite anomalies of various parameters of TYPE1 and TYPE2 cold wave events are shown in Fig. 6.1. The composite SST anomalies averaged over these 21 events in La Niña years show colder than normal SST anomalies along the equatorial central Pacific, extending from the central to the eastern Pacific, with concurrent warmer than normal SST anomalies in the equatorial western Pacific (Fig. 6.1 b). Similarly, the SST anomalies for the eight events corresponding to El Niño years show significantly positive SST anomalies in the equatorial Pacific, extending from the central to the eastern Pacific, with cooler than normal SST anomalies in the western Pacific (Fig. 6.1 c). Moreover, composite Tmin anomalies for TYP1 events show a marked decrease in Tmin over most parts of India (Fig. 6.1 d). On the other hand, for TYP2 events, a significant decrease in Tmin is mainly confined to north-western India, with positive anomalies along the east coast of India (Fig. 6.1.e).

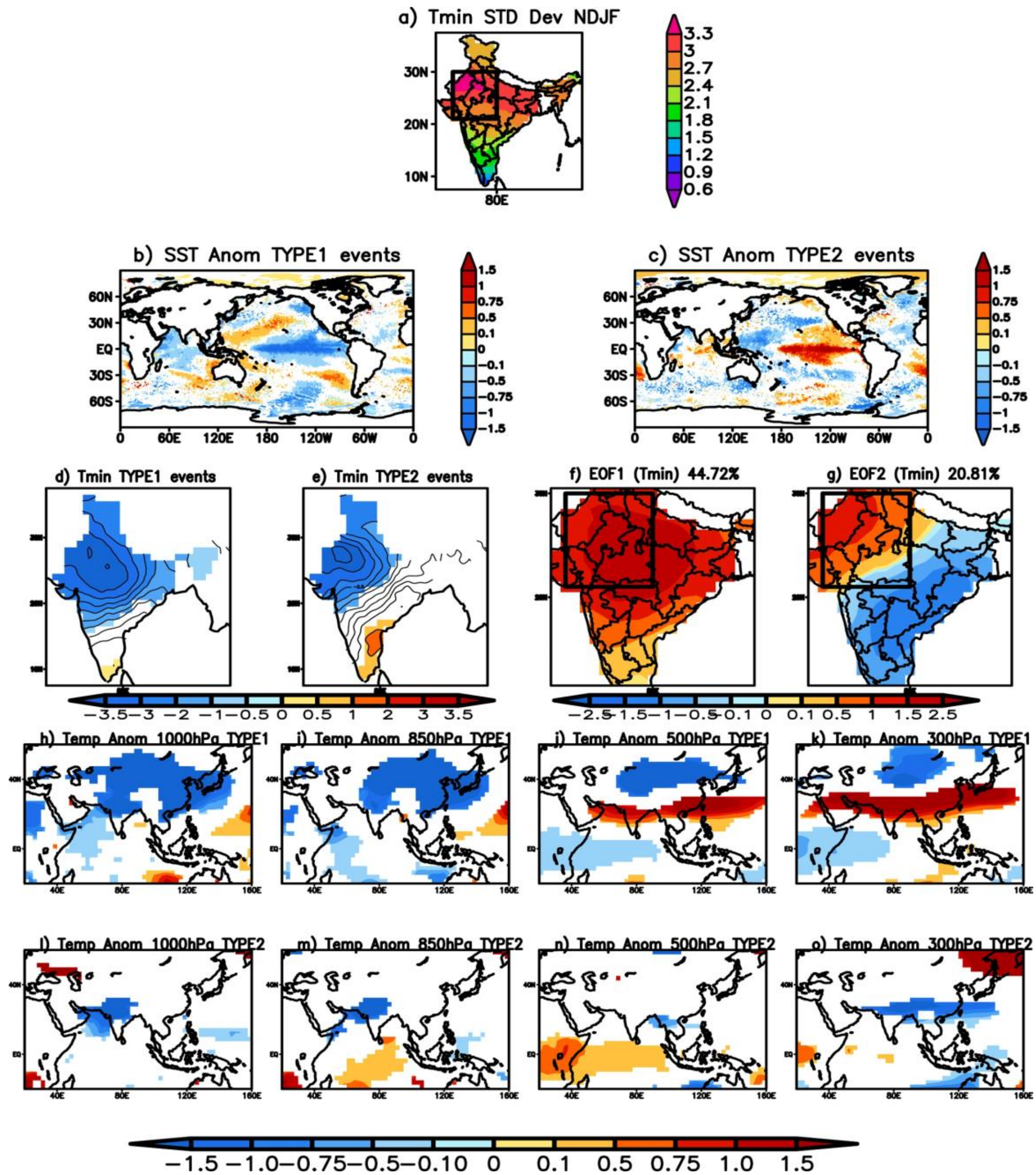


Fig 6.1 (a) Standard deviation of the Tmin (°C) from 1st Nov to 28th Feb over the period 1982 to 2013. (b) Spatial distribution of significant SST (°C) anomalies during TYPE1 events. (c) same as (b) but for TYPE2 events. (d) Significant Tmin (°C) anomalies associated with TYPE1 events (e) same as (d) but associated with TYPE2 events. (f) The first mode of EOF of Tmin anomalies. (g) The second mode of EOF of Tmin anomalies. (h–k) Significant air temperature anomalies (°C) at 1000 hPa, 850 hPa, 500 hPa and 300 hPa respectively during TYPE1 events. (l–o) Significant air temperature anomalies (°C) at 1000 hPa, 850 hPa, 500 hPa and 300 hPa during TYPE2 cold wave events. (Taken from Ratnam et al. 2016 b)

To objectively separate the modes of variation, an empirical orthogonal functional analysis (EOF) was performed over the region 70°E-90°E; 12°N-30°N. Figure 6.1f shows the first EOF mode, which explains 44.72% of the total variance. This mode has large loadings over the region with high standard deviation of Tmin temperatures (Fig. 6.1 a) and has a similar pattern to the spatial distribution of Tmin anomalies during TYPE1 cold wave events (Fig. 6.1 d). Moreover, the correlation between the Tmin anomalies averaged over the region 71°E-80°E; 21°N-30°N and the principal component of this mode is 0.91, which is very high. The second mode (EOF2) (Fig. 6.1 g) explains about 20.81% of the total variance and shows a dipole structure similar to the TYPE2 cold wave events (Fig. 6.1.e), with opposite phases over northwest India and along the east coast of India. The correlation of their principal component with the Tmin anomalies, averaged over the region 71°E-80°E; 21°N-30°N, is only 0.385. Thus, the analysis of EOF justifies the division of the observed cold wave events into TYPE1 and TYPE2 events.

During the TYPE1 cold wave events, colder air than normal is confined to about 850 hPa in the northern parts of India, while warmer air prevails at 500 hPa and above. Over India, the low pressure areas are an effective means of bringing in cold air from the north. During TYPE2 events, colder than normal temperatures are confined to the northwestern parts of India in the lower troposphere (Fig. 6.1 l-m). Temperatures over India are not significant at 500 hPa (Fig. 6.1 n), although significant anomalously cold temperatures are observed at 300 hPa over Indian latitudes during the TYPE2 events (Fig. 6.1 o).

Further details on the TYPE1 and TYPE2 events are discussed below.

6.1. TYPE1 Cold waves (associated with La Nina events)

Fig. 6.2a shows the spatial distribution of the composite anomalies of the output longwave radiation (OLR). In response to colder than normal SST anomalies, positive OLR anomalies (indicating less cloud cover) are observed over the equatorial central

Pacific, while negative OLR anomalies (indicating excessive cloud cover and more precipitation) are observed from the west of the Philippines to the east coast of India. Over northwestern India and into Pakistan, the prevailing colder air temperature in the boundary layer (Fig. 6.1 h-k) increases stability and thus limits convection development, resulting in positive OLR anomalies there (Fig. 6.2a).

To investigate whether remote teleconnection was the cause of the TYPE1 cold waves, composite 200 hPa vortices (without zonal mean) streamfunction anomalies (Fig. 6.2 b) were recorded. The composite (Fig. 6.2 b) shows the following prominent features that may have contributed to the TYPE1 cold wave events over India. i) A region of anomalous positive anomalies over the Ural-Siberian region and a wave train originating from there and extending to southern China, with a trough over most parts of China and a ridge over southern China and the northeastern parts of India, and ii) a region of anomalous anticyclone over the Indian landmass.

The feature that helps transport cold temperatures from higher latitudes to Indian latitudes and sustains the cold waves is also clearly seen in Fig. 6.2 b as an anticyclonic anomaly at 200 hPa over the Indian latitudes. The anomalous trough over China and the anomalous ridge over southern China extend from 500 hPa to 200 hPa (Fig. 6.2 c). At 850 hPa (Fig. 6.2 d), the anomalous ridge over the Ural-Siberian region and the associated trough over the Indochina region can be seen, causing cooler than normal temperatures over the region (Fig. 6.1 i). The north-south orientation of the cyclonic anomaly over northern India favours the advection of cold air from higher latitudes to India. The horizontal 850 hPa advection of the mean observed temperature by the mean observed winds was calculated (Fig. 6.2 e) to investigate whether the cold waves over India are caused by horizontal advection of cold air from higher latitudes.

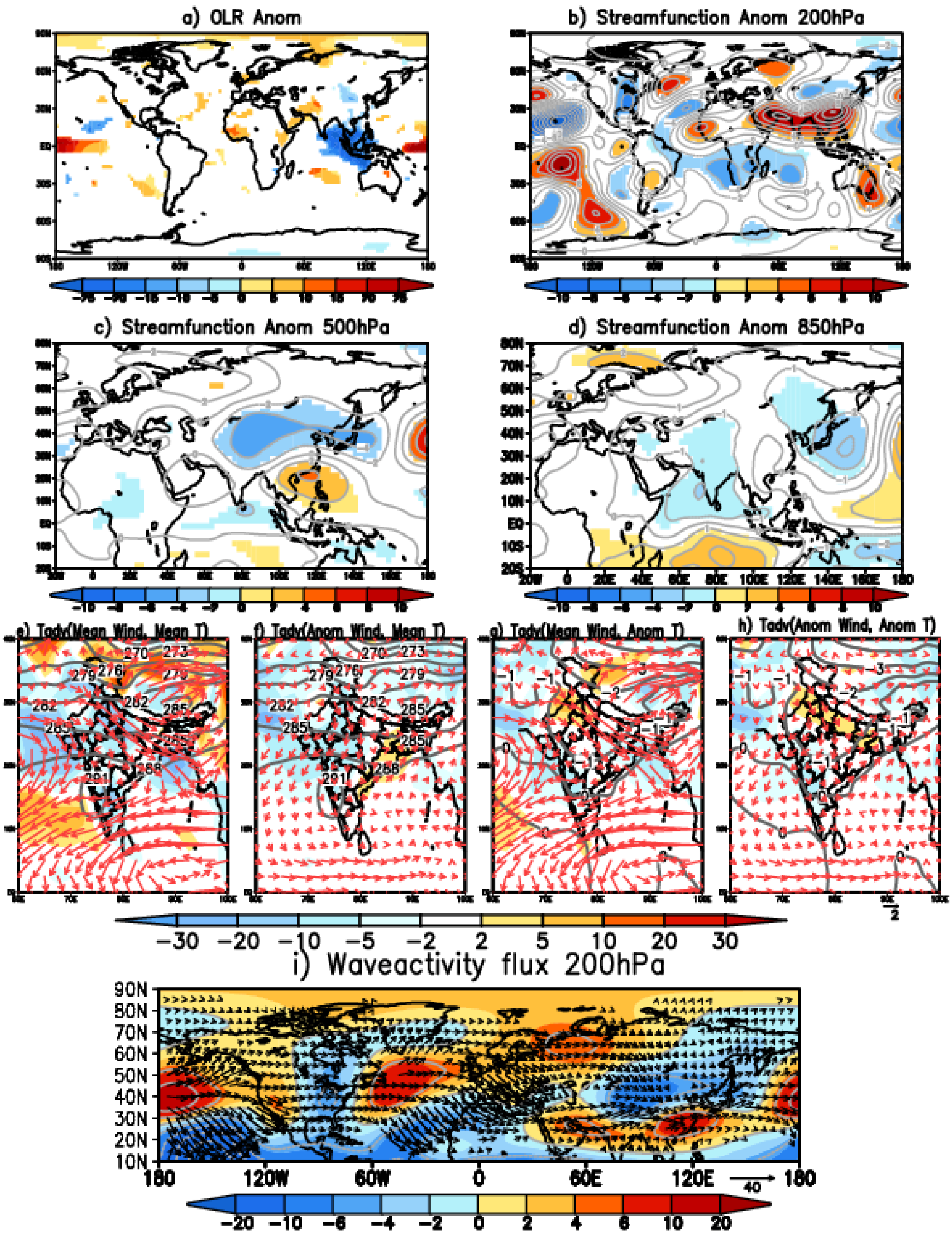


Fig 6.2. (a) Significant OLR (W/m^{-2}) anomalies of the composite of TYPE1 cold wave events. (b,c and d) same as (a) but for significant eddy streamfunction ($\times10^{6}$ m^{2} s^{-1} ; shaded) at 200 hPa, 500 hPa and 850 hPa levels respectively. (e) Horizontal temperature advection (shaded; $\times10^{-6}$ °K s^{-1}) of mean temperature by mean winds at 850 hPa during

TYPE1 events. Contours represent mean temperatures and mean wind at 850 hPa is shown by vectors (f) same as (e) but advection of mean temperature by anomalous wind (shaded). Mean temperature (contour) and anomalous winds (vectors) are also shown (g) same as (e) but advection of anomalous temperature by mean winds (shaded). 850 hPa temperature anomalies are shown as contours and mean winds as vectors (h) same as (e) but advection of anomalous temperature by anomalous winds (shaded). Contours represent temperature anomalies and vectors represent anomalous winds at 850 hPa (i) Significant wave activity flux anomalies at 200 hPa (vector; either zonal or meridional component is significant) and the stream function anomalies (shaded) for TYPE1 cold wave events. (Taken from Ratnam et al. 2016 b).

During TYPE1 events, northwesterly winds are observed bringing cold temperatures from higher latitudes to the Indian subcontinent, resulting in a drop in temperatures over the Indian landmass (Fig. 6.2 e). From Fig. 6.2 f-h, it is evident that the advection of the observed mean temperature by the anomalous cyclonic response (Fig. 6.2f) largely explains the cold air advection over large parts of India. This term (Fig. 6.2f) makes a larger contribution than all the other terms (Fig. 6.2 g-h). The anomalous cyclonic winds bring warmer temperatures from the equatorial region, resulting in above-average temperatures on the east coast of India (Fig. 6.2f). The effect of cold advection by the anomalous winds is reduced over the northern parts of India by warm advection of anomalous temperature by the mean winds (Fig. 6.2 g) and also by advection of anomalous temperature by the anomalous winds (Fig. 6.2h). Both the advection of anomalous temperature by the mean observed winds (Fig. 6.2g) and by the anomalous winds (Fig. 6.2h) bring cooler temperatures to the upper Bay of Bengal and also to the western parts of India.

The low-level cyclonic anomaly observed over India during TYPE1 cold waves (Fig. 6.2 d) can be partly attributed to the seasonal mean equatorial cyclonic anomaly observed during the La Niña events. Fig. 6.3 shows composite OLR anomalies, 850 hPa eddy current function (shaded) and 850 hPa wind anomalies (vector) created by averaging monthly December-February anomalies during La Niña years from 1982 to 2013. In response to a spatially coherent negative OLR anomaly over the maritime continent and western Pacific regions (Fig. 6.3a), a pair of cyclones can be seen spanning the equator over the Indian Ocean (Fig. 6.3b). The poleward flank of the northern hemispheric part of the cyclonic anomalies (Fig. 6.3 b) is favourable for bringing cold temperatures from higher latitudes to the Indian region in La Niña years.

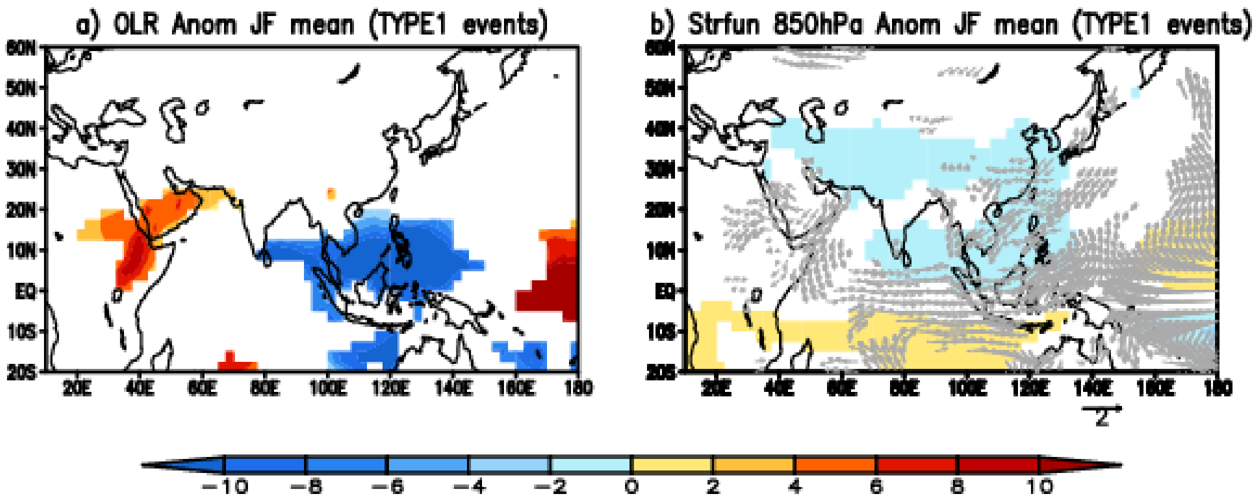


Fig. 6.3. (a) Significant OLR anomalies composited over Dec–Feb months during the La Niña years over the period 1982 to 2013. (b) same as (a) but is for significant eddy stream function (×10^6 m^2s^{-1}) anomalies at 850hPa and significant wind anomalies (vectors; either zonal or meridional component is significant).

To examine the progress of cyclonic circulation over northwest India and initiation of cold wave events, the 850 hPa eddy stream function anomalies of all the TYPE1 cold wave events from 5 days (DAY-5) before the event to the day the event started (DAY0).

The results are presented in Fig. 6.4. The Day-0 is considered the day when the events started. Five days before the TYPE1 cold wave events occurred over India (DAY-5) (Fig. 6.4a), anomalous high in the higher latitudes and the associated wave with the

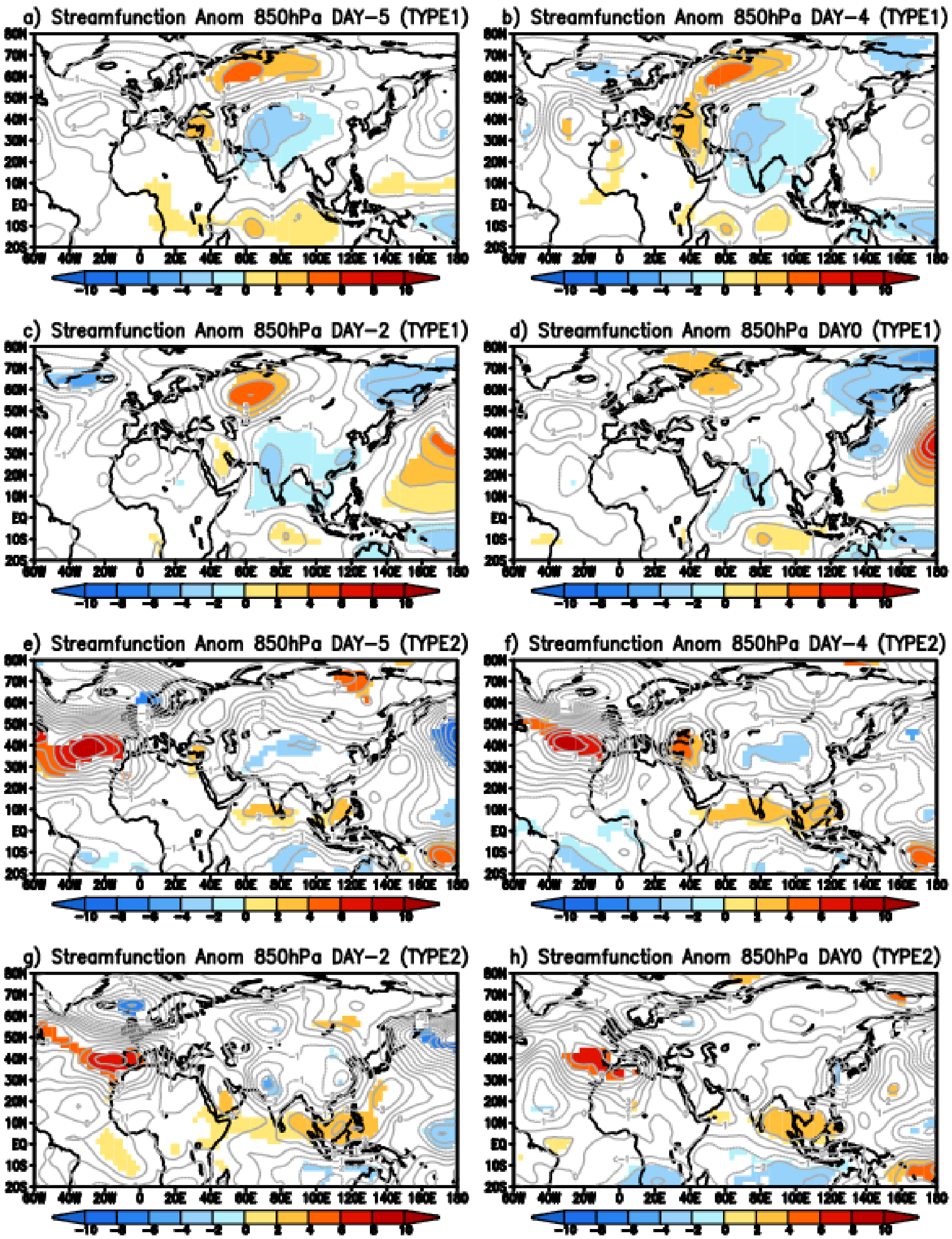


Fig. 6.4. (a) Composite of significant eddy streamfunction (×106m2 s−1) anomalies at 850 hPa five days before TYPE1 events (DAY-5). (b,c and d) same as (a) but four days (DAY-4) before, two days (DAY-2) before and on the day (DAY0) respectively of the TYPE1 event. (e–h) same as (a–d) but for TYPE2 cold wave events.

anomalous trough over China and over India are oriented north to south. The trough has a maximum to the northwest of India (Fig. 6.4a). The anomalous trough is seen moving eastward from DAY-4 (Fig. 5.4 b–d) and is seen covering the whole of the Indian landmass. Maxima in the cyclonic anomaly is seen over India from DAY-2, two days before the events started (Fig. 6.4 c). On DAY-0, the anomalous wave is oriented such that an anomalous cyclone is seen anchored to the Indo-China region. The anomalous cyclone to the south of equator in the Indian Ocean is seen from DAY-5 to DAY-0 (Fig. 6.4 a–d), however it intensifies from DAY-2 (Fig. 6.4c).

The anomalous high pressure over the Ural-Siberian region (Fig. 5.22b-d) that occurred during the TYPE1 cold wave over India is sometimes associated with an atmospheric blocking event. The question arises whether all atmospheric blocking events over the region can be associated with TYPE1 cold waves over India. When comparing the 76 blocking events during the La Niña years with the 21 TYPE1 cold wave events, Ratnam et al. (2016 b) found that 13 of the TYPE1 cold wave events were associated with atmospheric blocking events over the Ural-Siberian region. However, blocking over the Ural Siberia region is not a necessary condition to favour TYPE1 cold waves over India.

6.2 TYPE2 Cold waves (associated with El Nino events)

In this section, the details of TYPE2 Cold wave events are discussed. The composite of Tmin anomalies during TYPE2 cold wave events shows a significant negative anomaly confined to northwest India (Fig. 6.1e). The composite of OLR anomalies (Fig. 6.5a) shows negative anomalies in the equatorial central Pacific due to warmer SST anomalies in the region (Fig. 6.1c) and positive OLR anomalies over the west Pacific (Fig. 6.5a).

The associated eddy stream function anomaly at 200 hPa shows cyclonic anomalies covering whole of the Indian subcontinent and parts of China (Fig. 6.5b). The cyclonic anomaly over the Indo-China region is seen extending to lower levels and is also seen at 500 hPa (Fig. 6.5c) and 850 hPa (Fig. 6.5d), similar to the often-observed extension of upper level troughs associated with western disturbances as closed lows in the lower troposphere. At 850 hPa (Fig. 6.5 d), the cyclonic anomaly is seen confined to the west coast of India. The other significant feature of the eddy streamfunction anomaly at 500 hPa and 850 hPa is a pair of anticyclones over the west Pacific, which is the well-known Matsuno-Gill response to the equatorial west Pacific SST anomalies.

The main difference between TYP1 and TYP2 events is the barotropic pattern of cyclonic anomalies over India in TYP2 (in TYP1 it is baroclinic). Therefore, the cyclonic anomalies over India in TYPE1 and TYPE2 low-level events appear to be driven by different processes. During the TYPE2 cold wave, northwesterly winds bring cold temperatures to the northwestern parts of India, causing cold temperatures, while southerly winds bring warm temperatures from the equatorial region to the central and northern parts of India, causing warm temperatures over the region (Fig. 6.5e) (Ratnam et al. 2016 b). The western flank of the anomalous depression over the west coast of India, a response to the Pacific convection anomalies, brings cooler temperatures from higher latitudes to northwestern India (Fig. 6.5f) and the eastern flank of the anomalous cyclonic circulation brings warmer equatorial temperatures to central and northern parts of India (Fig. 6.5f). The advection of cold temperatures to northwestern India and warm temperatures to other parts of India is also due to the advection of anomalous temperatures by the observed mean and anomalous winds (Fig. 6.5 g-h). The anticyclonic anomaly over the western Pacific and the Bay of Bengal also contributes to the advection of warm temperatures onto the Indian landmass (Fig. 6.5 e-h). The above analysis shows that the maintenance of TYPE2 cold waves over India and their limitation to the northwestern parts of India can be largely explained by the advection of temperatures from the higher latitudes and equatorial regions by the mean and anomalous winds observed during the TYPE2 cold waves.

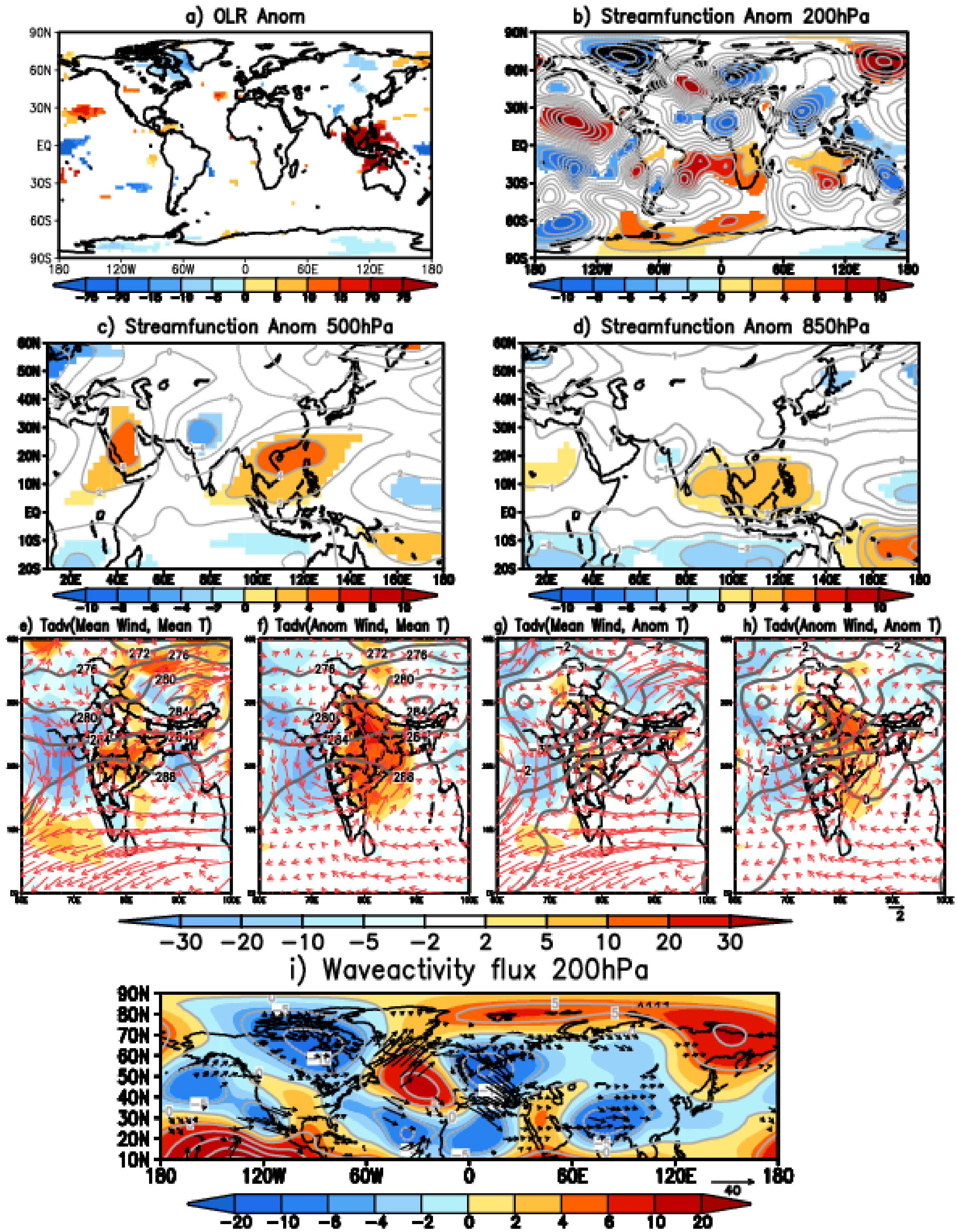


Fig 6.5. Same as Fig. 6.2 but for the TYPE2 events.

Mandal et al (2022) analyzed the skill to predict cold waves (CW) over India over a long period of time. They suggested that long CW events (> 7 days) are favoured by the La Nina condition and short CW events by the neutral condition in the Pacific. The blocking high northwest of the Indian longitude with a very slow movement of the westerly trough eastward is also associated with the long CW events. For short events, the blocking high is not so significant. Their study found that CW events are usually observed in association with the passage of the westerly trough on its back side (behind the trough) due to cold air advection from the higher latitudes. There is an anomalous westerly trough along the longitude of about 80^0 E, which attracts cold air from higher latitudes at 850 hPa due to the anomalous winds. La Nina conditions probably intensify the southwesterly jets and lead to cold winters over the northern and central parts of the country.

6.3 Case Study of a Cold Wave

In this section, a case study of cold wave which affected northern parts of the country is examined. During 26-31 December 2019, a cold wave gripped north India with negative temperature departures exceeding 5^0C (Fig 6.6). Negative temperatures anomalies were observed over most of north India (north of 20^0N). It may be important to note that 2019 was a La Nina year and as discussed earlier, the occurrence of cold waves during La Nina years is more frequent.

Fig. 6.7 shows the wind circulation anomaly at 200 hPa (top) and 500 hPa (bottom), a few days before the onset of the cold snap (24-26 December 2019). The circulation anomalies clearly indicate the presence of an anomalous cyclonic circulation just north of India and a deep trough extending from there across northwest India into the north Arabian Sea. This indicates the passage of a westerly disturbance over northern India, a few days before the cold wave started. During the cold wave, strong winds from northern India flow into central and northwestern India (Fig. 6.8 a) with strong meridional winds from the north (Fig. 6.8 b). These northerly winds bring cold air to central and north-western India. The meridional northerly flow is not only observed at 700 hPa, but extends throughout the troposphere up to 150 hPa (Fig. 6.9), indicating that deep northerly winds from the north are flowing towards the Indian subcontinent, bringing cold and dry air towards north India.

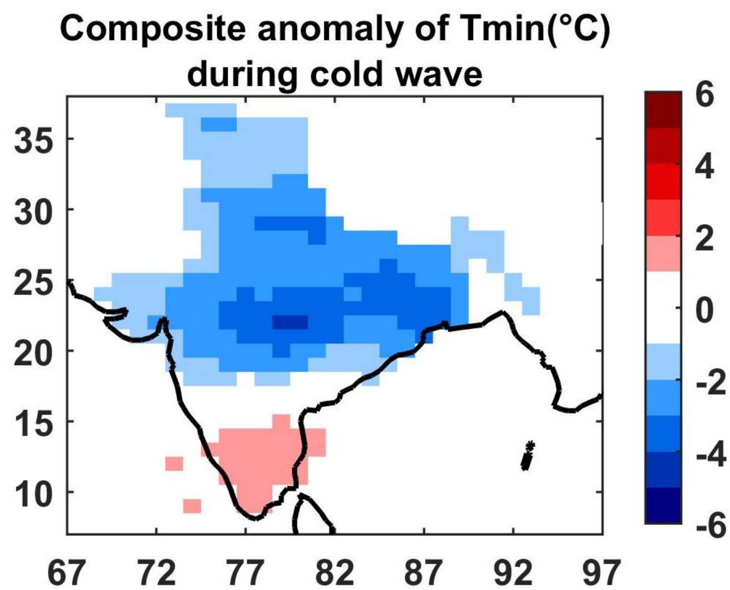
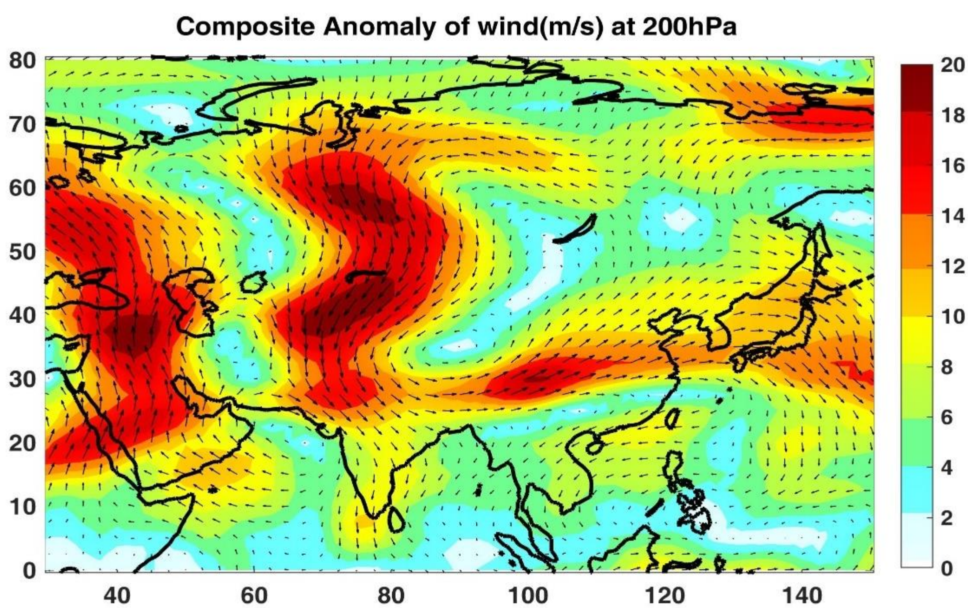


Fig 6.6. Minimum Temperature anomalies during the cold wave (26-31 Dec 2019) over north India.



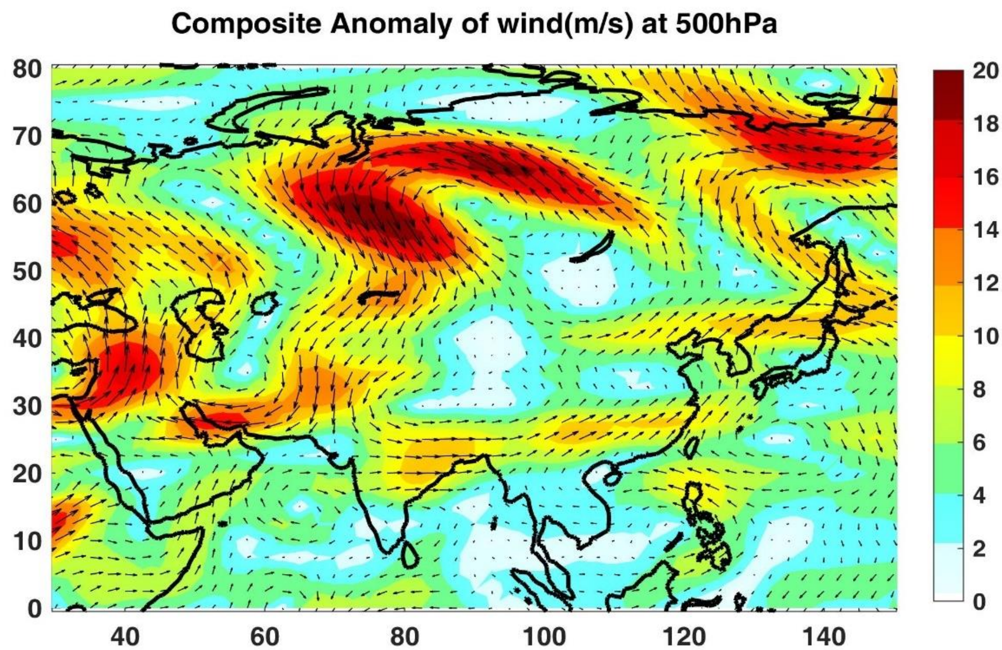
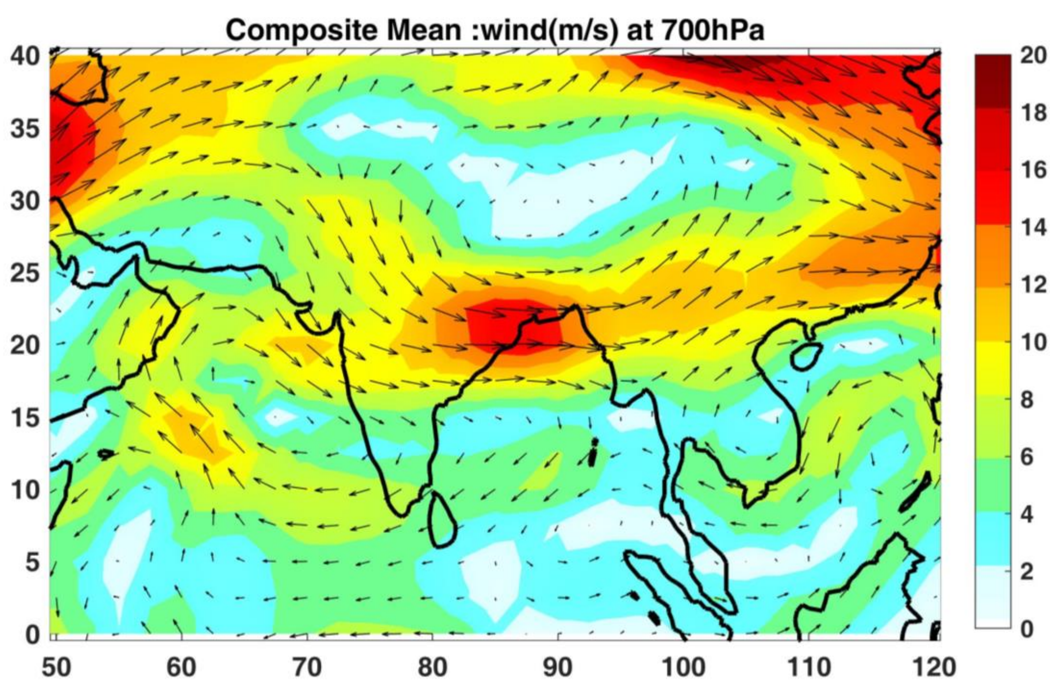


Fig 6.7 Composite wind anomalies at 200 hPa (above) and 500 hPa (below) during 24-26 Dec, 2019, just before the start of the cold wave. The anomalies have been computed using the climatology of 1972-2010.



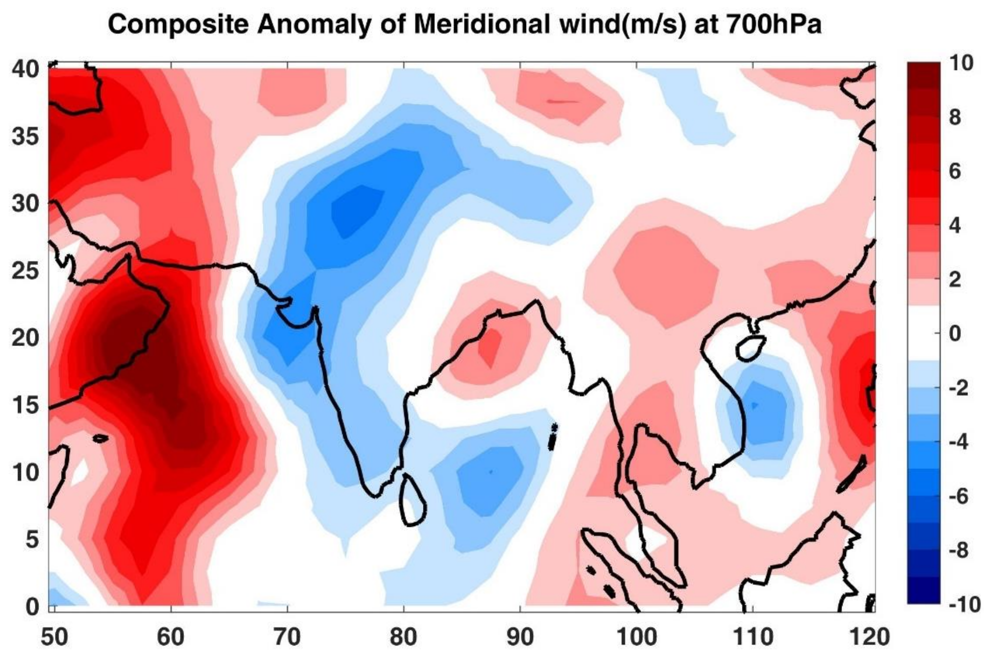


Fig 6.8. a) Composite 700 hPa mean vector winds during 26-27 Dec, 2019 (above) and b) meridional wind anomalies at 700 hPa (below) during the same period.

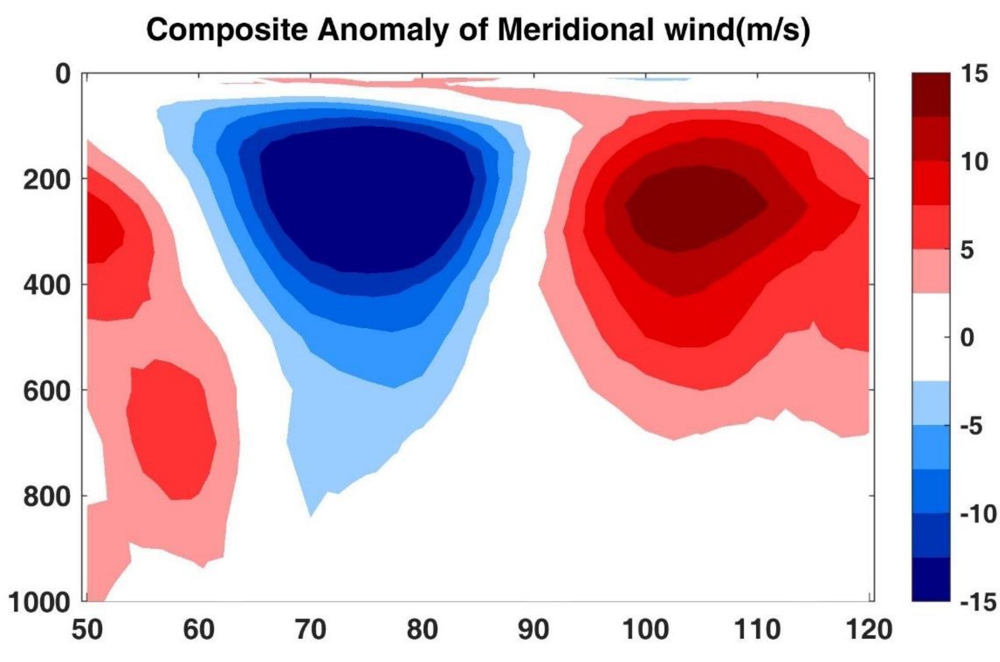


Fig 6.9. Longitude-Height profile of meridional wind anomalies (m/s) during the period 26-28 Dec, 2019, averaged over latitude 20^0-30^0N.

It is interesting to note that before the onset of the cold wave, cold air temperature anomalies are observed in the upper troposphere over the northern parts of India, but towards the eastern side of the core zone of the cold wave. This cold air anomaly is associated with the passage of a westerly disturbance prior to the cold wave event (Fig 6.10 a). Bedekar et al (1974) also discussed this aspect in the IMD forecast manual and suggested that meteorologists can get signals of a cold wave, even two days before, if we look at the temperature anomalies in the middle and upper troposphere. Negative temperature anomalies are first observed in the upper troposphere in the Indian subcontinent before they manifest in a cold wave over the surface. This aspect can be clearly seen in Fig. 6.10 b, the longitude-altitude profile of average temperature anomalies during the cold wave period (26-28 December 2019). A westward tilt of the temperature anomalies can be seen. The maximum temperature anomaly in the middle and upper troposphere is seen east of the cold wave region over the surface.

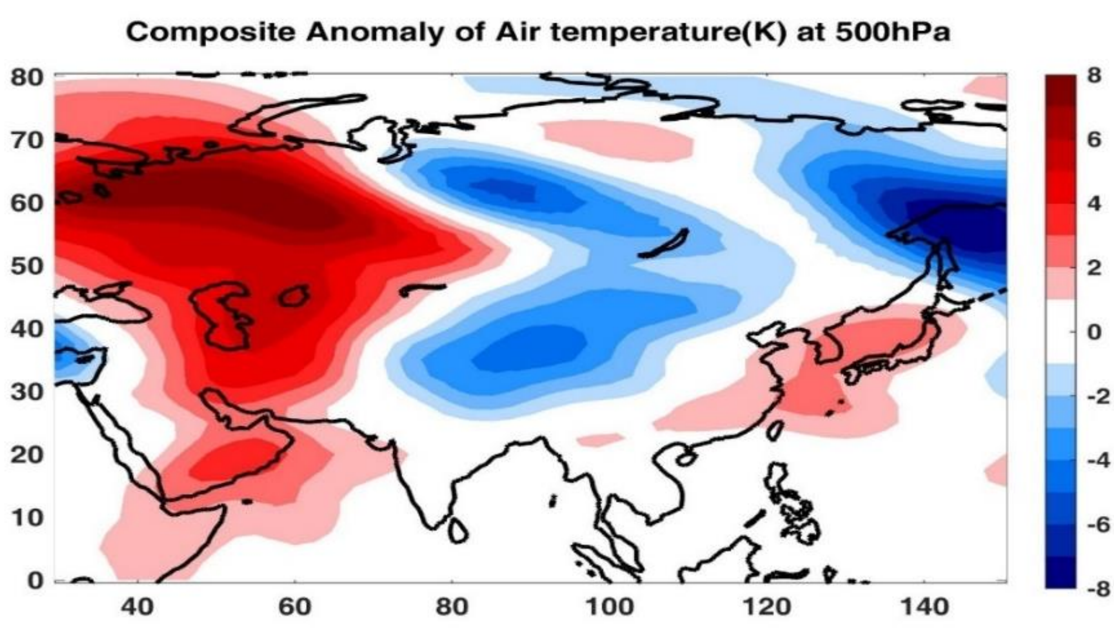


Fig 6.10 a. Composite air temperature anomalies (K) at 500 hPa during 24-26 Dec 2019.

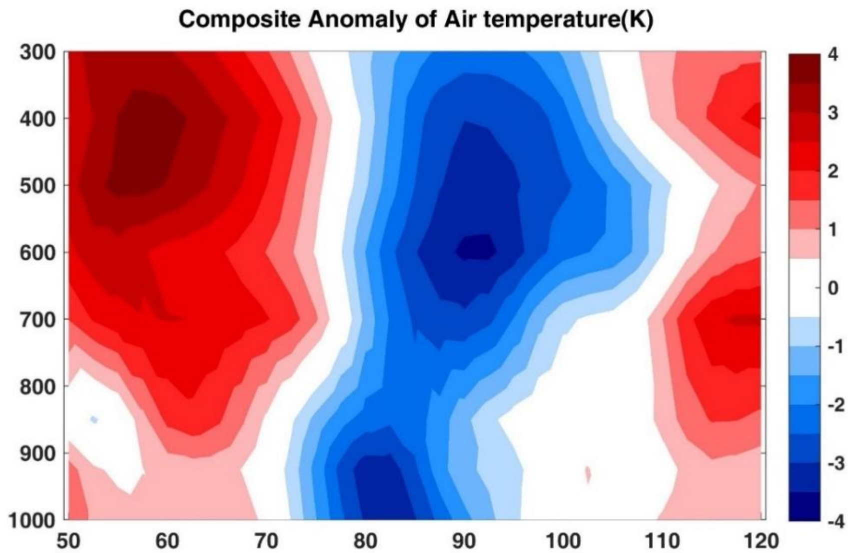


Fig 6.10 b. Longitude-Height profile of air temperature anomalies (K) from 1000-300 hPa, averaged over latitudes 20^0-30^0N, during 26-28 December 2019.

Fig. 6.11 shows the same vertical profile but for specific humidity. This indicates the presence of dry air from the surface up to 500 hPa during the cold wave over central India. Positive specific humidity anomalies are observed east of 100^0 E, which could be associated with the passage of the western disturbance and the associated moisture intrusion. Behind the western disturbance (west of the upper air trough), cold and dry air flows into northwest and central India, triggering a cold wave.

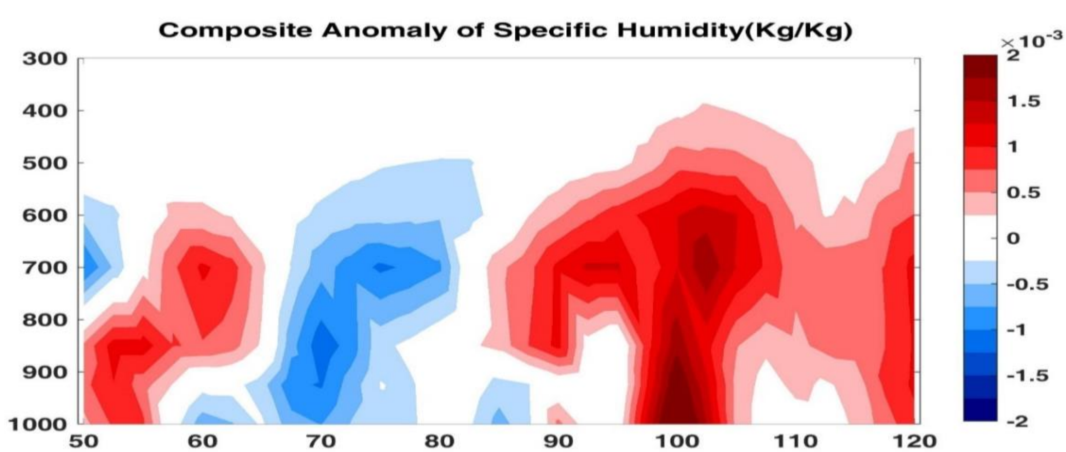


Fig 6.11. Longitude-Height profile of Specific Humidity anomalies (Kg/kg) from 1000-300 hPa, averaged over latitudes 20^0-30^0N, during 26-28 December 2019.