A heavy winter monsoon rainfall episode influenced by easterly waves, a westerly trough, blocking and the ITCZ

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A recent five-day cricket Test Match between England and India held at Bangalore, India, from 19 to 23 December 2001 ended in a disappointing draw. England was leading with a very respectable first innings score when heavy rains started on Day 3 of the match and led to the cancellation of the game. Just before that, one of the authors of this paper had received an e-mail from a Bangalore colleague inquiring about the prospects of rain for the following days. This led to our interest in the examination of the synoptic situation during that period. Here we present a short account of our findings, which turned out to be quite intriguing.

In this note we focus on the scenario that preceded the heavy rainfall episode over south-east India during the winter monsoon period in December 2001. A persistent anticyclonic circulation in the upper troposphere over east Africa, centred near 5°N, 50°E, contributed to the bifurcation of the strong westerlies near 20°N into two streams. An intense and persistent blocking situation was present near 60°E. One branch of the split flow in the westerlies moved equatorward in the Arabian Sea, resulting in a trough in the Northern Hemisphere and a ridge in the Southern Hemisphere, the latter residing over the Southern Hemisphere intertropical convergence zone (ITCZ) near 5°S. This ridge–trough system provided a moist stream of south-westerly flow over the south-east coast of India where the frequent westward passage of easterly waves near 850 mbar provides the setting for heavy rain. Another important feature within the easterly trades are the frequent wind surges. These surges move from east to west within the easterly trades at a speed of roughly 7° longitude per day. The average strength of the trades is around 12 m s^{-1} and the surges often carry a wind speed as high as 13 to 14 m s^{-1}. Commonly, convection and rain are found ahead of the surge, due to the convergence of mass and moisture. At the time of the heavy rain over Chennai (13.13°N, 80.25°E) we could clearly see the simultaneous arrival of an easterly wave and a trade surge over the south-east coast of India.

Winter monsoon rains over the coast of south-east India usually occur during October, November and December, with heavier rains occurring in November and December. The large-scale flow field over the region exhibits a very strong vertical wind shear. At the surface levels, the flow is generally from the north-east (also called the north-east monsoon). As the winds veer with height, at the 850 mbar level the flow is more easterly. In the upper troposphere the winds generally tend to be more westerly (Krishnamurti *et al.* 1997a,b). The north-easterly monsoonal flow is very shallow, occupying only the lowest 2 km of the atmosphere.

Importance of the study

The features described here are quite unusual. Upper-tropospheric westerlies over the Northern Hemisphere normally do not penetrate south of 10°N. Typically, the region of the ITCZ near 5°S is characterised by a zonally oriented anticyclonic belt that does not usually carry strong cross-equatorial flow. Wintertime precipitation over the south-east coast of India is generally attributed to westward-propagating tropical waves near 10°N over the Bay of Bengal.

It is now being recognised (Krishnamurti *et al.* 1997a,b) that, although this is indeed a source of moisture for the rainfall over the south-east coast, other possible moisture sources exist as well. The trade wind easterlies, the waves imbedded within these easterlies, and the trade wind surges and associated mass convergence also convey moisture zonally near 10°N. In addition to these processes, this paper highlights the possible role of a large-amplitude extended westerly trough in trapping and transporting moisture from the ITCZ region of the Southern Hemisphere to the south-east coast of India.

The formation of the extended trough was evidently related to a persistent intense anticyclone over north Africa. An additional feature, making this rainfall episode quite complex and interesting, was the flow of the strong westerlies north of this anticyclone into a major downstream block.

Analysis of the episode

The normal rainfall over Chennai for the winter monsoon months of November, December and January is 308, 157 and 24 mm respectively (Rudloff 1981). A time history of the daily rainfall at Chennai during the December 2001 episode of heavy precipitation is illustrated in Fig. 1. The rainfall totalled 184 mm during 21, 22 and 23 December 2001. Rainfall amounts as high as 84 mm in 1 day were noted on the 21st, mainly from widespread rainfall over the province of Tamil Nadu. A better picture of the broader aspects of precipitation can be seen from rainfall estimates derived from the National Aeronautics and Space Administration (NASA) TRMM satellite and the US Air Force DMSP-SSM/I satellites. These datasets, which were extracted from the archive at the Florida State University (FSU) real-time multimodel superensemble website (Krishnamurti *et al.* 2001), are shown in Fig. 2 (p. 377). This illustration shows the ITCZ rainfall near 5°S and the daily rainfall distribution over the

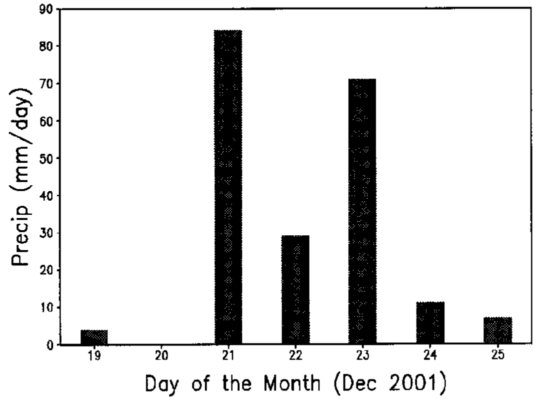

Fig. 1 Daily rainfall totals for 19–25 December 2001 at Chennai. These are 24-hour totals ending at 0000 GMT on the respective days.

winter monsoon belt. We can see the rainfall associated with the easterly wave and the large increase in rainfall over Tamil Nadu on 21 and 22 December. An examination of our data files on the real-time analysis since 1998 showed that the scenario presented here is quite infrequent, with roughly one such example per winter season noted during the past four years.

Figure 3 illustrates a sequence of 500 mbar level geopotential heights for a 6-day period covering 17 to 22 December 2001 at 1200 GMT. Here one can see a persistent anticyclone over Africa, centred around 50°E. The westerlies to its north exhibit a blocking bifurcation with part of the westerlies going as far north as 55°N. Of interest to this study is the southern branch of the split westerlies that carves out a trough at around 60°E. The related wind field exhibits an extended trough into the Southern Hemisphere extending directly over the ITCZ at 5°S. In the geopotential field, because of the change of polarity of the pressure field across the equator, this feature shows up as a weak anticyclone. This feature assists in the moistening of the upper troposphere over south-east India, where the easterly trades of the lower troposphere are also active.

The trade wind easterlies at 850 mbar (Fig. 4, p. 378) extend between 5°N and 20°N all the way from the date line to 50°E. The trade wind easterlies show an easterly wave (slanted dark line) that propagates from roughly 90°E to 70°E during a 6-day period between 17 and

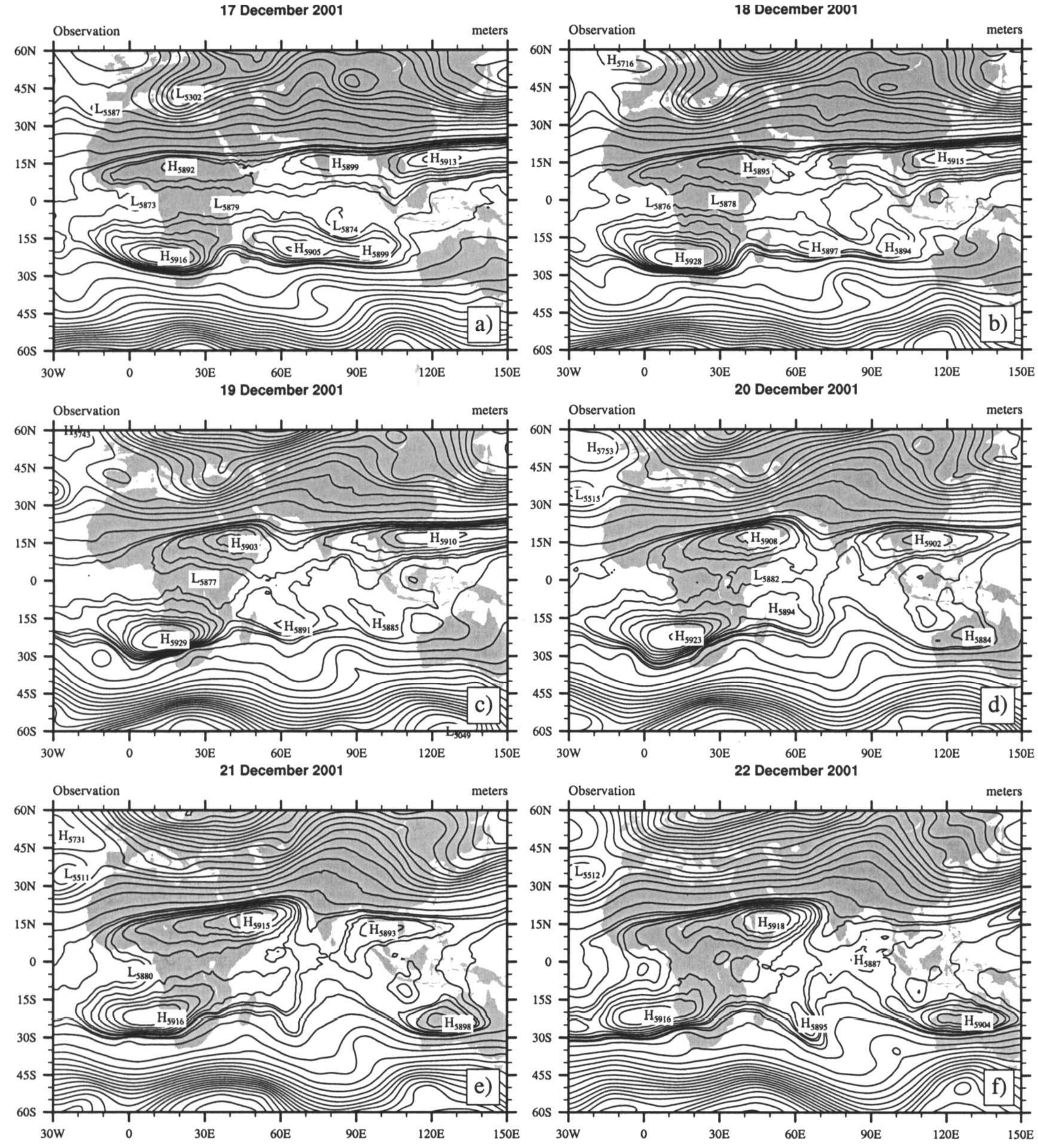

Fig. 3 500 mbar geopotential heights for 17–22 December 2001 at 1200 GMT. The contour interval is variable in the units of geopotential metres.

22 December 2001. The yellow colouring depicts a belt of strong easterlies where the wind speed is in excess of $10\,m\,s^{-1}$. Within this belt, wind surges were noted on 20 December that moved westward and abated in intensity by the 22nd.

The strong 200 mbar subtropical jet over Africa near 20°N splits into two branches (Fig. 5, see inside back cover), one reaching as far north as 55°N, and the other extending towards the Arabian Sea and eventually into the Southern Hemisphere. The resulting feature is a blocking situation between 60°E and 80°E. The mechanisms leading to the establishment of this block are not clear, but the formation of the large-amplitude trough near 60°E that crosses over into the Southern Hemisphere and taps moisture from the ITCZ at 5°S appears to be related to the block's presence. A search for insight into the origin of the block and the splitting of the flow takes us to the west of the Arabian Sea. An unusual feature of the upper troposphere at the time was a very intense high pressure area near 25°N over north Africa. That high persisted for almost a week after 17 December. To the north of this high pressure area, waves in the strong westerlies, carrying winds of up to 60 m s^{-1}, moved east at a speed of roughly 10° longitude per day. The block appeared to be related to the dynamical instability of this westerly jet.

The subtropical westerly jet, as it accelerates from the Indian subcontinent towards southern Japan, is generally oriented from roughly 25°N to 30°N. In this example of the extended upper-level trough over the Arabian Sea, the location of the subtropical jet was much farther south than its normal latitude (Fig. 5). This may be a large-scale consequence of the blocking pattern at 60°E that brought in the upper westerlies to very low latitudes over the Arabian Sea.

Ahead of the trough one would expect to find a region characterised by positive vorticity advection aloft and quasi-geostrophic rising motions. We examined the vertical motions at 1200 GMT on 21 December 2001 and confirmed the presence of large-scale upward motions over the south-east coast of India during this period of heavy rain.

Summary

A number of factors contributed to the heavy rainfall episode over Chennai in southern India during December 2001. These include the westward passage of wind surges at the 850 mbar level in the trade wind easterlies around 10°N. The speed convergence resulted in mass and moisture convergence ahead of the wind maxima, contributing to rising motions and rainfall. A rapid build-up of an extended trough around 60°E over the Arabian Sea was able to tap moisture from the ITCZ near 5°S. This feature contributed to the moistening of the upper troposphere over south-east India during the period of investigation. The trough dynamics also provide a favourable environment for sustained rising motions ahead of the upper trough over the south-east coast of India. The extension of the upper-level trough resulted in an anticlockwise flow and a prevailing high pressure area above the ITCZ convection region. That upper-level high appeared to provide a favourable environment for the maintenance of the ITCZ and its continuous supply of moisture to the heavy rainfall episode.

This observational note on the features cited above, *i.e.* the African anticyclone, the blocking pattern, extended westerly trough interacting with the ITCZ, the easterly waves and the heavy rain over south India, is illustrative, but does not provide rigorous explanations of the exact mechanisms involved. Detailed modelling studies can perhaps provide further insight.

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