Role of atmospheric stability over the Arabian Sea and the unprecedented failure of monsoon 2002

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The anomalous behaviour of the monsoon 2002 has been studied. We have made an attempt to combine satellite and other data sources to characterize the thermal stratification over the Arabian Sea during different phases of monsoon 2002. Using NOAA–ATOVS-derived atmospheric temperature and moisture profiles, we have calculated a daily stability index (SI) over the entire Indian region and surrounding oceans. The time series of SI clearly brings out the three major significant epochs of monsoon 2002. The relatively dry atmosphere west of 65°E, signifying lack of convection and an unstable atmosphere over the southeast Arabian Sea with west-to-east gradients in water vapour, SI and cloud liquid water content are noted. The unfavourable stratification during July over the entire Arabian Sea has been investigated in detail.

The dominant modes of instability oscillations have been seen to be ~ 30 days both over the western and eastern Arabian Sea, while for the high-frequency modes preference was seen over the eastern part.

Using the analysed fields of the National Centre for Medium Range Weather Forecasts, the relative contributions of advective and subsidence components in the maintenance of stratification have been investigated. The latter has been found to have played a more dominant role in the deficit monsoon 2002.

THE monsoon of 2002 was intriguing. The seasonal rainfall (June–September) for the country as a whole was 19% below normal; 29% area of the country experienced drought conditions. The July deficit of all-India rainfall was an unprecedented 49%. Such large-scale deficit in the summer monsoon rainfall led to a lot of concern and speculation about the causes.

One of the significant observations of the monsoon 2002 is the scarcity of cloud systems over the Arabian Sea and large deficits in rainfall over the west coast[1]. This perhaps is due to the unfavourable stratification of the atmosphere over the Arabian Sea, which determines the initiation and subsequent development of convection as well as its vertical extent.

The investigation of Arabian Sea stratification (low-level inversion) was one of the major objectives of the ARabian sea Monsoon EXperiment (ARMEX)[2] organized during the monsoon of 2002, as was also during MONEX-1979. A variety of platforms and an array of sophisticated instrumentation had been deployed to collect oceanic and meteorological observations of relevance to ARMEX. These data were to help measure the fluxes of heat and moisture and study the mechanisms of the formation of offshore vortex over the eastern Arabian Sea. An attempt has been made here, using space-based observations, to get information on the stability of the atmosphere over the data-sparse oceans, in order to supplement the efforts of the ARMEX programme (with limited field observations confined in central and southeast Arabian Sea). This has helped extend the observations to larger regions covering both the western and eastern Arabian Sea.

National Oceanic and Atmospheric Administration (NOAA) series of operational satellites in USA with atmospheric sounding capabilities are providing information on the vertical temperature and moisture structure since 1978. Narayanan and Rao[3] successfully used the profile information to delineate from satellite observations, the temperature inversions over the Arabian Sea despite the satellite's relatively poor vertical resolution and accuracy[4]. By combining the information on temperature (thermal inversion) and convection (equivalent potential temperature), a quantitative stability index was computed over the Arabian Sea to study the thermal stratification of the atmosphere for the growth or suppression of convection[5].

In this study the anomalous behaviour of monsoon 2002 has been investigated using satellite-derived stability indices during the various epochs of monsoon from the point of the Arabian Sea low-level inversion. An attempt has also been made to quantify the relative roles of advection and subsidence in the maintenance of the inversion over the Arabian Sea.

Arabian Sea low-level inversion

The inversion over the Arabian Sea is low (base between ~ 900 and 800 hPa) and strong over the western part; it weakens and rises towards the west coast of India. It is not observed especially during active monsoon seasons.

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The presence of dry, warm continental air from Africa and Arabia riding above the maritime air from the south Indian Ocean is thought to be associated with this inversion. Another cause is thought to be associated with the large-scale subsidence. Once this inversion is destroyed by some mechanism, there is a favourable stratification for rapid release of moisture upwards leading to precipitation[6,7].

Narayanan and Rao[3] demonstrated that these features can indeed be detected from the TIROS-N (NOAA-8)-derived ocean skin temperature and the 1000–850 hPa layer mean temperature (LMT) by a simple differencing procedure

$$\Delta T = \text{skin temperature} - (\text{1000–850 hPa LMT}).$$

Using the observations of about 160 aircraft dropsonde profiles as ground truth (during FGGE's Monsoon Experiment–MONEX of 1979), they found that if the index ΔT is equal to or less than 2°C, it was indicative of inversion; higher values indicating non-inversion (but not necessarily convection) regions. They also showed how these inversion regions shifted to eastern regions (covering the entire Arabian Sea) during the weak monsoon conditions and then back to western Arabian Sea with the revival of monsoon. From these temperatures and simultaneous satellite-derived mid-tropospheric water vapour content, a close link between the extent of inversion regions and the convective processes with the Indian monsoon at its different phases was established by them.

India is surrounded by oceans and convection over these oceans plays a major role in the monsoon rainfall over India. Thus, an understanding of the factors that control deep convection over the tropical oceans (and thereby the performance of the summer monsoon) is important to many aspects of ocean–atmosphere interaction studies. While it is generally known that the climatological distribution of deep convection is closely linked to the distribution of sea surface temperature and prevailing low level winds, the processes responsible for variations in the location and intensity of deep convection on synoptic, intraseasonal and interannual timescales are the focus of many investigations.

Deep convection in the tropics can be maintained only when there is a positive cloud buoyancy over a large depth of atmosphere. The buoyancy of the cloud depends not only on the properties of the air near the surface of the ocean, but also on those of the upper air through which it rises. Many parameters that incorporate the effects of surface as well as upper air have been devised to study the stratification of the atmosphere in order to determine the initiation and subsequent development of convection as well as its vertical extent[8]. Bhat *et al*.[9] suggested that the convective available potential energy (CAPE), which determines whether the surface air will ascend, is one such parameter. They showed that the frequency of deep convection is highly correlated with CAPE, determined from monthly mean profiles. Similarly, Srinivasan[10] suggested another parameter, the vertical moist stability of the atmosphere, viz. the difference between the moist static energy of the lower and upper layers of the troposphere.

A criterion that incorporates the vertical distribution of water vapour is convective or potential instability, expressed as $dq_e/dz < 0$, where q_e is the equivalent potential temperature. Khalsa and Steiner[11] sought a simple index that approximated the atmospheric stability representing the gross features of these profiles. On the basis of evaluations of numerous tropical soundings, they suggested a stability index (SI). This index has been slightly modified by us incorporating the levels at which the ATOVS products are now available, and is

$$SI = q_{es}(620) - q_e(920).$$

The index compares the q_e of the lowest TOVS layer – 920 hPa with the saturated equivalent potential temperature, q_{es}, of the 620 hPa layer.

Narayanan and Rao[5], using *in situ* data of about 80 aircraft dropsonde and ship upsonde profiles during the monsoon of 1979, analysed the SI threshold for deep convection over the Arabian Sea. Low positive SI values were shown to be indicative of stable stratification, while SI less than – 4 K represented unstable stratification and favoured deep convection.

Data

The basic data used in this study consist of operational sounding products generated by NESDIS/NOAA of USA from ATOVS – a combined infrared–microwave instrument on current NOAA satellites. They pertain to the period 1 May to 10 October 2002. These products are at grids of 1.2° × 1.2° lat–long box and include, skin temperature, 42-level temperature profile from 1000 to 0.4 hPa and 19-level (humidity) mixing ratios. The data used in this study from the above dataset are the skin temperature, atmospheric temperature and humidity at 920 and 620 hPa levels. Besides the above data from NOAA satellite, the cloud liquid water (CLW) content data from Tropical Rain Measuring Mission–Microwave Imager (TRMM–TMI) instrument, an indicator of cloudiness (convection), and analysis fields of the National Centre for Medium Range Weather Forecasts (NCMRWF) have also been used in this study.

Radiosonde observations – Comparison with satellite data

As part of the ARMEX–1 programme, vertical profiles of temperature, humidity and wind were obtained for a limited period (24 June–15 August 2002) using high-resolution Vaisala radiosonde. However, these *in situ* observations were limited to a small 3° × 3° area (15–18°N and 70–73°E) over the eastern Arabian Sea.

A direct comparison of the radiosonde and satellite profiles was not possible. The feature under investigation, viz. the convection/stratification over the Arabian Sea, is a phenomenon of relatively large time (nearly five to ten or more days) and spatial (about 10° × 10°) areal extent. To take account of this, as a first step, all the available satellite and Vaisala observations for each day were averaged (to minimize diurnal effects). From a comparison of these daily data it was observed that on individual days and at particular levels, there were differences of even up to 3 K in temperature and about 0.003 kg/kg in moisture between the satellite and Vaisala observations.

To account for the large temporal scale, five-day running mean of temperature and humidity at 920 and 620 hPa (which are relevant height levels in the computation of SI) were made (Figure 1). Also, in Table 1, we have shown the bias and RMS of all the concurrent observations bet-

Table 1. ATOVS – radiosonde comparison statistics (ARMEX–1: 24 June–15 August 2002)

Parameter	Bias	RMS
T 920 K	– 0.99	1.57
T 620 K	– 0.30	1.29
Q 920 kg/kg	0.00002	0.0012
Q 620 kg/kg	– 0.00060	0.0017

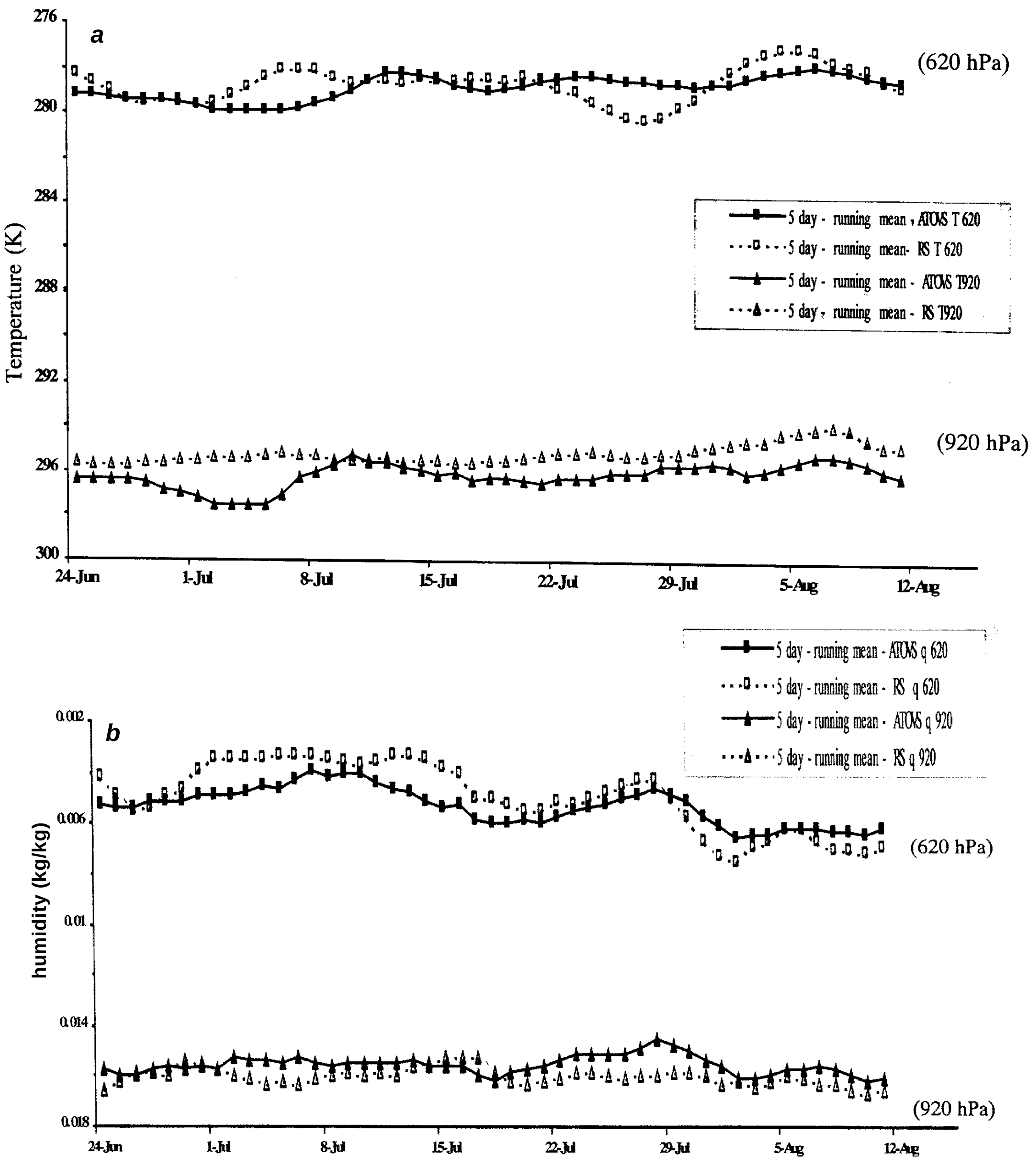

Figure 1. ATOVS and Vaisala radiosonde temperatures (***a***) and humidity (***b***) (five-day running mean) at 920 and 620 hPa during 24 June–15 August 2002.

ween the satellite and Vaisala system of these parameters at these two levels. Spatial scale averaging was done only on a 3° × 3° grid, as all ship Vaisala data were confined in this small grid box.

From Figure 1 and Table 1, it may be concluded that on the larger time and spatial scales, the differences between *in situ* and satellite estimates are better than 1.6 K and 0.002 kg/kg. Similar results have been obtained by Singh *et al.*[12] using NOAA 16–AMSU sounding data over the Indian region. Moreover, we are studying especially the spatial and temporal variations in SI during different epochs, rather than the absolute values of SI. In an earlier study[3,5] using MONEX 1979 data, we made a detailed comparison of satellite and *in situ* measurements on a larger spatial range, both in eastern and western Arabian Sea. This study also suggested that satellite data can be used reliably on larger time–spatial scales for stability analysis.

Results and discussion

In order to extend the analysis to the entire Arabian Sea and adjoining areas, based on the formulations discussed above, we have computed average SI for the entire monsoon season over two selected 5° × 5° lat–long boxes centred around 12°N/62°E (representing western Arabian Sea, WAS) and around 17°N/67°E (representing eastern Arabian Sea, EAS). Figure 2 *a* and *b* shows the daily SI time series for the period 1 May–10 October 2002 for these two boxes.

The range of SI values encountered during the entire four months was between + 7 and – 18 K. The SI time series clearly brings out the active and weak epochs during the season. The active phase around 15 June (with SI around – 15 K), the weak phase – whole of July 2002 (SI ~ 0 K) – and a partial revival of the monsoon around 8 August (SI around – 10 to – 15 K) are the important features to be noted. The features seen in western and eastern Arabian Sea boxes agree well, except for the weak phase in July. Although there is a significant decrease in the instability as compared to the active epoch of 15 June the SI values are still in the range of 0 to – 6 K throughout July in the eastern box. It appears that although weak monsoon conditions persist, the stratification over the eastern Arabian Sea still could favour convection, though not deep convection.

The time series of mid level water vapour (MWV) in the altitude region 700–500 hPa for the eastern box 17°N/67°E along with those of SI and CLW is shown in Figure 3. It is seen that in the EAS (east of 65°E), MWV values greater than 6 mm are maintained after the onset of the monsoon, with MWV values reaching up to 12 mm during the most active phase. In the WAS box (west of 65°E, not

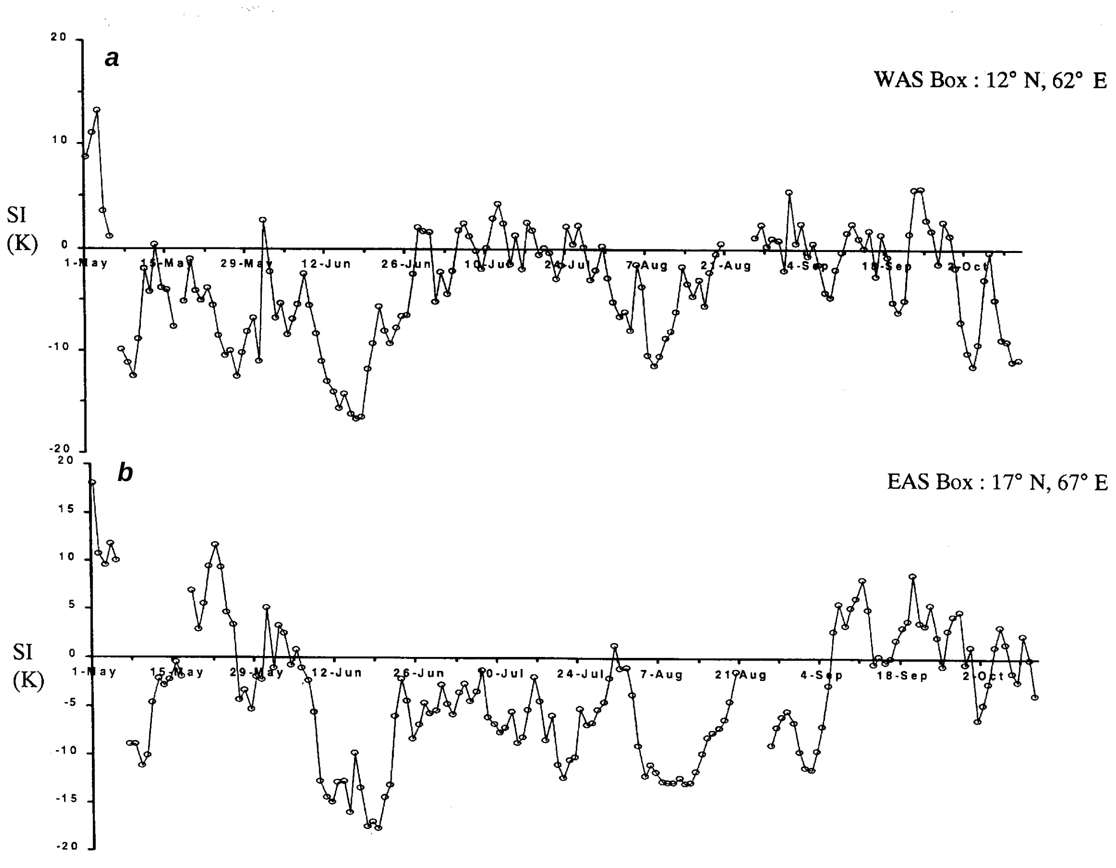

Figure 2. Time series (1 May to 10 October 2002) of stability index (SI) for the two boxes in the Arabian Sea.

shown), the MWV ranges between 4 and 10 mm. MWV decreased from 14 mm in June to around 7 mm in July. It is noted that in general, MWV in the range of 2–4 mm corresponds to positive SI values, while MWV in the range 6 mm and above corresponds to negative SI, with higher MWV values in general corresponding to high negative SI values – implying deep convection.

Figure 3 *c* shows the time series of CLW (from TMI). The single high peak in CLW during the active period (15 June) corresponds well with high MWV values and the unstable stratification (shown by SI) favouring deep convection. However, decrease in SI and MWV, and low values of CLW are seen during July. The close correspondence (anti-correlation) between SI (Figure 3 *a*) on one hand and MWV and CLW on the other, is clearly discernible.

The east-west cross-section of various stratification-related parameters (e.g. SI, MWV and ΔT from ATOVS–NOAA and CLW from TRMM–TMI) at different latitudes for the active and weak phases have been studied. However, here we present the cross-sections of these parameters only at 17°N latitude during the active period (Figure 4 *a* and *b*). It is interesting to note that all these

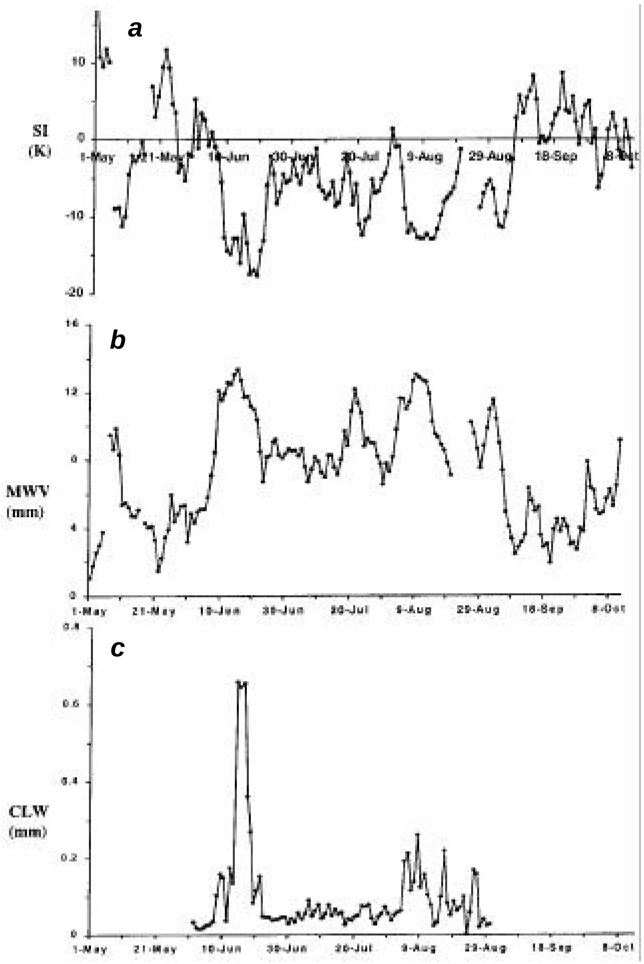

Figure 3. Time series of SI (***a***), MWV (***b***), and CLW (***c***) for the EAS box (17°N, 67°E).

parameters show a characteristic west-to-east gradient. The anti-correlation between ΔT and SI is evident (as was also shown by Narayanan and Rao[5] from MONEX data). The western Arabian Sea is dominated by low SIs, while eastern Arabian Sea is represented by SI in the range – 10 to – 14 K.

Similar west-to-east gradient in TMI-measured CLW content is also seen. The increase from low values of 0.03 mm (equivalently g/cm^2) in the WAS to 0.18–0.20 mm in EAS is clearly noted.

Active and weak epochs – satellite SI, MWV and CLW

To study in detail the time-averaged behaviour of these parameters at the important monsoonal epochs, particularly over the Arabian Sea, composites showing spatial distribution of these parameters have been made. Figure 5 shows the composite maps of SI for two of the above-mentioned three epochs, viz. 11–20 June (active phase) and 5–31 July (weak phase) for the region 20°S–35°N and 30–110°E. For the sake of clarity, figures for the third epoch (revival) are not shown, though they have been discussed at appropriate places in the text.

During the active phase (Figure 5 *a*), the entire Arabian Sea, north of the equator, is characterized by high negative SI values in the range – 8 to – 12 K, conducive for deep convection. The corresponding figures for the Bay of Bengal region are also high (~ – 16 K). Figure 5 *b* corresponds to the weak monsoon epoch of 5–31 July. Positive SI values west of 65°E (WAS) and negative SI values in the range – 2 to – 8 K over the EAS (east of 65°E) are observed. The overall decrease of SI from the active to the weak phase over the Arabian Sea and change in the orientation of SI contours (from east-west during the active phase to north-south in the weak phase) and relatively less change over the Bay of Bengal are noteworthy features.

The revival phase during 5–12 August (not shown) has SI values in the range 4 to – 12 K over the Arabian Sea. The unfavourable stratification over WAS is destroyed, except for a small area between 20 and 25°N, thereby allowing initiation of convection and thus revival phase of monsoon.

The composites of mid-level precipitable water (mm) for the two epochs are shown in Figure 6. During the active phase, the entire Arabian Sea is represented by MWV values in the range 8–12 mm and the Bay of Bengal by 10–12 mm (Figure 6 *a*). The significant decrease in MWV during entire July (Figure 6 *b*) with values around 6–8 mm in the Arabian Sea, and 8–12 mm over the Bay of Bengal can be seen. During the revival phase (not shown), higher MWV values (~ 10 mm) over the entire Arabian Sea are noted. Similar features in the total vertical columnar water vapour composites are also seen.

The composites of CLW content using TMI data clearly bring out the contrasting features associated with these two epochs (Figure 6 *c* and *d*). The abundance of deep convection resulting in clouds with high CLW (0.3–0.4 mm), particularly over central Arabian Sea, explains the role played by them during the active monsoon (Figure 6 *c*). In contrast, absence of deep convection over the entire Arabian Sea during the whole of July, causing large-scale failure of the monsoon can be noted (Figure 6 *d*). The Bay of Bengal, although with less vigour, still favours the formation of convective clouds. The TMI–CLW data combined with other sources (e.g. temperature and humidity profiles from future INSAT–3D satellite) would make an ideal dataset for real-time monitoring and progress of the monsoon activity.

Intraseasonal oscillations of atmospheric stability

The dominant modes of intraseasonal oscillations during monsoon have been extensively studied using a variety of parameters (cloudiness, OLR, water vapour, winds, etc.) by many investigators over the past two and half decades, starting from the well-known works of Sikka and Gadgil[13], Yasunari[14], etc. Here we have studied this feature from the satellite-derived atmospheric stability index over the Arabian Sea area using the wavelet technique. The SI time series of 128 days (from 26 May through 30 September) has been subjected to wavelet analysis. Figure 7 *a* and *b* shows the wavelet patterns of the SI-dominant modes

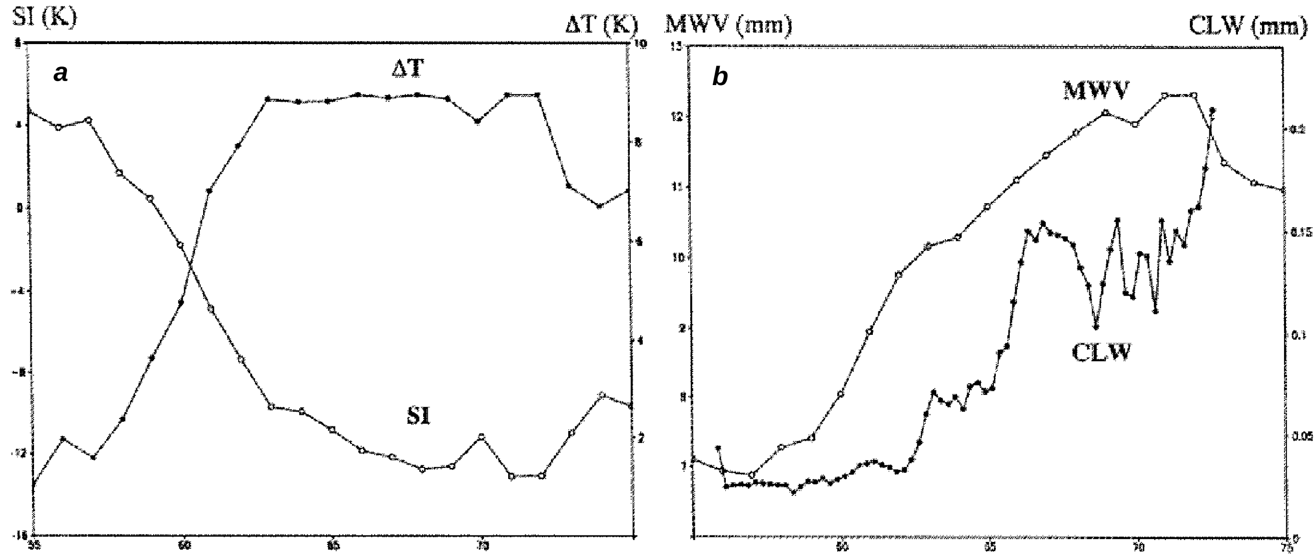

Figure 4. East-west profiles along 17°N during active epoch (5–15 August) of (***a***) SI and Δ*T* and (***b***) MWV and CLW.

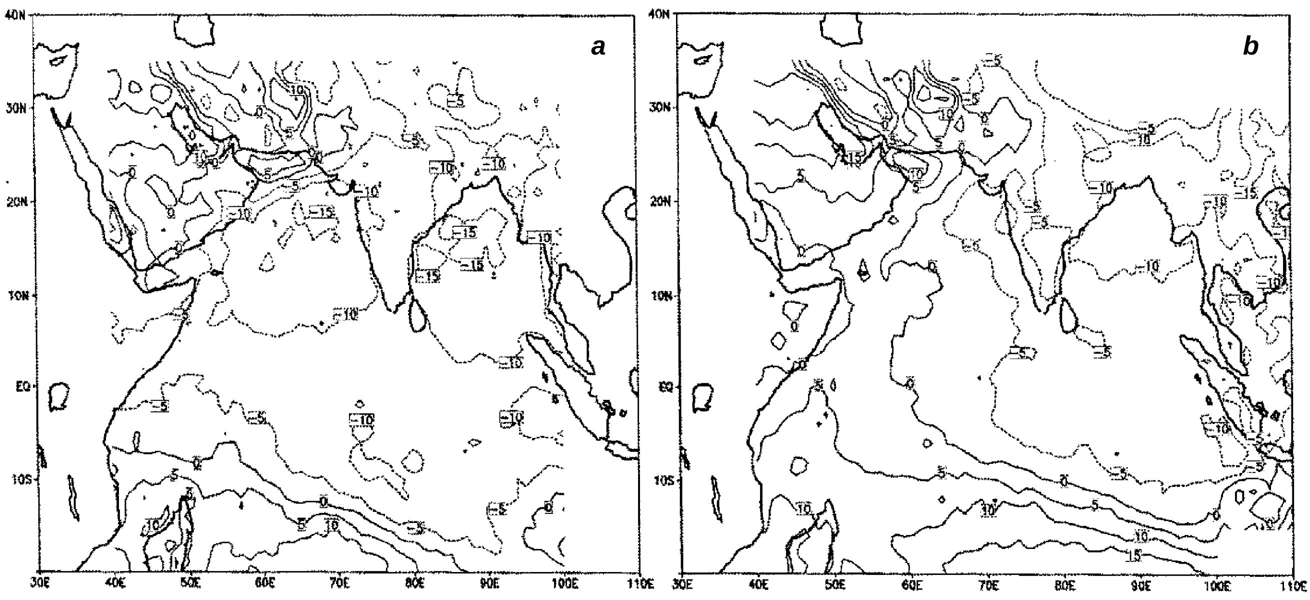

Figure 5. Composite maps of SI for the active (***a***) and weak phase (***b***) (Contour interval 5 K).

during the monsoon period for the western and eastern Arabian Sea boxes respectively. The low frequency oscillation around 40–60 days is well marked in both the boxes. The higher frequency modes (~ 10–20 days) are seen to be more dominant in the eastern box. The details of these results (viz. amplitude and phase propagation, phase association with other parameters, etc.) are being addressed in a separate study.

Advection and subsidence contributions

To study the relative roles of advection and subsidence in the formation and sustenance of inversion over the Arabian Sea, the circulation features during the three epochs have been analysed. The composites of *u* and *v* fields at 850 and 700 hPa levels and average vertical winds (in the 700–400 hPa vertical domain) from NCMRWF analysis fields (global spectral T80 model) have been used for this analysis.

The composite of winds at 850 hPa (not shown) corresponding to the active phase depicts southwesterly winds south of 18°N over the Arabian Sea. These winds range between 15 and 20 m/s and bring cold maritime air from the south. During the weak phase (5–31 July), winds in the range 12–16 m/s are seen (south of 20°N). Strong westerlies over the peninsula and up to 25°N over the Indian land mass and weakening of the winds over Arabian Sea are the significant features of interest. During the revival phase (5–12 August), strengthening of the winds over the Arabian Sea and strong winds over the Bay of Bengal have been noted.

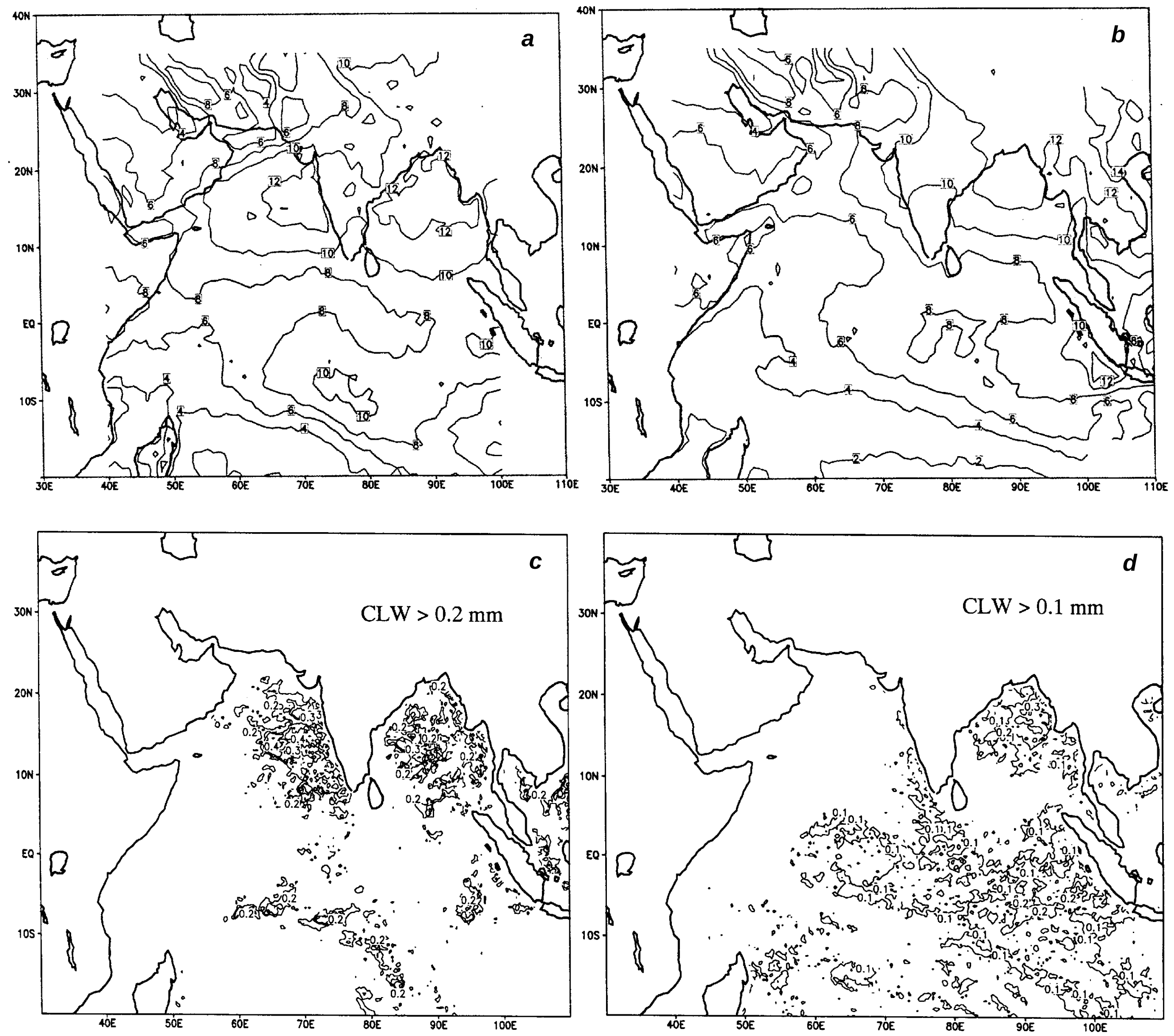

Figure 6. Composite maps of MWV for the active (***a***) and weak phase (***b***), and those of CLW for the active (***c***) and weak phase (***d***) (contour interval 2 nm).

The composites of winds at 700 hPa for the active and weak epochs are shown in Figure 8 *a* and *b*). The significant changes in the circulation patterns during these two periods are striking. During July (Figure 8 *b*), dry continental air from the desert regions (north of 15°N) is seen to flow over northern Arabian Sea. The intrusion of strong continental winds, north of 15°N over the Arabian Sea and the well-marked changes in circulation patterns explain some of the observations of changes in contour patterns in MWV and SI during these contrasting epochs (Figures 5 and 6). The differences are quite small at 850 hPa, whereas significant changes are seen at 700 hPa. The winds with predominantly northerly component could account for the dry middle layer and stable stratification during July.

To investigate the contributions made by the upper tropospheric descent over the Arabian Sea resulting in an isothermal stable layer, we have analysed composites of average vertical velocity (‘*w*’ fields) for the 700–400 hPa altitude region corresponding to active and weak epochs. The active epoch (Figure 9 *a*) shows strong vertical (upwards) motion north of 5°north. The ascending motion in the mid troposphere is well-marked over the central Arabian Sea and Bay of Bengal.

Figure 9 *b* corresponding to the weak epoch, shows that except for a small area along the west coast, over most

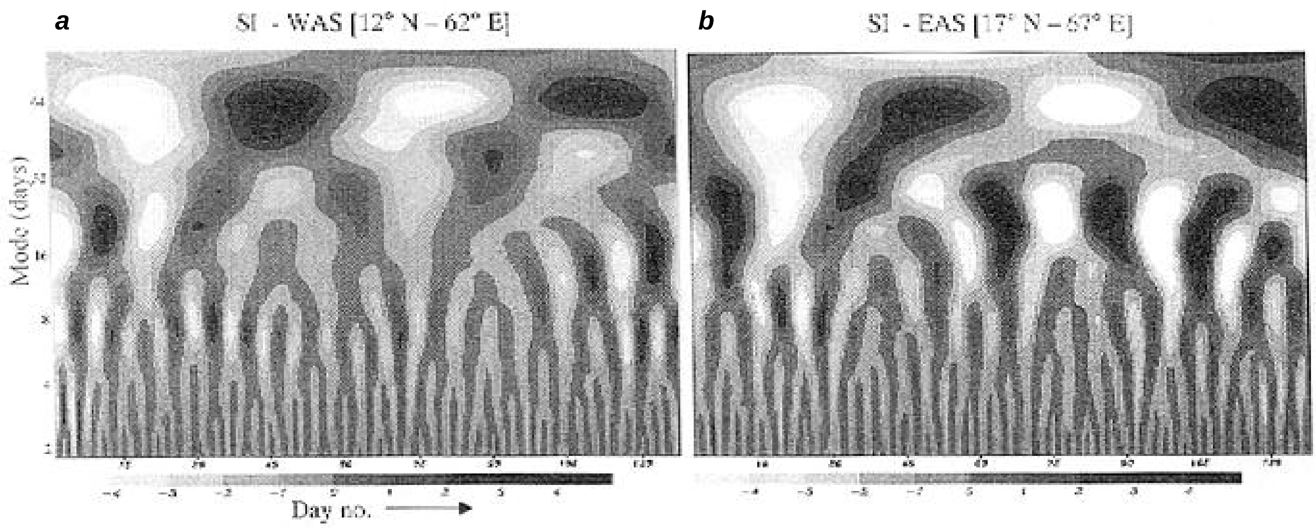

Figure 7. Wavelet analysis of SI for WAS (***a***) and EAS (***b***) during 26 May–30 September 2002. (The darkness of the shade represents the dominance of the mode).

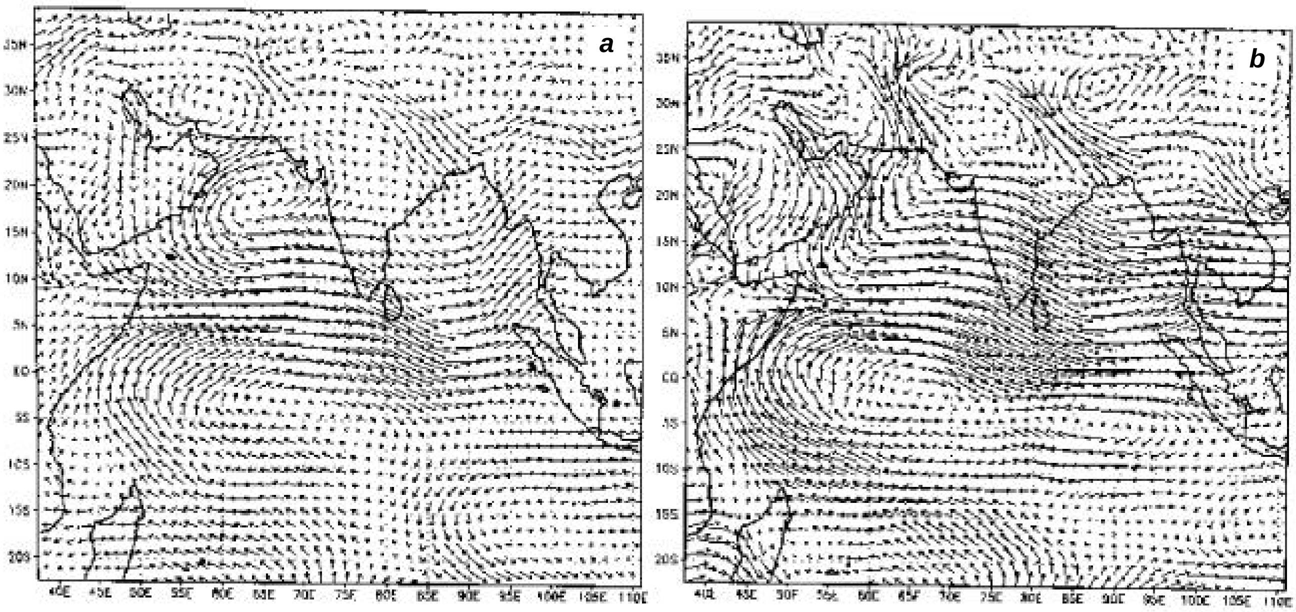

Figure 8. Composite maps of NCMRWF horizontal winds at 700 hPa during active (***a***) and weak phase (***b***).

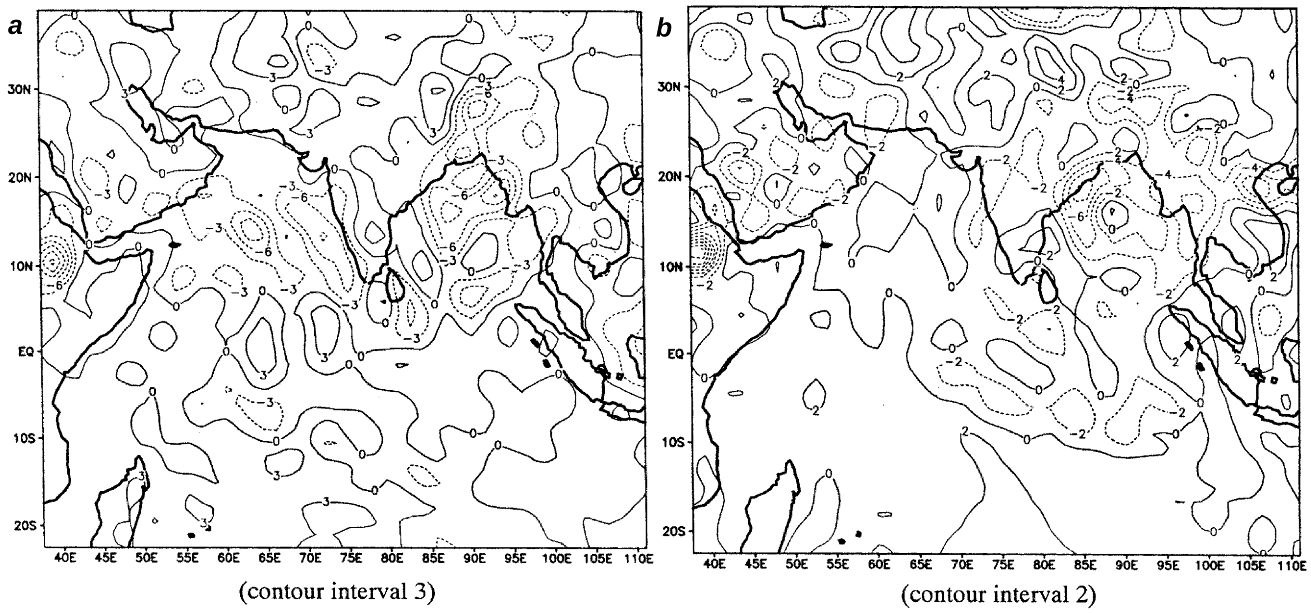

Figure 9. Average *w* (× 3600 m/s) in 700–400 hPa vertical domain during active (***a***) and weak phase (***b***).

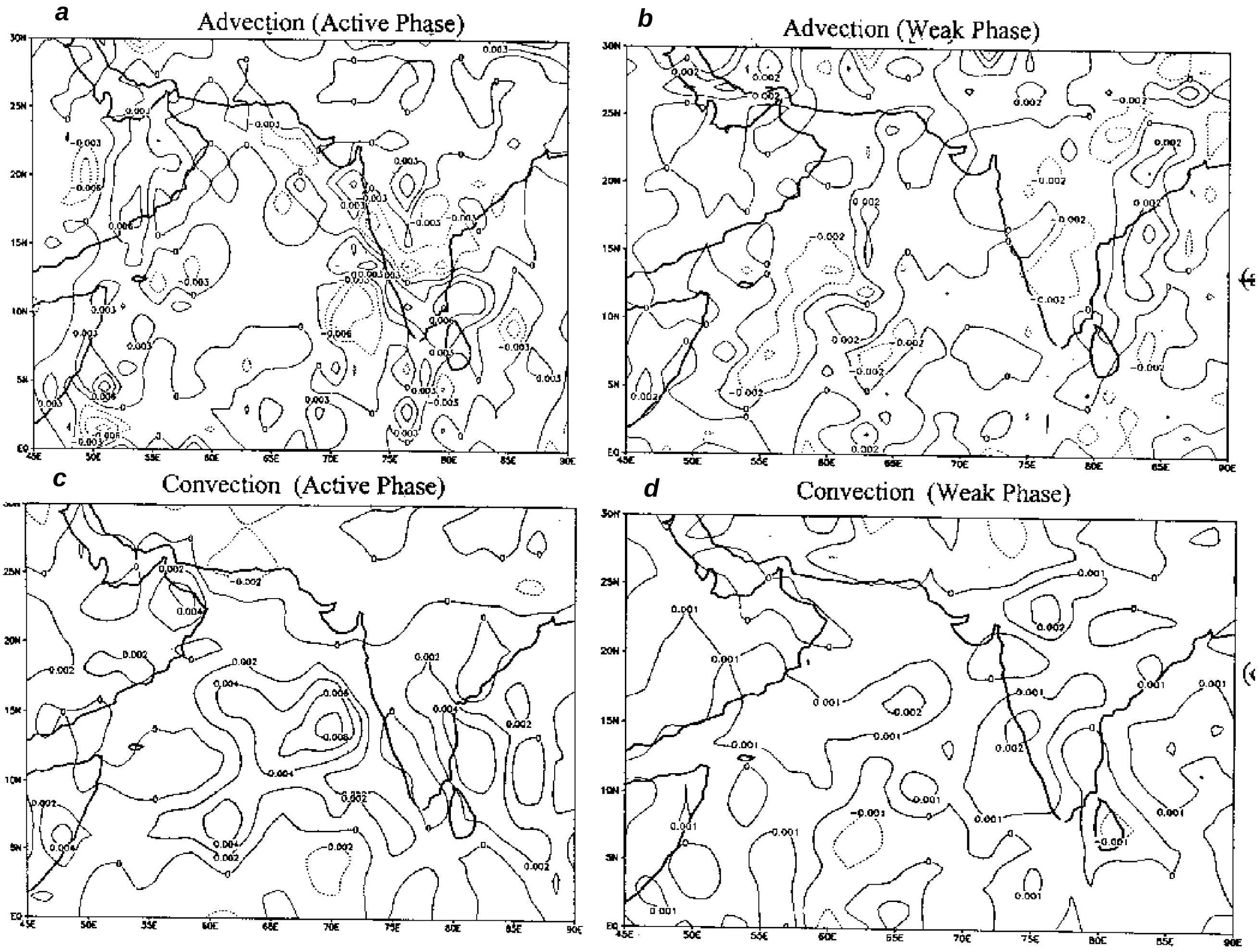

Figure 10. Contribution of advective and convective components (K/s) in the thermodynamic equation.

of the Arabian Sea weak upward or null w values are noticed, resulting in a stable isothermal layer. The intrusion of dry continental (desert) air at 700 hPa over the Arabian Sea and further maintenance of the dry mid layer by subsidence seem to explain the anomalous situation in July. The revival phase in August (not shown) is associated with considerable ascending motion, although confined only to east of 65°E over the Arabian Sea.

We have further computed the advective and convective contributions in the thermodynamic equation for each epoch as follows:

Advective component:

$$-\left(u\,\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right).$$

Convective component:

$$-\left(w.\frac{\partial T}{\partial p}\right).$$

Both meridional (northerly winds) and zonal (westerly winds) components contribute to the advective part in the formation/maintenance of inversion over the western Arabian Sea. Figure 10 *a* and *b* shows these two terms for the Arabian Sea and its neighbourhood. It is seen that over a major portion of the Arabian Sea, the change between the two epochs in the advection term is small, ~ 0.001 units on an average. However, during the same period, the area-averaged convection term (Figure 10 *c* and *d*) reduced almost by a factor of 3 to 5, particularly over the eastern Arabian Sea.

It may, thus, be inferred that subsidence has played a greater role in the creation and maintenance of inversion during the prolonged weak monsoon of 2002.

Conclusion

Using the satellite-derived temperature and moisture profiles, an attempt has been made to quantify the thermal stratification over the Arabian Sea to understand the anomalous behaviour of monsoon 2002. The time series of SI brings out clearly the active and dry spells during the monsoon. The major differences in the characterization of the western and the eastern Arabian Sea are highlighted by the west-to-east gradients in the MWV, CLW, ΔT and SI.

Using the NCMRWF-analysed fields of u, v and w, it has been shown that the anomalous long dry spell of July 2002 (low SI) may be largely attributed to the significant role played by large-scale subsidence *vis-à-vis* advection.

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