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Analysis of moist convective instability over Indian monsoon region and neighbourhood

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सार – राष्ट्रीय पर्यावरण पूर्वानुमान केन्द्र (एन.सी.ई.पी.) के पुनः विश्लेषण से प्राप्त 13 वर्षों (1982–1994) के मासिक माध्य आँकड़ों से परिकलित की गई शुष्क स्थैतिज ऊर्जा (डी.एस.ई.) आर्द्र स्थैतिज ऊर्जा (एम.एस.ई.), वर्षणीय जल मात्रा (पी.डब्ल्यू.सी.) और संवहनी उपलब्ध स्थितिज ऊर्जा (सी.ए.पी.ई.) का विश्लेषण करते हुए विभिन्न मौसमों के दौरान भारतीय मानसून के क्षेत्र और उसके चारों ओर के क्षेत्रों पर गहन संवहन की प्रकृति की जाँच की गई है।

इस अध्ययन में यह देखा गया है कि अन्य मौसमों की तुलना में मानसून वर्षा ऋतु के दौरान अस्थिरता की अधिकतम अवस्था और अधिकतम वर्षणीय जल मात्रा के साथ भारतीय मानसून क्षेत्र सभी मौसमों के दौरान औसत वायुमंडल निम्न स्तरों पर संवहनी रूप से अस्थिर होता है। इनसे प्राप्त परिणामों से यह भी ज्ञात होता है कि जून से सितंबर तक की मानसून वर्षा ऋतु के दौरान सवंहनी रूप से सबसे अधिक अस्थिर क्षेत्र बंगाल की खाडी के शीर्ष (एच.बी.ओ.बी.) के क्षेत्र पर स्थित है और यह अस्थिरता पश्चिमी प्रशांत महासागर (डब्ल्यू.पी.), भूमध्यरेखीय दक्षिणी हिंद महासागर (ई.एस.आई.ओ.) और अरब सागर (ए.एस.) के क्षेत्रों में धीरे–धीरे कम होने लगती है। इसी प्रकार से बंगाल की खाड़ी के शीर्ष क्षेत्र में संवहनी उपलब्ध विभव ऊर्जा के मान भी अधिकतम है और यह पश्चिमी प्रशांत महासागर क्षेत्र में सी.ए.पी.ई. के मानों से लगभग 362 जूल्स/के.जी.(24 प्रतिशत) अधिक है। प्रबल और कमजोर मानसून के वर्षों के लिए मिश्रित आर्द्र स्थैतिज ऊर्जा प्रोफाइल से यह पता चलता है कि कमजोर मानसून वर्षों की तुलना में प्रबल मानसून वर्षों के दौरान के सभी स्तरों पर आर्द्र स्थैतिज के मान उच्चतम होते हैं। यह भी देखा गया है कि जून से सितंबर के दौरान के भारतीय मानसून क्षेत्र में धरातलीय आर्द्र स्थैतिज ऊर्जा और वर्षणीय जल मात्रा अखिल भारतीय ग्रीष्मकालीन मानसून वर्षा (ए.आई.एस.एम.आर.) के साथ महत्वपूर्ण सकारात्मक संबंध रखती है।

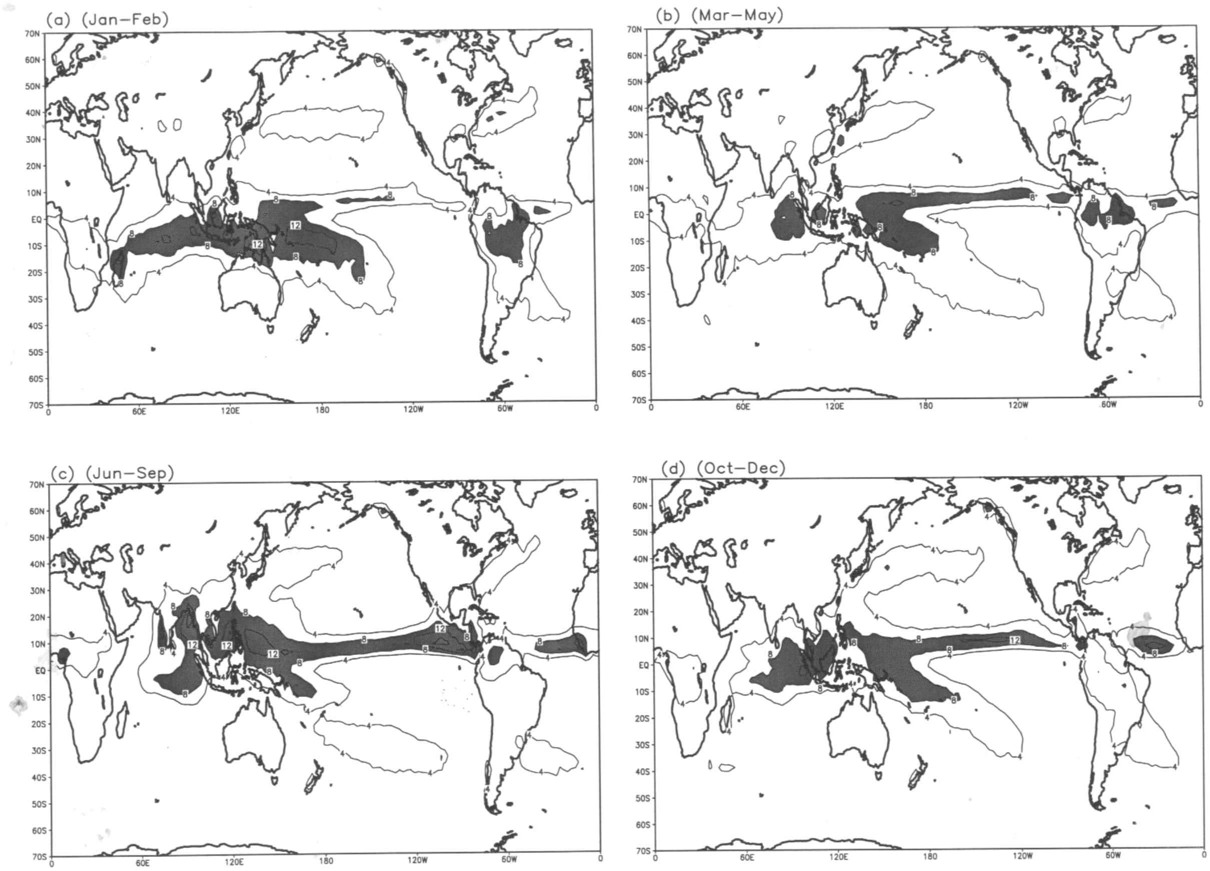
ABSTRACT. The nature of deep convection over the Indian monsoon region and neighbourhood during different seasons is investigated by analysing Dry Static Energy (DSE), Moist Static Energy (MSE), Precipitable Water Content (PWC) and Convective Available Potential Energy (CAPE) computed from 13 years (1982-1994) monthly mean data obtained from the National Centre for Environmental Prediction (NCEP) reanalysis.

It is seen from this study that the mean atmosphere over the Indian monsoon region is convectively unstable at lower levels during all seasons with highest degree of instability and maximum PWC during the monsoon season compared to other seasons. The results also show that during the monsoon season from June to September the convectively most unstable region is situated over the Head Bay of Bengal (HBOB) region and decreases gradually from West Pacific (WP), Equatorial South Indian Ocean (ESIO) and to Arabian Sea (AS) regions. Similarly the CAPE value is also highest over HBOB region and it is about 362 Joules/kg (24%) more than the CAPE value over WP region. The composite MSE profiles for strong and weak monsoon years indicate higher values of MSE at all levels during the strong monsoon years compared to weak monsoon years. It is also observed that the surface MSE and PWC over Indian monsoon region during June to September show significant positive correlation with All India Summer Monsoon Rainfall (AISMR).

Key words – Convective available potential energy, Convection, Moist static energy, All India summer monsoon rainfall, Precipitable water content, Stability.

1. Introduction

It is well-known that phenomena like tropical cyclones, Madden-Julian oscillation, meso-scale convective complexes, global general circulation etc. mostly depend on the energy released by tropical cumulus convection. Cumulus convection plays an important role in determining the large-scale thermodynamic and dynamic state of the atmosphere. It affects the large-scale flow through diabatic heating due to latent heat release,



Figs. 1(a-d). Climatological mean seasonal rainfall (mm/day) prepared from 17 years (1979-1995) Xie-Arkin rainfall. (a) Winter (Jan-Feb), (b) pre-monsoon (Mar-May), (c) monsoon (Jun-Sep) and (d) post-monsoon (Oct-Dec). More than 8 mm/day are shaded

vertical turbulent transport of heat, moisture and momentum and interaction with radiation. The release of latent heat by cumulus convection is the primary process by which the solar energy input to the equatorial regions is transferred to the upper troposphere and hence polewards by the Hadley circulation. Riehl and Malkus (1958) showed the importance of cumulus convection in the heat balance of tropical atmosphere. Some recent studies also show that the treatment of moist convection in a general circulation model has significant effect on the simulation of Indian summer monsoon (Pattanaik, 2000; Pattanaik and Satyan, 2000). There exist preferred regions of deep convection over the globe during summer and winter seasons. The active convective regions during different seasons throughout the globe can be seen from the heavy rainfall belt area as shown in Fig. 1 during different seasons as obtained from 17 years' (1979 to 1995) monthly mean rainfall (Xie and Arkin 1996). It is seen from Fig. 1 that the West Pacific (WP) region is one of the most active convective regions throughout the year. During the northern winter, the southern hemisphere is very active as it is represented by maximum rainfall belt with rainfall more than 8 mm/day [Fig. 1(a)], whereas during the northern summer monsoon season from June to September, the Indian monsoon region and the warm pool region of WP are very active convective regions [Fig. 1(c)]. During the pre-monsoon and post-monsoon seasons Figs. 1(b&d) of northern hemisphere, the rainfall patterns are nearly identical and are on the transition states between winter to summer and *vice versa* respectively. Again, during the southwest monsoon season from June to September [Fig. 1(c)], the Head Bay of Bengal (HBOB) region is very active convective region associated with Indian monsoon. In the very earlier studies (Normand, 1921, Pisharoty, 1945; Anantakrishnan & Yegnanarayanan, 1949), Meteorologists have discussed the thermodynamics of moist air over Indian region using available data.

It is well known that the latent heat released over the deep convective region of Bay of Bengal is the primary heat source, which is responsible for the maintenance of summer monsoon over India. Another pocket of active convective region is also observed over the Equatorial South Indian Ocean (ESIO) during June to September. The activity of convective region over ESIO has strong links with intraseasonal activity of All India Summer Monsoon Rainfall (AISMR). Many studies (Krishnamurti and Bhalme 1976; Gadgil 2000; Krishnan *et. al*., 2000) have identified that during breaks (*i.e*., dry spells) of the monsoon, the ESIO region is very active. There is always a competition between convergence zone over monsoon trough region [Continental Convection Zone (CCZ)] and convergence zone over ESIO [Oceanic Convection Zone (OCZ)] during the southwest monsoon season from June to September (Sikka and Gadgil, 1980 & others). Southwest monsoon is active over India when CCZ is active, whereas it is weak when OCZ is active. Thus, the deep convection regions surrounding Indian monsoon regions are associated with and have influence on the activity of Indian monsoon within a season. The strong monsoon current over the Arabian Sea (AS) region also influences the low-level moisture convergence and thereby the activity of deep convection over the region. Thus, many studies in the past have used the available surface and upper air data for the study of convective instability over India and neighbourhood. But the question arises how the nature of deep convection differs in all these regions, which affect the Indian monsoon activity. Now with the availability of reanalysed surface and upper air grid point data over the whole globe from the NCEP and other reanalysis centres, it is possible to study the thermodynamics of moist air and also to make a comparative study over different convective regions. Thus the objective of the present study is to highlights the importance of moist convection over different convective regions surrounding the Indian monsoon region during the southwest monsoon season from June to September and to make a comparative study about the nature of deep convection over the different convective regions *viz.* WP, HBOB, ESIO and AS by using reanalysed data obtained from the NCEP. A comparative study is performed to analyse the seasonal variation of convective instability over the Indian monsoon region. Interannual variability of convective parameters over the Indian region during monsoon season and its association with AISMR is also investigated in the present study.

2. Data and methodology

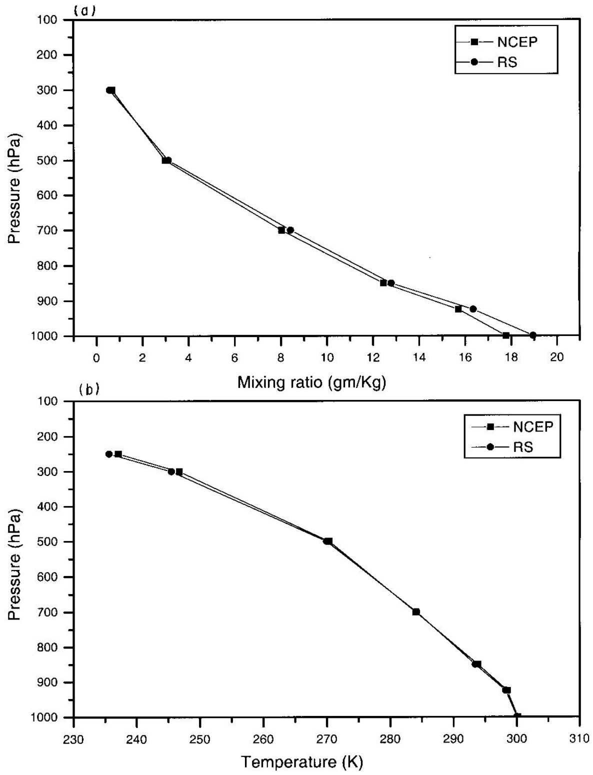
Some convective parameters have been computed and analysed for ascertaining the convective instability over the Indian monsoon region and other surrounding regions. These parameters include Precipitable Water Content (PWC), Dry Static Energy (DSE), Moist Static Energy (MSE) and Convective Available Potential Energy (CAPE). In order to take the area averaged values of above convective parameters, these parameters have been computed over different grid points (2.5° × 2.5° latitude-longitude) from the monthly mean data set obtained from the NCEP reanalysis for 13 years from 1982 to 1994. After computation of all the parameters, a climatology profile is prepared for each parameter for four seasons in a year *viz*. winter (January to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to December) seasons. Then the climatology of seasonal profile is prepared by taking the 13 years' mean value. Similar computation is also performed to study the nature of deep convection during the southwest monsoon season from June to September over the WP, ESIO, HBOB and AS regions as discussed in section 1.

3. Convective parameters

Before study of convective parameters over the Indian region, it will be appropriate to see the reliability of the NCEP data over the region. To test the reliability of the NCEP data (particularly temperature and moisture profile) over the Indian region during southwest monsoon season, a grid area extending from 20° N-27.5° N, 70° E-87.5° E is selected covering 8 radiasonde observatories (Ahmedabad, Santacruz, Jodhpur, Gwalior, Lucknow, Ranchi, Nagpur & Bhubaneswar) and the averaged profiles of temperature and moisture over the area based on these 8 upper air observatories are compared with corresponding profiles obtained from the NCEP reanalysis. The mean climatological profile of temperature and moisture over these 8 radiosonde observatories are based on the period 1971 to 1980, which is presently available in the publication of India Meteorological Department. The area was selected to include more number of radiosonde observatories in the main land of India excluding the oceanic part. The same period of NCEP data is considered for comparison purpose. The mean profiles of moisture and temperature obtained from radiosonde observatories and the NCEP reanalysis are shown in Figs. 2(a&b). It is seen that both temperature and moisture obtained from radiosonde observatories are closely matching with that obtained from the NCEP reanalysis except slight deviation in moisture values at lower levels. This shows that the NCEP data is reliable and can be used for many research studies like the present one. Behaviour of convective parameters *viz*. DSE, MSE, PWC and CAPE considered for the analysis of nature of deep convection over different regions is discussed below :

3.1. *Static energy (DSE & MSE)*

After 1950s, the energy parameter ($h = C_p T + gz + Lq$) has received considerable importance and is being



Figs. 2(a&b). (a) Climatological mean profile of moisture based on 10 years (1971-1980) averaged over the area 20° N-27.5° N, 70° E-87.5° E during June to September obtained from the 8 radiosonde observatories and from the NCEP reanalysis and (b) Same as in 'a' but for temperature

commonly referred to as MSE. The DSE is denoted as $s = C_pT + gz$. Where C_p is the specific heat of air at constant pressure; L is latent heat of condensation; T is absolute temperature; z is geopotential height and q is mixing ratio of water vapour. C_pT represents the heat content of air at constant pressure which is equivalent to the internal energy of air parcel, gz is the potential energy of air parcel at height z and Lq represents the latent energy. In the atmosphere, DSE increases monotonically but slowly with height, Lq decreases monotonically but rapidly with height. The result is that the MSE first decreases with height, becomes a minimum in the middle troposphere and again increases with height. The standard static stability criteria for a layer of unsaturated or saturated air may be expressed in terms of the vertical gradient of s and h respectively. Since above 300 hPa level the contribution of Lq is nearly zero as q is very small, so both s and h are identical.

3.2. *Precipitable water content (PWC)*

The PWC in the atmosphere is a moisture parameter which represents the depth of moisture in the atmosphere. Convective instability only is not sufficient to study the nature of deep convection over a region. Sufficient moisture in the atmospheric column is another requisite for the deep convection to sustain. During the southwest monsoon season there is accumulation of moisture over the Indian monsoon region through the low level convergence. The PWC which represents the depth of moisture is given by the formula :

$$\mathrm{PWC} = \frac{1}{g}\int_{P_{sur}}^{P_{top}} q\,\mathrm{d}p$$

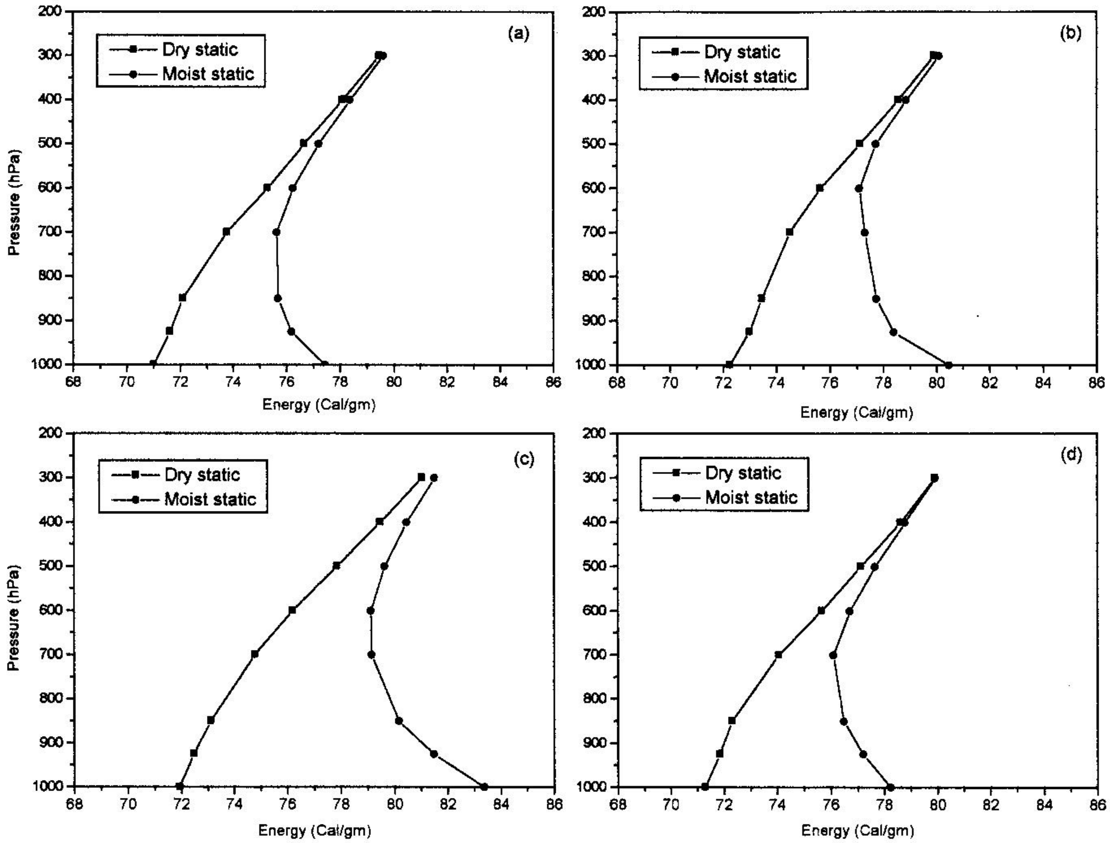
Where the limit of integration is from the surface to top of the atmosphere up to which the value of q is available and g is acceleration due to gravity. In the present computation, the upper limit of integration is taken as 300 hPa. The quantity PWC is measured in terms of gm/cm^2.

3.3. *Convective available potential energy (CAPE)*

Deep convection in the tropics can be maintained only when there is a positive cloud buoyancy over a large depth of the atmosphere. The buoyancy through which the air parcels move upward depends not only on the properties of air near the surface but also on those of the upper air through which it rises. The CAPE is one such parameter which takes care of surface as well as upper air. A quantity conceptualized first by Margules (1905), the CAPE is nothing but the energy available for convection which represents the work potential of atmospheric heat engine and is correlated to deep convection. The energy, according to parcel theory when conditional instability is released is CAPE. In between Level of Free Convection (LFC) and Level of Neutral Buoyancy (LNB), the buoyancy force will take the parcel upward where the LFC and LNB represent cloud base and cloud top levels respectively. The formula for CAPE calculation as given by Williams and Renno (1993) is :

$$\mathrm{CAPE} = \int_{\mathrm{LFC}}^{\mathrm{LNB}} \left(T_{vp} - T_{va}\right) R_d \,\mathrm{d}\left(LnP\right)$$

where T_{vp} and T_{va} are the virtual temperature of the parcel and the environment, respectively. R_d is the gas constant for dry air and P is the pressure. The value of CAPE represents the positive area on a thermodynamic chart (Temperature - Entropy diagram or tephigram) bounded by the pseudo adiabatic curve of parcel temperature and the ambient temperature profile and is being used as kinetic energy of the air parcel in this region. Normand (1938) has applied the term latent



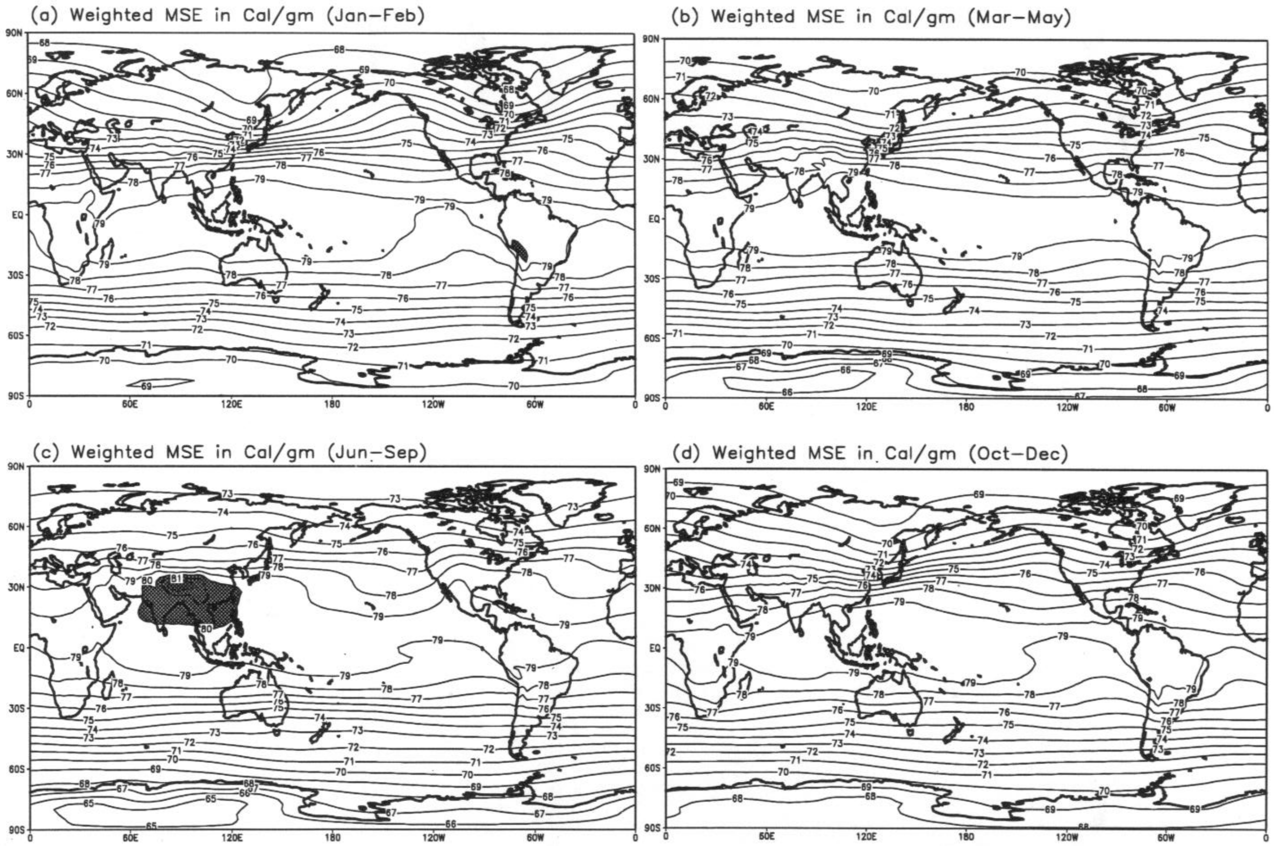
Figs. 3(a-d). 13 years (1982-1994) climatological mean profile of dry static energy *s*, and moist static energy *h* during different seasons over the Indian region (5° N-30° N, 70° E-90° E).(a) Winter (Jan-Feb), (b) pre-monsoon (Mar-May), (c) monsoon (Jun-Sep) and (d) post-monsoon (Oct-Dec)

instability to study the stability of air parcel. He showed that if the positive area in the tephigram is more than the negative area of the tephigram, the latent instability can be realizable.

4. Results and discussion

4.1. *Seasonal variation of deep convection over the Indian monsoon region*

To see the vertical distribution of static energy over the Indian monsoon region, the vertical profile of DSE and MSE averaged over the region 5° N-30° N and 70° E-90° E during all the four seasons have been plotted. The vertical profiles of these two parameters during all the four seasons are shown in Fig. 3. Like the profiles obtained by Saha and Singh (1972) for mean monsoon atmosphere, here also, the value of DSE increases with height and the MSE initially decreases with height, reaches a minimum and then increases with height (Fig. 3). During winter season, the surface value of MSE is very less [less than 78 cal/gm as shown in Fig. 3(a)] in comparison to other seasons with highest value during the monsoon season (about 83.4 cal/gm as in Fig. 3(c). In case of tropical atmosphere the magnitude of decrease of Lq is very large in the lower troposphere because of the rapid decrease in moisture content with height. As such, the MSE in this case decreases with height initially, reaches a minimum and then again increases with height as z increases more rapidly than decrease in q. Thus, the results indicate that like mean tropical atmosphere, the mean atmosphere over the Indian monsoon region during different seasons is conditionally unstable. However, the degree of instability is not identical during different seasons as the rate of decrease of MSE at lower troposphere is different during different seasons. One measure of moist static stability as defined by Krishnamurti and Bhalme (1976) is the difference of MSE at 700 hPa and that at 1000 hPa. The values of moist static stability of the layer between 1000 hPa to 700 hPa measured as 'MSE (700 hPa) – MSE (1000 hPa)' averaged over the Indian monsoon region during different



Figs. 4(a-d). 13 years (1982-1994) vertically weighted mean moist static energy over the globe. (a) Winter (Jan-Feb), (b) pre-monsoon (Mar-May), (c) monsoon (Jun-Sep) and (d) post-monsoon (Oct-Dec)

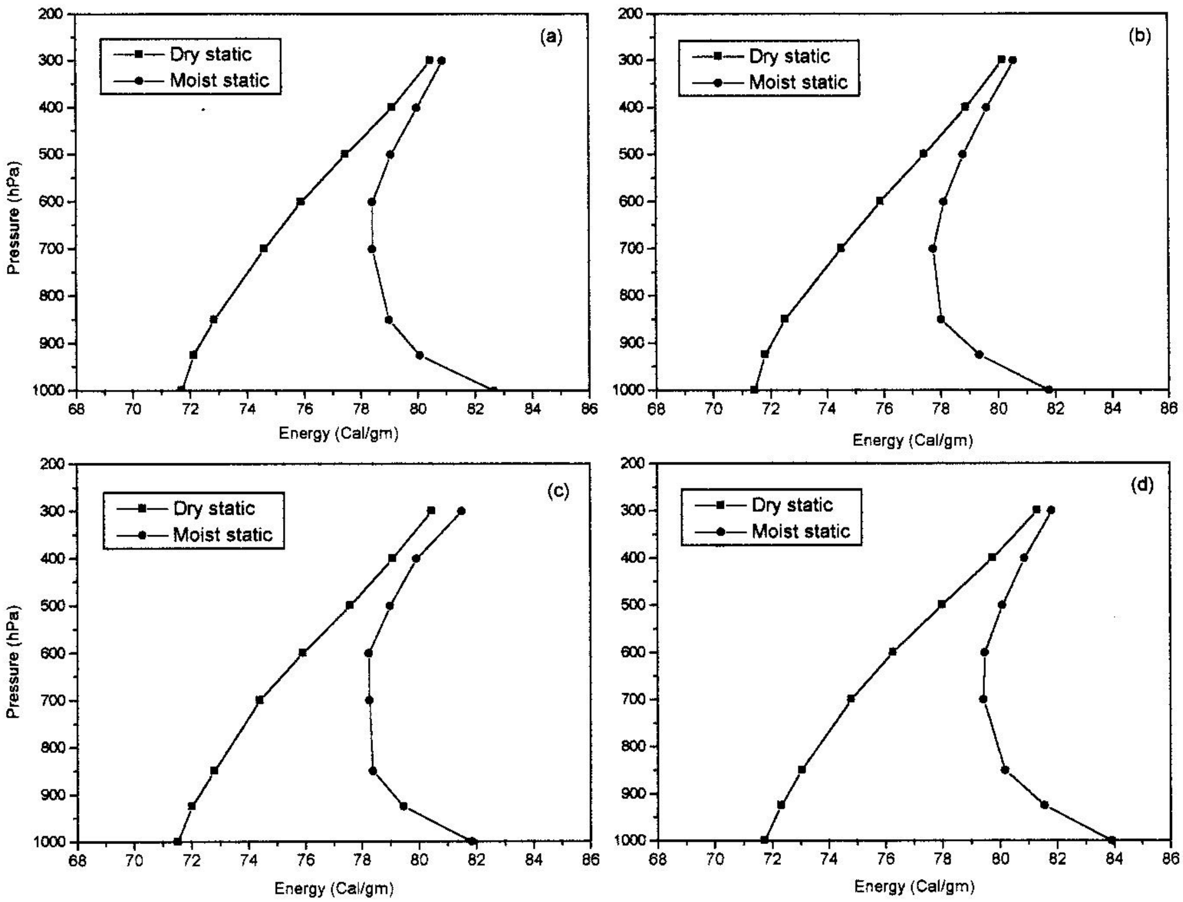
seasons are given in Table 1. It is seen from Table 1 that although the mean atmosphere over the Indian monsoon region is convectively unstable during all seasons, it is most unstable during monsoon season followed by pre-monsoon, post-monsoon and winter seasons respectively. Maximum convective instability in the monsoon season over India prevails within the monsoon trough region and its neighbourhood. Srinivasan and Sadasivan (1975) while studying the thermodynamic structure of the atmosphere over India and adjoining areas during southwest monsoon season have shown that the seasonal monsoon trough has been identified as the area of maximum total energy. They have also shown that the monsoon trough area is the area where convective instability is present upto greater heights than elsewhere.

It is not only the convective instability which is very intense during the southwest monsoon season but also the presence of moisture in deep layer. Looking at Fig. 3, it is clear that the difference of DSE and MSE is also more during the monsoon season [Fig. 3(c)] than any other season throughout the troposphere up to 300 hPa. The PWC computed over the Indian monsoon region (70° E-90° E, 5° N-30° N) by taking the mean sounding from NCEP reanalysis data set over the region for all the four seasons are also given in Table 1. The values of PWC over the Indian region (Table 1) show that during the monsoon season from June to September, the presence of moisture is maximum as compared to other seasons. The values in Table 1 also show the PWC computed during monsoon season (5.17 gm/cm^2) is about 60% more than

TABLE 1

Seasonal mean convective parameters computed from the monthly mean NCEP data for 13 years (1982 to 1994) over the Indian monsoon region (averaged over the region 5° N-30° N, 70° E-90° E). PWC stands for precipitable water content & '*h*' is for moist static energy

Parameters	Winter (Jan-Feb)	Pre-monsoon (Mar-May)	Monsoon (Jun-Sep)	Post-monsoon (Oct-Dec)
h(700 hPa) – *h* (1000 hPa) (cal/gm)	-1.80	-2.13	-4.23	-3.17
PWC gm/cm^2	2.63	3.00	5.17	3.24



Figs. 5(a-d). 13 years (1982-1994) climatological mean profile of dry static energy 's', and moist static energy '*h*' during June to September over different regions. (a) WP (5° S-15° N,120° E-150° E), (b) ESIO (10° S-Eq, 70° E-95° E), (c) AS (5° N-15° N, 55° E-70° E) and (d) HBOB (15° N-25° N, 85° E-95° E)

next lower value of PWC obtained during post-monsoon season (3.24 gm/cm^2).

4.2. *Comparative study of deep convection over different regions during monsoon season*

As is clear from Fig. 1 that there exist several other convective regions during northern summer coinciding with Indian monsoon season. The vertically weighted average MSE computed over the whole globe during different seasons by taking the monthly mean data of 13 years from 1982 to 1994 is shown in Fig. 4. Where the vertically weighted average value of MSE is represented as $\sum MSE(i) \times z(i)/\sum z(i)$. Where $z(i)$ and $MSE(i)$ are the geopotential height and MSE at different pressure levels. For this calculation, the upper limit is considered upto 300 hPa, above which the moisture presence is very negligible. It is seen from Fig. 4 that the value of vertically weighted average MSE shows higher value over the equatorial belt during all the four seasons and decreases in both the hemispheres as we go towards the polar region. This is due to the more moisture over the equatorial region due to the evaporation from the surface. One important observation is that the maximum value of vertically weighted average MSE is reported over the Indian region during June to September and it clearly highlights the dominant effect of moist convection over the region. During June to September, the weighted MSE value over Indian region is even more than that from the warm pool region of western Pacific Ocean. This is due to the difference in vertical profile of MSE between these two regions. This indicates that in the regions of intense time-mean latent heating in the tropics, precipitation is primarily balanced by low level moisture convergence rather than evaporation (*e.g.* Shukla and Wallace, 1983; Neelin and Held 1987).

TABLE 2

Seasonal mean convective parameters computed from the monthly mean NCEP data for 13 years (1982 to 1994) over West Pacific (WP), Equatorial South Indian Ocean (ESIO), Arabian Sea (AS) and Head Bay of Bengal (HBOB) regions during June to September. PWC stands for precipitable water content & '*h*' is for moist static energy

Parameters	Regions			
	WP (5° S-15° N, 120° E-150° E)	ESIO (10° S-Eq, 70° E-95° E)	AS (5° N-15° N, 55° E-70° E)	HBOB (15° N-25° N, 85° E-95° E)
h(700 hPa) – *h* (1000 hPa) (cal/gm)	-4.23	-4.01	-3.58	-4.49
PWC gm/cm^2	4.59	4.15	4.33	5.26

The vertical profile of MSE and DSE during June to September over other convective regions like WP (5° S-15° N, 120° E-150° E), ESIO (10° S-Eq, 70° E-95° E), AS (5° N-15° N, 55° E-70° E) and HBOB (15° N-25° N, 85° E-95° E) are shown in Fig. 5. Comparing the profile of MSE over WP [Fig. 5(a)] and HBOB regions [Fig. 5(d)], it is seen that the value of MSE at all levels is higher over the HBOB region than WP region. Also, the DSE at all levels is more over HBOB region than WP region, which represents warmer troposphere over the HBOB region than the WP region. The moist static stability, as defined by Krishnamurti and Bhalme (1976) over the above mentioned convective regions (obtained from Fig. 5) are given in Table 2. It is seen from Table 2 that the convectively more unstable regions are in the order of HBOB region, WP region, ESIO region and AS region. As mentioned earlier the strength of monsoon over India fluctuates between active and break spells with fluctuation in activity of OCZ over the equatorial Indian ocean. The value of moist convective instability over ESIO region is comparable with that of HBOB region and also with that of entire Indian monsoon region during the southwest monsoon season. The results of earlier studies (De *et al*., 1995; Krishnan *et al*., 2000) also show that there exist an active convective region over south Indian ocean (known as Southern Hemispheric Equatorial Trough SHET), whose activity has strong association with intra-seasonal activity of monsoon rainfall over India within a season. It is also observed that the nature of convection over the Arabian Sea is very shallow. Again to compute the moisture parameter over different regions, the PWC value over all the four regions mentioned above during the southwest monsoon season from June to September is given in Table 2. The PWC value is also maximum over HBOB region compared to other three regions as seen from Table 2. Comparing the values of Table 2 with that of June to September value of Table 1, it

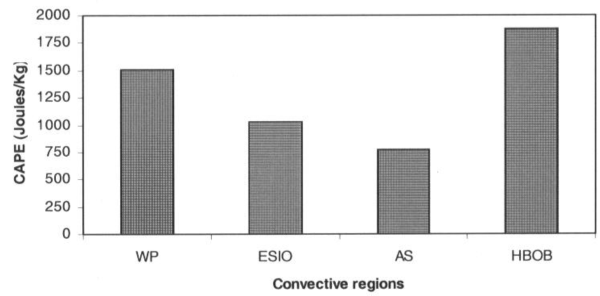


Fig. 6. Convective available potential energy computed from 13 years mean profile during June to September. (a) WP (5° S-15° N,120° E-150° E), (b) ESIO (10° S-Eq, 70° E-95° E), (c) AS (5° N-15° N, 55° E-70° E) and (d) HBOB (15° N-25° N, 85° E-95° E).

is also clear that the PWC value is still more over the entire Indian monsoon region (70° E-90° E, 5° N-30° N) during the southwest monsoon season compared to remaining three convective regions outside the Indian monsoon region (WP, ESIO & AS regions).

As the CAPE is one important convective parameter which incorporates both surface and upper air, it can also be considered for the comparison of convective activity over these regions during the southwest monsoon season over India. The CAPE calculated for all these regions during June to September is shown in Fig. 6. Like the MSE difference between 700 hPa and 1000 hPa, the CAPE value is also highest over HBOB region and it is about 362 Joules/kg (24%) higher from the CAPE value over WP region. It is basically the result of intense deep convection over the HBOB region as compared to WP region. This is represented by larger positive area associated with higher cloud top height in the thermodynamic diagram over the HBOB region than the WP region. Similar to PWC, by considering broader area over Indian monsoon region (70° E-90° E, 5° N-30° N), the CAPE value is still more (1702.4 Joules/kg) over this region compared to WP region during June to September as shown in Fig. 6.

For the maintenance of deep convection over the tropical belt, the presence of positive buoyancy over a large depth of the atmosphere is prerequisite condition. The CAPE is one parameter which represents the work potential of the atmospheric heat engine. Again, only the positive value of CAPE is not sufficient condition for the occurrence of deep convection. Calculations carried out by William and Renno (1993) over tropical regions indicated that stored energy of the order of 1000 J/kg of air are present over large areas of the tropics, over the land areas and warmer parts of the oceans as well. It is also observed that CAPE is sustained throughout the course of a day as well. Our calculations as shown in Fig. 6 also show that the CAPE value is more than 1000 J/kg over all convective regions except over Arabian Sea. Despite this widespread availability of energy for instability, observations show that deep convection breaks out over a relatively small area and on certain synoptically favoured days. One of the barriers to the inhibition of conditional instability is the Convective Inhibition Energy (CINE) and is represented by negative area on the tephigram at low levels. William and Renno (1993) have found that, in order to overcome a negative area of 20 J/kg, a parcel velocity of 6.3 m/sec is required, which is quite high over the boundary layer region (Lenschow & Stephens, 1980). Thus, CINE can frequently present a significant barrier to the release of the conditional instability in the tropics.

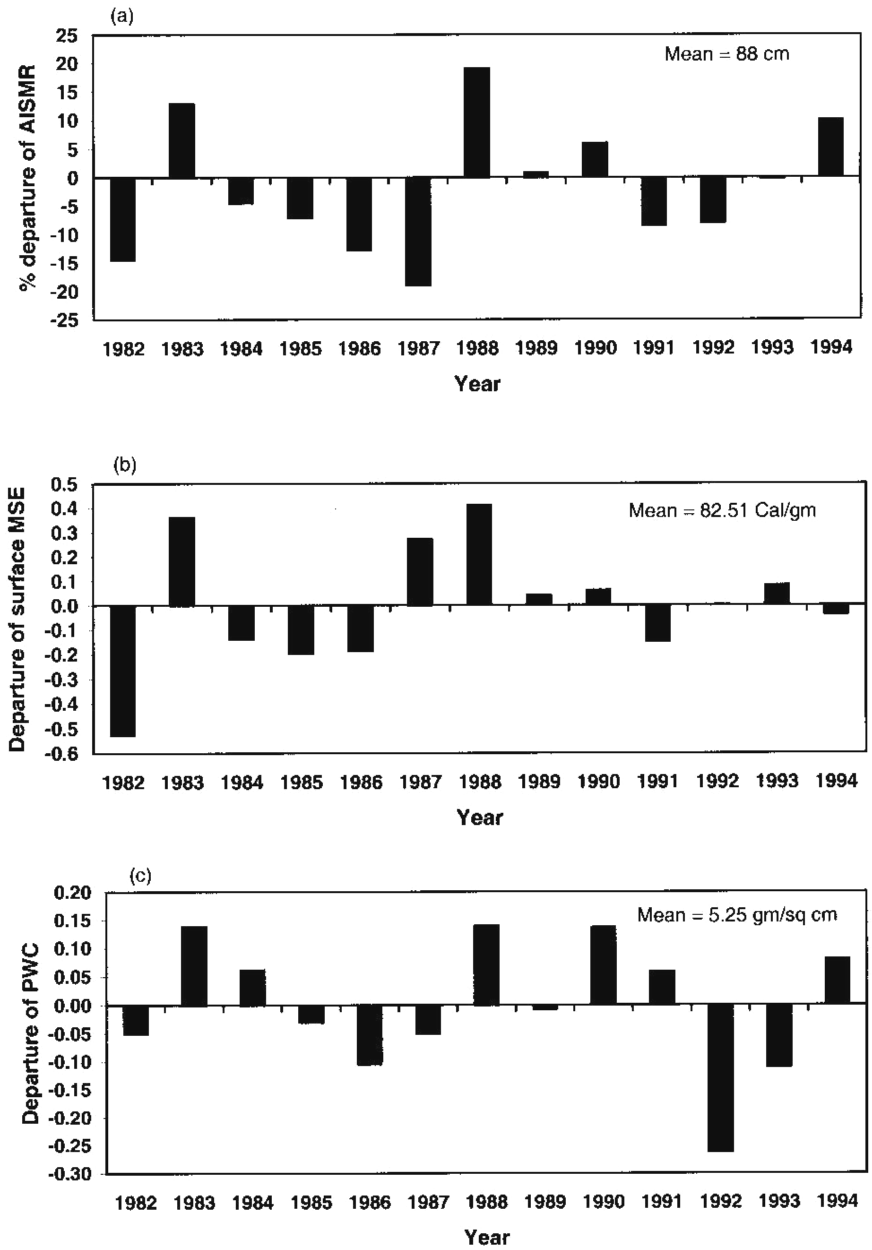
The factors which govern the existence of deep cloud clusters over continental and oceanic regions were examined by Srinivasan (1997). He suggested that another parameter for determining organized convection over tropical oceans and land is the MSE of the lower troposphere (surface to 400 hPa). While examining the relationship between Outgoing Longwave Radiation (OLR) and mean MSE of the lower troposphere, he showed that deep cloud clusters can exist in continental and oceanic regions when the mean MSE of the lower troposphere exceeds the threshold value of 335 k J/kg (≈ 79.8 cal/gm). Looking at Fig. 3 for the MSE profiles over Indian monsoon region during different seasons, it is seen that the mean MSE in lower troposphere (surface to 400 hPa) in winter, pre-monsoon, monsoon and post-monsoon seasons are 76.7, 78.2, 80.5 and 77.3 cal/gm respectively. Thus only during the monsoon season the threshold value of 79.8 cal/gm as fixed by Srinivasan (1997) is exceeded and is favourable for occurrence of deep cloud clusters.

In the Neelin and Held (1987) model in which the role of thermodynamics in the location of deep cloud clusters has been highlighted, the deep cloud clusters can be represented by a two layers troposphere in which convergence occur in the lower troposphere (surface to 400 hPa) and divergence in upper troposphere (400 to 100 hPa). According to their model, the deep cloud clusters will occur in regions with low Gross Moist Stability (GMS), where it is represented by the difference of mean MSE of upper troposphere to the mean MSE of lower troposphere. It may be mentioned here that GMS is related to stability of two adjacent layers but not to stability of a parcel lifted from the surface and it depends upon environmental profile of temperature and moisture and is not concerned with conditions within a parcel lifted from the surface. Srinivasan (1997) also shows that the regions with high precipitation are confined to regions with low GMS. He has shown that low GMS is only necessary but not sufficient condition for the occurrence of deep cloud clusters as there was evidence of low or small precipitation in the region of low GMS. Because over these regions the net energy convergence in the troposphere is small or negative. He has also shown that if the net energy available in the troposphere is negative then there can be no convergence of mass in the lower troposphere and hence deep cloud clusters cannot exist in such regions.

Another region in the tropical summer hemisphere which is remarkable is the warm pool of west Pacific. Looking at the MSE profiles during monsoon season over Indian monsoon region [Fig. 3(c)] and west Pacific region [Fig. 5(a)], it is seen that at each levels the MSE value over the Indian region is more than that over warm pool region with mean value of MSE upto 400 hPa level is 80.5 and 79.6 cal/gm respectively. The threshold value of MSE of lower troposphere defined by Srinivasan (1997) for the occurrence of deep cloud clusters is 79.8 cal/gm which is slightly more than the mean MSE value at lower troposphere over the warm pool region of west Pacific. Over the west Pacific region, the Sea Surface Temperature (SST) is always above 28° C and hence satisfies the condition necessary for the existence of deep cloud clusters. However, this region is not always covered by deep cloud clusters. Waliser and Graham (1993) have shown that deep cloud clusters occur less often in regions with SST above 29° C in the warm pool of west Pacific ocean than in regions with SST between 28° C and 29° C. It can be understood by applying Srinivasan (1997) condition for the occurrence of deep cloud clusters. Over some regions of the warm pool of west Pacific, the surface wind speed is very small. In such regions the latent heat flux can be small and hence may not be able to overcome the radiative cooling of the troposphere as a result the net energy convergence in the troposphere can be negative and hence deep cloud clusters would not always or frequently occur in such regions although the SST may be above 28° C.

4.3. *Interannual variability of convective parameters over the Indian region*

As discussed, the degree of instability over the Indian monsoon region is highest and accompanied with highest value of PWC during the southwest monsoon season compared to other seasons. Question arises whether there exists any relationship between interannual variability of convective parameters with interannual variability of AISMR. Desai (1986) has highlighted the difference in vertical profiles of MSE over seven stations in the Indian monsoon region during strong and break monsoon periods within a season and showed that at all levels the MSE values during strong monsoon situation was more than that during break monsoon situation. Again



Figs. 7(a-c). (a) Percentage departure of AISMR from 1982 to 1994, (b) departure of surface moist static energy over the Indian monsoon region (5° N-30° N, 70° E-90° E) during June to September from 1982 to 1994 and (c) same as 'b' but for precipitable water content.

Srinivasan (1997) showed that the threshold value of surface MSE over continent and oceanic region is also a convective parameter, which can determine and influence the nature of convective activity. Here it is investigated to find out the interannual variability of surface MSE along-with interannual variability of PWC during the period considered from 1982 to 1994. An attempt is also made to compute and analyse the interannual variability of vertical profile of MSE during excess and deficient monsoon years. During the 13 years period considered (1982 to 1994), the excess years are 1983, 1988 & 1994 and deficient years are 1982, 1986 & 1987. The departure of surface MSE over the Indian region (70° E-90° E, 5° N-30°N) during June to September for 13 years period from 1982 to 1994 is shown in Fig. 7(b). Comparing Figs. 7(a&b) it is observed that there exist a good

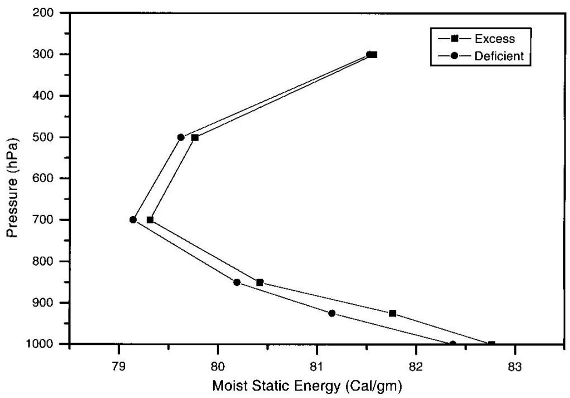


Fig. 8. Composite mean profile of moist static energy '*h*' during strong and weak monsoon years over the Indian region (5° N-30° N, 70° E-90° E) during June to September. The strong monsoon years are 1983, 1988 & 1994 and the weak monsoon years are 1982, 1986 & 1987

correlation between surface MSE and AISMR. It is seen that except on 4 occasions (1987, 1992, 1993 and 1994) out of 13 years from 1982 to 1994, the AISMR and departure of surface MSE are in same phase with either both are positive or negative. Thus during the excess year of 1994 and deficient year of 1987 the surface MSE and AISMR is not well correlated. For explaining the departures from the general behaviour in these two extreme years, daily data have to be computed as the synoptic scale variability could have dominated the profiles in these two years. The Correlation Coefficient (CC) between AISMR and surface MSE [Figs. 7(a&b)] is found to be 0.59, which is significant at 95% level of significance. Like surface MSE, the interannual variability of PWC during these 13 years period over the same region from June to September is given in Fig. 7(c). Again comparing [Figs. 7(a&c)], it is also seen that except 3 seasons (1984, 1989 and 1991) remaining 9 years show similar phase relation with departure of both parameters are either on the positive side or on the negative side. Out of three years when both parameters show out of phase relation, the year 1989 show very marginal departure. Again unlike the surface MSE the PWC and AISMR is well correlated during extreme years (excess years; 1983, 1988 & 1994 and deficient years; 1982, 1986 and 1987). Thus, it is clear from this analysis that AISMR and PWC show strong correlation and the CC between these two [Figs. 7(a&c)] is found to be 0.65, which is significant at 98% level of significance.

In order to see the vertical profile of MSE during excess and deficient years, the composite MSE profiles averaged over the region 5° N-30° N and 70° E-90° E during June to September for excess (1983, 1988 & 1994) and deficient (1982, 1986 & 1987) monsoon years are plotted in Fig. 8. Like the results obtained by Desai (1986) for MSE profiles during active and break monsoon situations, It is also seen here from Fig. 8 that the MSE values during excess monsoon seasons is more than that during weak monsoon seasons at all levels.

5. Conclusions

The following conclusions can be drawn from this study :

(*i*) The degree of instability over the Indian monsoon region is highest due to highest values of moist static instability and Precipitable Water Content (PWC) during the southwest monsoon season from June to September compared to other seasons. The PWC computed during monsoon season (5.17 gm/cm^2) is about 60% more than the next lower value of PWC obtained during post-monsoon season (3.24 gm/cm^2).

(*ii*) The maximum value of vertically weighted average moist static energy is obtained over the Indian region during June to September and is even more than that found over warm pool region of West Pacific (WP) Ocean. Thus, the low-level moisture convergence contributes significantly over the Indian monsoon region during June to September for the occurrence of deep convection.

(*iii*) Comparative study of deep convection over different convective regions during southwest monsoon season from June to September shows that deep convection is more intense over Head Bay of Bengal (HBOB) region than WP region followed by Equatorial South Indian Ocean (ESIO) region. Convection over the Arabian Sea (AS) region is shallow in nature.

(*iv*) The Convective Available Potential Energy (CAPE) during June to September is highest over HBOB region and it is about 362 Joules/kg (24%) more than the CAPE value over WP region. Similar to HBOB and WP regions, a comparable deep convective region is also seen over ESIO region during the monsoon season from June to September which generally influences the intra-seasonal activity of monsoon rainfall over India within a season.

(*v*) The interannual variability of convective parameters like surface MSE and PWC over the Indian region show significant correlation with AISMR with CC of 0.59 between surface MSE and AISMR and CC of 0.65 between PWC and AISMR during the period from 1982 to 1994. It is also seen that the composite profile of MSE during excess monsoon years show higher values compared to MSE profile during deficient monsoon years at each levels.

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