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Atmospheric boundary layer during northeast monsoon over Tamilnadu and neighbourhood - A study using TOVS data

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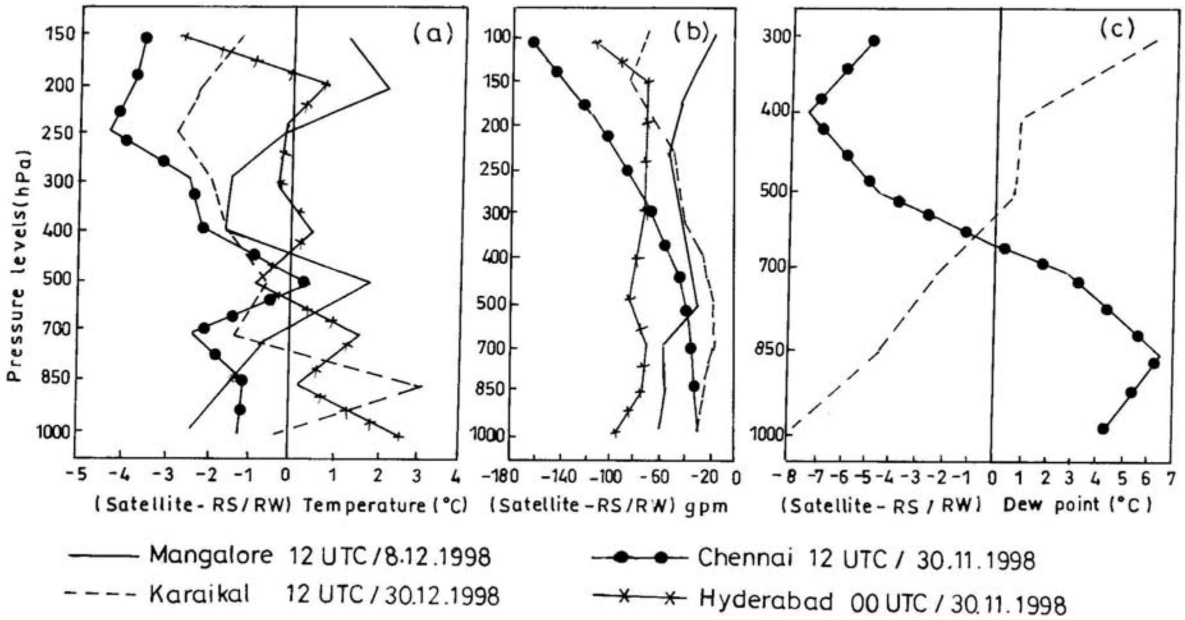
सार - 1996 से 1998 तक के टायरस ऑपरेशनल वर्टिकल साउंडर (टी.ओ.वी.एस.) आँकड़ों की सहायता से तमिलनाडु के अंदरूनी भागों,(आई.टी.एन.), तमिलनाडु के तटीय भागों (सी.टी.एन.) और समीपवर्ती बंगाल की खाड़ी (बी.ओ.बी.) में अक्तूबर-दिसंबर के दौरान दक्षिणी पश्चिमी मानसून और उत्तरी पूर्वी मानसून की गतिविधियों के समय वायुमंडलीय परिसीमा सतह की उष्मागतिक संरचना का अध्ययन किया गया है। स्तरित मिश्रित निष्प्रभावी सतह, मेघ सतह और भूमंडलीय परिसीमा सतह (पी.बी.एल.) की उच्चता का आकलन, मानक दाब स्तर के उपलब्ध आँकड़ों के उपयोग से किया गया है। भूमंडलीय परिसीमा सतह उत्तरी पूर्वी मानसून की सक्रियता के दौरान उच्चतम पाई गई है। उत्तरी पूर्वी मानसून के कमजोर पड़ने के समय तमिलनाडु के तटीय भागों और बंगाल की खाड़ी की अपेक्षा भी तमिलनाडु के अंदरूनी भागों में मेघाच्छादन विशेष रूप से सघन पाया गया है। 850-700 हैक्टापास्कल की सतह में वायुमंडल के संवहनी स्थायित्व उत्तरी-पूर्वी मानसून के कमजोर पड़ने/वापसी अवस्था के अनूरूप पाया गया है। तमिलनाडु के अंदरूनी भागों में उत्तरी-पूर्वी मानसून के कमजोर पड़ने के दौरान वर्षा धीमी होने के कारणों में से एक विश्वसनीय कारण इस क्षेत्र में 850-700 हैक्टापास्कल सतह में संवहनी अस्थिरता हो सकती है। किन्तु तटीय तमिलनाडु और बंगाल की खाड़ी में जहाँ मानसून की कमजोर अवस्था के दौरान वर्षा नहीं होती है, यह स्थिति नहीं पाई गई है। 6° के /कि.मी. (से कम) की अधिकता वाली 850-700 हैक्टापास्कल सतह में आभासी तापमान ह्रासदर, का संबंध तमिलनाडु के अंदरूनी भागों, तटीय भागों तथा बंगाल की खाड़ी की उत्तरी पूर्वी मानसून की सक्रिय अवस्था से होती है।

ABSTRACT. Thermodynamic structure of atmospheric boundary layer during October - December covering southwest and northeast monsoon activities over interior Tamilnadu (ITN), coastal Tamilnadu (CTN) and adjoining Bay of Bengal (BOB) has been studied using TIROS Operational Vertical Sounder (TOVS) data of 1996-98. Heights of neutral stratified mixed layer, cloud layer and planetary boundary layer (PBL) have been estimated through available standard pressure level data. Highest PBL occurs during active northeast monsoon. Cloud layer thickness during weak northeast monsoon over interior Tamilnadu is significantly higher than that over coastal Tamilnadu and also over Bay of Bengal. Convective stability (instability) of the atmosphere in 850-700 hPa layer is associated with weak / withdrawal (active) phase of northeast monsoon. One of the plausible reasons for subdued rainfall activity during weak northeast monsoon over interior Tamilnadu could be convective instability seen over this region in 850-700 hPa layer. But the same is absent in CTN and BOB where no rainfall activity exists during weak monsoon phase. Virtual temperature lapse rate in 850-700 hPa layer exceeding (less than) 6^{o}K/km is associated with active (weak) phase of northeast monsoon over the interior, coastal Tamilnadu and Bay of Bengal.

Key words – Planetary boundary layer, Cloud layer, Convective instability, Equivalent potential temperature, Virtual potential temperature, Lifting condensation level, Northeast monsoon.

1. Introduction

Planetary Boundary Layer (PBL) comprises of surface layer, neutral stratified mixed layer, transition layer and a cloud layer. On an average the surface layer extends upto a height of about 100m above ground and is characterised by super-adiabatic lapse rate. Immediately above surface layer is the neutral stratified (having dry adiabatic lapse rate) mixed layer extending approximately upto 500m. The top of transition layer of about 100m thickness in which specific humidity is constant normally coincides with lifting condensation level (Augustein *et al.*, 1974). The study of



Figs. 1(a-c). Sample validation of TOVS data with colocated RS/RW data during November – December 1996-98. (a) Temperature, (b) gpm and (c) dew point temperature

PBL assumes significance as it is this layer in which the turbulent exchange of momentum heat and moisture takes place from the underlying land/ocean. PBL during southwest (SW) monsoon season over Indian sub-continent and adjoining ocean and sea areas have been studied using ISMEX and MONTBLEX data by many authors [Pant (1978), Ramanathan (1978) and Tyagi *et al.* (1994)]. Northeast (NE) monsoon affects southern peninsular India south of 14° N, especially the Tamilnadu state. Detailed study of PBL during NE monsoon has not been attempted for want of upper air soundings from this region. As the study of PBL requires vertical exploration of atmosphere at very small intervals through special ascents and/or sophisticated instrumentation, such a study could not be made through conventional RS/RW data. Moreover, the RS/RW data over ocean is practically absent but for one each in BOB and Arabian sea. However, with the availability of TIROS Operational Vertical Sounder (TOVS) data from NOAA satellites at Chennai, it has now become possible to get upper air soundings over data sparse and oceanic areas. An attempt has been made to use the TOVS derived upper air meteorological data to study the vertical structure of the PBL over southern peninsular India and adjoining BOB during NE monsoon.

2. TOVS

TOVS data obtained from NOAA satellite gives temperature, dew point, gpm values at standard pressure levels besides liquid water content (LWC), outgoing long wave radiation, total ozone content and stability index at the point of sounding. These data are available approximately at 80sq km horizontal resolution at the sub-satellite points through different sounding units. Details of TOVS sounding have been described, in detail, by Smith and Schreiner (1985). Validation of TOVS data has been done for Indian region by Khanna and Kelkar (1993) and Gupta *et al.* (1996). The validation has shown that the TOVS derived temperature profile is in good agreement with radio-sonde derived temperature between 850 and 200 hPa levels.

3. Data

High Resolution Picture Transmission (HRPT) direct readout ground station at Chennai has the facility to receive and process imageries and TOVS data from NOAA 12 and 14 satellites. The system configuration and its capabilities have been described by Gupta *et al.* (1996). One step physical retrieval scheme of the International TOVS Processing Package (ITPP) version 4.0 developed by the University of Wisconsin, Madison is used to derive the vertical profiles of upper air data. As the microwave sounding unit (MSU) undergoes calibration at every scan and the microwave radiation is well-nigh unaffected by cloud contamination (Kidder and Vonder Harr, 1995) this data together with stratospheric level High Resolution Infrared Scanner (HIRS) channels data have been used to get regression estimates which in turn are used as first guess

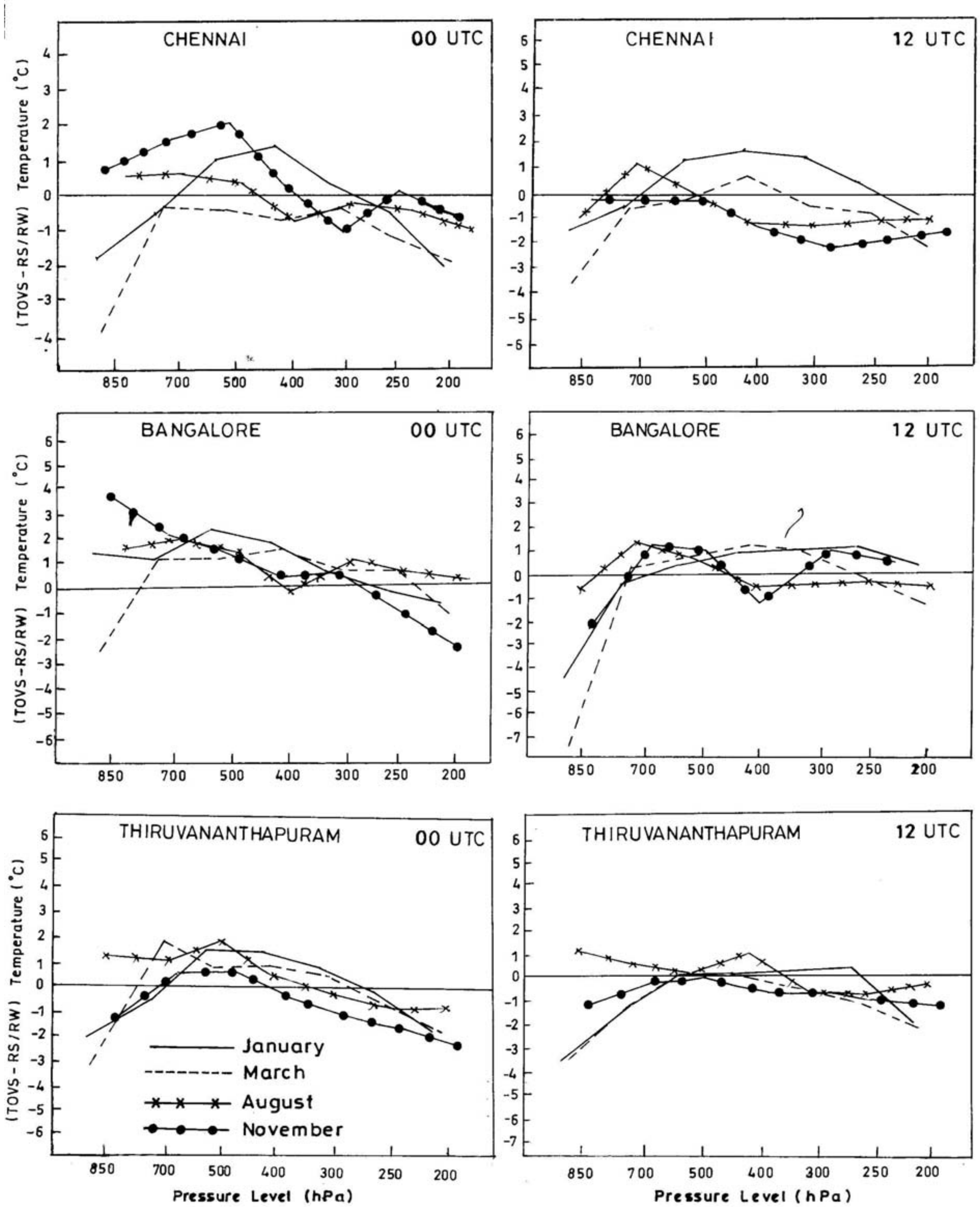


Fig. 2. Mean monthly temperature biases (satellite – radiosonde) during 1996-1998

profile to retrieve atmospheric temperature at various levels. TOVS data from August 1995 to December 1998 have been used in this paper for the validation and understanding the vertical structure of PBL during northeast monsoon.

TABLE 1

Depth of mixed and cloud layers (metres) over southern peninsular India during October-December 1996-98

Area	Active NE		Weak NE		Wdl NE		Active SW		Weak SW	
	Mixed layer	Cloud layer	Mixed layer	Cloud layer	Mixed layer	Cloud layer	Mixed layer	Cloud layer	Mixed layer	Cloud layer
ITN	901	2189	689	2405	724	714	945	2179	953	2170
CTN	870	2214	888	549	911	525	951	2146	941	2156
BOB	891	2190	910	525	921	509	926	2166	895	2201

NE-Northeast monsoon, SW-Southwest monsoon, Wdl - Post withdrawal,
CTN - Coastal Tamilnadu, ITN - Interior Tamilnadu, BOB - Bay of Bengal

4. Methodology

4.1. *Validation of TOVS data*

Validation of temperature, dew point and gpm data at standard pressure levels derived through TOVS has been done for all satellite passes within three hours of 0000 and 1200 UTC RS/RW soundings at locations within a radial distance of about 100 km from the RS/RW stations. Sample validation, selected at random, is shown in Fig 1. Validation of temperature, dew point and height (gpm) of pressure levels from TOVS derived data from August 1995 to December 1998 indicates that the average root mean squared differences (also called biases) between conventional RS/RW soundings and TOVS derived upper air soundings is from 1.9 to 2.5^{o} C in respect of temperature, 2.2 to 4.5^{o} C in respect of dew point and 30 to 55 gpm in respect of height of standard pressure level between 1000 and 200 hPa. It was also found that on some days there had been perfect agreement between these values within an absolute bias of 1o C (40 gpm) in respect of temperature (height of standard pressure levels - gpm) between 1000 and 100 hPa. However such validation done elsewhere for more than three years with three to four passes a day close to conventional RS/RW sounding timings was not readily available to the authors.

There is every likely that the values of meteorological parameters derived through TOVS and RS/RW may differ considerably, since (*i*) the sounding devices, timings and methods are different. (*ii*) the meso scale variability in the upper air is not readily known to us in the absence of RS/RW sounding values at less than 50 × 50 km grid points and (*iii*) the root mean squared difference between the TOVS and RS/RW values includes the error from the RS/RW as well. However since the root mean squared differences of temperature and height values are less than the natural variability, the TOVS soundings explain a substantial fraction of the variance of temperature and heights. In order to compare TOVS derived data on a larger scale with the climatological normal of RS/RW data, monthly means of all the parameters were computed. The comparison is presented in Fig. 2. It can be seen that biases vary with seasons, geographical locations and with height. This is in agreement with earlier studies reported by Kidder and Vonder Harr (1995). As the TOVS data is in reasonable agreement with conventional data and as we have voluminous data over data sparse and oceanic region which are unrepresented through conventional sondes, a study on the PBL during NE monsoon has been attempted in this paper with the available standard pressure level data. For this purpose, soundings close to even degree latitude × longitude (within 75 km) are averaged in the domain Lat. 8 to 14^{o} N / Long. 78 to 86^{o} E. Through this the ITN is represented by Long. 78^{o} E, CTN by Long. 80^{o} E and BOB by Long. 82 to 86^{o} E. As the soundings are averaged over even degree Lat. × Long., CTN may sometimes cover upto 75 km in the oceanic region also.

4.2. *Lifting condensation level*

As we do not have data at the surface and between 1000 and 850 hPa, it is very difficult to estimate the lowest layers of PBL, *viz*., surface layer, neutral stratified mixed layer, transition layer separately with the available data set. Lifting Condensation Level (LCL) is considered as the top of the mixed layer (Augustein *et al*., 1974; Pant,1978). Hence in the absence of TOVS derived surface data, LCL of 1000 hPa is considered as the top of mixed layer, as an approximation, since surface pressure during NE monsoon season over peninsular India is around 1000 hPa. LCL has been computed numerically based on method outlined in WMO (1986). The depth of mixed layer has been estimated in this fashion for ITN, CTN and BOB for the active, weak and post withdrawal phases of NE monsoon and also for the active and weak phases of southwest (SW) monsoon during October prior to onset of NE monsoon. The results are summarised in Table 1. Over ITN during active NE monsoon, the mixed layer height is about 175 to 200 m

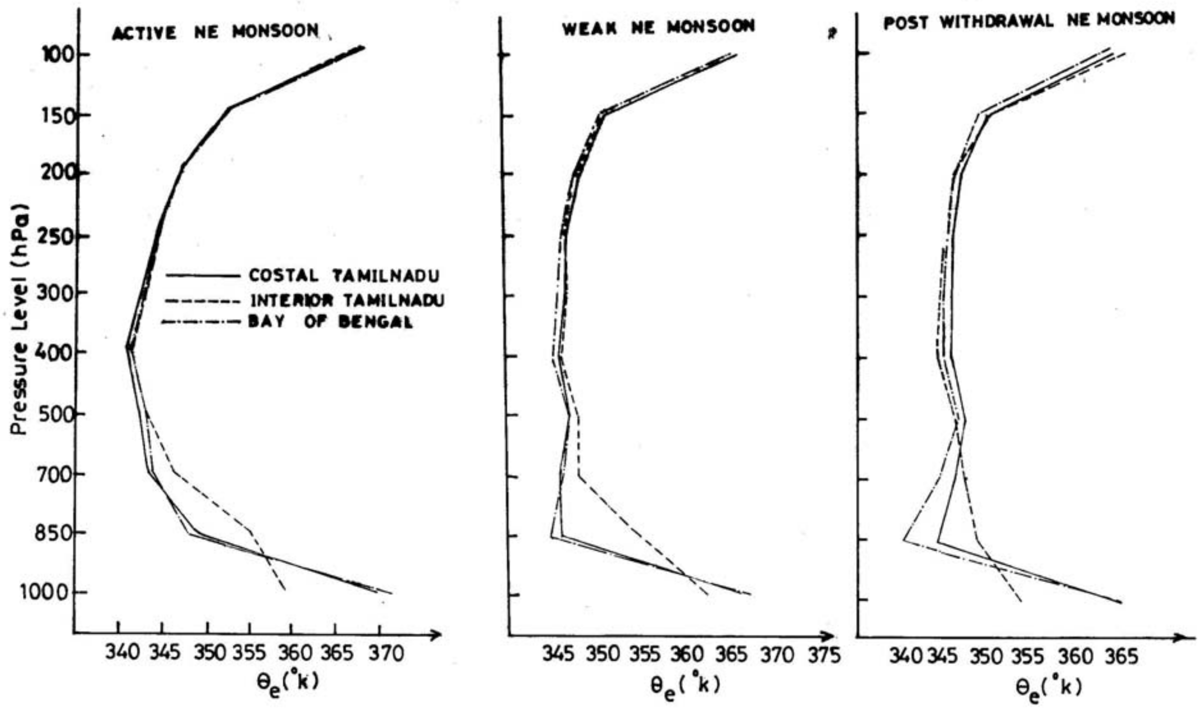


Fig. 3. Equivalent potential temperature profiles during various phases of northeast monsoon, 1996-98

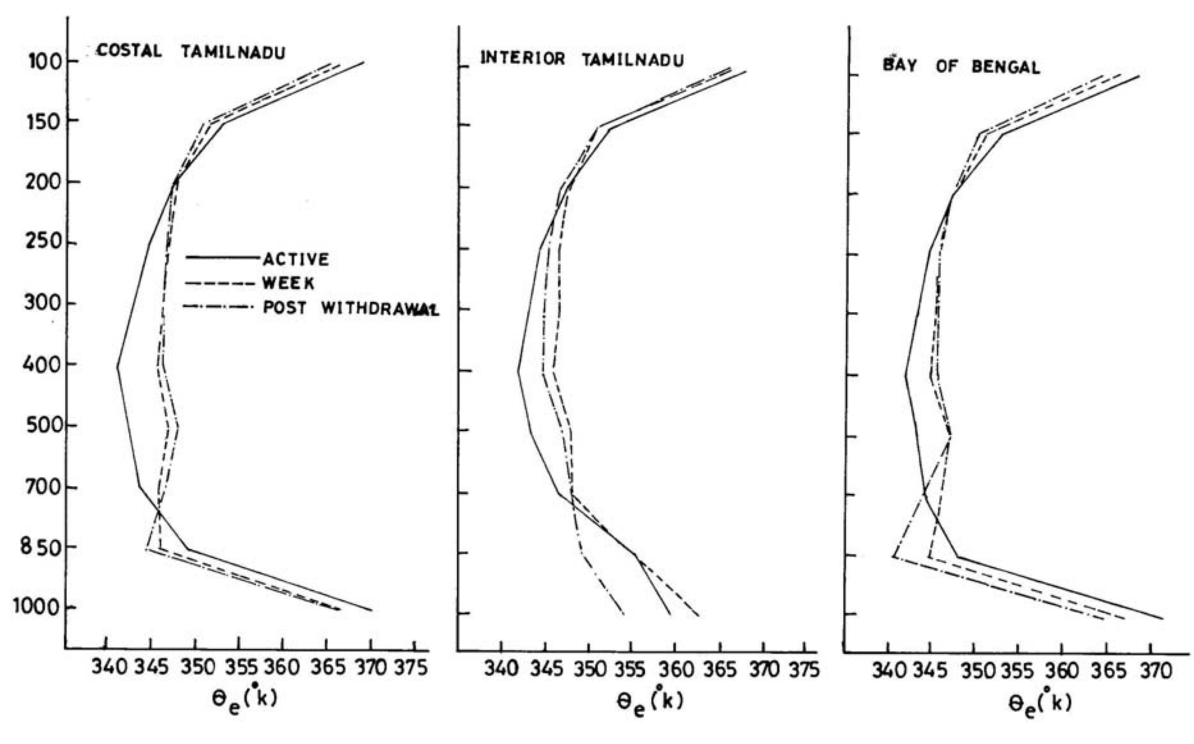


Fig. 4. Equivalent potential temperature profiles over coastal, interior Tamilnadu and adjoining Bay of Bengal during northeast monsoon, 1996-98

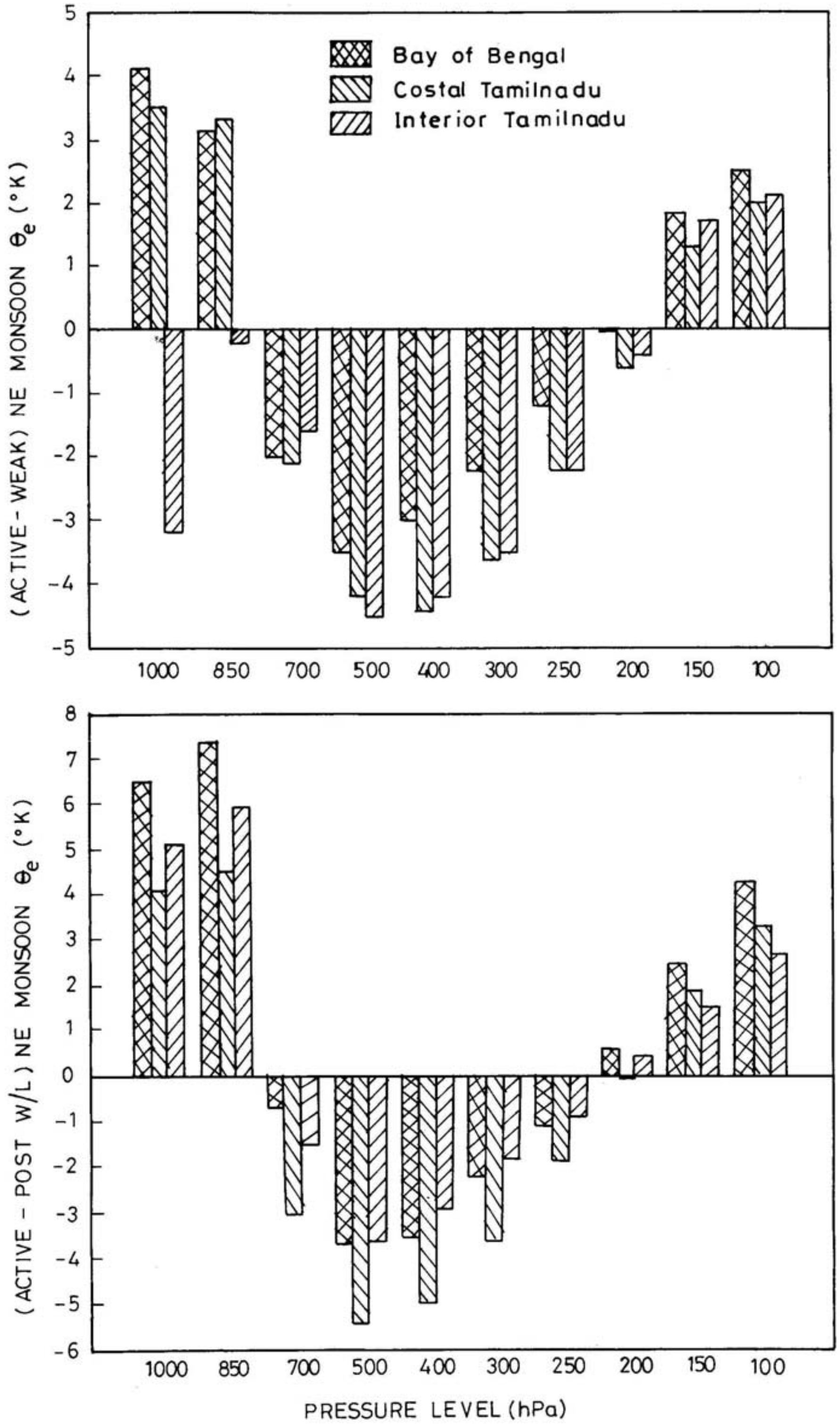


Fig. 5. Plot of equivalent potential temperature difference between (a) active and week, (b) active and post withdrawal phases of northeast monsoon, 1996-98

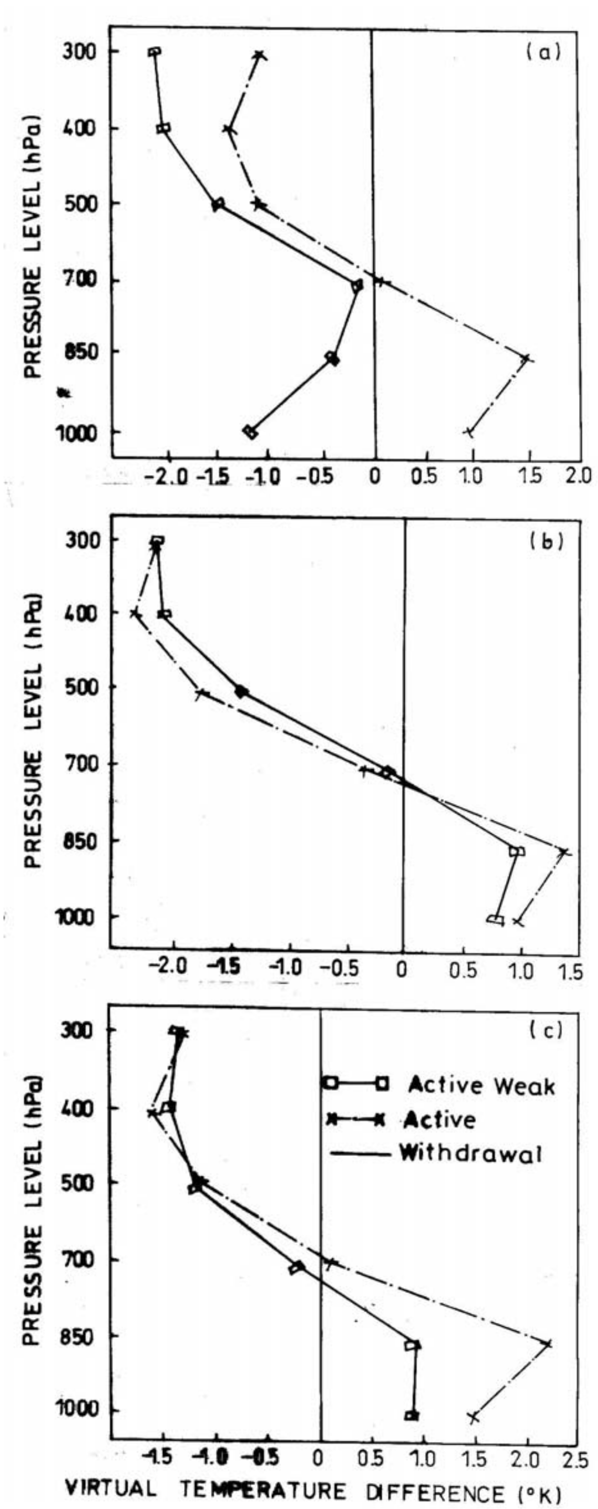


Fig. 6. Plot of virtual temperature difference between various phases of northeast monsoon, 1996-98 over (a) interior, (b) coastal Tamilnadu and (c) Bay of Bengal

TABLE 2

Profiles of equivalent potential temperature and virtual potential temperature (°K) during active northeast monsoon 1996-98

Pressure (hPa)	Coastal Tamilnadu		Interior Tamilnadu		Bay of Bengal	
	θ_e	θ_v	θ_e	θ_v	θ_e	θ_v
1000	369.9	304.7	359.4	302.2	371.3	305.0
850	349.0	307.6	355.2	309.2	347.9	307.3
700	343.5	314.2	346.4	315.1	344.1	314.2
500	342.6	327.5	343.4	327.8	343.3	327.7
400	341.1	333.9	341.8	334.3	341.8	334.3
300	342.8	340.6	343.2	340.9	343.3	341.0

higher than that of post withdrawal/weak phase. However over CTN and BOB instead of such a contrasting difference, it is seen that mixed layer height is 20 to 30 m lower during active phase than the other two phases. In other words, the mixed layer height is almost constant during all the three phases of NE monsoon over BOB and CTN presumably due to the perpetual availability of moisture. This is also confirmed during active and weak phases of SW monsoon over these regions albeit there is no contrasting difference over ITN also from active to weak phase.

4.3. *Cloud layer*

4.3.1. *Equivalent potential temperature profile*

Cloud layer extends from LCL to the base of trade inversion wherein the lapse rate is slightly steeper than moist adiabat and specific humidity decreases weakly upward. This layer could not be clearly determined during disturbed conditions during SW monsoon (Pant,1978; Tyagi *et al.*, 1994). In order to identify this layer in the absence high vertical resolution data, equivalent potential temperature (θ_e) has been computed for standard pressure levels for all phases of NE monsoon. The mean values of θ_e have been presented for the active phase of NE monsoon, as a sample, in Table 2. Gradient of equivalent potential temperature ($d\theta_e / dz$) has been worked out for all phases of NE and SW monsoon over all the three regions and presented in Table 3. Typical plots of θ_e during various phases of NE monsoon over different regions are depicted in Figs. 3&4. During active NE monsoon conditions, convective instability was seen in the lower level upto 500 hPa. This layer is capped by convective stability which is most favourable for the development of convective clouds.

Compared to CTN and BOB, ITN has a low vertical gradient of θ_e in 1000-850 hPa layer in view of temperature contrast in these layers between oceanic and land region. $d\theta_e/dz$ in 850-700 hPa layer is crucial in determining various

TABLE 3

Gradient of equivalent potential temperature and virtual potential temperature (^{o}K/km) during northeast monsoon 1996-98

Pressure (hPa)	Coastal Tamilnadu		Interior Tamilnadu		Bay of Bengal	
	$d\theta_e/dz$	$d\theta_v/dz$	$d\theta_e/dz$	$d\theta_v/dz$	$d\theta_e/dz$	$d\theta_v/dz$
			Active northeast monsoon			
1000-850	-14.7	2.0	-2.9	4.9	-16.5	1.6
850-700	- 3.3	4.0	-5.4	3.6	- 2.3	4.2
700-500	- 0.3	4.9	-1.1	4.7	- 0.3	5.0
500-400	- 0.9	3.7	-1.0	3.7	- 0.9	3.8
400-300	0.8	3.2	0.7	3.2	0.7	3.2
			Weak northeast monsoon			
1000-850	-14.6	1.9	-5.1	4.3	-15.8	1.6
850-700	- 0.1	4.8	-4.5	3.5	0.8	5.0
700-500	0.4	5.4	-0.0	5.3	0.3	5.4
500-400	- 0.8	4.3	-1.1	4.2	- 1.2	4.0
400-300	0.4	3.3	0.3	3.3	0.4	3.2
			Post-withdrawal of northeast monsoon			
1000-850	-15.0	1.7	-3.5	4.5	-17.2	1.0
850-700	1.2	5.1	-0.9	4.5	2.6	5.6
700-500	0.6	5.5	-0.3	5.2	0.8	5.5
500-400	- 1.1	4.2	-1.3	4.0	- 1.0	4.2
400-300	0.2	3.2	0.1	3.0	0.1	3.1
			Active southwest monsoon			
1000-850	-13.0	2.6	- 7.6	4.3	-14.2	2.3
850-700	- 4.3	3.9	-12.0	2.3	- 3.5	4.1
700-500	0.5	5.4	0.0	5.2	1.0	5.6
500-400	- 1.3	4.1	- 1.1	4.3	- 1.1	4.4
400-300	0.5	3.5	0.2	3.5	0.4	3.6
			Weak southwest monsoon			
1000-850	-13.3	2.6	- 7.9	4.3	-13.9	2.4
850-700	- 3.9	3.8	-11.1	2.3	- 3.1	4.0
700-500	1.1	5.7	0.1	5.4	1.0	5.7
500-400	- 1.2	4.4	- 1.7	4.5	- 1.4	4.3
400-300	0.2	3.5	0.1	3.4	0.3	3.5

phases of monsoon. θ_e either very slowly decreases with height at the rate of 0.1^o K/km or increases with height at the rate of 0.8 to 2.7^o K/km over CTN and BOB during weak and post withdrawal of NE monsoon. This suggests the prevalence of dryness in this convectively stable layer. In the active phase of NE monsoon θ_e drops with height by more than 2.3^o K/km. In the case of ITN, θ_e decreases at psuedo-adiabatic rate during active phase while during post withdrawal of NE monsoon very small decrease at the rate of 0.9^o K/km only could be noticed. However, during weak phase $d\theta_e/dz$ over ITN is on par with that of active phase implying existence of convectively unstable atmosphere and thereby causing some rainfall activity over ITN while rainfall activity is normally absent over CTN and BOB during weak phase of NE monsoon.

Strong convective instability extends in 850-700 hPa layer over ITN during active SW monsoon in October than during active NE monsoon in October to December. This is in conformity with the observed fact that ITN receives maximum rainfall during active SW monsoon than active NE monsoon. Middle level dryness/convective stability is a common feature during active and weak SW monsoon over CTN, ITN and BOB while convective instability (though not so strong) extends upto 400 hPa during active phase of NE monsoon over these regions.

Fig. 5 shows the difference between active and weak/post withdrawal NE monsoon over different regions. θ_e values during active NE monsoon are warmer than the weak (post withdrawal) NE monsoon by 3 to 4^o C (4 to 7^o C) at 1000 and 850 hPa and colder by 2 to 4^o C (1 to 5^o C) from 700 to 250 hPa over BOB and CTN. Warmer θ_e at lower levels and colder θ_e at middle and upper troposphere reflect the warmer lower troposphere and colder middle and upper troposphere which is a favourable sign for active monsoon conditions. However it is seen over ITN that θ_e values during weak monsoon are warmer than that during

TABLE 4

Virtual temperature profile during northeast monsoon over southern peninsular India, October-December 1996-98

Type	Pressure levels (hPa)					
	1000	850	700	500	400	300
			Active northeast monsoon			
CTN	304.7	293.7	283.7	268.6	256.9	241.4
ITN	302.2	295.1	284.6	268.9	257.2	241.6
BOB	305.1	293.3	283.7	268.8	257.2	241.7
			Weak northeast monsoon			
CTN	304.0	292.7	283.9	270.0	259.0	243.5
ITN	303.4	265.5	284.7	270.4	259.2	243.7
BOB	304.1	292.4	284.0	270.0	258.6	243.0
			Post withdrawal of northeast monsoon			
CTN	303.8	292.3	284.1	270.3	259.2	243.5
ITN	301.3	293.7	284.5	270.0	258.6	242.7
BOB	303.5	291.1	283.6	270.0	258.8	243.0
			Active southwest monsoon			
CTN	305.5	295.2	285.0	271.0	259.8	244.5
ITN	307.2	299.2	286.5	272.0	261.0	245.7
BOB	305.5	294.8	284.9	271.4	260.5	245.3
			Weak southwest monsoon			
CTN	305.6	295.2	284.9	271.7	260.8	245.5
ITN	307.1	299.0	286.2	272.1	260.8	245.3
BOB	305.6	294.9	285.0	271.6	260.6	245.3

CTN - Coastal Tamilnadu, ITN - Interior Tamilnadu, BOB - Bay of Bengal

active monsoon by 3.2^o C at 1000 hPa and 0.2^o C at 850 hPa. This shows the presence of warmer lower atmosphere during weak NE monsoon - a condition conducive for convective activity.

4.3.2. *Thickness of cloud layer*

The cloud layer was determined during undisturbed condition for SW monsoon over Indian ocean and over Arabian Sea by Pant (1978) and over monsoon trough regions by Tyagi *et al.* (1994) by identifying the region wherein θ_e shows a decrease from surface upto the base of trade inversion. Under disturbed conditions, minimum θ_e at inversion base is less pronounced and it nearly vanishes whence there is no inversion (Pant, 1978). The importance of minimum θ_e and thereby prevalence of dry air at mid level in producing strong wet microburst has been well documented by Caracena and Maier (1987). During active NE monsoon, the minimum θ_e is seen at 400 hPa over CTN, ITN and BOB indicating the presence of convective instability upto 400 hPa. However in other phases of monsoons, the minimum θ_e was mostly restricted to 850 hPa except in ITN wherein very weak dropping with height is observed upto 400 hPa. *i.e.* convective instability ceases atop 850 hPa during weak and post withdrawal phase of NE monsoon over CTN and BOB while very weak convective instability extends upto 400 hPa over ITN. During SW monsoon minimum θ_e was seen at 700 hPa in both phases over all the regions. This is in agreement with Srinivasan and Sadasivam (1975).

As we are unable to identify the capping inversion from the data set considered, the top of the cloud layer is identified as the height above which $d\theta_e/dz$ either drops very slowly, say between 0 and -1.0^o K/km, or becomes positive in the case of oceanic areas and between 0 and -2.0^o K/km or positive in the case of land areas. In other words, as the cloud development requires moisture and convective instability, without loss of generality the layer upto which $d\theta_e/dz$ is relatively more negative is considered as cloud

TABLE 5

Heights of planetary boundary layer during October- December 1996-98 over southern peninsular India

Phase	Latitude (°N)				Region		
	8	10	12	14	ITN	CTN	BOB
Act NE	2142	2155	2197	2203	2362	2165	2089
Wk NE	1961	2066	2072	2056	2232	1995	1952
Wdl NE	1953	1966	2010	2001	2165	1957	1904
Act SW	1977	2054	2050	2046	2205	2031	1936
Wk SW	2090	2110	2103	2088	2289	2087	2016

Act NE - Active northeast monsoon, Wk NE - Weak northeast monsoon
Wdl NE - Post-withdrawal of northeast monsoon
Act SW - Active southwest monsoon; Wk SW - Weak southwest monsoon
CTN - Coastal Tamilnadu, ITN - Interior Tamilnadu, BOB - Bay of Bengal

layer in this study. The cloud layer thickness thus worked out has been presented in Table 1. Cloud layer during active phase of NE monsoon is higher than its weak phase over CTN and BOB. However over ITN, weak NE monsoon cloud layer is higher than its active phase. This is perhaps due to the fact that the lower level temperatures are warmer during weak phase over ITN. More over, the thickness of cloud layer over ITN during weak NE monsoon is significantly higher than that over CTN and BOB. No appreciable difference in cloud layer thickness could be noticed during active and weak phases of SW monsoon over all the three regions. The assumption we made to work out the cloud layer appears to be valid as

(*i*) The cloud layer worked out tallies with that computed through special ascents by Tyagi *et al*. (1994) using MONTBLEX data and by Pant (1978) using ISMEX data and

(*ii*) They are similar to those made by Holt and Raman (1985) and Parasnis and Goyal (1990) in some earlier studies.

4.4. *Variation of virtual temperature*

Virtual temperature (T_v) has been computed based on the formula $T_v = T\,(1.0+0.61q)$ where T is the temperature and q is specific humidity, for all regions for different phases of monsoon. Table 4 lists the values of T_v and Fig. 6 presents the virtual temperature difference between active and weak/withdrawal phases of NE monsoon over ITN, CTN and BOB. T_v at 1000 hPa over BOB is warmer than ITN by 2.8 (0.7 / 2.2)°K during active(weak/post withdrawal) phase. During active NE monsoon T_v at 1000 hPa, over BOB is 0.9(1.5)°K warmer than weak (withdrawal) phase of while over CTN it is warmer by 0.8(1.0)°K respectively. Contrastingly over ITN, weak phase T_v is warmer than active phase upto 300 hPa (1.2°K at 1000 hPa, 1.5 to 2.0°K in 500 to 300 hPa). During active phase of NE monsoon, CTN and BOB are warmer by more than 2.5°K at 1000 hPa and cooler by more than 1.5° K at 850 hPa and about 0.9°K at 700 hPa than ITN. This causes higher lapse rate at lower levels over CTN. Lapse rate of T_v (*i.e*. $-dT_v/dz$) in 850-700 hPa is above 6.0°K/km during active NE monsoon while it is less than 6.0° K/km in weak and post withdrawal phase over all the regions. The increased gradient of T_v produces a larger negative buoyancy in active phase causing intense convective activity and vertical development of clouds. However over ITN, lapse rate of T_v in this layer during weak NE monsoon is more than 6.0°K/km which contributes the rainfall activity even during weak phase. No signal could be detected above 700 hPa level to identify the different phases of monsoon.

4.5. *Variation of virtual potential temperature*

Virtual potential temperature (θ_v) has been computed from the virtual temperature. Mean values of θ_v have been tabulated in Table 2 and its gradient in Table 3. Over CTN and BOB compared to active NE monsoon, $d\theta_v/dz$ increases by 0.7 to 1.4 °K/km in 850-700 hPa layer during weak/post withdrawal phase. Cooling in lower troposphere is observed in weak/post withdrawal phase. However over ITN during weak NE phase such an increase of $d\theta_v/dz$ in 850-700 hPa layer could not be seen but on the contrary the gradient is almost equal to that of active phase. Increased gradient of θ_v during weak monsoon phase could be seen from 700 to 400 hPa over ITN though the magnitude of its difference from that of active NE phase is very small (varying from 0.5 to 0.6°K/km). Warming upto 700 hPa and cooling aloft could be the reason for some convective activity over ITN during weak NE monsoon. This sort of variation of gradient is not seen during active and weak phases of SW monsoon during October over these regions. This result agrees with the earlier findings by Srinivasan and Sadasivam (1975).

TABLE 6

Gradient of specific humidity (d*q*/dz) during October-December 1996-98 over southern peninsular India

d*q*/dz	Pressure levels (hPa)				
	1000-850	850-700	700-500	500-400	400-300
			Active northeast monsoon		
CTN	-3.1	-3.3	-1.5	-0.9	-0.2
ITN	-1.4	-3.1	-1.5	-0.9	-0.2
BOB	-3.2	-3.7	-1.3	-0.8	-0.2
			Weak northeast monsoon		
CTN	-3.2	-4.5	-0.9	-0.5	-0.1
ITN	-2.2	-5.4	-1.1	-0.6	-0.1
BOB	-3.3	-4.4	-0.8	-0.5	-0.1
			Post withdrawal of northeast monsoon		
CTN	-3.3	-4.4	-0.9	-0.4	-0.1
ITN	-2.1	-4.8	-1.0	-0.4	-0.1
BOB	-3.3	-4.1	-1.0	-0.4	-0.1
			Active southwest monsoon		
CTN	-3.1	-3.6	-1.5	-0.7	-0.2
ITN	-1.9	-3.5	-2.0	-1.3	-0.3
BOB	-3.1	-3.6	-1.4	-0.8	-0.2
			Weak southwest monsoon		
CTN	-3.1	-4.4	-1.2	-0.7	-0.2
ITN	-2.0	-4.7	-1.5	-0.9	-0.3
BOB	-3.3	-4.4	-1.2	-0.6	-0.2

CTN - Coastal Tamilnadu, ITN - Interior Tamilnadu, BOB - Bay of Bengal

4.6. *PBL heights*

PBL is the lowest part of atmosphere in which humidity is almost constant it decreases sharply above this layer. The height of PBL can be found out by working out the point of inflexion *i.e.* where the derivatives of humidity with height changes its sign. The computation has been carried out iteratively using the interpolated humidity values between standard pressure levels. The PBL heights are thus estimated for different phases of NE and SW monsoon. The mean PBL heights for CTN, ITN and BOB are tabulated in Table 5. The highest PBL height is seen during active NE monsoon and it is maximum over ITN. The mean PBL heights during active NE monsoon phase over CTN/BOB/ITN are higher than that of weak phase by 169/137/129 m and that of the post withdrawal phase by 207/185/196 m respectively. The higher PBL during active NE monsoon phase is in conformity with realised precipitation over Tamilnadu in this phase. Active NE monsoon PBL height is higher than that of active SW monsoon and the maximum height difference is observed over ITN and also over low (8^{o} N) latitude.

4.7. *Specific humidity*

Specific humidity (*q*) has been estimated from dew point temperature using Teten's formula (WMO,1986). Gradient of *q* has been worked out for all phases of NE and SW monsoon over all the three regions. The mean values of d*q*/dz are summarised in Table 6. Drop of *q* with height is comparatively very less over ITN in 1000-850 hPa layer during active phase of NE monsoon. Compared to active phase, d*q*/dz of weak phase of NE monsoon diminishes in 850-700 hPa layer by 1.2g/kg/km over CTN, 0.7g/kg/km over BOB. The drop over ITN is substantially high (2.3g/kg/km). Despite this higher drop in *q*, ITN gets some precipitation during weak phase due to the prevalence of convective instability in the lower atmosphere which is normally absent over CTN and BOB in this phase. Specific humidity and its gradient is very small over all three regions atop 700 hPa during weak and withdrawal phases of NE monsoon. However substantial amount of moisture extends upto 500 hPa during active NE monsoon and weak SW monsoon over all the three regions but upto 400 hPa over ITN during active SW monsoon. This is in partial agreement with Raj (1996) who reported higher liquid water content over CTN during the active phase of SW monsoon in October than the active phase of NE monsoon based on computation using only Chennai RS/RW data.

5. Conclusions

(*i*) Neutral stratified mixed layer of active northeast monsoon over interior Tamilnadu is 175-200 m higher than that observed during weak/post withdrawal phase.

(*ii*) During weak NE monsoon, cloud layer thickness over interior Tamilnadu is higher than that over coastal Tamilnadu and Bay of Bengal.

(*iii*) The existence of convective instability upto 700 hPa decides the active phase of NE and SW monsoon over interior, coastal Tamilnadu and adjoining Bay of Bengal.

(*iv*) During weak phase of NE monsoon, convective stability prevails over CTN and BOB in 850-700 hPa whereas convective instability exists in this layer over ITN causing some rainfall activity.

(*v*) Convective instability extends upto 400 hPa during active NE monsoon whereas stability prevails atop 700 hPa during active SW monsoon over all the regions.

(*vi*) Substantial amount of moisture extends upto 500 hPa during active NE monsoon whereas very little moisture is available aloft 700 hPa over CTN, ITN and BOB.

(*vii*) PBL height of active NE monsoon is higher than active SW monsoon and the maximum height difference is noticed over ITN and also at 8^{o} N latitude. Compared to all phases of NE and SW monsoons over ITN, CTN and BOB, the maximum height of PBL is seen during active phase of NE monsoon over ITN.

(*viii*) Virtual temperature lapse rate in 850-700 hPa exceeding (less than) 6^{o} K /km is associated with active (weak) phase of NE monsoon over ITN, CTN and BOB.

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References

Augustein, E.H., Schmiedt, H. and Ostapotf, F., 1974, "The vertical structure of the planetary boundary layer in undisturbed trade winds over the Atlantic Ocean", Boundary Layer Meteorol., **6**, 129-160.

Caracena, F.J. and Maier, M., 1987, "Analysis of a microburst in the FACE meteorological meso network in southern Florida", *Mon. Wea. Rev*., **115**, 969-985.

Gupta, H.V., Rengarajan, S., Suresh, R. and Gupta, R.C., 1996, "Reception of HRPT data from NOAA satellites at IMD, Madras", *Vayu Mandal*, **26**, 3&4, 56-59.

Holt, T. and Raman, S.S., 1985, "Aircraft and ship observations of the mean structure of the marine boundary layer over Arabian Sea during MONEX-79", Boundary Layer Meteorol., **33**, 259-282.

Khanna, P.N. and Kelkar, R.R., 1993, "Temperature sounding of the atmosphere over the Indian region using satellite data", *Mausam*, **44**, 2, 167-174.

Kidder, S.Q. and Vonder Harr, T.H., 1995, "Satellite Meteorology -An introduction", Academic Press Inc., San Diego, CA, p466.

Pant, M.C., 1978, "Vertical structure of planetary boundary layer in the west Indian Ocean during Indian summer monsoon as revealed by ISMEX data", *Indian J. Met. Hydrol. & Geophys*., **29**, 1&2, 88-98.

Parasnis, S.S. and Goyal, S.B., 1990, "Thermodynamic features of the atmospheric boundary layer during summer monsoon", *Atmos. Environ*., A**24**, 743-752.

Raj, Y.E.A., 1996, "Inter and Intra-seasonal variation of thermodynamical parameters of the atmosphere over coastal Tamilnadu", *Mausam*, **47**, 259-268.

Ramanathan, Y., 1978, "A study of the atmospheric boundary layer over the Arabian Sea", *Indian J. Met. Hydrol. & Geophys*., **29**, 4, 643-654.

Smith, W.L. and Schreiner, A.J., 1985, "Simultaneous retrieval of surface and atmospheric parameters: A physical and analytical direct approach", in : Advances in Remote Sensing, A. Deepak Pub., ISBN O-937194-027, 221-232.

Srinivasan, V. and Sadasivam, V., 1975, "Thermodynamic structure of the atmosphere over India during southwest monsoon", *Indian J. Met. & Geophys*., **26**, 2, 169-180.

Tyagi, A., Mohanty, U.C. and Ramesh, K.J., 1994, "Planetary boundary layer structure in the monsoon trough region", *Mausam*, **45**, 3, 213-222.

World Meteorological Organisation, 1986, "Workbook on Numerical weather prediction for the tropics for training of class I and class II meteorological personnel", prepared by T. N. Krishnamurti, WMO No. 669, WMO, Geneva, Switzerland, p355.