

## Role and impact of Siberian High on the temporal variation of Indian northeast monsoon rainfall

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**सार** — इस शोध-पत्र में वर्ष 1971 से 2004 तक 34 वर्षों की अवधि के लिए तमिलनाडु (एन.एम.आर.) के मासिक/मौसमी माध्य पी.एस.एच. और मासिक/मौसमी वर्षा के आँकड़ों के आधार पर पूर्ववर्ती और समवर्ती अवस्थाओं में 87.5 और 102.5° पू. देशांतर और 47.5 और 52.5° उ. अक्षांशों (पी. एस. एच.) से घिरे हुए साइबेरिया क्षेत्र में माध्य समुद्र सतह तापमान के रूप में परिभाषित साइबेरिया हाई और भारतीय उत्तरपूर्वी मानसून वर्षा के मध्य संबंध का अध्ययन किया गया है। इसमें यह पाया गया है कि अक्टूबर-नवंबर (ओ.एन.) के पी.एस.एच. और एन.एम.आर. के मध्य सकारात्मक संबंध होता है जो पूर्ववर्ती अवस्था [(पी.एस.एच.) (ए.एस./सितंबर)] में महत्वपूर्ण होता है और समवर्ती अवस्था में संतुलित रहता है। यह संबंध पी.एस.एच. (सितंबर) (पूर्ववर्ती) और पी.एस.एच. (दिसंबर) (समवर्ती) दोनों के साथ एन.एम.आर. (दिसंबर) के लिए नकारात्मक हो जाता है। कुल मिलाकर सितंबर-नवंबर (एस.ओ.एन.) के दौरान पी.एस.एच. के नकारात्मक असंगति वाले प्रोफाइल और तत्पश्चात् — सकारात्मक पी.एस.एच. (दिसंबर) असंगति वाले प्रोफाइल न्यून एन.एम.आर. से संबंध होते हैं किन्तु ये एस.ओ.एन. में सकारात्मक पी.एस.एच. असंगति वाले प्रोफाइल के लिए सामान्य होते हैं जो दिसंबर में नकारात्मक हो जाते हैं और ये एन.एम.आर. कि अधिकता के साथ संबद्ध रहते हैं। प्रायद्वीप भारत के दक्षिण पूर्वी तट से दूर बंगाल की खाड़ी में निम्न स्तर की पूरवैया की क्षमता के माडुलन सहित भारत में 200 हैक्टापास्कल (एस.टी.आर.) पर उप-उष्णकटिबंधीय रिज के अक्षांशीय स्थितियों और 850 हैक्टापास्कल (ई.टी.) पर भूमध्यरेखीय द्रोणी के द्वारा एन.एम.आर. पर पी.एस.एच. के उदगम का पता चला है। एक तीव्र पी.एस.एच. (सितंबर), बंगाल की खाड़ी के साथ-साथ एस.टी.आर./ई.टी. के दक्षिणाभिमुखी स्थान पर पूरवैया की सुदृढ़ता के साथ संबंध है जो एक अच्छे एन.एम.आर. (ओ. एन.) के अनुकूल है। दिसंबर में भूमध्यरेखा के निकट अपने सामान्य अक्षांशीय स्थिति से ई.टी. के उत्तराभिमुखी स्थान से एक सामान्य की अपेक्षा कमजोर पी.एस.एच. (दिसंबर) संबद्ध है जो अच्छे एन.एम.आर. (दिसंबर) के लिए सहायक बन जाता है। पी.एस.एच. की समय श्रंखलाओं के विश्लेषण से दिसंबर में सामान्य की अपेक्षा कमजोर पी.एस.एच. अच्छे एन.एम.आर. (दिसंबर) के साथ सम्मिलित होते हैं इसमें यह देखा गया है कि पी.एस.एच. में अपने आप कुल मिलाकर तीव्र पी.एस.एच. (नवंबर) के पश्चात् सामान्य की अपेक्षा कमजोर पी.एस.एच. (दिसंबर) और इसके विलोमतः जैसी अधिकांश स्थितियों में दिसंबर में चरणवद्ध ढंग से परिवर्तित होता है।

**ABSTRACT.** The relation between the intensity of Siberian High, defined as the mean sea level pressure over the Siberian region bounded by 87.5 & 102.5° E longitudes and 47.5 & 52.5° N latitudes (PSH) and Indian northeast monsoon rainfall has been studied in antecedent and concurrent modes based on monthly/seasonal mean PSH and monthly/seasonal rainfall data of Tamil Nadu (NMR) for the 34 year period, 1971 to 2004. It has been found that a positive relationship exists between the PSH and NMR of October-November (ON) which is significant in the antecedent mode [PSH(AS/Sep)] and modest in concurrent mode. The relationship turns negative for NMR (Dec) with both PSH(Sep) (antecedent) and PSH(Dec) (concurrent). By and large, negative anomaly profile of PSH during September-November (SON) followed by a positive PSH (Dec) anomaly is associated with a deficient NMR, but, a normal to positive PSH anomaly profile in SON becoming negative in December is associated with an excess NMR. The manifestation of PSH on NMR has been shown to be by way of modulating the strength of low level easterlies over the Bay of Bengal off the southeast coast of peninsular India as well as the latitudinal positions of Sub Tropical Ridge at 200 hPa (STR) and Equatorial Trough at 850 hPa (ET) over India. An intense PSH (Sep) is associated with strengthening of easterlies over the Bay of Bengal as well as southward location of STR/ET thereby favouring a good NMR (ON). During December, a weaker than normal PSH (Dec) is associated with northward location of ET from its normal latitudinal position near the equator which becomes conducive for good NMR(Dec). That a weaker than normal PSH in December is associated with good NMR(Dec) is comprehended from an analysis of time series of PSH. It has been found that the PSH itself undergoes a phase change in December on most occasions, *i.e.*, an intense PSH (Nov) is by and large, followed by a weaker than normal PSH (Dec) and *vice versa*.

**Key words** — Northeast monsoon rainfall, India, Tamil Nadu, Siberian High, Low level easterlies, 200 hPa level, Sub Tropical Ridge, Equatorial Trough, Onset, Withdrawal, Correlation, Conditional mean, Time series analysis.

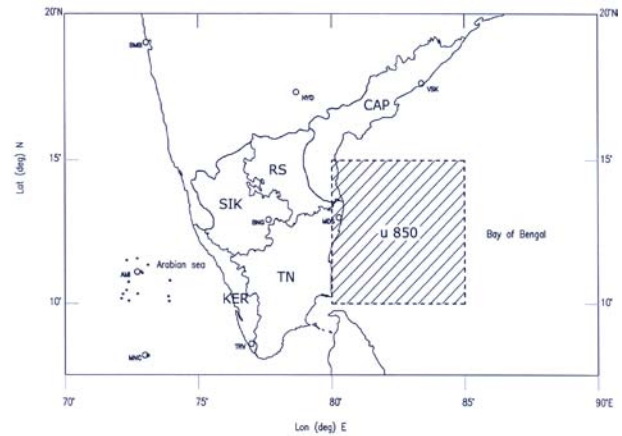
## 1. Introduction

Monsoons are planetary scale circulations associated with seasonal reversal of pressure, wind and temperature caused by differential heating of land and ocean. During the northern hemispheric summer, differential heating of land and ocean result in a strong pressure gradient on a planetary scale over the Indian sub continent. This serves as a driving force for the Asian summer monsoon circulation of which the Indian southwest monsoon of June-September (JJAS) is a major component [Ramage (1971), Das (1986)].

In September, during the final phase of the summer monsoon over India, the equatorial trough moves southwards [Rao (1976), Raj *et al.* (2007)] and simultaneously, vast expanse of land over extreme northern parts of Asia undergoes rapid radiative cooling and a high pressure area starts developing over Siberia at the surface and lower levels of the atmosphere which builds up further with time and becomes most intense in December/January at about 80-120° E and 45-60° N. Coupled with warmer equatorial Pacific and Indian oceans where the pressures are relatively low, the Siberian High establishes the Asian winter monsoon circulation wherein the outflow from the Siberian anticyclone at 850 hPa level establishes cold northeasterly winds at low levels over eastern and southern Asia (Das, 1986, Zhang *et al.*, 1996).

The Asian winter monsoon of December to February (DJF) is most active over East Southeast Asia and gets activated from the following two features – (i) frequent cold surges emanating from the Siberian High and (ii) interaction between the cold continental outflow from the Siberian High and warm maritime equatorial air mass over the North Indian Ocean. Thus the Siberian anticyclone plays a very important role in the Asian winter monsoon circulation and hence is generally taken to play the role of Mascarene High of the summer monsoon (Krishnamurti, 1979, Das, 1986).

Over the Indian region, well defined reversal of surface and low level winds from southwesterly to northeasterly direction takes place in October prior to the onset of northeast monsoon over peninsular India (IMD, 1973a). The Indian northeast monsoon (NEM) of October to December (OND) is by and large considered as a part of the Asian winter monsoon circulation despite the fact that the duration of the Asian winter monsoon is DJF whereas the Indian NEM is experienced during a slightly different time frame of OND. In this context, it may be mentioned that according to Zhang *et al.* (1996) the period of East Asian winter monsoon should be taken as November to March instead of DJF since the frequency of cold surges from Siberian High is maximum in November.



**Fig. 1.** Southern Indian sub-divisions influenced by northeast monsoon and a representative region off the southeast coast of India

A number of research works on East Asian winter monsoon during the last few decades have brought out the significance of the Siberian High and the cold surges in explaining the winter monsoon performance [Zhang *et al.* (1996), (Lau and Chang (1987), Ding (1990), Chen *et al.* (2004), Panagiotopoulos *et al.* (2005) and Wu *et al.* (2006)]. Also, of late, a number of works on teleconnections between Indian NEM and various global oceanic and atmospheric features such as ENSO (Medha Khole & De, 2003; De & Mukhopadhyay, 1999), Indian Ocean Dipole (Kumar, 2006), North Atlantic Oscillation (Balachandran *et al.*, 2006) have been undertaken with a look out for possible predictors for NEM performance.

### *Scope of the present study*

The low level northeasterlies of NEM over peninsular India may be viewed as the outflow from the massive land based anticyclone anchored by the Siberian High and so a conceptual relation between the intensity of Siberian High and the Indian northeast monsoon rainfall (NMR) can be conceived of, notwithstanding the very long distance separating the two areas. The present study, therefore, sets out to explore this conceptual relationship based on actual data, both in concurrent and antecedent modes and also try to bring out teleconnections, if any, between the Siberian High and important meteorological features associated with NEM. While analysis in concurrent mode may throw some light on the role of Siberian High on the performance of NEM, analysis in the antecedent mode may enable us identify a potential predictor for long range forecast of NMR. Availability of reliable global datasets in the websites of renowned meteorological services such as NCEP/NCAR, NOAA has made this study possible.

TABLE 1(a)

**Monthly / seasonal normal rainfall of five southern Indian sub-divisions influenced by northeast monsoon**

Sub-division	Normal rainfall (mm) during					CV (OND) (%)	CC between OND rainfall of SR and that of each sub-division
	Oct	Nov	Dec	OND	Jan		
CAP	194.0	113.1	22.4	329.2	10.1	38.0	0.71
RS	122.4	78.1	24.1	224.8	7.0	39.6	0.80
SIK	150.9	60.0	14.2	225.0	3.6	36.0	0.76
TN	191.8	197.5	98.5	488.3	30.6	27.1	0.85
KER	297.6	179.1	46.8	523.8	14.8	27.5	0.78

(based on data of 1901-2000)

CAP: Coastal Andhra Pradesh; RS: Rayalaseema

SIK : South Interior Karnataka; TN: Tamil Nadu; KER: Kerala

SR : Southern Region (all 5 sub divisions taken together)

CV : Coefficient of Variation

TABLE 1(b)

**Normal dates of onset and withdrawal of northeast monsoon  
alongwith their standard deviations**

Parameter	Normal date	SD (days)
Onset of easterlies	14 October	7-8
Onset of northeast monsoon	20 October	7-8
Withdrawal of northeast monsoon	27 December	13-14

(based on data of 1901-2000), SD: Standard Deviation

## 2. Indian Northeast monsoon

The northeast monsoon is most pronounced over the southern parts of peninsular India comprising of five meteorological sub-divisions of coastal Andhra Pradesh (CAP), Rayalaseema (RYS), south interior Karnataka (SIK), Tamil Nadu (TN) and Kerala (KER) (Fig. 1) (IMD, 1973b) which together receive about 35% of their annual rainfall during this season. Table 1(a) presents the normal rainfall received by all these five sub-divisions during the northeast monsoon season and their coefficients of variation (CV). As seen, the sub-division of Tamil Nadu receives nearly 48% of its annual rainfall of 100cm and is the major beneficiary of northeast monsoon rainfall. Further, coastal Tamil Nadu receives about 75-100 cm of normal rainfall constituting nearly 60% of the annual total. Table 1(b) presents the normal dates of onset and withdrawal of NEM over coastal Tamil Nadu along with their standard deviations (SD) (Raj, 2003). The normal duration of the monsoon is about 67 days with a SD of 14-15 days. By and large, the features of northeast monsoon are clearly defined over Tamil Nadu especially over the coastal region (Raj, 2003 & Raj *et al.*, 2004). India Meteorological Department (1973a&b) provides a detailed

description of this monsoon. The CVs of normal rainfall received during NEM indicate strong inter annual and intra seasonal variability of NMR. Whereas the onset of NEM is well defined, the withdrawal is not so and has to be determined from an analysis of rain spells.

## 3. Data used in the study

### 3.1. Region of NEM and time series of NMR

As stated in Sec.2, the sub-division of Tamil Nadu is the area wherein the various features of NEM are well defined and rainfall activity occurs throughout the NEM season. The October-December rainfall of the southern region and Tamil Nadu are closely related with a high CC of 0.87 (Raj *et al.*, 2004). In Table 1(a), the CCs between the area weighted seasonal (OND) rainfall of the combined area of the five subdivisions and each of the 5 sub-divisions is also presented. The sub divisional rainfall of Tamil Nadu has been taken as a proxy for the northeast monsoon activity over the southern Indian peninsula (Pant & Rupakumar, 1997). As such, in this study, sub divisional rainfall of Tamil Nadu during the period October to January is taken as an index to represent NMR

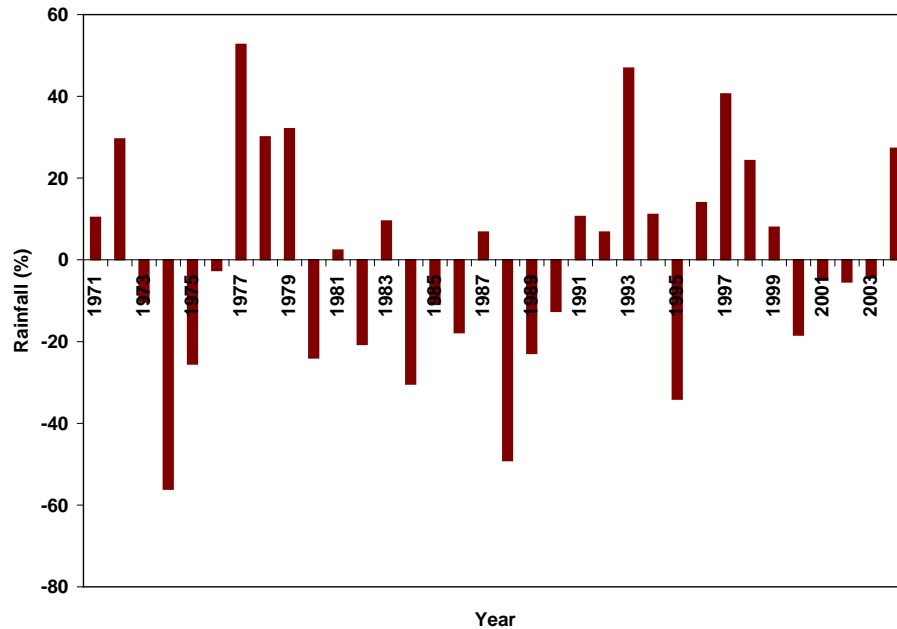


Fig. 2. Time series of sub-divisional rainfall of Tamil Nadu as percentage departure from normal, October-December, 1971-2004

as was done in an earlier work (Raj & Geetha, 2008). Time series of sub-divisional rainfall of Tamil Nadu during October – January for 34 years (1971-72 to 2004-05) was utilised for the study. For the years from 1971 to 2003, homogeneous rainfall series generated by the National Climate Centre, India Meteorological Department (IMD), Pune were used. Data for 2004 and 2005 were taken from the National Data Centre (NDC), IMD, Pune. Fig. 2 represents the time series of NMR of Tamil Nadu expressed as percentage departure from normal during October - December for the period 1971-2004.

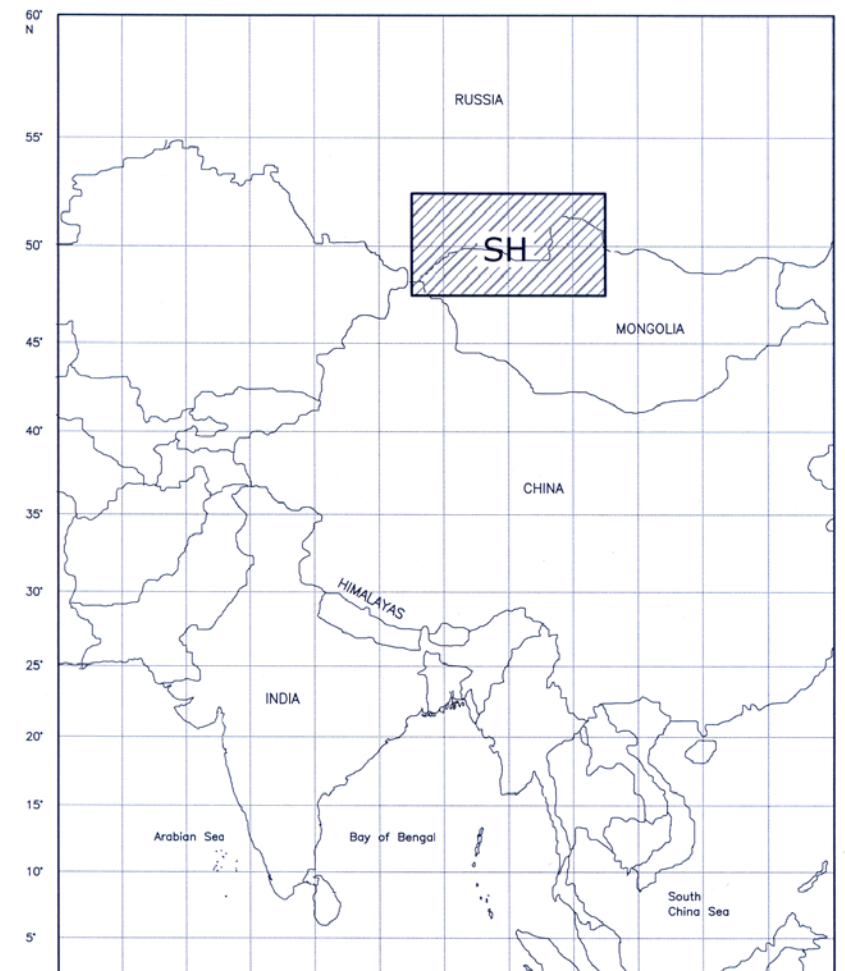
*Onset and withdrawal dates :* Dates of onset and withdrawal of northeast monsoon over Tamil Nadu as determined in (Raj 1992, 1998 & 2003) have been taken for the period 1971-2000. Data for 2001-2004 have been independently determined by following the same criteria.

### 3.2. Region of Siberian high and time series of Siberian high mean sea level pressure

Most of the earlier workers studying the relation between Siberian High and East Asian winter monsoon have identified the mean sea level pressure (MSLP) averaged over the area bounded by 80-120° E and 45-65° N during DJF as the Siberian High parameter. A Siberian High Index for the period of DJF is also in vogue (D'Arrigo *et al.*, 2005). However, no dataset on the intensity of Siberian High is readily available for the NEM period of OND. A preliminary analysis on the long term

means of the MSLP over the above area throughout the year based on NCEP reanalysis data has revealed that the MSLP over that area is minimum in July. It starts building up modestly in August-September centred at about 90° E and 50° N, intensifies with the advance of the season and slowly expands eastwards. It reaches its peak by December / January and extends up to around 110-120° E and 50° N.

By trial and error, we located the most intense high pressure region in the Siberian High area during November at about 95° E & 50° N. As such, an area bounded by 87.5 & 102.5° E and 47.5 & 52.5° N longitudinal/latitudinal circles has been found suitable to represent the Siberian High (SH) region during OND (Fig. 3). NCEP reanalysis datasets containing 2.5° grid point values of monthly means of the MSLP over the above area were extracted and time series of MSLP over SH were generated for all the 12 months of the year from 1951-52 to 2006-07. A preliminary analysis of the data revealed a slippage of mean between datasets of 1951-52 to 1970-71 and 1971-72 to 2006-07. A slippage of mean of MSLP during DJF in the recent years has also been observed (Panagiotopoulos *et al.*, 2005). As the stationary character of the time series generated for this study held true after 1971, the 36 year dataset of 1971-72 to 2006-07 was chosen for analysis. The MSLP over the SH area is denoted by PSH and the MSLP anomaly by P<sub>a</sub>SH. Table 2 presents the mean monthly/seasonal MSLP and its Standard Deviation (SD) and Fig. 4 depicts the monthly mean profile of MSLP over the SH area. It is seen that the



**Fig. 3.** Area of Siberian High region (SH) considered for the study

mean PSH gradually decreases from its peak value of 1034.5 hPa in January to 1007 hPa in July. Thereafter it builds up rather steeply with a rise of about 17-18 hPa in three months from July to October when the NEM sets in over coastal Tamil Nadu, crossing the 1030 hPa mark in November and nearing the peak value in December. The SDs are quite high (above 3 hPa) during November to February.

### 3.3. Mean zonal wind at 850 hPa over southwest Bay of Bengal and latitudinal positions of sub tropical ridge at 200 hPa and equatorial trough at 850 hPa over 77.5° E

For subsequent analysis, low level zonal wind strength at 850 hPa over a box bounded by 80-85° E longitudes and 10-15° N latitudes ( $u$ ) (Fig. 1) and latitudinal positions of sub tropical ridge at 200 hPa (STR)

and equatorial trough at 850 hPa (ET) levels over 77.5° E were used. These datasets were also generated for the months of September to January from NCEP reanalysis data for the period 1971-72 to 2005-06.

## 4. Influence of SH on temporal variations in NMR

### 4.1. Relation between SH and NMR in the antecedent mode

To study the relation, if any, between SH and NMR, Correlation Coefficients (CC) between time series of PSH (antecedent) and NMR were computed for all the months and seasons of the period from 1971-72 to 2004-05. Significant and important results are presented in Table 3. The influence of SH on NMR was examined from the month of August when the PSH starts building up after reaching its lowest value in July (Fig. 4

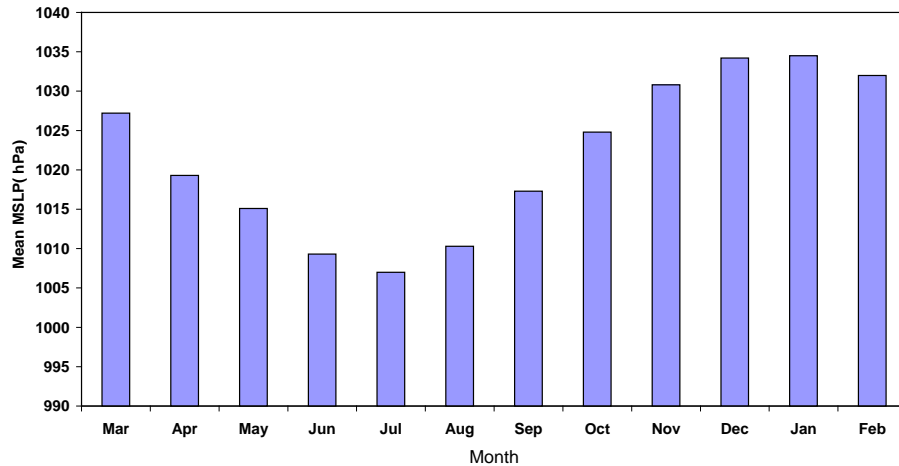


Fig. 4. Mean monthly mean sea level pressure averaged over the Siberian High region ( $87.5^{\circ}$  -  $102.5^{\circ}$  E and  $47.5^{\circ}$  -  $52.5^{\circ}$  N) (data based on 1971-72 to 2006-07)

& Table 2). No significant relationship emerged between PSH and NMR (OND) in the antecedent mode. Significant positive CCs between PSH of August-September (AS)/ September and NMR of November (CC = 0.48 / 0.36) / October-November (ON) (CC=0.36 / 0.34) were obtained. However, relationship between PSH of September and NMR of December turns negative (CC = -0.30).

To get a further insight into this changing nature of relationship between antecedent SH (Sep) and NMR, we computed Conditional Means (CM) of percentage anomalies of NMR(ON/Dec) and also CMs of onset and withdrawal dates as number of days from normal for various intervals of  $P_aSH$  (Sep). The results are presented in Table 4 and Fig. 5(a). It is seen that the event of  $P_aSH$  (Sep)  $<-1$  hPa (about half the S.D), is associated with occurrence of negative anomaly of NMR (ON) (-15%) and positive anomaly of NMR (Dec) (74%). Further, this event is associated with persistence of negative profile of  $P_aSH$  during September to November (-2.5, -1.7 & -1.1 hPa), a late onset and a late withdrawal of NEM by about 2 and 3 days respectively. On the other hand, the event  $P_aSH$  (Sep)  $>1$  hPa favours normal/ positive anomaly of NMR (ON) (6%) and negative anomaly of NMR (Dec), viz., -21%. It is also associated with positive  $P_aSH$  anomalies during September and October (2.3 & 1.4 hPa), a slightly early onset and early withdrawal of NEM by 2 and 5 days respectively.

#### 4.2. Relation between SH and NMR in concurrent mode

As in the case of SH in antecedent mode, even in the concurrent mode, no relationship emerged between SH (OND) and NMR (OND). Month by month analysis in the concurrent mode yielded CCs of 0.13, 0.25, 0.28, -0.21, for October, November, ON and December respectively

(Table 3). The CCs are not significant, but continue to be positive during October, November, ON and negative during December. The CC between PSH (Dec) and NMR (ND) is -0.35.

The above analysis has brought out the nature of relationship between NMR and PSH in antecedent and concurrent modes. Relation between PSH and NMR is positive for the ON rainfall but becomes negative during December and is better defined with antecedent PSH (Sep) than with concurrent PSH. An intense antecedent PSH (Sep) is associated with a slightly early onset of NEM and a good NMR during ON. But, it also favours an early withdrawal of NEM and a poor NMR (Dec). A weak antecedent PSH (Sep) leads to a slightly late onset and a poor NMR during ON. However, by and large, it is associated with a late withdrawal and leads to a good NMR (Dec). Thus  $P_aSH$  (Sep) does provide a pre indication of intra seasonal performance of NEM. In the concurrent mode too, an intense PSH (ON) is modestly associated with good NMR (ON), but an intense PSH (Dec) is modestly associated with poor NMR (Dec).

Another feature that emerges is that there is no signal from antecedent  $P_aSH$  (Sep) on inter annual variability of NMR (OND), with little correlation between the two. For  $P_aSH$  (Sep)  $<-1$  and  $>1$ , contrasting profiles are obtained for mean  $P_aSH$  (Sep/Oct/Nov) but with little variation in the mean  $P_aSH$  (Dec) [Table 4, Fig. 5(a)] and NMR (ON) & NMR (Dec) are of opposite signs. Thus, a deficient (excess) NMR (ON) is followed by an excess (deficient) NMR (Dec) such that NMR (OND) just becomes normal in both cases. Both the contrasting profiles lead to normal NMR (OND) as the changing nature of intra seasonal relationship between PSH and NMR during the NEM season annuls the inter annual relationship between PSH and NMR.

TABLE 2

Monthly mean MSLP in hPa averaged over the Siberian High region defined by the box bounded by 87.5° & 102.5° E longitudes and 47.5° & 52.5° N latitudes along with their standard deviation

Month / Season	MSLP (hPa)	SD (hPa)
Mar	1027.2	2.4
Apr	1019.3	2.4
May	1015.1	1.8
Jun	1009.3	1.6
Jul	1007.0	1.5
Aug	1010.3	1.0
Sep	1017.3	1.9
Oct	1024.8	2.4
Nov	1030.8	3.1
Dec	1034.2	3.2
Jan	1034.5	3.0
Feb	1032.0	3.5
MAM	1020.5	1.5
JJAS	1011.0	1.2
OND	1029.9	1.5
JF	1033.3	2.8

(based on 36 year data of 1971-72 to 2006-07)  
MSLP: Mean Sea Level Pressure, SD: Standard Deviation

4.3. Mean profiles of PSH associated with deficient and excess NMR

To study the relation between PSH and NMR, especially during extreme rainfall years, mean monthly PSH profiles associated with deficient/excess NMR (OND) were derived. The benchmarks for defining excess and deficient NMR (OND) were taken as  $\pm 25\% \approx CV$ ; Table 1a). These results are also shown in Table 4 and Fig. 5(b). It is seen that during years of deficient OND rainfall, mean ON and December rainfall departures are -35% and -55% respectively. Such occasions are associated with a late onset of NEM by 10 days but there is no signal on withdrawal. It is further seen that a profile of P<sub>a</sub>SH with negative values during September to November (-1.2 to -2 hPa) followed by a positive value in December (2.7 hPa) is associated with deficient NMR (OND). On the other hand, during years of excess OND rainfall, departures for ON and December are 38% and 33% respectively. Such occasions are associated with an early onset of NEM by about 2-3 days and early withdrawal by 5 days. The profiles of P<sub>a</sub>SH are normal to positive during September-November (0.1 to 1 hPa) and negative in December (-1.9 hPa). The signal though is not as strong as in the former case of deficient rainfall. It is interesting to note that the profiles of P<sub>a</sub>SH for deficient and excess NMR (OND) by 25% show sharp variation in P<sub>a</sub>SH (Dec) also. During deficient NMR years, the PSH

TABLE 3

CCs between SH and NMR in antecedent and concurrent modes

Month of PSH	Month of NMR	CC
<b>Antecedent SH</b>		
AS	Oct	0.02
	Nov	0.48**
	ON	0.36*
	Sep	0.13
Sep	Oct	0.13
	Nov	0.36*
	ON	0.34*
Dec	Dec	-0.30
	<b>Concurrent SH</b>	
	Oct	Oct
Nov	Nov	0.25
ON	ON	0.28
Dec	Dec	-0.21
Dec	ND	-0.35*

(based on 34 year data from 1971 to 2004)  
CC: Correlation Coefficient;  
PSH: MSLP over the Siberian High region  
NMR: Northeast monsoon rainfall; AS: Aug-Sep;  
ON : Oct-Nov; ND : Nov-Dec  
\*\* / \* : Significant at 1% / 5% level

which is significantly negative anomalous in November reduces to significantly positive anomalous in December, the change in pressure anomaly is as much as 4.7 hPa. During excess years, the anomaly changes from positive to negative with a change of 2.9 hPa. Thus, P<sub>a</sub>SH (Dec) plays an important role in determining NMR (Dec) whose contribution to seasonal total during extreme rainfall years is quite significant.

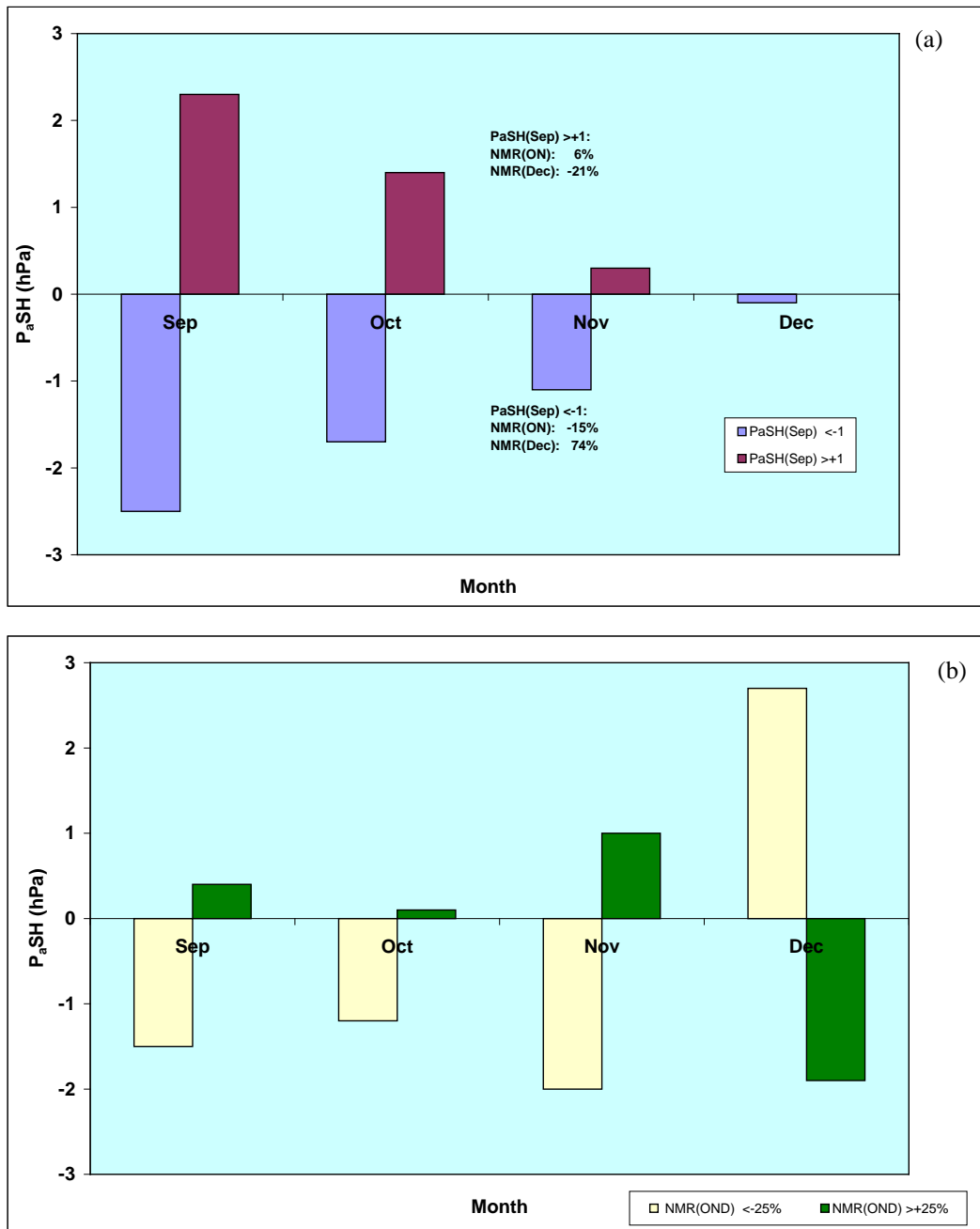
Thus, the relation between PSH and temporal variations in NMR is very well brought out by the above analysis. We next analyse how the intensity of PSH is related to the physical features associated with NMR. Before that, we shall reiterate the conceptual relationships that are known to exist between NMR and the various physical features associated with NMR, by an empirical analysis.

5. Physical features associated with NMR in relation to PSH

5.1. Relation between NMR and zonal winds at 850 hPa off the southeast coast of India/ latitudinal positions of STR at 200 hPa & ET at 850 hPa over India

Latitudinal movement of upper tropospheric Sub Tropical Ridge (STR) and lower tropospheric Equatorial Trough (ET) over the Indian peninsular region are the





**Figs. 5(a&b).** (a) Profiles of  $P_aSH$  during the northeast monsoon months given  $P_aSH(Sep) <-1$  &  $>+1$  hPa and the associated performance of northeast monsoon over Tamil Nadu and (b) Profiles of  $P_aSH$  during the northeast monsoon season for  $NMR(OND) <-25\%$  and  $NMR(OND) >+25\%$

major features that modulate the NEM activity and its inter annual variability. Conceptually, a strong relationship is expected to exist between NMR and the zonal wind off the southeast coast of India/latitudinal positions of STR & ET. The actual relation between NMR and these parameters is expressed quantitatively in terms

of CCs in Table 5. The database of these parameters utilised in this study has been described in Sec. 3.3. The normal latitudinal positions of STR at 200 hPa level (STR200) / ET at 850 hPa level (ET850) during October to December and the area over which the zonal wind off the southeast coast of India ( $u_{850}$ ) are shown in Fig. 6.



TABLE 4

Intra seasonal profiles of P<sub>a</sub>SH & NMR and conditional means of dates of onset and withdrawal of NEM for excess/deficient NMR (OND) years and given P<sub>a</sub>SH (Sep)

Parameter	Freq	Mean P <sub>a</sub> SH (hPa)					Mean NMR (% departures from normal)			NEM onset / withdrawal (No. of days from normal)	
		Sep	Oct	Nov	Dec	OND	OND	ON	Dec	Onset	Wd
P <sub>a</sub> SH(Sep) <-1 hPa	9	-2.5	-1.7	-1.1	-0.1	-0.9	1	-15	74	2	3
P <sub>a</sub> SH(Sep) >+1 hPa	9	2.3	1.4	0.3	0.0	0.6	1	6	-21	-2	-5
NMR(OND) <-25%	5	-1.5	-1.2	-2.0	2.7	-0.2	-39	-35	-55	10	1
NMR(OND) >+25%	7	0.4	0.1	1.0	-1.9	-0.2	37	38	33	-3	-5

(based on 34 year data of 1971 to 2004)

P<sub>a</sub>SH: MSLP anomaly in hPa over the Siberian High region taken for the study;

NEM: Northeast monsoon; Wd: withdrawal;

NMR, ON: as in Table 3; NMR in % departure from normal

TABLE 5

Relation between NMR and zonal wind at 850 hPa level off the southeast coast of India (*u*) / STR at 200 hPa / ET at 850 hPa level over India

Month(s) of <i>u</i> / STR / ET	Month(s) of NMR	CC with		
		<i>u</i>	STR	ET
Oct	Oct	-0.39*	-0.10	-0.35*
	Nov	-0.52**	-0.52**	-0.53**
	DJ	0.21	0.13	0.19
Nov	Nov	-0.57**	0.21	-0.07
	Dec	0.17	-0.04	0.09
ON	ON	-0.68**	-0.31	-0.52**
ND	Dec	0.01	0.37*	0.40*
Dec	Dec	-0.32*	0.43**	0.49**
Dec	DJ	-0.21	0.35*	0.36*
OND	OND	-0.48**	-0.14	-0.26

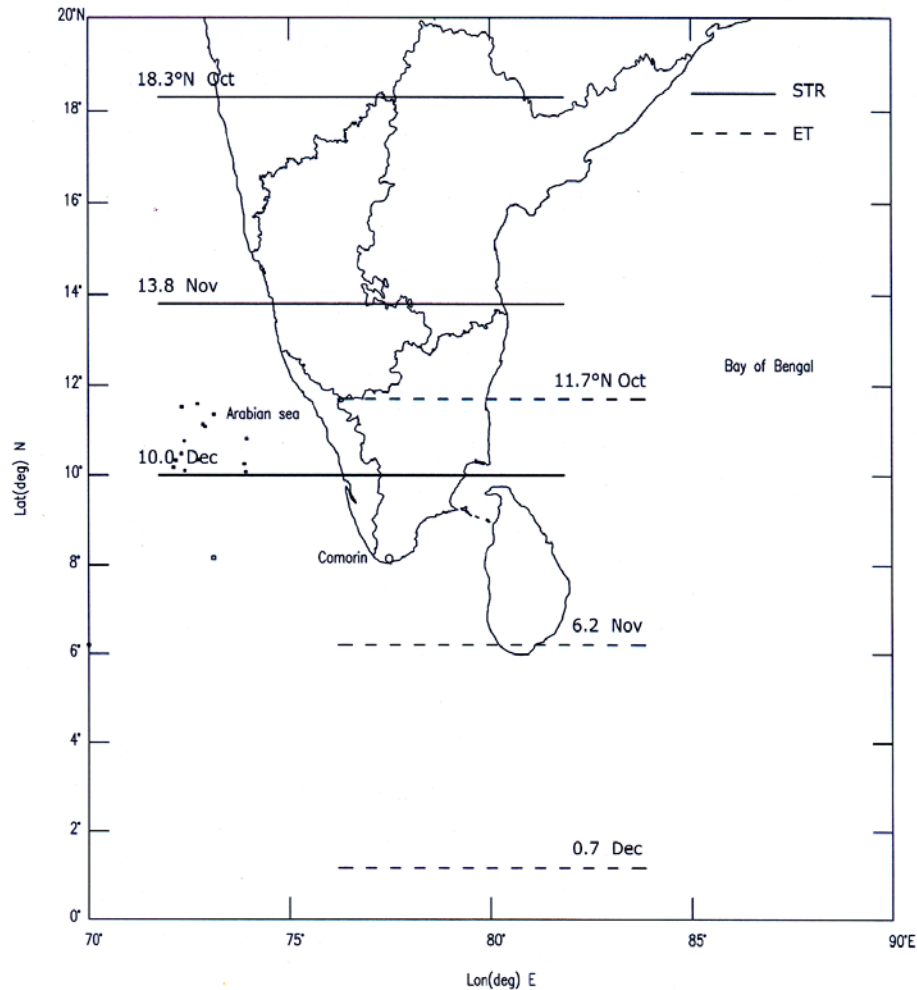
(based on 34 year data of 1971-72 to 2004-05)

CC, NMR, ON, ND, \*\* / \* : as in Table 3; DJ : Dec-Jan

Correlation analysis conducted on NMR and zonal wind, *u*<sub>850</sub> over the area defined in Sec. 3.3 and indicated in Fig. 6, shows a very strong negative relationship (CC = -0.48, significant at 1% level) (Table 5), existing between NMR (OND) and *u*(OND). Month by month analysis shows that this negative relationship between NMR and *u*<sub>850</sub> exists throughout the NEM season with CCs of -0.40, -0.57 and -0.35 respectively for October, November and December. The CC with highest

magnitude of -0.68, significant at 0.1% level is obtained between *u* (ON) and NMR (ON). Thus, prevalence of strong easterlies over the Bay of Bengal off the southeast coast of India is associated with good NMR.

Table 5 also presents CCs between NMR and latitudinal positions of STR<sub>200</sub> / ET<sub>850</sub> over 77.5° E. The relationship between NMR and latitudinal positions of STR<sub>200</sub> / ET<sub>850</sub> changes sign towards the end of the



**Fig. 6.** Normal monthly latitudinal movement of Sub Tropical Ridge at 200 hPa level over peninsular India at 77.5° E and surface equatorial trough off the southeast coast of India during October - December

season (Raj & Geetha, 2008). Good negative CCs (-0.31 and -0.52) are obtained between latitudinal positions of STR200 / ET850 during ON and NMR (ON). Significantly positive CCs (0.43 and 0.49) between latitudinal positions of STR200 / ET850 of December and NMR (Dec) have also been realised. Thus, southward location of STR200 / ET850 during the first half of NEM and its northward location during the end of the season are favourable features for good NMR.

#### 5.2. Relation between SH and $u_{850}$ / STR200 / ET850 over India

It is logical to expect that  $u_{850}$  / STR200 / ET850 over the Indian region be influenced by the intensity of SH in view of SH being a dominant surface feature during winter and also the relation between PSH and NMR

(Sec. 4). To bring out manifestation of SH on NMR, we shall now set out to examine how  $u_{850}$ , STR200 and ET850 are influenced by the intensity of the SH. For this, time series of PSH was correlated with  $u_{850}$ , STR200 & ET850. All significant and important CCs are presented in Table 6.

##### 5.2.1. Relation between PSH and $u_{850}$

It can be seen from Table 6 that antecedent PSH of September is strongly negatively related to  $u_{850}$  of October, November, ON and OND, the CCs being -0.51, -0.30, -0.50, -0.46 respectively (LS 1%). But, the relationship becomes insignificant for  $u_{850}$  of December (CC = 0.15). In the concurrent mode also, PSH (ON) is strongly negatively correlated with  $u$  (ON), CC being -0.50 (1% LS). However, CC between PSH (Dec) and is

TABLE 6

Relation between SH and zonal wind ( $u$ ) off the southeast coast of India/latitudinal position of STR at 200 hPa / ET at 850 hPa over India (77.5° E)

Month of SH	Month of $u$ / STR / ET	CC between SH and		
		$u$	STR	ET
Sep	Oct	-0.51**	-0.49**	-0.47**
	Nov	-0.30	-0.29	-0.27
	ON	-0.50**	-0.54**	-0.45**
	Dec	0.15	-0.24	-0.28
	OND	-0.46**	-0.54**	-0.49**
ON	ON	-0.50**	-0.12	-0.29
ON	DJ	-0.15	-0.10	-0.44**
Dec	Dec	0.01	-0.09	0.19

(based on 35 year data of 1971-72 to 2005-06)  
CC, ON, DJ, \*\* / \* : as in Tables 3 & 5

$u$  (Dec) nil. Thus, an intense PSH is associated with strong  $u_{850}$  in both antecedent and concurrent modes during ON, but, the relationship dramatically breaks down during December.

### 5.2.2. Relation between PSH and latitudinal positions of STR200 / ET850

From Table 6 it is seen that PSH in antecedent mode is negatively related with STR200 and ET850 over India during NEM, the CC between PSH (Sep) and STR (OND) / ET (OND) being -0.54 / -0.49. However, the relationship is not uniform throughout the season. It is quite strong between PSH (Sep) and STR (Oct) / ET (Oct), but decreases with the advancement of the season. The CCs between SH (Sep) and STR200/ET850 (Oct/Nov/Dec) are -0.49 / -0.47 (Oct), -0.29 / -0.27 (Nov) and -0.24 / -0.28 (Dec) respectively. The relationship is best defined between PSH (Sep) and STR (ON) / ET (ON) with a CC of -0.54 / -0.45, (1% LS). Further, PSH (ON) is also strongly negatively related to ET (DJ), the CC being -0.44. In the concurrent mode no relationship emerged between PSH and STR200; with ET850, PSH manifested a modest negative relationship (CC = -0.29) for ON but no relation for December. Thus, an intense antecedent PSH (Sep) is associated with southward location of STR200/ET850 throughout the NEM season, but, the strength of the relationship decreases with the advancement of the season. The relationship is ill defined in the concurrent mode.

### 5.3. Relation between PSH and NMR through STR200/ET850

Now that we have brought out the relationship between PSH and various physical features associated

with NMR, we next look for any link between these relationships and the relation between PSH and NMR to understand the manifestation of PSH on the performance of NMR. Before we proceed on these lines, we recall the significance of normal latitudinal movement of STR200 & ET850 over India (Fig. 6) in relation to the latitudinal location of the NEM area. During the initial phase of NEM, STR200/ET850 is normally located north of Tamil Nadu and towards the end of the season they are normally located south of Comorin (Fig. 6). Hence a southward (northward) position of STR / ET during the initial phase (final phase) of NEM would be favourable for good NMR (Raj & Geetha, 2008). Therefore, an intense PSH (ON) which is favourable for good NMR (ON) becomes unfavourable for NMR (Dec) as it is associated with southward location of ET (DJ) which would be further south of the NEM area. Thus, the relation between PSH and NMR could be comprehended by invoking the latitudinal positions of STR200/ET850 over India.

### 5.4. Analysis of NMR (Dec) in relation to PSH

It is evident from the above analysis that NEM (ON) behaves in a different way compared to NEM (Dec) in that several synoptic features including the Siberian High which favour the former do not favour the latter and *vice versa*. This called for a further detailed analysis of the relationship between PSH and NEM (Dec), the latter represented by NMR (Dec) and the date of withdrawal of NEM which normally takes place in December/January. The variations in latitudinal positions of STR200 /ET850 which constitute the all important link to comprehend the relation between Siberian High and NMR is also to be studied. For this analysis of NMR (Dec), 50% excess/deficient rainfall anomaly has been taken as excess/deficient in view of the high CV of 76% of NMR (Dec).

TABLE 7

Mean  $P_a$ SH(Dec) and mean anomaly in latitudinal positions of STR(Dec) and ET(Dec) over India ( $77.5^\circ$  E) for excess and deficient NMR(Dec) by 50%

Parameter	Mean value of parameter for NMR (Dec) >50%	Mean value of parameter for NMR (Dec) <-50%
NMR (%)	116% (10 years)	-62% (9 years)
$P_a$ SH (Dec) in hPa	-1.5 (2+, 8-)	-0.2
STR (Dec) anomaly ( $^\circ$ Lat.)	1.6 (8+, 2-)	-0.8 (3+, 6-)
ET (Dec) anomaly ( $^\circ$ Lat.)	1.7 (9+, 1-)	-2.2 (1+, 8-)
No. of days from normal date of withdrawal	2	-4

(based on data 34 year data from 1971 to 2004)

$P_a$ SH, NMR: as in Table 4

+ / - : positive / negative anomalies

Analysis of PSH profile for an excess and deficient NMR (Dec) (Table 7) has brought out the following results:

(i) Incidences of excess NMR (Dec) by greater than 50% (10 years, mean PDN : 116%) (Table 7) are associated with negative PSH (Dec) anomalies (8 out of 10 cases with a mean -1.5 hPa) and also with northward location of ET (Dec) (mean anomaly of  $1.6^\circ$  latitude) and a late withdrawal by about 2 days.

(ii) During incidences of deficient NMR (Dec) by 50% or more (9 years, mean PDN: -62%), no direct signal emanates from  $P_a$ SH (Dec). However, STR200 and ET850 positions are south of normal by  $0.8^\circ$  and  $2.2^\circ$  latitudes respectively and NEM withdrawal occurs 4 days earlier than normal thus clearly showing the contrasting relationship STR200/ET850 have with NMR towards the end of the season.

Even though there is no preferred nature of anomaly of PSH (Dec) when NMR (Dec) is deficient by 50%, in all the 9 cases, a positive PSH (Nov) anomaly is followed by a negative PSH (Dec) anomaly and *vice versa* such that the difference between PSH (Nov) and PSH (Dec) is quite high. Such a sharp change in PSH anomaly from November to December tie in well with sharp changes in the latitudinal positions of STR200/ET850 from November to December (in years when NMR (Dec) is deficient by 50%) such that irrespective of their location in November they are by and large located south of their normal positions during December. Even incidences of slightly northward to normal position of ET850 in November are followed by a southward location in December by about  $2^\circ$  latitude. Such events may lead to an early and abrupt withdrawal of NEM and hence a deficient NMR (Dec).

### 5.5. An analysis of time series of PSH

We have clearly shown that an intense PSH is associated with good NMR during the beginning of the season, but not during the end of the season. This kind of changing nature of influence of SH on NMR and other meteorological features associated with NMR as the season advances into December warrants a close scrutiny of time series of PSH (Dec) in relation to that of PSH (Oct/Nov). An analysis of time series of PSH by computing the month to month inter correlations from August to January (Table 8) has indicated a good positive relationship between PSH (Jul) and PSH (Aug/Sep/Oct/Nov/Jan) and modest negative relationship between PSH (Jul) and PSH (Dec). There is also a modest negative relationship between PSH (Nov) and PSH (Dec) indicating that an intense PSH (Nov) is followed by a weaker than normal PSH (Dec) and *vice versa*. This is supportive of the results of change of sign of  $P_a$ SH from November to December obtained for excess and deficient NMR (OND) years (Table 4). However, it may be mentioned that the period and area taken to represent the SH feature for this study are not the same as those used in most of the studies on Asian winter monsoon and hence nothing can be said on the characteristics of the SH time series from this study.

### 5.6. Outflow from the SH region and northeasterly winds over peninsular India

Now that the role of PSH in modulating the NMR over the southeastern parts of peninsular India has been brought out in the previous sections, we next verified whether the outflow from the SH region which is located north of the massive Himalayas, at about  $95^\circ$  E &  $50^\circ$  N could actually reach the southeastern parts of peninsular India from the mean wind flow pattern at 850 hPa level

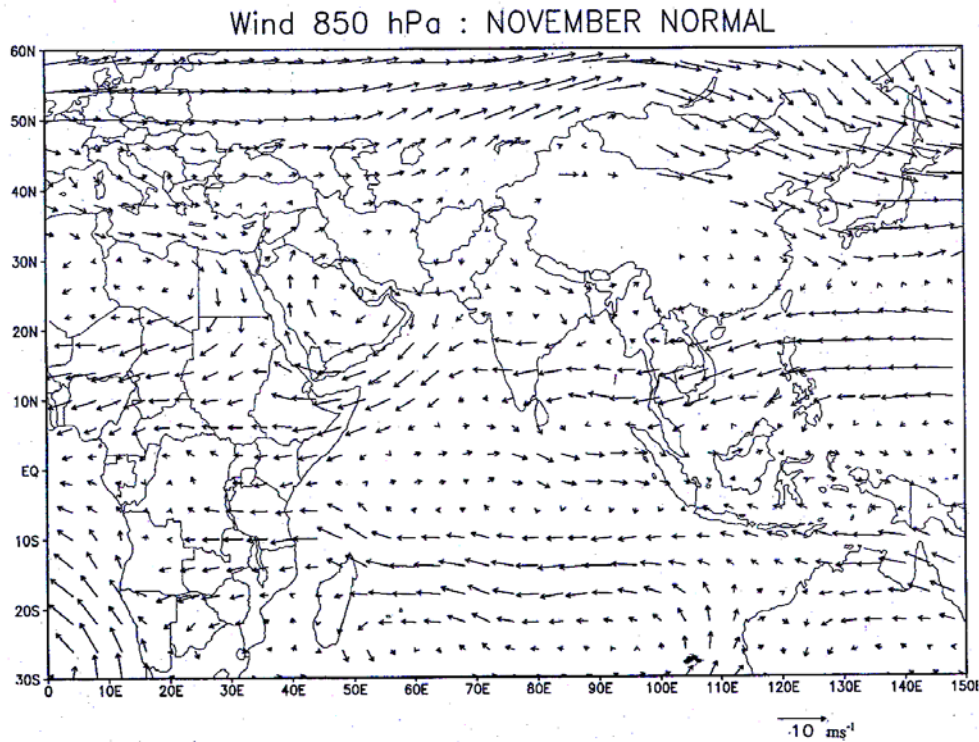


Fig. 7. Mean wind flow pattern at 850 hPa level during November (Source : Asnani G.C., 2005, "Tropical Meteorology", Vol.3, Ch-11)

over the Asian region during November – the representative month of the Indian northeast monsoon season (Fig. 7; Asnani, 2005). From Fig. 7 it appears that the wind blowing out of the SH region is likely to reach the Indian region by traveling via East China, Pacific ocean, South China sea, Indo China and then eventually reach Bay of Bengal and the Indian coast. However, SH being a dominant surface feature of northern hemisphere, its intensification could well be associated with the simultaneous strengthening of north to south pressure gradient over the Indian region. This could also result in immediate strengthening of northeasterlies over the Bay of Bengal.

6. Case studies

We shall now present a few illustrations (Table 9) that authenticate the relationships brought out in Sec.4 and Sec.5.

Case (i) - Deficient NMR : The years 1974 (-56%) and 1975 (-26%) were deficient NMR years (Fig. 2), the rainfall deficient during all the months of the NEM season. The P<sub>a</sub>SH profile during both the years has been highly negative during September, October and November (-4.1,-1.4 & -4.0 hPa during 1974 and -5.3, -4.6 & -2.7 hPa during 1975); but drastically changed to strongly

TABLE 8

Important inter correlation coefficients between monthly mean M.S.L.P. over SH

Month 1	Month 2	CC
Jul	Aug	0.66**
	Sep	0.40*
	Oct	0.41*
	Nov	0.36*
	Dec	-0.20
Sep	Jan	0.31*
	Oct	0.43**
	Nov	0.18
	Dec	-0.08
Nov	Jan	0.36*
	Dec	-0.25

(based on 36 year data of 1971-72 to 2006-07)  
 \*\* / \* : as in Table 3

positive in December (5.0 & 3.0 hPa in 1974 and 1975 respectively). As brought out by our analysis (Sec.4), both these situations are unfavourable for a good NMR. In fact, the NMR was negative during ON as well as December and the NEM season ended up as deficient during both the years.

Case (ii) – Excess NMR: The year 1997 saw a bountiful NMR with about 41% excess. During this year

TABLE 9

Illustrations on the relation between P<sub>a</sub>SH and NMR

Year	NMR (PDN)				P <sub>a</sub> SH (hPa)			
	Oct	Nov	Dec	OND	Sep	Oct	Nov	Dec
<b>Deficient NMR (OND)</b>								
1974	-35.7	-70.6	-70.7	-56.1	-4.1	-1.4	-4.0	5.0
1975	-11.7	-26.5	-54.0	-25.5	-5.3	-4.6	-2.7	3.0
<b>Excess NMR (OND)</b>								
1997	10.3	58.4	70.4	40.6	3.5	1.3	0.6	-3.2
<b>Normal NMR (OND)</b>								
1987	-1.1	-10.5	61.1	6.8	0.5	2.5	0.7	-3.0

P<sub>a</sub>SH and NMR: as in Table 4

P<sub>a</sub>SH profile was positive to normal during September to November (3.5, 1.3 & 0.6 hPa) but became negative in December (-3.2 hPa). Such a situation is favourable for good NMR during ON as well as December which is reiterated by positive NMR during all the months of the season.

*Case (iii) – Normal NMR:* During the year 1987, P<sub>a</sub>SH anomalies during September to November were normal to slightly above normal (0.5, 2.5 & 0.7 hPa), but became strongly negative during December (-3.0). This favours normal NMR (ON) and an excess NMR (Dec). The realised NMR also has been near normal during ON and excess during December.

*Case (iv) – Excess NMR (Dec) :* During the years 1971, 1972, 1978, 1983, 1996 and 1998, NMR (Dec) was excess by over 100%. P<sub>a</sub>SH (Dec) during these years were -3.3, -2.0, -4.1, 2.6, -4.2 & -1.4 hPa respectively. The anomalies in the latitudinal location of ET at 850 hPa level over India during these years were 4.3, 1.1, -0.5, 1.6, 1.5 & 3.7° respectively. It can be seen that except for 1983, the P<sub>a</sub>SH (Dec) has been negative during all the years and the ET at 850 hPa level over India was located north of its normal position save for 1978 when it was located at a near normal position.

## 7. Result & discussions

The surface winds over the whole Indian region during winter are northerly to northeasterly and are taken as out flow from the SH even though the Himalayas act as a barrier. In the case of the Indian southwest monsoon, based on the results of MONEX (1979), it was established that the trajectory of low level winds could be traced from the Mascarene High to the Arakan coast *via* the western parts of peninsular India to trigger the onset and sustain

the monsoon activity. On a similar analogy, the northeasterly winds over the peninsular India during the northeast monsoon can be conceptually thought of as the outflow from the Siberian high traversing over the Pacific and the north Indian Oceans, gaining moisture, triggering and sustaining the NEM activity over the peninsular India. [Other global parameters such as El Nino/La Nina also influence NEM rains of Tamil Nadu (De and Mukhopadhyay, 1999). The authors intend to examine the relationship between El Nino/La Nina and PSH in depth in a separate study].

The region of SH chosen for this study is smaller than the vast area of 80-120° E and 40-60° N taken to represent the Siberian high region in most of the studies on Asian Winter monsoon. It may be mentioned here that during November, which is taken as the representative month for the Indian northeast monsoon season of OND, building up of intense high pressure over Siberia has not reached its peak and MSLP is high only over a part of the region which has been taken to represent SH, for this study.

That the PSH is able to explain early/late onset, deficient/excess NMR, more active monsoon conditions during the beginning than during the later half of the season and also extension of NEM beyond the normal date of withdrawal clearly reiterates the role of SH in explaining the temporal variations in NEM activity during OND. Persistence between PSH (Sep) and PSH (Oct) leads to a good signal for the onset and performance of NEM during the beginning of the season. Inter CCs between PSH of subsequent months being very poor, the relationship does not build up. But, PSH (Sep) does have some predictive value for NMR (ON). An intense PSH (Sep) strengthens the surface easterlies off the southeast coast of India and also pushes the STR at 200 hPa and

the ET southwards over the NEM area during the initial phase of NEM thereby causing good NMR (ON).

During the later half of the season, when rainfall activity is substantially dependent on latitudinal position of ET, the extent to which the ET is disposed northward/southward would determine its relative position with respect to NEM area and hence performance of NEM activity. As such, no strong relationship emerged between PSH (Nov/Dec) with NMR (Nov/Dec). But, a weaker than normal PSH (Dec) associated with northward location of ET in December seems to be conducive for a good NMR (Dec).

It may not be out of place to point out here that in another work on relation between Southern Oscillation Index (SOI) and NMR (Raj & Geetha, 2008) a similar kind of change in the nature of relationship during the fag end of the season has been established, *i.e.*, negative SOI during the beginning of the season changing into positive during the fag end of the season has been found to be associated with a good and prolonged NMR.

Though this kind of changing nature of relation between NMR and its predictors poses a great challenge to the forecasters, it nevertheless kindles greater interest amongst the scientific community for further research in this direction. Why PSH (Nov) and PSH (Dec) are out of phase is a question left unanswered as it is beyond the scope of this paper but needs to be addressed to in future for better understanding of relation between Siberian High and Indian northeast monsoon.

## 8. Summary

(i) The intensity of high pressure over the Siberian region (87.5° E - 102.5° E, 47.5° N - 52.5° N) is associated with intra seasonal variations of the Indian NMR. An intense PSH (Sep) is associated with a slightly early onset, a good NMR during ON and a poor NMR during December. A weak PSH (Sep) is associated with a late onset, a poor NMR (ON) and a good NMR (Dec). The relationship is better defined for NMR (ON) than for NMR (Dec).

(ii) A positive PSH profile throughout the NEM season (OND) results in a good NMR (ON) but a poor NMR (Dec) with an early and abrupt withdrawal. A negative PSH profile during OND is associated with a late onset, poor NMR (ON) and a good NMR (Dec).

(iii) An excess NMR (OND) is associated with the PSH anomaly profile remaining positive during September to November, but changing sign in December. But a deficient NMR (OND) is associated with a PSH anomaly

profile that is negative during September to November but changing to positive in December.

(iv) The manifestation of PSH on NMR appears to be by way of modulating the strength of low level easterlies over the Bay of Bengal off the southeast coast of peninsular India as well as the latitudinal positions of STR at 200 hPa and ET at 850 hPa over India. An intense PSH (Sep) is associated with strengthening of easterlies over the Bay of Bengal as well as southward location of STR and ET which are favourable for a good NMR (ON).

(v) During December, a weaker than normal PSH (Dec) is associated with northward location of ET from its normal latitudinal position near the equator which becomes conducive for good NMR (Dec).

(vi) That a weaker than normal PSH in December is associated with good NMR (Dec) is comprehended from an analysis of time series of PSH. It is found that the P<sub>a</sub>SH itself undergoes a phase change in December on most occasions, *i.e.*, P<sub>a</sub>SH (Nov) and P<sub>a</sub>SH (Dec) are modestly out of phase. An intense PSH (Nov) is followed by a weaker than normal PSH (Dec) and *vice versa*.

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