Teleconnections of Indian summer monsoon with global surface air temperature anomalies

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सार – भारतीय ग्रीष्मकालीन मानसून वर्षा की अंतःवार्षिक परिवर्तनशीलता से जुड़े भूमंडलीय ग्रिड वाले धरातलीय वायु तापमान की मासिक विसंगतियों से संबंधित तीव्र सुदूर संबंधों के पेटर्नों के विकास की जाँच, 1901-98 तक की अवधि के आँकड़ों का उपयोग करते हुए की गई है। भारतीय ग्रीष्मकालीन बाद की मानसून वर्षा से संबंधित उपयोगी प्रारंभिक संकेतों का पता भी चला है। सुदूर संबंधों के पेटर्नों से समूचे भूमंडल के विभिन्न भौगोलिक क्षेत्रों से संबंधित महत्वपूर्ण संकेत भी ज्ञात हुए हैं। स्थलीय क्षेत्रों में, उत्तरी अटलांटिक दोलन से विशेष रूप से प्रभावित होने वाले यूरेशियाई क्षेत्र में तापमान के वितरण और भारतीय ग्रीष्मकालीन मानसून वर्षा के साथ महत्वपूर्ण सुदूर संबंधों का पता चलता है। महासागरीय क्षेत्रों में, सुदूर संबंध संकेत उष्णकटिबंधीय सागर की अधिकांशतः द्रोणियों में पाए गए हैं।

ABSTRACT. Evolution of prominent teleconnection patterns in the monthly global gridded surface air temperature anomalies associated with the interannual variability of Indian Summer Monsoon Rainfall (ISMR) were examined using data for the period 1901-98. Useful precursory signals for the subsequent ISMR were also identified. Teleconnection patterns showed significant signals from various geographical areas all over the globe. In the land, the temperature distribution over the Eurasian region, which is significantly influenced by the Northern Atlantic Oscillation (NAO) showed the most significant teleconnection with the ISMR. In the oceanic region, teleconnection signals were observed from most of the tropical ocean basins.

**Key words** – Monsoon teleconnection, Interannual variability, Precursory signals, NAO.

1. Introduction

In India, the main source of water for agriculture, power production, industry and drinking is the summer monsoon rainfall. However, the Indian Summer Monsoon Rainfall (ISMR) has significant year-to-year variation. In view of this, better prediction of ISMR is important in enabling the government to initiate adequate contingency plans to face a year of abnormal monsoon. The interannual variability of the ISMR is linked to a number of forcings both local as well as remote. These forcing signals are very useful as predictors in the forecasting models for the ISMR. Among the various factors influencing the interannual variation of the ISMR, the slowly varying boundary conditions have better potential as predictors (Charney and Shukla (1981).

Summer heating of landmass relative to the surrounding oceanic water mass resulting in land-sea thermal contrast is regarded as the principal cause of the global monsoon circulation. There is a general understanding that the summer monsoon over the Indian subcontinent is closely linked to the hottest regions over the central Asia & neighbouring north-western parts of India during the pre-monsoon and monsoon seasons (Mooley and Paolino 1988, Parthasarthy *et al*. 1990). Verma *et al*. (1985) and Verma (1990) observed positive correlation between averaged northern hemisphere surface air temperature during winter months and subsequent ISMR. In a recent study, Rajeevan *et al*. (1998) observed significant differences in the winter temperature anomalies over Eurasian land mass during excess monsoon years from that during deficient monsoon years.

The inverse relationship between the sea surface temperatures (SSTs) over central and eastern Pacific Ocean and the ISMR is a well understood monsoon teleconnection (Sikka 1980, Angell 1981, Rasmusson and Carpenter 1982). There are also studies, which recognise the influence of SSTs from other ocean basins on the ISMR. Keshavamurty *et al*. (1975) and Joseph & Pillai (1984, 1986) observed positive SST anomalies over Arabian Sea prior to an excess monsoon. However, the sign of the anomaly changed in August and September,

ISMR Vs surface Air Temperature Anomaly - C.C. (1901-98)
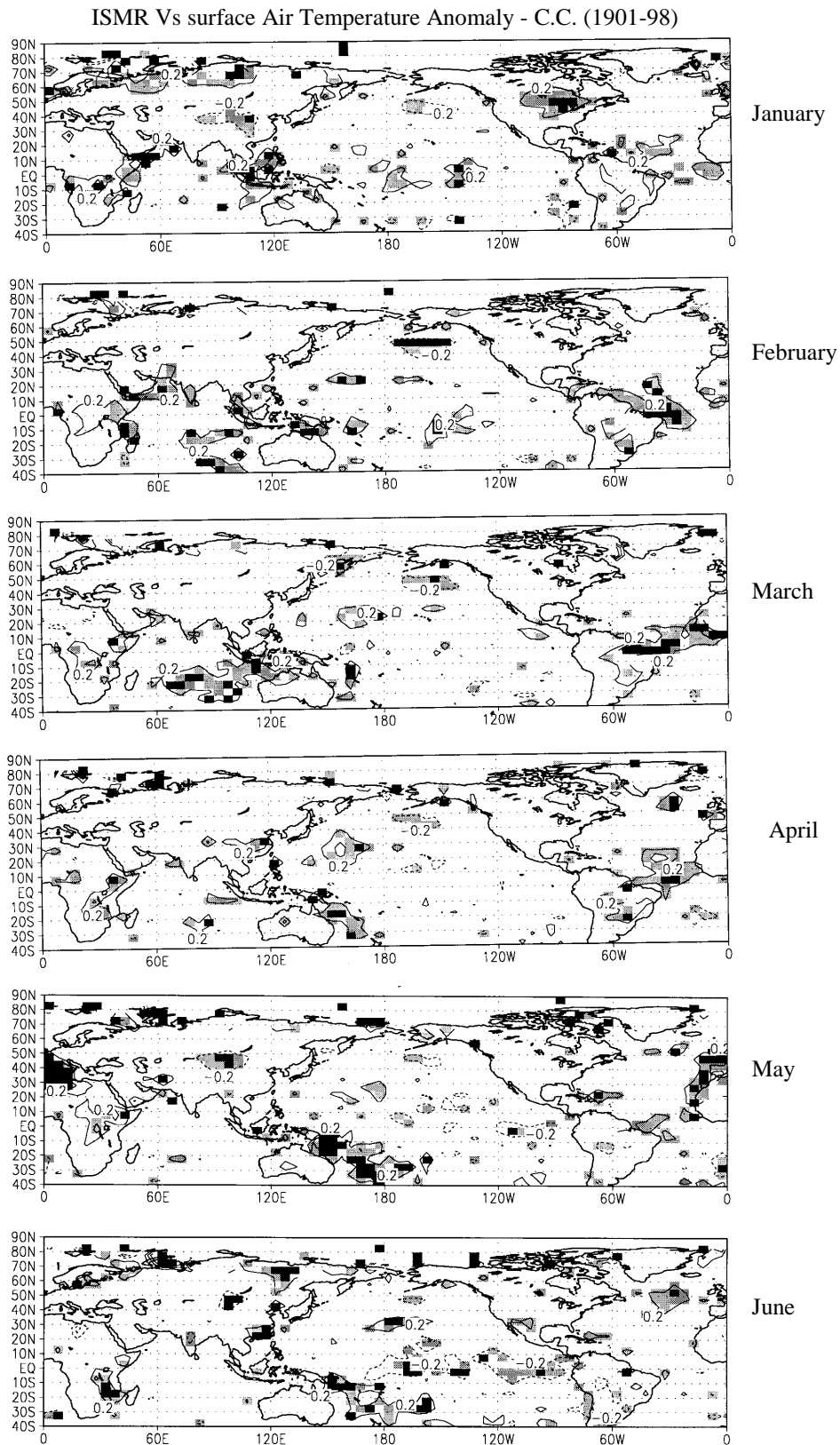
Fig. 1. Correlation coefficients (C.Cs) between ISMR and surface temperature anomalies during the months of January to June for the period 1901-98. Contour interval is 0.2. Grid boxes with C.Cs significant at 1% (5%) are shaded dark (light)
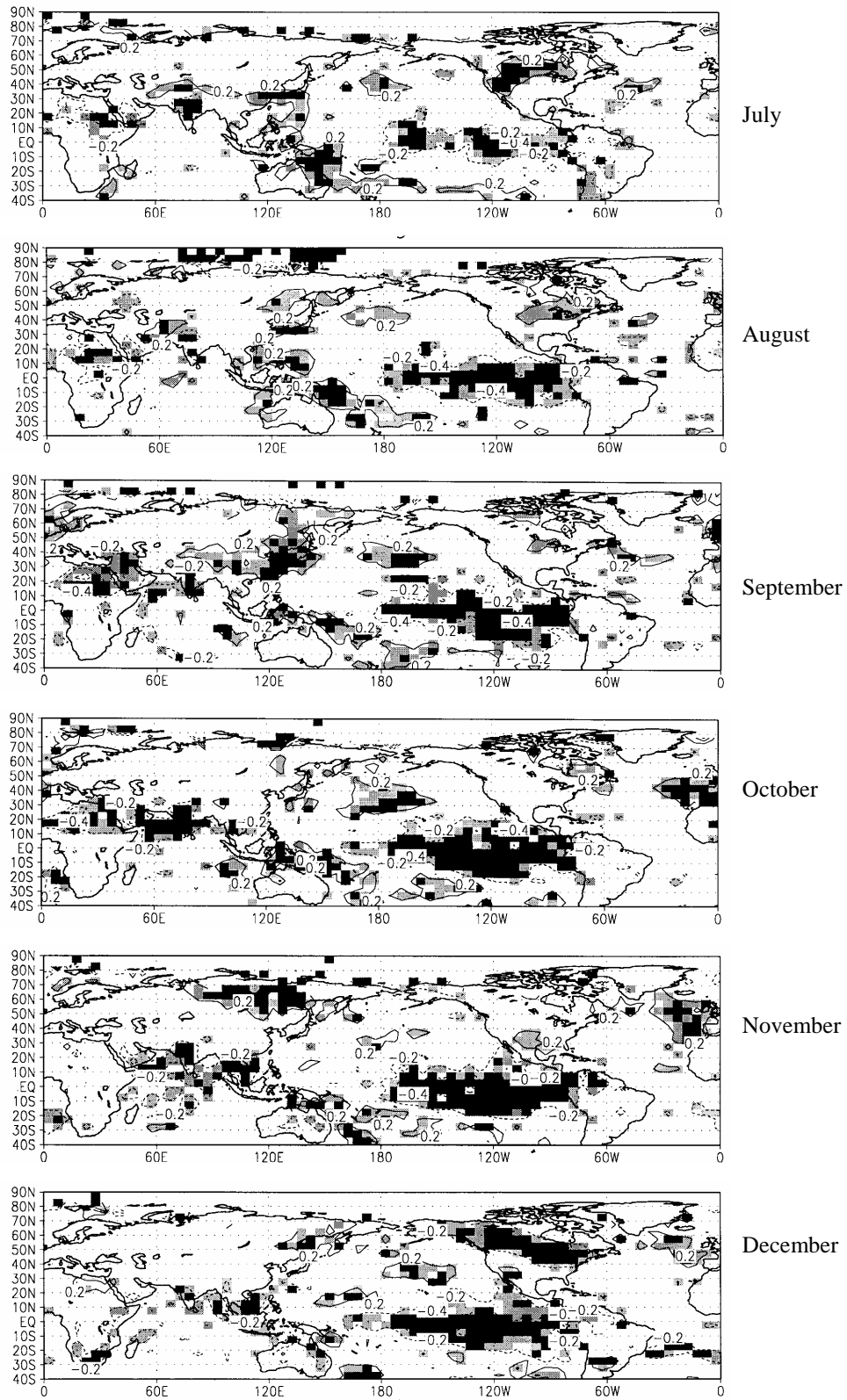
Fig. 1(Contd.). Correlation coefficients (C.Cs) between ISMR and surface temperature anomalies during the months of July to December for the period 1901-98. Contour interval is 0.2. Grid boxes with C.Cs significant at 1% (5%) are shaded dark (light)

presumably because of the stronger monsoon current and increased evaporation and stirring due to stronger winds. The opposite was the case of deficient monsoon. Shukla and Mishra (1977) obtained positive correlation coefficients (CCs) between SST anomalies along a ship track at about 10° N between 60° E & 70° E prior to the monsoon season and seasonal monsoon rainfall over western coastal regions of India. Krishnamurti *et al*. (1989) and Verma (1990) also have recognised the influence of SSTs over the Indian Ocean on the monsoon activity.

Nicholls (1983, 1995) obtained significant positive CC between ISMR and SSTs over Indonesia - northern Australia area. He also found that this SST as a predictor for ISMR has a longer lead-time than for the Darwin pressure and average of SSTs along the Peruvian coast. Recently, Ju & Slingo (1995) and Soman & Slingo (1997) by sensitivity studies using GCMs have observed that in addition to SST anomalies over equatorial central and eastern Pacific Ocean that over the western and northwestern equatorial Pacific Ocean may also be important in influencing the strength of the Asian summer monsoon. Tomita and Yasunari (1996) & Ose *et al*. (1997) obtained significant time lagged CC between SSTs in the south China Sea and ISMR.

Most of the works mentioned above on monsoon teleconnections mainly examined the relation of area averaged surface temperature anomalies over certain geographical areas with the ISMR. Also each of these studies pertains to different time periods. In this study, therefore, main aim is to examine the evolution of all possible monsoon teleconnections in the gridded global monthly surface air temperature anomalies during all the months of a year using data sets of long time periods. Significant signals in the surface temperature anomalies prior to the monsoon season are identified as useful precursors of ISMR.

2.   Details of data used

The main data set used is the global monthly grid box temperature anomaly time series. This data set is a combination of land surface air temperature anomalies and SST anomalies on a $5° \times 5°$, latitude $\times$ longitude, grid box (Jones *et al*. 1997). Both these components of the data set are expressed as anomalies from the base period of 1961-90. The land surface air temperatures in the data set were constructed from 2961 stations including 16 stations from Antarctica. The SST anomalies were constructed from the (*in situ* measurements only) updated version of Meteorological Office Historical Sea Surface Temperature (MOHSST6) of U. K. Meteorological Office. Here the SST anomalies are used as a surrogate for air temperature

anomalies over the ocean. The land surface air temperature and SST anomalies were combined using the algorithm developed by Parker *et al*. (1994). The actual data is available from 1851 onwards on the monthly basis. In this study, data for the 98 years period (1901-98) are used.

The ISMR series was prepared by area weighting sub-divisional seasonal (June-September) monsoon rainfall of all the 35 meteorological sub-divisions in India. The basic rainfall data on the sub-divisional scale for the period of 1901-98 were obtained from National Data Centre, India Meteorological Department, India. During the period 1901-98, there were 16 excess and 19 deficient monsoon years. Excess (deficient) monsoon years are defined as those during which the ISMR is more (less) than 10% of its long term normal value. Another data set used is the winter (December to February) North Atlantic Oscillation (NAO) index data for the period 1901-96. The NAO is a temporal fluctuation of the zonal wind strength across the north Atlantic Ocean due to the pressure variations in the subtropical anticyclone belt and in the sub-polar low near Iceland. A high (low) NAO index implies enhanced (attenuated) westerly winds between Iceland and Azores. These data were published in Loewe and Koslowski (1998). The index was defined as the difference of standardised winter sea level pressure anomaly at Ponte Delgada (37°45′ N, 25°43′ W), Azores from that at Akureyri (65° 41′ N, 18° 5′ W), Iceland. The anomalies were computed from the 1961-90 mean.

3.   Correlation patterns of surface air temperature anomalies *vs* ISMR

To examine the monthly monsoon teleconnection patterns grid box wise CCs between ISMR and surface air temperature anomalies for the period of 1901-98 were calculated. The CC patterns for the months of January to December are depicted in the Fig. 1. In the figure, the grid boxes with CCs significant at 1% (5%) are shaded dark (light). As there were no significant CCs observed over the regions south of 40° S, the spatial domain north of the 40° S only has been depicted in the figure. In the CC patterns, the positive CC regions indicate that when the ISMR is above (below) normal the surface temperatures over these areas are warmer (cooler) than normal. The opposite is the case of negative CC regions.

In January, significant positive CCs are observed over northwest Europe, Siberia & neighbouring Arctic regions, central north America and significant negative CCs are observed over east Asia to the north-east of India. Significant negative CCs are also observed over high latitudes of north Pacific just east of date line, which persisted till July. Over central parts of north American

DJF NAO index vs Sur.Temp.Anom. - C.C. (1901-96)
(a) January
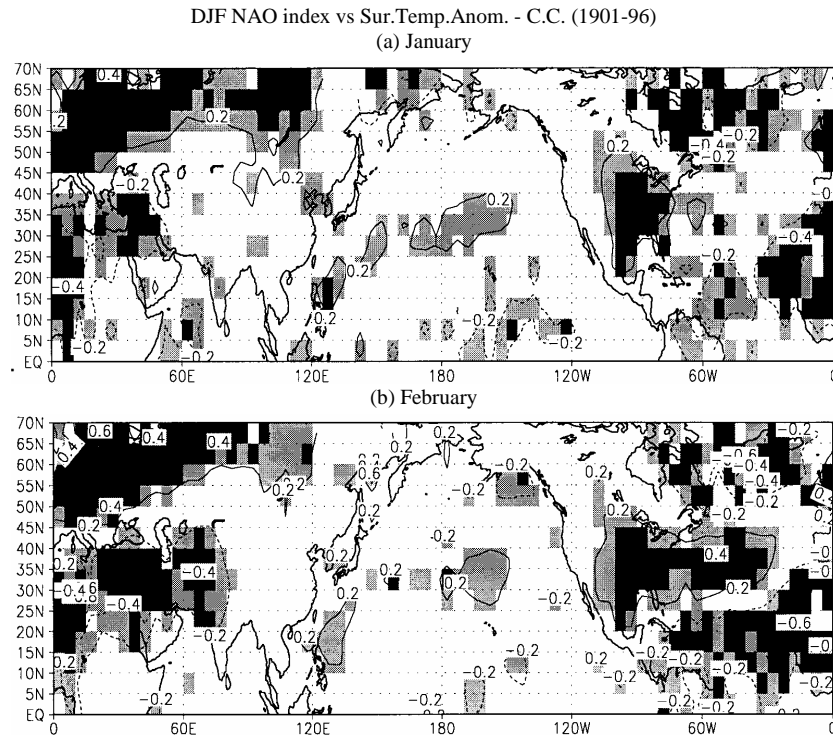
(b) February

Figs. 2(a&b). Correlation coefficients (CCs) between winter (Dec-Jan-Feb) North Atlantic Oscillation (NAO) index and surface temperature anomalies computed for the period 1901-1996 during (a) January and (b) February. Contour interval is 0.2. Grid boxes with CCs significant at 1% (5%) are shaded dark (light)

continent, significant positive CCs are observed. Other significant regions with positive CCs are central Africa, east coast of Arabia & neighbouring sea region, south China Sea & neighbouring Indonesian region, some parts of equatorial central & east Pacific and equatorial Atlantic Ocean. The significant positive CCs over Arabian Sea persisted till the start of monsoon, though they are observed only over small areas in the later months.

During February, significant positive CCs are observed over southeast Indian Ocean, Arabian Sea, eastern coast of north Africa, Mozambique channel, Timor Sea region and equatorial region of Atlantic Ocean northeast to the south American continent. In March, significant positive CCs are observed over large areas of south Indian Ocean and entire equatorial Atlantic Ocean. Over some subtropical areas of northwest Pacific also the CCs are positive. During April, except for the positive CCs over south Indian Ocean, most of the features of March persisted. In addition, significant positive CCs are also observed over the southwest Pacific north of Australia. In May, these significant positive CC regions are observed further south-eastward, which persisted till November. Other significant positive CC region during May is the heat low region northwest to India, western coast of north Africa & neighbouring area and equatorial region of African continent. Over east Asian region to the

northeast of India and southeast Pacific the CCs are significantly negative.

Over heat low region during July and August and over east Asia & neighbouring northwest Pacific region during all the monsoon months, the CCs are significantly positive. Over most of the Indian monsoon region and central Africa, the CCs are significantly negative. Another feature of monsoon season is the strong negative CCs over central and east equatorial Pacific and positive CCs over subtropical areas of central parts of north Pacific and east Pacific region to the northeast of Australia. This feature, which is clearly evident from June, persisted during the post monsoon months and continued till the next winter/spring season. During September and post monsoon months, significant negative CCs are observed over most parts of Arabian Sea and some parts of Bay of Bengal.

The warm (cold) temperature anomalies over Eurasia and north America observed during winter of above (below) normal ISMR years indicated by the positive CCs in these regions might be associated with the strength and phase of NAO. Van Loon & Rogers (1978) and Wallace & Gutzler (1981) have addressed various aspects of NAO and associated winter temperature anomalies observed over Europe, Greenland and America. To verify this

S. No.	Geographical region	Spatial domain	Month	CC with ISMR for various time periods (significant level)				
				1901-98	1901-30	1931-60	1961-90	1969-98
1.	Northwest Europe	55°N-70°N 10°E-60°E	January	0.24 (5%)	−0.02	0.01	0.55 (1%)	0.51(1%)
2.	Central north America	40°N-50°N 100°W-70°W	January	0.28(1%)	0.47(1%)	0.14	0.21	0.08
3.	Tropical north Atlantic	0°-10°N 60°W-0°	January	0.26(5%)	−0.02	0.12	0.42(5%)	0.36(5%)
4.	Arabian Sea	10°N-20°N 55°E-75°E	February	0.30(1%)	0.27	0.19	0.36(5%)	0.46(1%)
5.	South Pacific north of Australia	15°S-5°S 130°E-160°E	February April	0.39(.1%) 0.21(5%)	0.59(.1%) −0.07	0.02 0.03	0.42(5%) 0.62(.1%)	0.31(10%) 0.45(5%)
6.	Northeast Pacific	40°N-50°N 180°W-150°W	March	−0.26(5%)	−0.14	−0.13	-0.50(1%)	−0.36(5%)
7.	Central north Pacific	20°N-30°N 160°E-160°W	March	0.20(5%)	0.01	−0.02	0.57(.1%)	0.43(5%)
8.	South Indian Ocean	30°S-15°S 70°E-110°E	March	0.30(1%)	0.15	0.20	0.60(.1%)	0.58(.1%)
9.	Region northwest of India	30°N-40°N 50°E-70°E	May	0.20(5%)	−0.14	−0.01	0.53(1%)	0.55(1%)
10.	South Pacific north of New Zealand	35°S-10°S 150°E-180°E	May	0.39(.1%)	0.19	0.56(1%)	0.54(1%)	0.44(5%)

aspect, spatial patterns of CC between winter (December to February) NAO index and surface temperature anomaly for the winter months of January & February are depicted in Fig. 2. In the figure, the grid boxes with CCs significant at 1% (5%) are shaded dark (light). It is clearly evident from the highly significant areas in CC patterns that during positive phase of NAO, the temperature anomalies over northwest Europe, higher latitudes of Eurasia & neighbouring north Atlantic and central parts of north America are positive. On the other hand, over north-eastern parts of north America, southern Greenland and subtropical region extending from west Atlantic Ocean eastward to central Asia (upto ~60° E), anomalies are significantly negative. The reverse is true during the negative phase of NAO. Hurrel (1995) has shown that the winter surface westerlies over Europe during the positive phase are more than 8 ms^{-1} stronger than that during the negative phase of NAO. The stronger (weaker) surface westerlies advect more (less) warm oceanic air to the land regions resulting in the warm (cold) surface temperature anomalies over Eurasia. The January surface temperature anomalies observed over higher latitudes of Eurasia can also occur in associated with anomalous Eurasian snow cover (Bamzai and Shukla 1999).

The significant positive CCs observed over subtropical regions of south Indian Ocean during February and March represent above (below) normal solar heating

of these areas before the start of subsequent excess (deficient) summer monsoon over India. The above (below) normal heating induces more (less) than normal evaporation and hence more (less) moisture over the region to be carried to the monsoon region during the subsequent northern hemisphere summer by the low level monsoon cross equatorial flow. The positive CCs over region to the north-west of India observed during the pre-monsoon and monsoon months suggest stronger (weaker) than normal monsoon heat low prior to and during an excess (deficient) Indian summer monsoon. The relationship between surface heating over heat low region and Indian monsoon rainfall activity has been well documented by Mooley and Paolino (1988), Parthasarathy *et al.* (1990) & Li and Yanai (1996).

The changes in the sign and the spatial extension of the CCs over the central & east equatorial Pacific and that over the subtropical latitudes of north Pacific Ocean are clearly related to the spatial and temporal evolution of the teleconnection between ISMR & ENSO during a year. The negative CCs over the central and east equatorial Pacific region during monsoon and post monsoon seasons indicate that the summer monsoon play an active, not passive, role in its interaction with ENSO. The negative CCs over Arabian Sea and Bay of Bengal during September and post monsoon months indicate cooling (warming) of Arabian Sea after an excess (deficient)
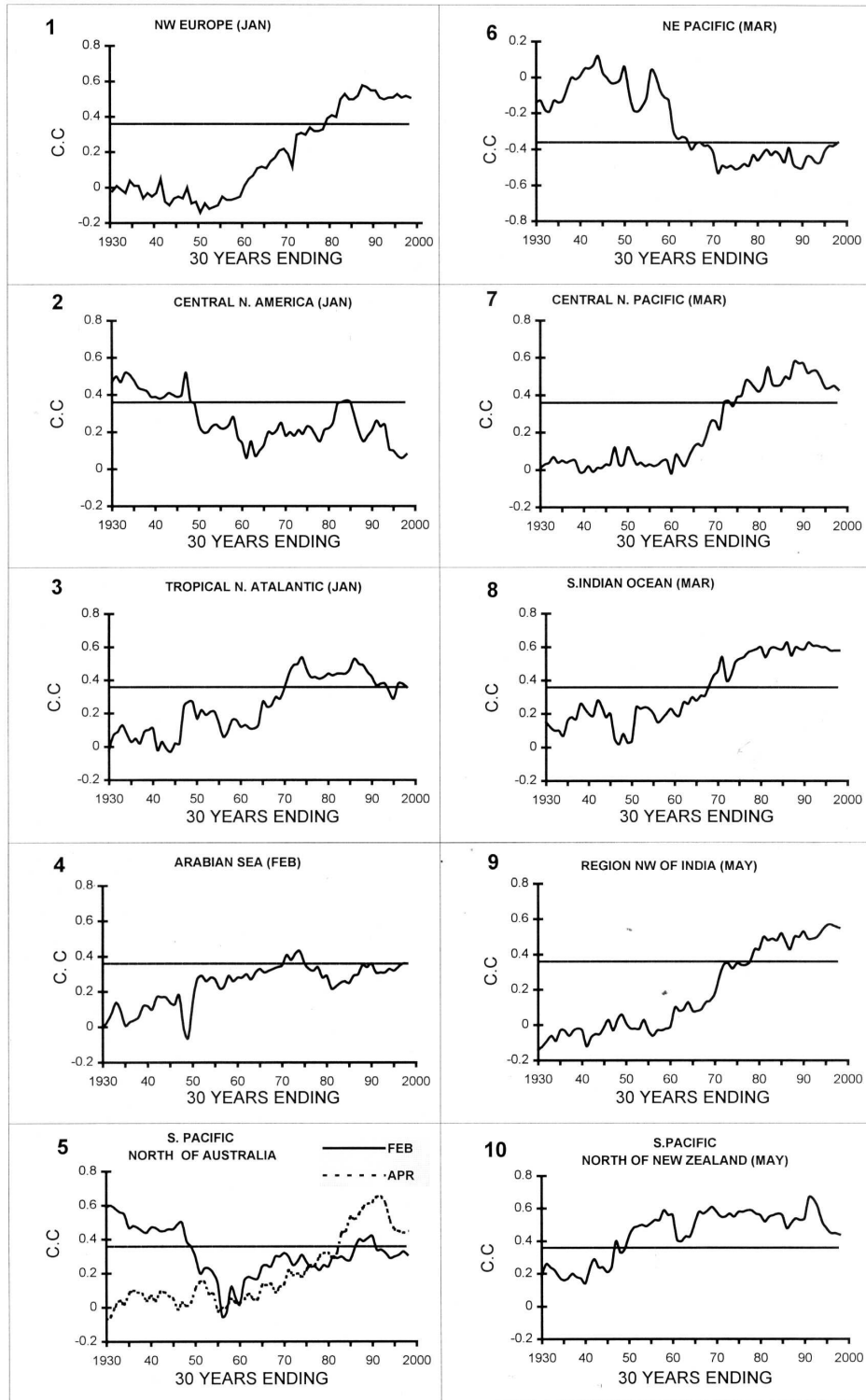
Fig. 3. 30 years moving CCs between ISMR and surface temperature anomaly indices from ten geographical regions as described in Table 1. The horizontal solid line corresponds to CC significant at 5%

normal monsoon rainfall. The cooling (warming) of Arabian Sea may be due to the stronger (weaker) monsoon currents resulting in the increased (decreased) evaporation and up welling of seawater. Joseph and Pillai (1984, 1986)

have noticed that such warming (cooling) of the Arabian Sea after a deficient (excess) monsoon persisted till the beginning of monsoon next year and contributed to a normal or excess (deficient) monsoon during that year.

Thus, the monsoon teleconnections in the global surface temperature anomalies and their month-to-month variations have definite physical linkages. The prominent features of the patterns of CC between ISMR and surface temperature anomalies can be summarised as follows. In January, CCs over the high latitude regions of Eurasia and north Arabian Sea are positive and those over high latitudes of northeast pacific and east Asia to the northeast of India are negative. The CCs over Arabian Sea and northeast Pacific persisted till the start of the monsoon season. During September and post-monsoon months, the sign of CCs over the Arabian Sea reversed. Over the south Indian Ocean east of 60° E, the CCs are positive in February and March. During May and monsoon months, the CCs over regions to the northwest of India are positive. The CCs over central India and east Asia during the monsoon months show inverse relationship. Over equatorial and subtropical Pacific, monthly CC patterns revealed evolution of ISMR-ENSO interaction and highlighted the active role of monsoon in this interaction.

4.   Potential precursory signals

In the earlier section it is observed that surface temperature anomalies at certain critical geographical areas have significant teleconnection with the ISMR. Table 1 lists the various geographical areas that are identified to have significant predictive signals for ISMR. The CC between the temperature anomalies averaged over these areas [hereafter Temperature Anomaly Index (TAI)] and ISMR for different periods are also given. Before computing the CCs, each of these TAIs is detrended. As seen in the table, for the period 1901-98, all the listed TAIs are correlated with ISMR at or above 5% significant levels. Fig. 3 depicts the 30 years moving CCs between ISMR and each of these TAIs.

In January, three TAIs show significant relationship with subsequent ISMR. They are from (*i*) northwest Europe (55° – 70° N, 10° – 60° E), (*ii*) central north America (40° – 50° N, 100° – 70° W) and (*iii*) tropical north Atlantic (0° – 10° N, 60° W – 0°). The C.C between TAI over northwest Europe and ISMR is small and negative till 1960 and thereafter increases to become significant in 1972 and further to reach its maximum value of 0.58 (significant at 0.1%) during the 30 years epoch ending in 1987. At the end of the year 1998 it is 0.51 (1%). Thus during the recent four decades the TAI over northwest Europe has significant relationship with the ISMR.

The CC between TAI over central north America and the ISMR for the first 30 years period is 0.47 (significant at 1%). The CC after remaining more or less near to 0.4, till 1948, decreases and is below the 5% level for the remaining period. Thus currently this precursor has no predictive value. The CC between TAI over tropical north Atlantic and ISMR show insignificant positive relationship with ISMR till 1970. Between 1971 & 1990 the CC is between 0.40 (5%) to 0.53 (1%). During 1990s the magnitude of CC decreases slightly and is on 0.36 (5%) for the 30 years ending in 1998. In February, the TAI over Arabian Sea (10° - 20° N, 50° - 75° E) shows a CC, which varies about the 5% significant level periodically. From 1986 the CC increases systematically and for the 30 years epoch ending 1998, it is 0.46(1%).

During March, the areas, which show significant teleconnection with ISMR, are (*i*) northeast Pacific (40° - 50° N, 180° - 150° W), (*ii*) central north Pacific (15° - 30° N, 160° - 160° W) and (*iii*) south Indian Ocean (15° - 30° S, 70° - 110° E). The negative C.C between TAI over northeast Pacific and ISMR is below the 5% significant level till 1965 and is above during the later period. During the period 1971-94, the CC is above the 1% level (0.46) with maximum value of 0.50 for the 30 years epoch ending in 1990. In fact the CC between average temperature anomaly over northeast Pacific for the months January to April obtained by using data for the period 1941-98 are all highly significant (not shown).

The TAI over the central north Pacific is more or less below the 5% level till 1975. In the later period the CC remains above 0.4 (1%) with the highest value of 0.58 (0.1%) observed for the 30 years epoch ending in 1990. It may also be mentioned that during the recent decades in addition to the average temperature anomaly over the central north Pacific during March, that during the months of April and May also are correlated significantly (5%) with ISMR (not shown). The TAI over south Indian Ocean show insignificant CC (below 5%) till 1967. For the 30 years epoch ending in 1968, it is 0.37 (5%) and from 1977 for most of the period it is above the 0.1% level (≥ 0.57). The highest value of CC (0.63) is observed for the 30 years epoch ending on 1991.

Another region that shows consistent significant teleconnection with ISMR is the large area over southwest Pacific extending from Coral Sea region to southwards to region north of New Zealand. Temperature anomalies are averaged over two separate areas over the region. One is the area north of Australia (15° - 5° S, 130° - 160° E) and the other is the area north of New Zealand (35° - 10° S, 150° - 180° E). The area north of Australia is almost the same area discussed by Nicholls (1983, 1995). During
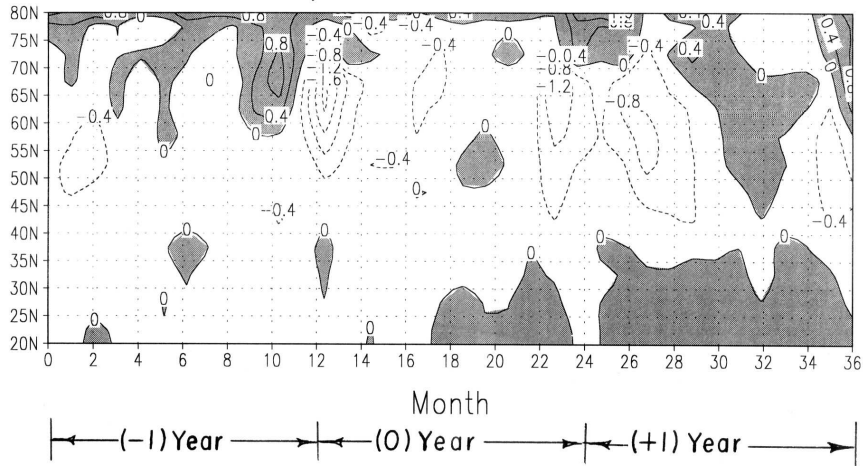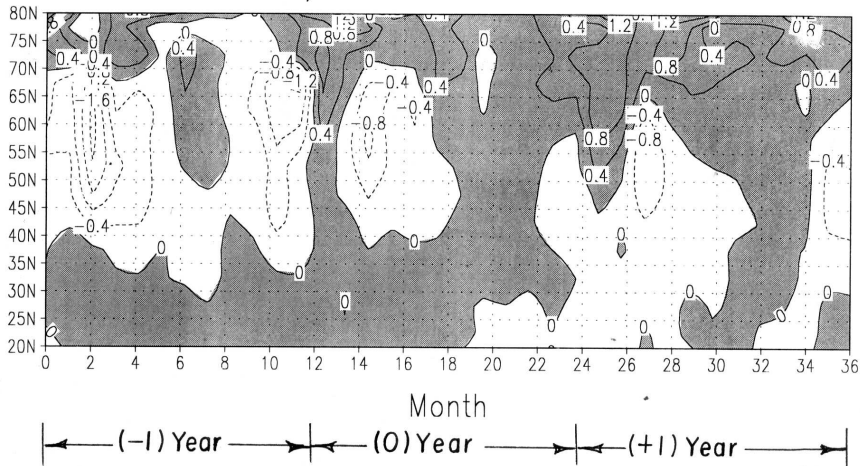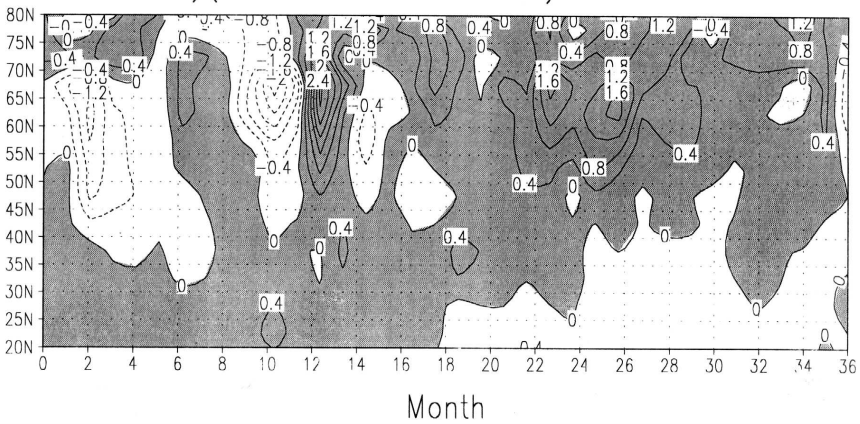
Figs. 4(a-c). Composite zonal surface temperature anomalies over Eurasia averaged across 70° E - 110° E longitudes region for (a) deficient monsoon years, (b) excess monsoon and (c) the difference between excess and deficient monsoon years (excess-deficient). The contour interval is 0.4°C and the positive anomaly regions are shaded. (0) Year, (−1) year and (+1) year denote the reference monsoon year, year preceding and year succeeding the reference monsoon year respectively

the period 1901-98, the TAIs over both the regions show significant CCs (5% level) with ISMR from February to November. Prior to monsoon, the most significant relationship between TAI over region north of Australia and ISMR is observed in February (0.39) and April (0.21). During February, the CC for the 30 years epoch ending in 1930 is 0.59 (0.1%). Thereafter it decreases regularly and becomes insignificant in 1950 and during later years except for one or two occasions remains below the 5% level. Thus, for recent years this TAI also has no predictive value. On the other hand for April, the CC is very small till 1982 and during later years it is above the 5% significant level. During the period 1988 to 1993 the CC is even above the 0.1% level (0.56) with highest value of 0.65 for the two 30 years epochs ending in 1991 and 1992.

The highest CC between TAI over region north of New Zealand & ISMR for the period 1901-98 is observed for the month of May (0.37). Till the 30 years epoch ending in 1949 the CC is slightly below the 5% significant level. After that during all the years the CC remains above the 5% significant level and majority of the times it is above the 1% (0.46) or 0.1% significant level (0.56) with maximum of 0.67 for the 30 years epoch in 1991. In fact in the few recent decades, the CC between this TAI and ISMR for the months April to October are significantly high (1%). Thus, this index seems to have high consistency and predictive value for the forecasting of ISMR for the recent years.

### 5.   Zonal temperature distribution over Eurasia

In the Fig. 1, it is seen that during the month of January, the CCs over Siberian region (east Asian region to the northeast of India) are positively (negatively) correlated with ISMR. In other words, above (below) normal ISMR years is associated with decreased (increased) south-north winter temperature gradient over Eurasia from subtropics to higher latitudes. This aspect has been examined here in detail. Figs. 4 (a-c) depict monthly march of composite zonal land surface air temperature anomaly averaged across the Eurasian longitudes (0° - 180° E) for deficient monsoon years, for excess monsoon years and for difference between excess and deficient monsoon years (*i.e.*, excess - deficient) respectively. In the figure, (0) year, (−1) year and (+1) year respectively denotes the designated monsoon year, year preceding the monsoon year and year succeeding the monsoon year.

It is seen that during deficient (excess) monsoon years, most parts of the Eurasian land are colder (warmer) than normal and the composite anomalies persisted till about half of the (+1) year. The anomaly differences are strongest during winter and over higher latitudes north of ~50° N. On the other hand, during the deficient (excess) monsoon years, in the fall season of the (−1) year, the zonal temperature anomalies over high latitudes of Eurasia are highly warmer (colder) than normal. Thus from fall season of (−1) year to the winter of the (0) year, the sign of the zonal temperature anomalies is reversed.

The above observation indicates that during (0) year of deficient monsoon, the gradient of temperature anomalies over Eurasia is directed towards pole. In the excess monsoon years this temperature anomaly gradient is reversed and is directed towards the equator. Particularly during the January of (0) year, the gradient is stronger as the magnitude of temperature anomalies over the high latitudes is large (1° - 2° C). After the winter months, this temperature anomaly becomes relatively weaker. Thus the equator ward (pole ward) directed temperature anomaly gradient across Eurasia seems to be an excellent precursor of above (below) normal Indian summer monsoon.

To examine the usefulness of the temperature anomaly gradient across Eurasia as a precursor signal for the long range forecasting of ISMR, a meridional temperature anomaly gradient index (MTAGI) directed from subtropics to high latitudes is defined. MTAGI is calculated as the difference between longitudinally (70° - 110° E) averaged temperature anomalies in the latitude zones of 50° - 70° N and 30° - 50° N. This longitude region corresponds to that part of the Eurasian region where temperature anomalies show the most significant relationship with ISMR (Fig. 1). The CCs between ISMR and MTAGI for various months for the period (1901-98) are computed and the most significant CC of –0.25 (5%) is obtained for January. In the section 3, it is seen that the winter temperature anomaly distribution over Eurasia is closely associated with the winter NAO. This aspect has been further confirmed here. The CCs between the winter NAO index (0) year and MTAGI during the period 1901-96, for the months of December [(−1) year], January, February & March [all (0) year] are –0.24 (5%), −0.27 (1%), −0.35 (0.1%) respectively. Thus, it is clearly evident that the temperature anomaly distribution over Eurasia can be influenced by the winter NAO. But the most interesting point is that though NAO and MTAGI are highly associated, the NAO index itself does not show any significant relationship with the ISMR on interannual scale. The C.Cs between ISMR and winter NAO indices of preceding, concurrent & succeeding year are 0.04, 0. 03 and 0.11 respectively. However, Dugam *et al*. (1997) has observed a statistically significant inverse relationship between winter NAO index and Indian monsoon rainfall on multi-decadel scales.

a)

MTAGI (JAN) Vs ISMR

30 YEARS ENDING

b)

TEMPERATURE ANOMALY TENDENCY Vs ISMR

30 YEARS ENDING
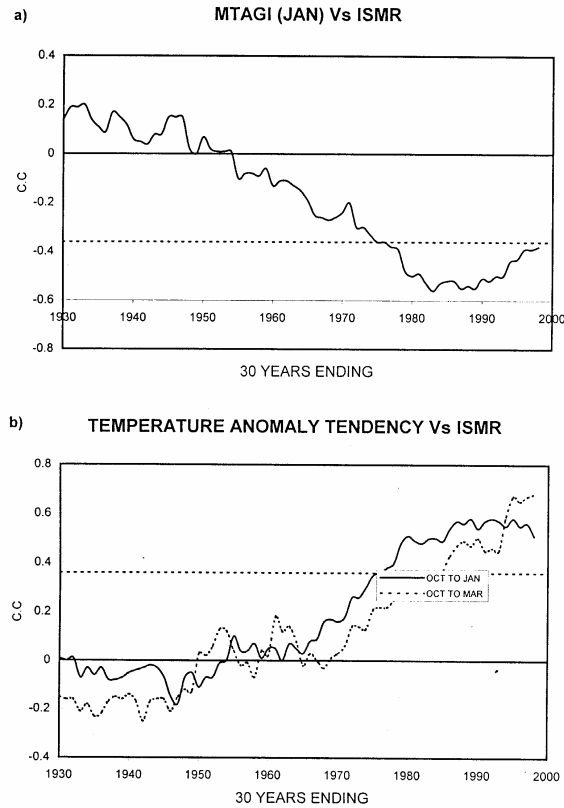
Figs. 5(a&b). 30 years moving CCs (a) between ISMR and meridional surface temperature anomaly gradient index (MTAGI) across Eurasia during January and (b) between ISMR and surface temperature anomaly tendency over Eurasia for October to January and October to March. The horizontal dotted line corresponds to CC significant at 5% level

The 30 years moving correlation between ISMR and January MTAGI is shown in Fig. 5(a). It is seen that the strength of the correlation has increased in magnitude with time. The CC between the January MTAGI and ISMR for the 30 years epochs of 1901-30, 1931-60 & 1961-90 are +0.14, −0.13 & −0.51 (significant at 1%) respectively. Till the year 1975 the CC is below the 5% significant level. The highest CC of −0.56 (1%) is observed for the 30 years epoch ending in 1983 and thereafter it remains more or less constant till early 1990 and then its magnitude decreases to reach −0.38 (5%) for the 30 years ending in 1998.

As observed in the Fig. 4, the zonal temperature anomalies over the high latitudes of Eurasia change from positive (negative) during fall season of (−1) year of deficient (excess) years to negative (positive) during winter of (0) year and that they are stronger. Therefore, a temperature anomaly tendency index is defined as the difference of averaged temperature anomalies over the high latitudes of Eurasia (50° - 70° N, 70° - 110° E) during January of (0) year from that during October of

(−1) year is calculated. The C.C between ISMR and the temperature anomaly tendency index for the periods 1901-98, 1901-30, 1931-60 & 1961-90 are 0.23 (5%), 0.01, 0.05, 0.54 (5%) respectively. The 30 years moving CC for this relationship is shown in Fig. 5(b). From the year 1976 the CC were above 5% level (0.36) and from 1979 it is above 1% level (0.46) with maximum value of 0.58 each for the 30 years epochs ending in 1984, 1992 & 1995. During recent years, the CCs are consistently above the 0.1% significant level. Another similar temperature anomaly tendency index as the change in the zonal temperature anomalies from October of (−1) to March of (0) year is also computed. The CC between this index and ISMR for the period 1901-98 is insignificant (0.11). However, in recent years, this index has shown strong relationship with ISMR, which is depicted in the Fig. 5(b). It is seen that during recent 30 years period (1969-98) the CC is 0.68 (1%).

6.   Conclusions

From this study, the following conclusions can be drawn.

(*i*)   The monsoon teleconnection patterns in the global monthly surface air temperature anomalies revealed significant signals from various geographical regions. Ten such signals having potential as predictors for the long range forecasting of ISMR are listed in Table 1. The 30 years running CC between these predictors and ISMR, however, showed significant secular variation.

(*ii*) Over the land, Eurasian region is one of the geographical areas, which showed significant monsoon teleconnection. On the other hand, the temperature anomaly distribution over Eurasia is significantly related to the phases of NAO. During January of excess (deficient) monsoon years, the meridional gradient in the surface air temperature anomalies over Eurasia was directed towards equator (pole). An index of meridional temperature anomaly gradient across Eurasia showed significant correlation with ISMR. The temperature anomaly tendency over higher latitudes of Eurasia from October (−1) year to January/April (0) year also showed significant correlation with the ISMR.

(*iii*) In addition to its well understood relationship with SST anomalies over equatorial east & central Pacific, ISMR showed significant relationship with SST anomalies from tropical and subtropical areas of most of the ocean basins.

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