Journal of the Meteorological Society of Japan, Vol. 87, No. 2, pp. 263–287, 2009.
DOI:10.2151/jmsj.87.263

Time-Space Characteristics of Seasonal and Interannual Variations of Atmospheric Water Balance over South Asia

Venkatraman PRASANNA

Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

and

Tetsuzo YASUNARI

Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Japan

(Manuscript received 5 February 2007, in final form 18 December 2008)

Abstract

The atmospheric water balance over different domains within the South Asian monsoon region has been studied using moisture convergence (C) computed from JRA-25, ERA-40 and NCEP/NCAR reanalysis datasets, GPCP precipitation data (P) and evaporation data (E) as a residual of these two parameters. The seasonal climatology of P, C, and E for the selected regions shows generally large contribution of E to P. The inter-annual characteristics of P, C and E over selected key domains within the South Asian monsoon region have also been examined for both the early (June and July: JJ) and late summer (August and September: AS) monsoon periods from 1979 to 2000. The spatial and temporal characteristics of the hydrological cycle and the contribution of E and C to P are discussed in detail. One important aspect on the seasonal timescale is that from the dry regions in the northwest to the central and the wettest northeast regions, the monthly variations of E or C are large during the monsoon months specific to those regions. However, the interannual variability of P over each domain is not necessarily influenced by the same criteria like C or E, which influences the mean seasonal precipitation. It is also evident that the structure of variability for early (JJ) and late (AS) summer precipitation is different over the South Asian monsoon region. Over northwest India E is dominant on the seasonal timescale, but C contributes higher to interannual variability of P. On the other hand, over central India C is dominant during early summer (JJ) on the seasonal timescale, but E contributes higher to P variability on the interannual timescale, and during late summer (AS) E is dominant on the seasonal timescale, but C contributes higher to P variability on the interannual timescale. Over northeast India, C is dominant on the seasonal timescale, but E contributes higher to interannual variability of P. The importance of land-atmosphere interaction over each domain is discussed. The regionality in the mechanism of precipitation generation and its contribution to the India summer monsoon precipitation variability are also discussed in detail. The role of evaporation variability of precipitation is stronger over the Bay of Bengal sector and the role of convergence on the interannual variability of precipitation is stronger over the Arabian Sea sector.

1. Introduction

The motivation of the present study is to examine the characteristic nature of the large-scale water balance over South Asia on seasonal and interannual timescales, to facilitate the understanding of hydro-meteorological processes in different regional

Corresponding author: Venkatraman Prasanna, Graduate School of Environmental Studies, Nagoya University, Nagoya, Aichi 464-8601, Japan.
E-mail: prasa_armala@yahoo.com

domains in the South Asian monsoon climate. For this purpose, the space-time characteristics of seasonal and interannual variations of precipitation (P), moisture convergence (C) and evaporation (E) during the period, starting from 1979 up to 2000 have been studied in detail. A particular attention has been paid to understand where the precipitation (P) comes from, i.e., from large-scale moisture convergence (C) due to atmospheric circulation, and/or from evaporation (E) from the surface.

Why is the atmospheric water balance analysis required here? Because the Indian summer monsoon or the South Asian monsoon has long been conventionally studied as the rainfall averaged over the entire country (India) and summed over four months June, July, August and September (JJAS) as a single seasonal mean index or simply denoted by All India Summer Monsoon Rainfall (AISMR) for characterizing wet or dry condition. The analysis based on water balance helps us to clearly establish the differences within the season and among the regions over the South Asian monsoon domain. Moreover, the origin of P, relationship of P with C and E, and its variability on seasonal and interannual timescales can be captured clearly using the atmospheric water balance method.

Following the seminal works on global water budget studies (Trenberth 1991, 1999; Oki et al. 1995; Trenberth and Guillemot 1998), we have attempted to understand the atmospheric water balance over South Asia. The objectively reanalysed gridded four-dimensional datasets (like JRA-25, ERA-40 and NCEP/NCAR) give us a great opportunity to study water balance on global and regional scales. Though there are physical constraints in the closed water budget calculation and it may be imperfect to use observed precipitation (P) to close the reanalyses water budget, it provides an opportunity to estimate the less observed variable evaporation (E) at each grid point on regional and global scales through the balance. Since the evaporation simulated by the reanalyses is heavily model dependent and the simulated precipitation is constrained by the model's parameterization schemes, we have tried to utilize the advantage of monthly observed precipitation (P) to find the evaporation (E) as a residual.

There are a few previous regional studies which used observed precipitation to obtain atmospheric water balance (Oki et al. 1995; Fukutomi et al. 2003; Marengo 2005). The evaporation obtained as a residual from the water balance method suffers from substantial errors; the accuracy of E depends on the accuracy of observed P as well as the accuracy of computed C. Oki et al. (1995) applied the global atmospheric water balance analysis to study the water balance over the Chao Phraya River basin and estimated a much better evapotranspiration on monthly timescales than the evaporation (E) obtained by the ECMWF operational model, using the same assimilated datasets and observed values of precipitation over the basin catchment area. Fukutomi et al. (2003) studied the interannual variability of summer water balance over three major river basins (Lena, Yennisey and Ob) using observed (CMAP) precipitation, runoff datasets and convergence computed from the NCEP-II reanalysis dataset in the water budget equation. Marengo (2005) studied the spatio-temporal variability of the Amazon River basin water budget using the NCEP/NCAR reanalysis and observed gridded gauge precipitation dataset and compared it with other datasets like GPCP, CRU. In this paper, we try to exploit the advantages of the atmospheric water budget analysis for understanding precipitation generation over different sub-domains within the South Asian monsoon region using the GPCP dataset and major reanalysis datasets.

In terms of the interannual variability of monsoon rainfall, Ailikun and Yasunari (2001) noted that the June (J) and July, August, September (JAS) rainfalls were characteristically different from each other over the Indian monsoon domain. They noticed that the early period (June) was strongly influenced by the anomalous state of ENSO in the previous winter, whereas the mid-late period (July-August-September) was related to the anomalous state of ENSO in the following winter rather than the previous winter. Kawamura et al. (2005) emphasized that, the monsoon-ENSO relationship was strong in late summer (AS) over central and northwest India before the 1970s, but in the recent decades it had shifted to early summer (JJ) over northeast India and argued that the change in the monsoon-ENSO relationship based on AISMR represented a change in the dominance of a spatial correlation pattern, from the northwest to the northeast after the late 1970s. Thus, from the papers of Ailikun and Yasunari (2001) as well as those of Kawamura et al. (2005), the early and late summer precipitation over India is characteristically different. Therefore, the summer monsoon period (JJAS) has been judiciously divided into early summer (JJ) and late summer (AS) for assessing the interannual variability of precipitation and atmospheric water budget components in the summer monsoon season. In this paper, we basically stress the time-space characteristics of water balance components on a seasonal timescale as well as their variability on an interannual timescale. Further we discuss the regional contrast of the water budget components and also how the budget components control the precipitation generation and its variability over each domain.

The structure of this paper is as follows. Section 2 describes the datasets and the computational procedures used in this study. In any analysis of geophysical parameters, the accuracy of the desired results depends on the method employed and the accuracy of the datasets used in the analysis, hence in this section the data products used and the methods employed for the interpretation of the results have been discussed in brief. Section 3 discusses the spatial correlations of AISMR with monsoon rainfall (JJAS), early summer rainfall (JJ) and late summer rainfall (AS) periods. Section 4 presents a discussion of the spatial differences between wet and dry years. In Section 5, we document the basic features of the monthly annual cycle of water balance components (P, C and E) and the seasonal march of precipitation over the selected domains. Section 6 presents the interannual variability of precipitation and atmospheric water balance components. Section 7 discusses the aspect of the regional variability of atmospheric water balance. In Section 8 the important discussions are addressed. Section 9 presents the main conclusions.

2. Data and method of analysis

The precipitation data used are Global Precipitation and Climatology Project (GPCP) Precipitation (Adler et al. 2003), VASClimO (Variability Analysis of Surface Climate Observations), the land gridded precipitation dataset (Beck et al. 2005), the monthly all India summer monsoon rainfall index (Parthasarthy et al. 1995). The atmospheric water budget equation can be written as (Peixoto and Oort 1992),

$$\langle \partial W/\partial \mathrm{t} \rangle + \langle \nabla \cdot Q \rangle = \langle E - P \rangle, \tag{1}$$

where P is precipitation, E is evaporation, and the angled brackets denote the area average. Precipitable water content is W, vertically integrated moisture flux vector is given by Q, and its divergence is given by $\nabla \cdot Q$.

On longer timescales like monthly or seasonal, under near equilibrium conditions, the time change of locally available precipitable water content is negligible compared to the variations of large-scale convergence and evaporation (Oki et al. 1995; Trenberth 1999). We approximate,

$$\langle \partial W/\partial \mathrm{t} \rangle \sim 0. \tag{2}$$

Therefore we can approximately write,

$$P \sim C + E, \tag{3}$$

where $C = -\langle \nabla \cdot Q \rangle$.

Vertically integrated moisture flux vector (Q) is given by,

$$Q = 1/g \int_{Pt}^{Ps} qv\, dp, \tag{4}$$

where q is the specific humidity, v is the horizontal wind vector, Ps is the pressure at surface level and Pt is the pressure at the top of the atmosphere, g is gravitational acceleration. Vertical integration is performed from the ground (surface pressure level) to 300 hPa for all the standard atmospheric pressure levels (1000, 925, 850, 700, 600, 500, 400, 300 hPa). We can neglect pressure levels above 300 hPa, as the specific humidity above this level is negligible. The moisture flux divergence that is the second term in the left-hand side of the equation (1) and the vertically integrated moisture fluxes are computed using the linear grids. Caution has been exercised, while interpreting the results on the sign of convergence and divergence. In this paper, convergence is shown as positive values and divergence as negative values.

The moisture convergence data are computed for every six hours from six hourly upper-level winds (u, v), specific humidity (q), geo-potential height (z), surface winds (u, v), surface-level specific humidity (q) and sea-level pressure (Ps) obtained from the Japanese 25-year Reanalysis (JRA-25) dataset (Onogi et al. 2007) and calculations are also performed using the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kalnay et al. 1996) and the European Center for Medium-Range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA-40) dataset (Uppala et al. 2005). The computed six hourly moisture convergence datasets are averaged into monthly means. The monthly residual evaporation dataset (E) is

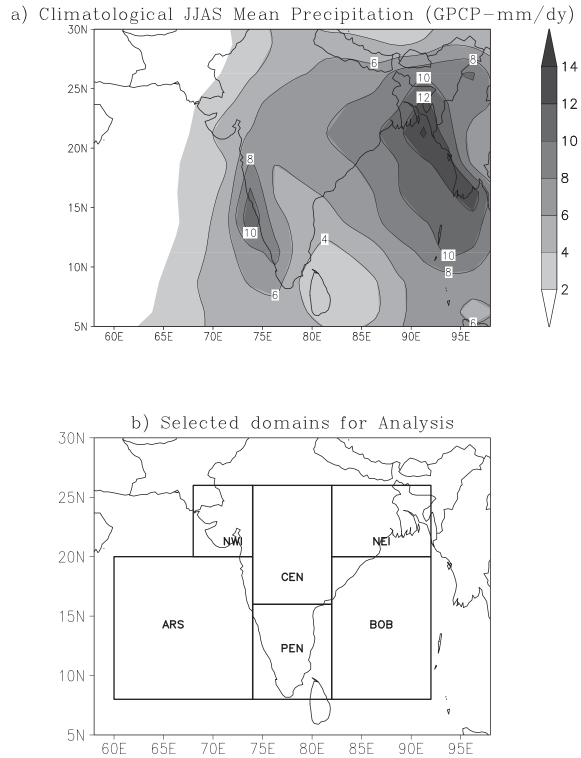

Fig. 1. a) Climatological JJAS mean precipitation from GPCP (mm day^{-1}) for the period 1979–2000. b) Selected boxes over South Asia for analysis of atmospheric water balance. NWI: North West India, NEI: North East India, CEN: Central India, PEN: Peninsular India, ARS: Arabian Sea, BOB: Bay of Bengal.

obtained from the monthly GPCP precipitation dataset (P) and the computed monthly moisture convergence dataset (C).

Water budget calculations and data analyses were performed for the 22-year period from January 1979 through December 2000, as the reliable precipitation data over both land and ocean were available from 1979. We have utilized GPCP precipitation estimate for both land and ocean as the precipitation estimate over land areas are quite realistic in GPCP. The advantage of the GPCP dataset over other land-based datasets is the blending of various observational datasets like gauge precipitation, infrared precipitation estimates and precipitation estimates from microwave sensors (Adler et al. 2003). The VASClimO dataset and the GPCP dataset showed a similar correlation pattern with the AISMR index over the South Asian land grid points (Fig. 2), making the GPCP dataset a reliable dataset for this study.

The mean JJAS precipitation over South Asia is shown in Fig. 1a. The study area over the South Asian monsoon region has been selected as six sub domains, Northwest India (NWI), Central India (CEN), Northeast India (NEI), Peninsular India (PEN), the Arabian Sea (ARS) and the Bay of Bengal (BOB) (Fig. 1b), but detailed discussions are restricted to only a few major sub domains like the driest (NWI), the wettest (NEI), transition between dry and wet (CEN) and ocean (BOB) are arbitrarily selected and analyzed for space-time features in detail. On monthly time scales, we can approximate $P \sim C + E$, by neglecting local time change. E is obtained as a residual from P and C, i.e., $E \sim P - C$. The mean monthly contribution of evaporation (E) or convergence (C) to precipitation (P) and the year-to-year change in evaporation (ΔE) or convergence (ΔC) to precipitation (ΔP) are used to understand the seasonal and interannual variability respectively over different domains of the South Asian monsoon region.

Generally, we adopted our results from the JRA-25 reanalysis dataset for discussion and compared our results with the ERA-40 reanalysis dataset and NCEP/NCAR reanalysis dataset wherever necessary. The JRA-25 reanalysis dataset has a high spatial resolution compared to the NCEP/NCAR reanalysis dataset and a comparable resolution to the ERA-40 reanalysis dataset. Moreover, good correlations between P and C are noted over CEN where both P and C are expected to be the most reliable because of high density of the original station data (Table 1). Differences in the vertically integrated precipitable water among NCEP/NCAR and ERA-40 and SSM/I datasets have already been discussed in detail and substantial problems have been found in the low latitudes in the ERA-40 dataset (Trenberth et al. 2005). Moreover, Graversen et al. (2007) have also noted atmospheric mass transport inconsistencies in the ERA-40 reanalysis. Spurious mass fluxes lead to considerable errors when zonally and vertically integrated quantities are considered. A detailed study on the atmospheric hydrological cycle in the ERA-40 datasets has been dealt with by Hagemann et al. (2005) and they found considerable bias over land and oceans. It is demonstrated that the correlation between P and C are the most reliable over the CEN domain in the JRA-25 reanalysis. Therefore, we assume

Table 1. Correlation between domain averaged GPCP Precipitation (P) versus domain averaged vertically integrated moisture convergence (C) (values are shown without brackets) and residual evaporation (E) (values are shown with brackets) from the three major reanalyses over the South Asian monsoon region. Bold numerals denote correlation significant at 95% level. The higher correlations are shown by larger numerals. Data Period: 1979–2000.

		GPCP P domain					
Reanalysis C (E)	Months	NWI	CEN	NEI	PEN	BOB	ARS
JRA-25 C (E)	JJ	**0.86**	**0.83**	**0.49**	**0.46**	**−0.47**	**0.42**
		(0.05)	(0.41)	(**0.63**)	(0.21)	(**0.51**)	(0.31)
	AS	**0.81**	**0.76**	**0.54**	**0.73**	0	**0.55**
		(0.22)	(0.08)	(**0.59**)	(0.32)	(**0.58**)	(−0.22)
ERA-40 C (E)	JJ	**0.56**	**0.68**	**0.66**	**0.62**	0.26	**0.78**
		(0.07)	(**0.65**)	(**0.55**)	(**0.45**)	(**0.58**)	(0.34)
	AS	**0.78**	**0.68**	0.35	**0.77**	**0.57**	**0.69**
		(0.01)	(0.28)	(**0.69**)	(**0.73**)	(0.11)	(0.33)
NCEP/NCAR C (E)	JJ	**0.56**	**0.64**	**0.58**	**0.56**	0.3	**0.63**
		(**0.75**)	(**0.78**)	(**0.81**)	(**0.81**)	(**0.59**)	(**0.76**)
	AS	**0.75**	**0.74**	0.4	**0.77**	0.02	**0.79**
		(**0.79**)	(0.38)	(**0.78**)	(**0.53**)	(**0.72**)	(0.17)

that the JRA-25 dataset could be an appropriate dataset for this study, as our intension is not to study the differences arising from the different reanalyses in this paper. Basically, the difference among the reanalysis datasets arises in the representation of surface to upper level humidity. The representation of wind vectors among the reanalysis datasets is quite good (Figure not shown).

3. Monsoon indices

The AISMR index has been a widely used index for discussing the strength of the South Asian summer monsoon and Indian monsoon in particular (Parthasarathy et al. 1995). To examine the differences in the representation of AISMR in the early and late summer and the associated regional differences, the AISMR index has been correlated with the spatial precipitation for the entire summer, early summer and late summer seasons. The correlation between the AISMR index and land gridded precipitation (VASClimO) for the entire summer (JJAS), early summer (JJ) and late summer (AS) seasons are shown in Fig. 2. The highly significant correlations are seen over the northwest and central Indian regions during JJAS (Fig. 2a). Similarly the significant correlations are also confined to northwest India and central India during the early summer (JJ) (Fig. 2b). During the late summer monsoon period (AS), the significant positive correlations are again confined to central and western India and a few pockets of significant negative correlation are seen over the Bangladesh region (Fig. 2c). These results suggest that the late summer regional rainfall (AS) over northeast India has a non-negligible negative correlation with the AISMR variability. The basic purpose of preparing the spatial correlation map between summer monsoon precipitation and the AISMR index is to highlight the regional differences in the precipitation variability among the selected sub-domains on interannual timescales.

4. Difference in large-scale anomalies of *P* and *C* between wet and dry years

AISMR from June to September for the period 1979–2000 is shown in Fig. 3. AISMR has been considered to be stable with less trend and large interannual variability compared to other regions of tropics (Pant and Rupakumar, 1997). The interannual precipitation anomalies are shown as standardised anomalies of JJAS from 1979 to 2000. The AISMR mean is given by 830 mm for the 22-year period (1979–2000) and the interannual standard deviation of AISMR for the 22-year period is given by 75.4 mm. The wet and dry years are identified by a departure of more than one standard deviation from the mean precipitation for the respective years. The wet years are identified as 1983, 1988, 1990, 1994 and the dry years are identified as 1979, 1982, 1986 and 1987 respectively.

To study the spatial pattern of anomalies of the summer monsoon precipitation over the whole of

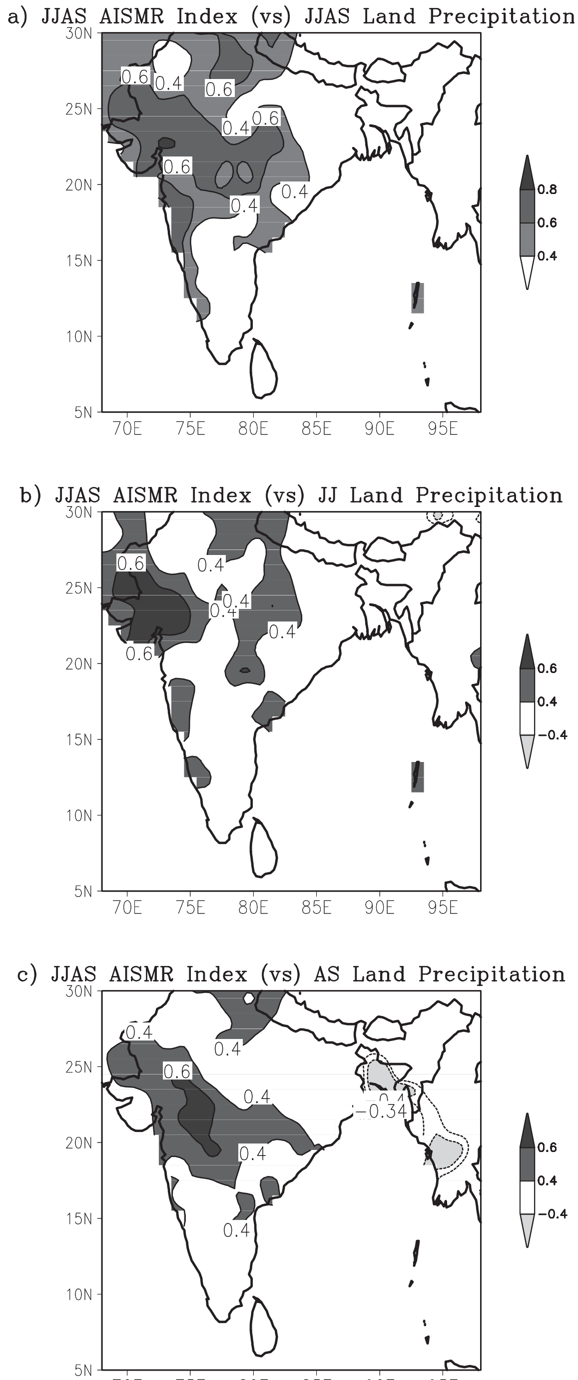

Fig. 2. Correlation between AISMR index (JJAS) and land gridded precipitation (VASClimO) for the period 1979–2000. a) AISMR vs. JJAS precipitation b) AISMR vs. early summer precipitation (JJ) c) AISMR vs. late summer precipitation (AS). Shaded values are significant at 95% level, while shaded bar indicates correlation coefficient.

India, the composite map for wet and dry years are prepared (wet-dry) from the interannual standard deviations of AISMR (JJAS) (Fig. 3). The composite difference (wet-dry) is made from four anomalous wet years and four anomalous dry years during 1979–2000. Figure 4 represents the composite difference of JJAS (Fig. 4a), JJ (Fig. 4b) and AS (Fig. 4c) between the wet and dry years of AISMR.

We notice large positive anomalies of precipitation (Fig. 4a) over the most part of the Indian region for the entire monsoon period (JJAS) and a small pocket of negative anomaly over northeast India. A similar composite only for the (JJ) early monsoon period is also made and large positive anomalies of precipitation envelopes the entire Indian region (Fig. 4b). During the late summer monsoon season (AS), however, the precipitation anomaly becomes negative (large) over the northeast Indian regions (Fig. 4c). Thus, positive rainfall anomalies over the entire subcontinent during the early summer (JJ) do not persist until late summer (AS) even during wet years, but large negative rainfall anomalies appear in late summer (AS) over the northeast Indian regions. Such appearance of large negative rainfall anomalies over the northeast Indian regions in the wet years of AISMR over the most part of the subcontinent, establishes the inverse relationship that exists between the northeast Indian regions and the rest of the subcontinent particularly for late summer (AS) months. A significant test of difference (two tailed t-test) has been performed for early and late summer precipitation (Figs. 4d and 4e). The regions of significant difference are confined to high precipitation regions of northeast and west coasts of India and also northwestern regions for both early and late summer precipitation (Figs. 4d and 4e).

The overall spatial patterns of the entire monsoon season (JJAS) precipitation anomalies do not represent the different situations of the early monsoon season (JJ) and the late monsoon season (AS), as the entire monsoon season (JJAS) based anomalies for the different composite (wet-dry) cannot capture the large differences between the early monsoon season (JJ) and the late monsoon season (AS). Thus instead of using the entire monsoon season (JJAS) as one season for interannual studies, we can split it into early (JJ) and late (AS) monsoon seasons. The atmospheric water budget on monthly, seasonal, interannual time scales and the associated regionality is presented in the following sections.

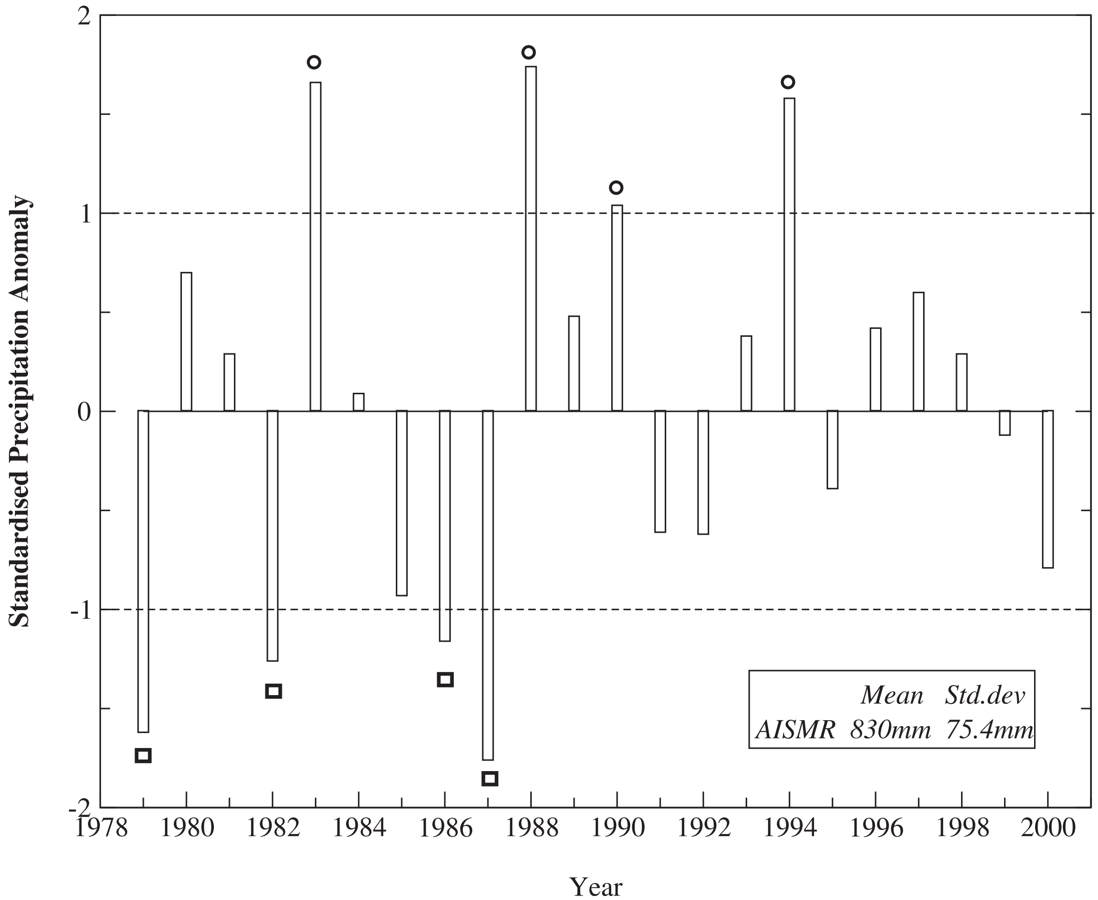

Fig. 3. All India Summer Monsoon Rainfall (AISMR) from 1979–2000. JJAS precipitation mean and standard deviations are given inside the box. Circles denote wet years and squares denote dry years.

5. Monthly annual cycle and interannual variation of moisture convergence among reanalysis datasets

To elucidate how we exploited the advantages of all the major reanalysis datasets, we here try to show the agreement or departure among datasets over different domains. The monthly mean cycle of computed convergence (C) and the interannual variability of computed convergence (ΔC) from all the three major reanalysis datasets over the selected domains are shown by Figs. 5 and 6 respectively. The similarity in the monthly cycle and the differences among the reanalyses over each domain are evident from Fig. 5. Generally, the reanalysis results are in good agreement over (CEN) the land domain, but large discrepancies are noted over the south peninsular Indian domain and oceans. The computed convergences (C) over CEN and NEI from the three reanalysis data show quite good agreement compared to those of other domains. Over most of the domains the computed convergence (C) from JRA-25 reanalysis exceeds both ERA-40 and NCEP/NCAR. JRA-25 has a unique advantage because of its relatively high resolution for water budget analysis and also good correlations between P and C are noted over the CEN domain (Table 1) and JRA-25 is not significantly inferior to other datasets. So, we believe that the JRA-25 dataset could also be a better dataset for regions with high orography (like NEI) due to the use of a high resolution model and as well as improvements in data assimilation while generating the reanalysis dataset compared to the other two reanalysis datasets. Figure 6 shows the interannual variability of computed convergence (ΔC) over NWI, CEN and NEI. The computed convergence (C) over NWI has large discrepancies among

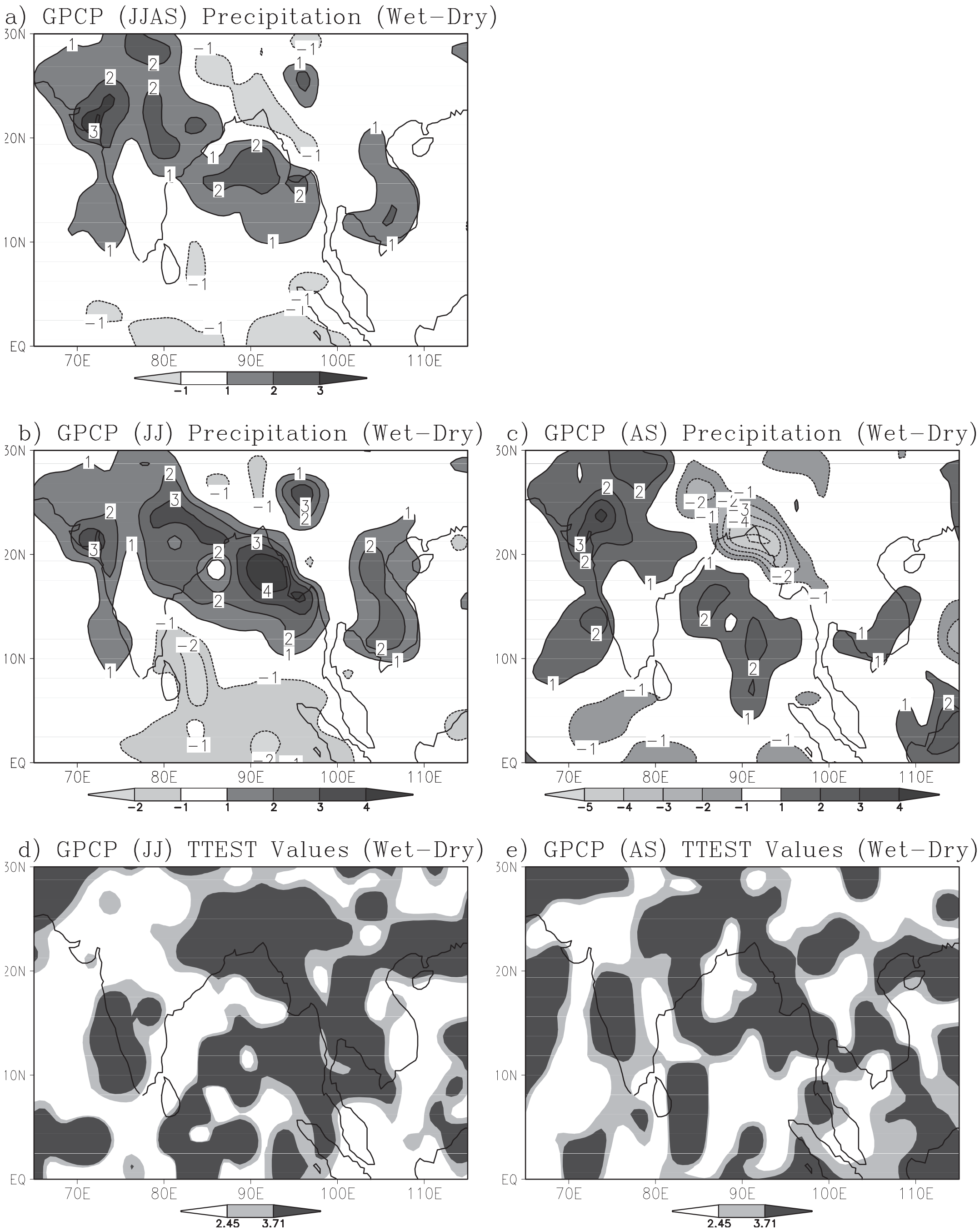

Fig. 4. Difference between Wet and Dry years [First panel] for entire summer (JJAS), a) GPCP Precipitation. [Second Panel] b) GPCP Precipitation for early summer (JJ), c) GPCP Precipitation for late summer (AS). [Third Panel] d) *t*-test for GPCP precipitation (JJ), e) *t*-test for GPCP precipitation (AS). Units for precipitation: mm/day, *t*-test values above 3.71 (99% level) and above 2.48 (95% level), are heavy and light shaded, respectively in d) and e).

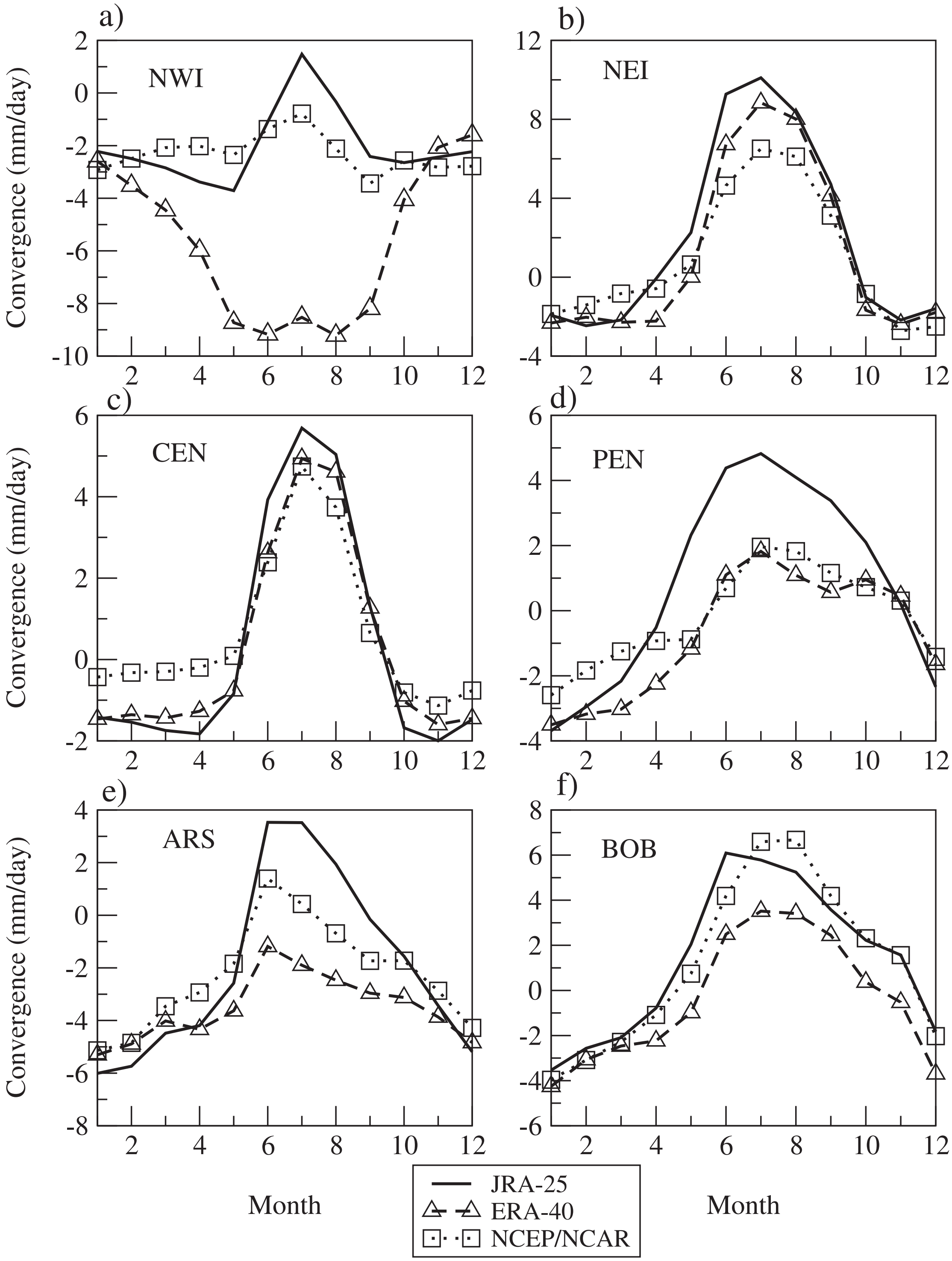

Fig. 5. Observed monthly mean cycle of convergence (C) over different domains of South Asia in three major reanalysis (JRA-25, ERA-40 and NCEP/NCAR) datasets.

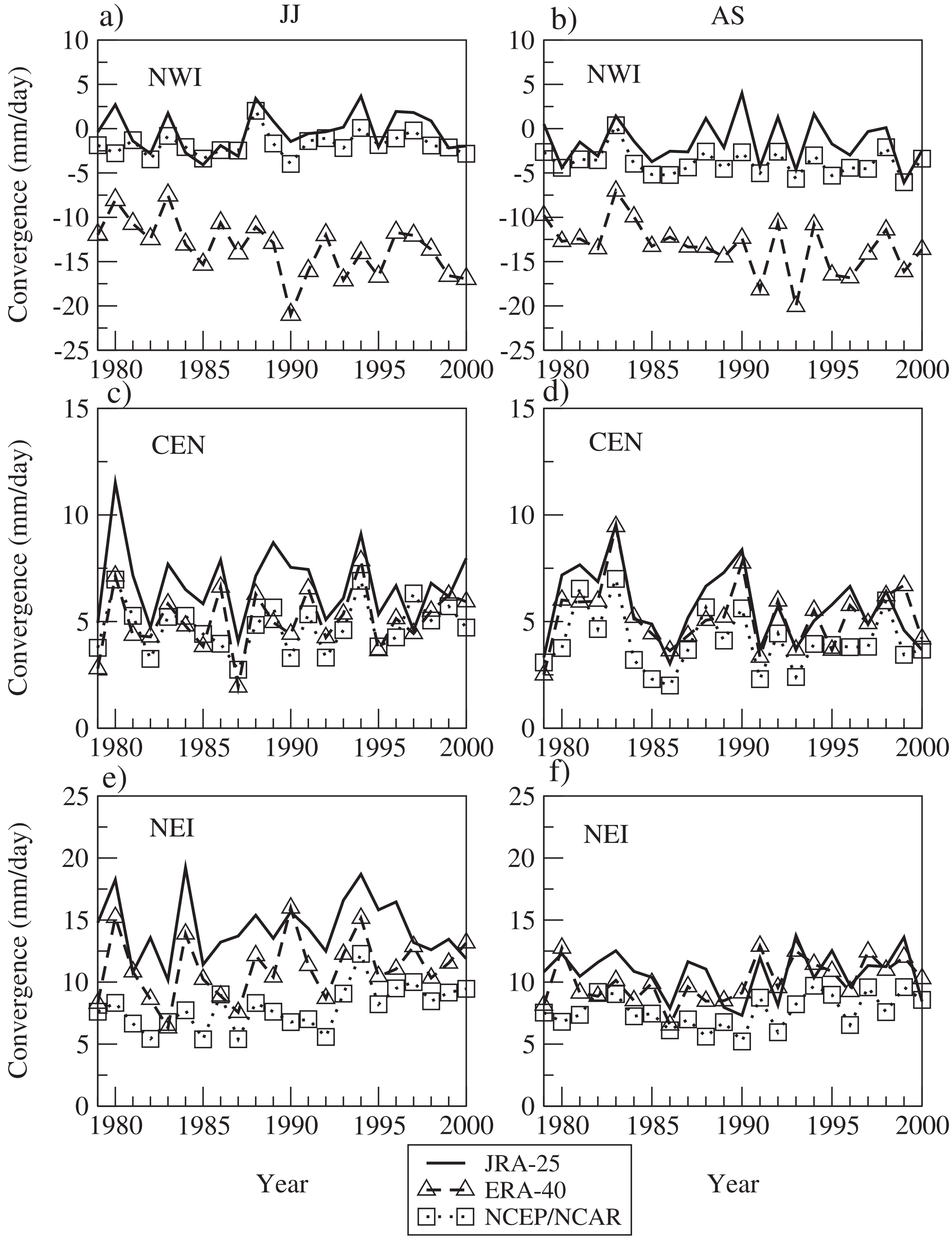

Fig. 6. Interannual variations of convergence (C) over different domains of South Asia in three major reanalysis (JRA-25, ERA-40 and NCEP/NCAR) datasets. [Top Panel] for NWI domain a) early summer (JJ) and b) late summer (AS), [Middle Panel] for CEN domain c) early summer (JJ) and d) late summer (AS). [Bottom Panel] for NEI domain e) early summer (JJ) and f) late summer (AS).

reanalysis datasets, while the ΔC from the JRA-25 and NCEP/NCAR results are comparable to each other in their magnitudes in early summer and late summer (Figs. 6a and 6b). Over CEN domain all the reanalysis results have comparable magnitude of C (Fig. 5c) and ΔC (Figs. 6c and 6d). Whereas over the NEI domain, the early summer shows large deviations of C and ΔC (Fig. 6e), the deviations of C and ΔC are less during late summer (Fig. 6f).

5.1 *Monthly annual cycle of atmospheric water budgets*

The monthly mean annual cycle of P, C and E over the six sub domains using the JRA-25 reanalysis results are shown in Fig. 7. Before explaining the relative contribution of C or E to precipitation (P) on a monthly scale, let us briefly explain the seasonal march of precipitation over the different domains. The rainy seasonal months are identified for each sub domain when the observed precipitation exceeds 3 mm day^{-1} and are demarcated by vertical dotted lines.

a. *Seasonal march of P*

Figure 7a shows P, C and E for the northwest Indian (NWI) domain, the driest region of the Indian subcontinent. The summer monsoon rains start from June, and precipitation attains the peak in July. The month of July gets a decent 5 mm day^{-1} of precipitation. Though the summer monsoon continues till the end of September, the precipitation amount is very low. We can see a sudden increase of precipitation as the summer monsoon month arrives and during the pre-monsoon months the precipitation amount is nearly 0 mm day^{-1}.

In contrast, over northeast India (NEI) (Fig. 7b), the wettest region of the Indian subcontinent, precipitation amount gradually increases from April and extends till the end of September, i.e., the rainy period over NEI is longer in the subcontinent of around 6 months duration, but considerable amount of precipitation is realized within the period of the summer monsoon (JJAS).

Over central India (CEN) (Fig. 7c), the precipitation increases suddenly between the months of May and June, from around 1 mm day^{-1} to 5 mm day^{-1}. Precipitation reaches its peak during July (8 mm day^{-1}) and the peak values are maintained until August and then precipitation falls gradually thereafter, but significant precipitation is confined to the four months of the summer monsoon (JJAS).

Peninsular India (PEN) (Fig. 7d) exhibits a long summer monsoon season; relatively low magnitude of precipitation compared to that in the NEI region. The precipitation amount gradually increases from May above 3 mm day^{-1} and attains the peak in the month of June and sustains the peak till July and slowly falls in the successive months, but does not fall completely and the second peak-like pattern appears near October–November. This is because of the precipitation from the northeast monsoon, mainly due to reversal of winds from southwesterly to northeasterly. The moisture carried from the Bay of Bengal through northeasterly during October–December brings about precipitation over peninsular India as the northeast monsoon. The northeast monsoon precipitation (October–December) is especially significant over the state of Tamil Nadu in southeast India (Dhar and Rakhecha, 1983).

Over the Arabian Sea (ARS) (Fig. 7e), the active summer monsoon precipitation period is very short compared to that of other domains. The precipitation peak is seen during June, around 5 mm day^{-1}.

Over the Bay of Bengal (BOB) (Fig. 7f), the seasonal march is quite similar to the Peninsular India (PEN) region; the precipitation is prolonged for a longer duration, starting from May till November. The precipitation peak during June around 8 mm day^{-1} gets sustained in its vigour until October with the precipitation amount roughly 5 mm day^{-1}, and a small peak-like groove appears in November due to the northeast monsoon activity over the Bay of Bengal.

b. *Seasonal contribution of C and E to P*

Over the NWI region, the precipitation during the summer monsoon months (JJA) is predominantly due to high evaporation (Fig. 7a), where E exceeds C throughout the year ($P \sim E$). The higher evaporation over the NWI domain is brought out in all the reanalysis results. The magnitude of residual E is higher in the ERA-40 and NCEP/NCAR over NWI i.e., ($P < E$) (Figures not shown).

Over the NEI region (Fig. 7b), the heavy precipitation during summer monsoon months (JJAS) is mainly due to the influence of active moisture convergence, i.e., ($C > E$) and ($P \sim C$) during the entire summer monsoon months (JJAS), which slightly differs with the ERA-40 reanalysis but the NCEP/NCAR reanalysis reveals C slightly exceeds E, i.e., ($C \sim E$) during the peak summer monsoon months (Figures not shown).

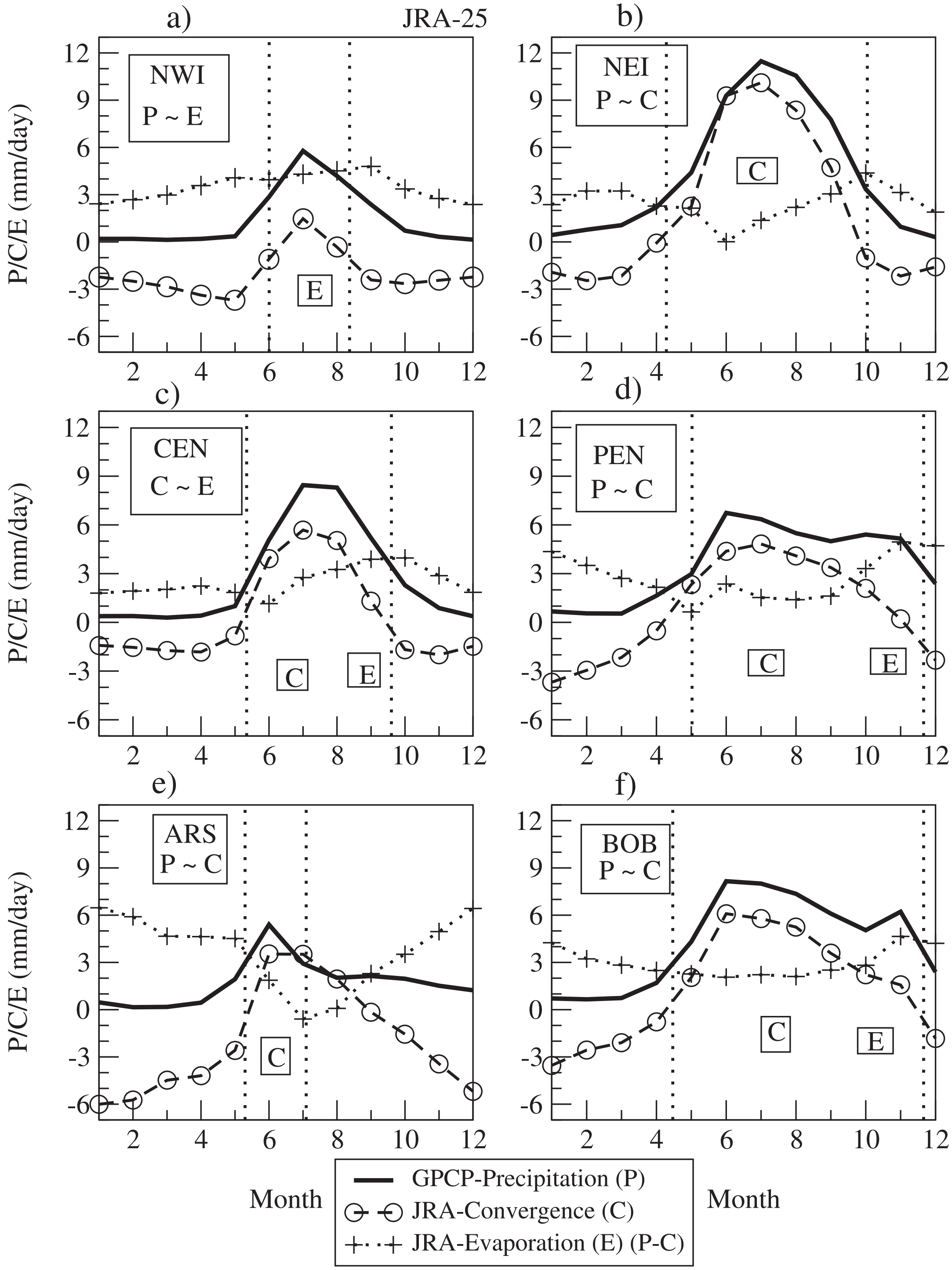

Fig. 7. Monthly mean annual cycle of P, C and E over different domains of South Asia using JRA-25 dataset. Dominance of convergence or evaporation is shown as C or E in boxes. Vertical dotted lines delineate the rainy months from the rest of the months where dominance of E or C is valid. Box in the left top shows the relationship among P, C, and E during the summer monsoon season over the respective domains.

Over the CEN region, the monsoon rains are contributed by both moisture convergence and evaporation during the summer monsoon months (Fig. 7c) with the early summer period (JJ) dominated by convergence followed by evaporation in the late summer period (AS). During September, rainfall over central India is very much influenced by higher evaporation, i.e., $(C > E)$ during early summer and $(E > C)$ during late summer (Fig. 7c). The dominance of convergence during early summer and evaporation during late summer has been brought out by the other two reanalysis datasets too (Figures not shown). The result suggests that the moisture availability during the later period of the monsoon months may aid in higher evaporation during the latter months and thus the structure of the precipitation generation during early and late summer monsoon months is different over this region.

Rainfall over the PEN region (Fig. 7d) during summer monsoon months is favoured by strong convergence throughout the summer monsoon season, whereas, the evaporation is strong during the NE monsoon season (OND).

Over the ARS region, convergence is higher (shown as the box $[C]$) (Fig. 7e) during the summer monsoon season (JJAS) of the year, i.e., $(C > E)$ during summer monsoon months.

Over the BOB region, convergence is dominant throughout the JJAS season (Fig. 7f). Convergence approximately equals precipitation, i.e., $(P) \sim (C)$ during summer monsoon months, which has been brought out with the NCEP/NCAR reanalysis data too (Figure not shown); on the other hand, in ERA-40 (Figure not shown), evaporation is higher than convergence in magnitude during JJAS, suggesting both evaporation and convergence may contribute to precipitation during the summer monsoon months. During the NE monsoon season (OND), the evaporation is strong over BOB, suggesting that convergence is stronger only during the summer monsoon season (JJAS).

6. Interannual variation of atmospheric water budgets

To study the precipitation variability on the interannual time scale, the interannual variations of water budget components are plotted for both early and late summer for each domain. The correlation coefficient (CC) between ΔP and ΔC, ΔP and ΔE are used to understand the relationship of these three components in the interannual variability. The CC's are examined to know how they are related and how they differ from the early to late summer period. Since E is obtained as a residual from P and C, E contains the P signature when C does not vary, so care has been taken while interpreting the correlation between P and E. For understanding the interannual variability of P, C and E over the land domains like NWI, NEI and CEN, only land grid points are considered for area average, but for the domains like PEN, BOB and ARS, the area average of the box is considered.

Though the contribution of evaporation to the mean seasonal precipitation is high over the northwest Indian region both in the early and late summer monsoon period, the correlation between ΔP and ΔC exceeds 95% significant level for early and late summer, respectively (Figs. 8a and 8b). The CC results from ERA-40 and NCEP/NCAR also support the conclusion from JRA-25 (Table 1). Therefore, ΔC contributes higher to the year-to-year variability of ΔP over the NWI monsoon region.

The NEI monsoon region shows correlation coefficients between ΔP and ΔC at just above 95% of significant level for early and late summer respectively. Between ΔP and ΔE, the correlation coefficients are above 95% of significant level for early and late summer respectively (Figs. 8e and 8f). These results suggest that evaporation also partly play a role in modulating the precipitation anomalies, which are well supported by both the ERA-40 and NCEP/NCAR results (Table 1).

Similarly, over the CEN region precipitation (ΔP) is highly correlated with convergence (ΔC) (above 95% of significant level) for both the early and late summer monsoon periods (Figs. 8c and 8d) and the CC between ΔP and ΔE in CEN considerably changes from JJ (significant) to AS (less significant) suggesting that the climatology is $C > E$ in the early summer and $E > C$ in the late summer, while the interannual variability for respective seasons are reversed, i.e., ΔE contributes higher to ΔP for early summer and ΔC contributes higher to ΔP for late summer respectively. This has been reinstated in all the reanalysis results, i.e., the CC between ΔP and ΔE in CEN for ERA-40 changes from JJ (significant) to AS (less significant) (Table 1) and also CC changes from JJ (significant) to AS (less significant) in the NCEP/NCAR results (Table 1). CC between ΔP and ΔE is above 95% of significant level during early summer in all the reanalysis results, but ΔE looses its significance during late summer.

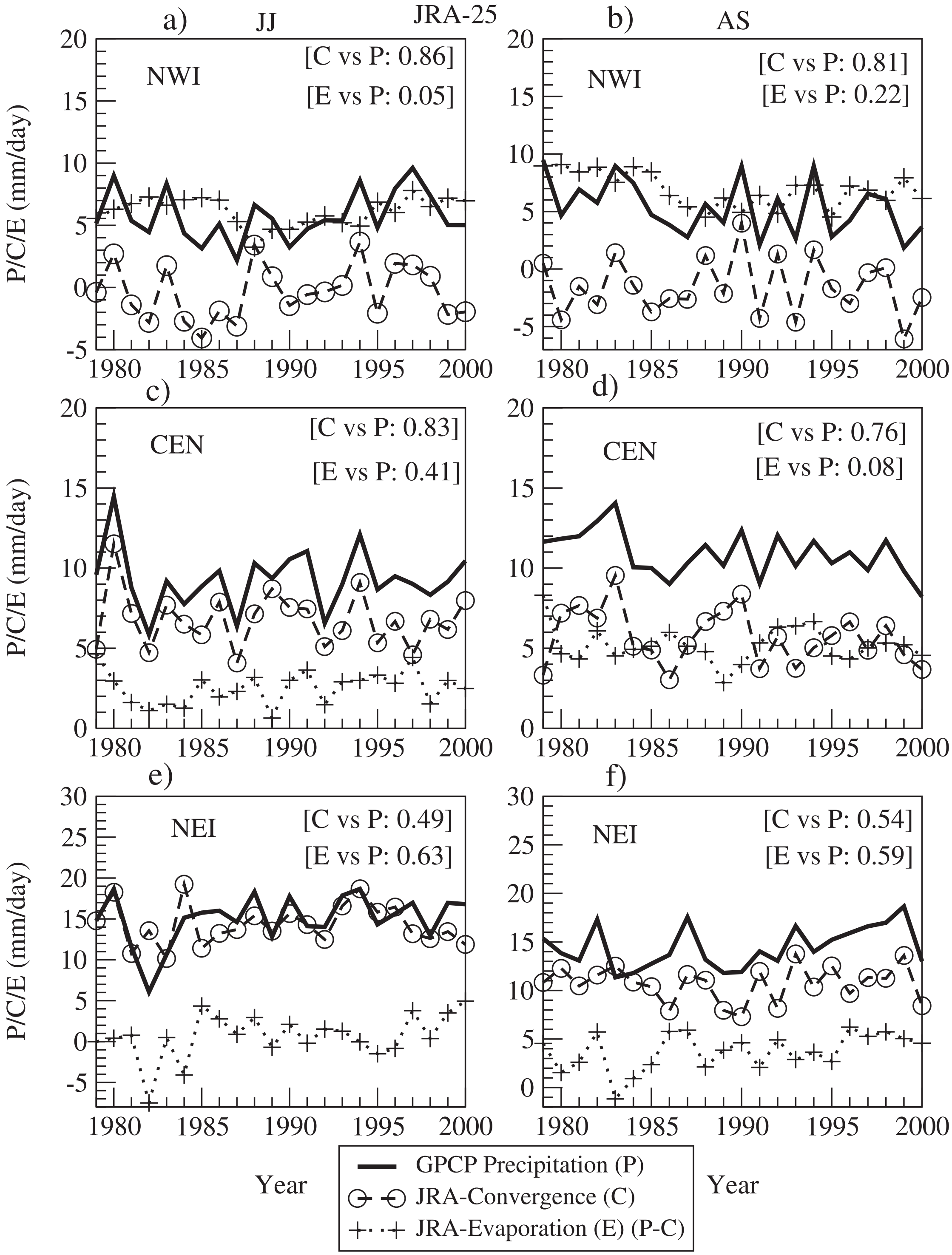

Fig. 8. Interannual variations of P, C and E over different domains of South Asia from JRA-25 dataset. [Top Panel] for NWI domain a) early summer (JJ) and b) late summer (AS), [Middle Panel] for CEN domain c) early summer (JJ) and d) late summer (AS). [Bottom Panel] for NEI domain e) early summer (JJ) and f) late summer (AS). (Value of correlation coefficient between P and C & P and E are shown in each graph) [95% significant level is $+/-0.42$]

In contrast, over the BOB monsoon region, though the active convergence during the monsoon months contributes to higher mean seasonal precipitation, the year-to-year variability of precipitation is not completely dependent on moisture convergence (similar to the NEI domain), which is evident from the poor positive correlation (negative correlation for early summer) between precipitation (ΔP) and convergence (ΔC) for early and late summer, respectively (Figs. 9a and 9b) and between ΔP and ΔE during JJ and AS (above 95% of significant level), respectively (Figs. 9a and 9b). These results suggest that evaporation plays a key role in modulating the precipitation anomalies over BOB.

Over the PEN monsoon domain, the correlation between ΔP and ΔC (Figs. 9c and 9d) is above 95% significant level for early and late summer, respectively, and correlation between ΔP and ΔE are less significant. The results from ERA-40 and NCEP/NCAR also support the conclusion from JRA-25 (Table 1). Therefore, ΔC contributes higher to the year-to-year variability of P over the PEN domain.

Similarly, over the ARS monsoon domain, the correlation between ΔP and ΔC are above 95% significant level for early and late summer, respectively, and correlation between ΔP and ΔE is less significant (Figs. 9e and 9f). Therefore, ΔC plays a major role in the year-to-year variability of P over the ARS monsoon region. The results from ERA-40 and NCEP/NCAR also support the conclusion from JRA-25 (Table 1).

Otherwise in brief words, according to the analysis of JRA25, signals in ΔP are dominated by ΔC in NWI, PEN, ARS; ΔE in BOB; both ΔC & ΔE (with nearly equal weights) in NEI; mainly ΔC, but also ΔE in JJ, in CEN. With different sets of reanalysis results, following different features are added: ΔE also important in PEN (both ERA and NCEP); ΔC also important in BOB in AS (ERA); ΔE also important in NWI (NCEP); ΔE also important in ARS in JJ (NCEP).

7. Regional variability in atmospheric water budget

The Indian summer monsoon exhibits a large variety of spatial and temporal variability. In this section we discuss the characteristics of atmospheric circulation, moisture transport responsible for precipitation generation during early and late summer among the selected domains. Precipitation (P), large-scale convergence (C), winds, moisture transport vectors and evaporation (E) are regressed with the area averaged GPCP precipitation index over each domain in order to understand the structure of P variability, over the respective domains. A test of local statistical significance for spatial correlation coefficient was performed using standard t-test for plotting above 95% significant level.

Figures 10a and 10b show the GPCP precipitation and 850 hpa winds regressed with the NWI domain averaged GPCP precipitation for early and late summer, respectively. During early summer (JJ) (Fig. 10a), the regression pattern reveals that the precipitation anomalies over NWI are strongly associated with local P and moderately associated with P along the west coast, Arabian Sea and the Bay of Bengal region, whereas during late summer (AS) (Fig. 10b) the precipitation anomalies have profound effect only over the west coast and northwest of India. The precipitation during early summer (JJ) are generally caused by the disturbances from the Arabian sea sector and the strong convergence over the Arabian sea sector and the positive precipitation anomalies over NWI are coupled with the cyclonic circulations over the Arabian sea and the land regions, especially over central India (Figs. 10a and 10c). During late summer (AS), the cyclonic circulation is confined to the Arabian Sea sector and the regression coefficients are confined only to northwest India. Therefore, the positive precipitation anomalies over NWI for late summer (AS) are coupled with cyclonic circulation over the Arabian Sea only and strong moisture transport vectors predominantly originate from the Arabian Sea sector (Figs. 10b and 10d). From the regressed pattern of E, one can notice that there is no role of evaporation during early summer and late summer over NWI to P variability (Figs. 10e and 10f). Therefore, ΔC plays a major role in the interannual variability P over northwest India in early summer (JJ) and also in late summer (AS).

Figures 11a and 11b show the regressed GPCP precipitation and 850 hpa winds against the CEN domain averaged GPCP precipitation for early and late summer, respectively. During early summer (JJ) (Fig. 11a), the regression pattern reveals that the highly correlated precipitation area is east-northwest aligned, whereas during late summer (AS) (Fig. 11b), the highly correlated precipitation area is west-central aligned, and we can also notice CEN precipitation negatively associated with northeast India precipitation in the late summer months (AS). The regression map of large-scale convergence and moisture transport for early summer (JJ) is shown in Fig. 11c. Strong convergence

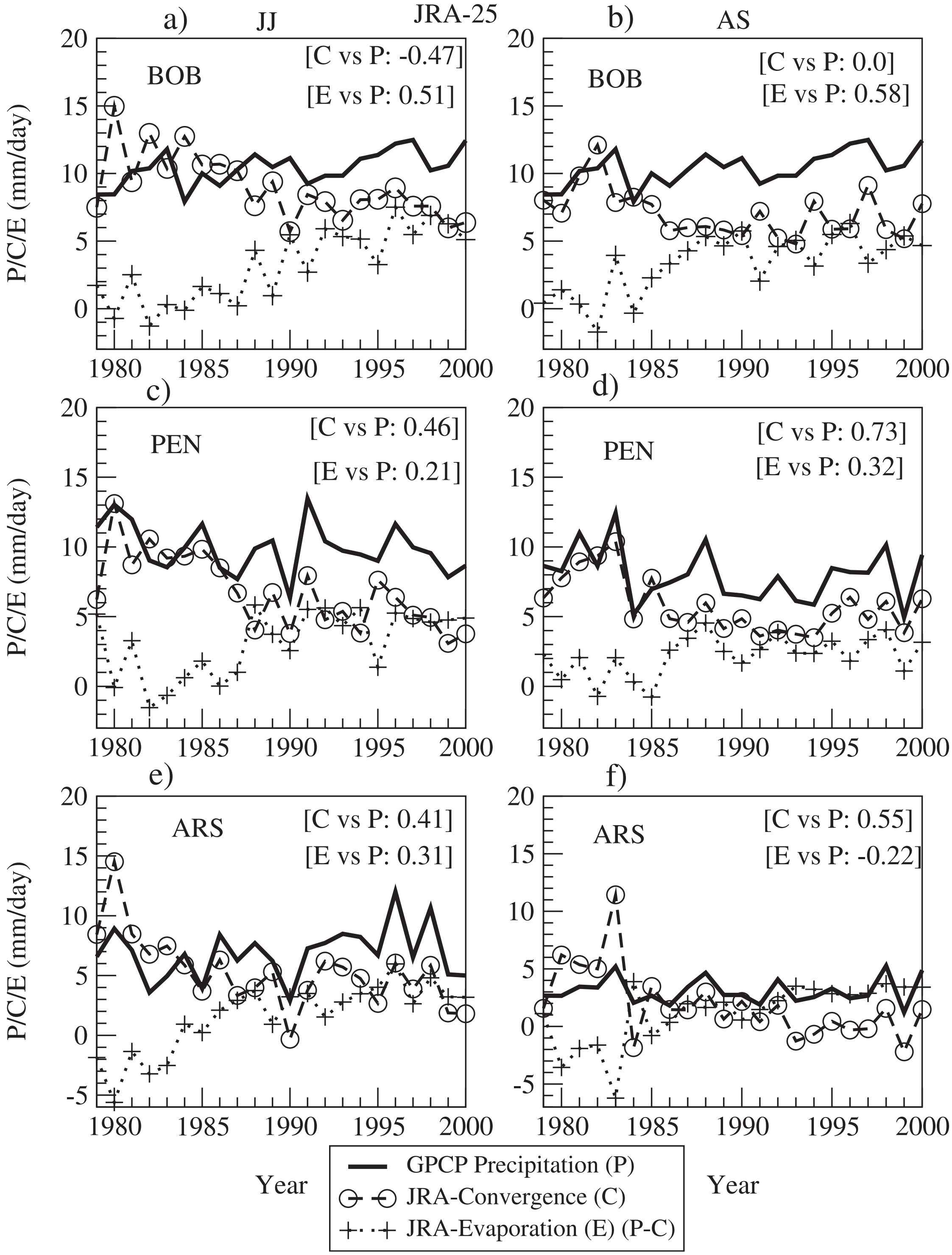

Fig. 9. As in Fig. 8, but for the domains BOB, PEN and ARS.

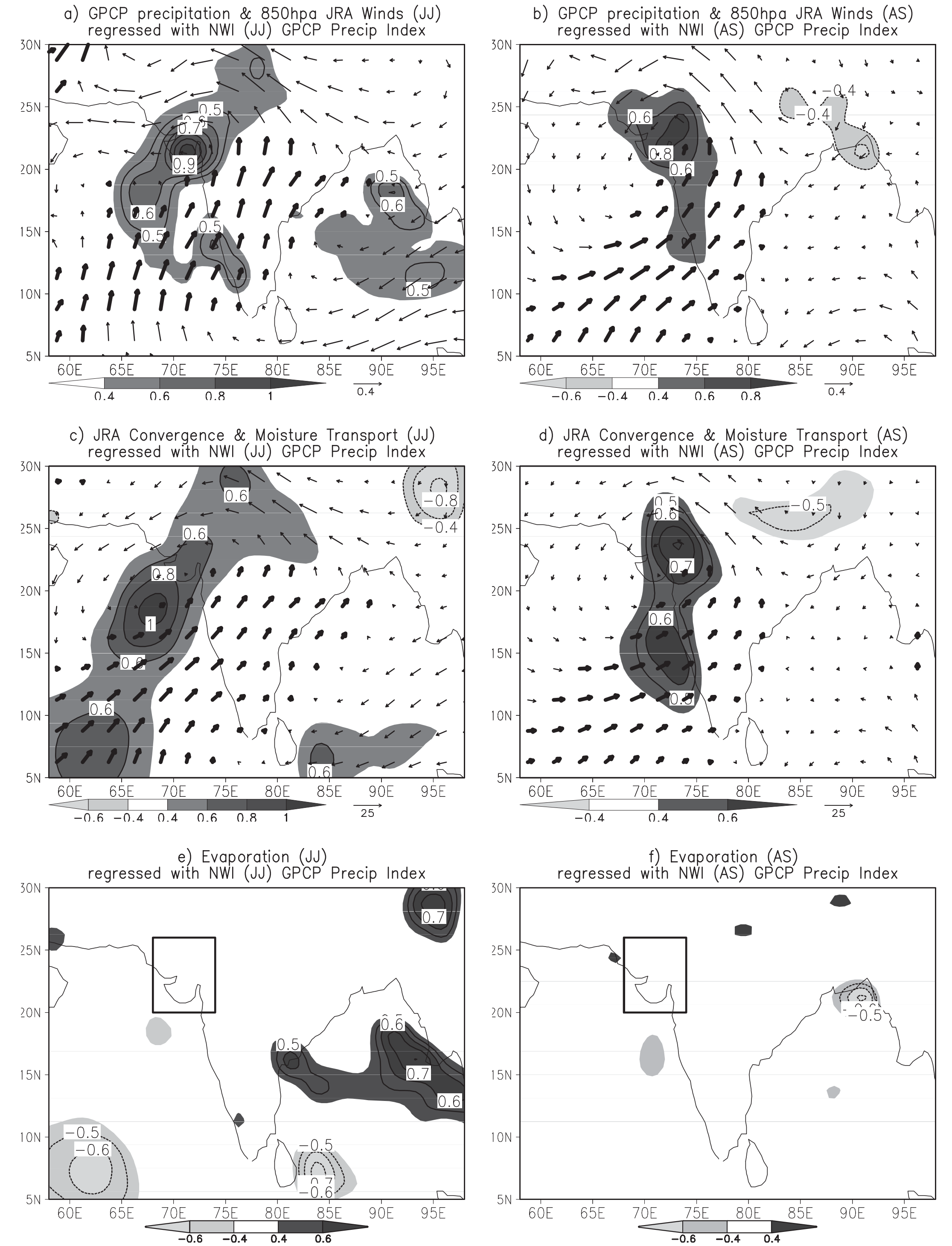

Fig. 10. Regression maps based on Northwest India (NWI) domain averaged GPCP precipitation for JRA-25 dataset. [Top panel] GPCP Precipitation and 850 hpa winds, a) for early summer (JJ) b) for late summer. [Middle Panel] Moisture Convergence and moisture flux transport, c) for early summer d) for late summer. [Bottom Panel] Evaporation, e) for early summer f) for late summer. Domain for precipitation index is shown by a box in the Bottom panel. Shaded values and thick arrows are significant at 95% level. Shaded bar indicates regression coefficient. Units for precipitation & convergence: mm/day, winds: m s^{-1}, moisture flux: kg m^{-1} s^{-1}.

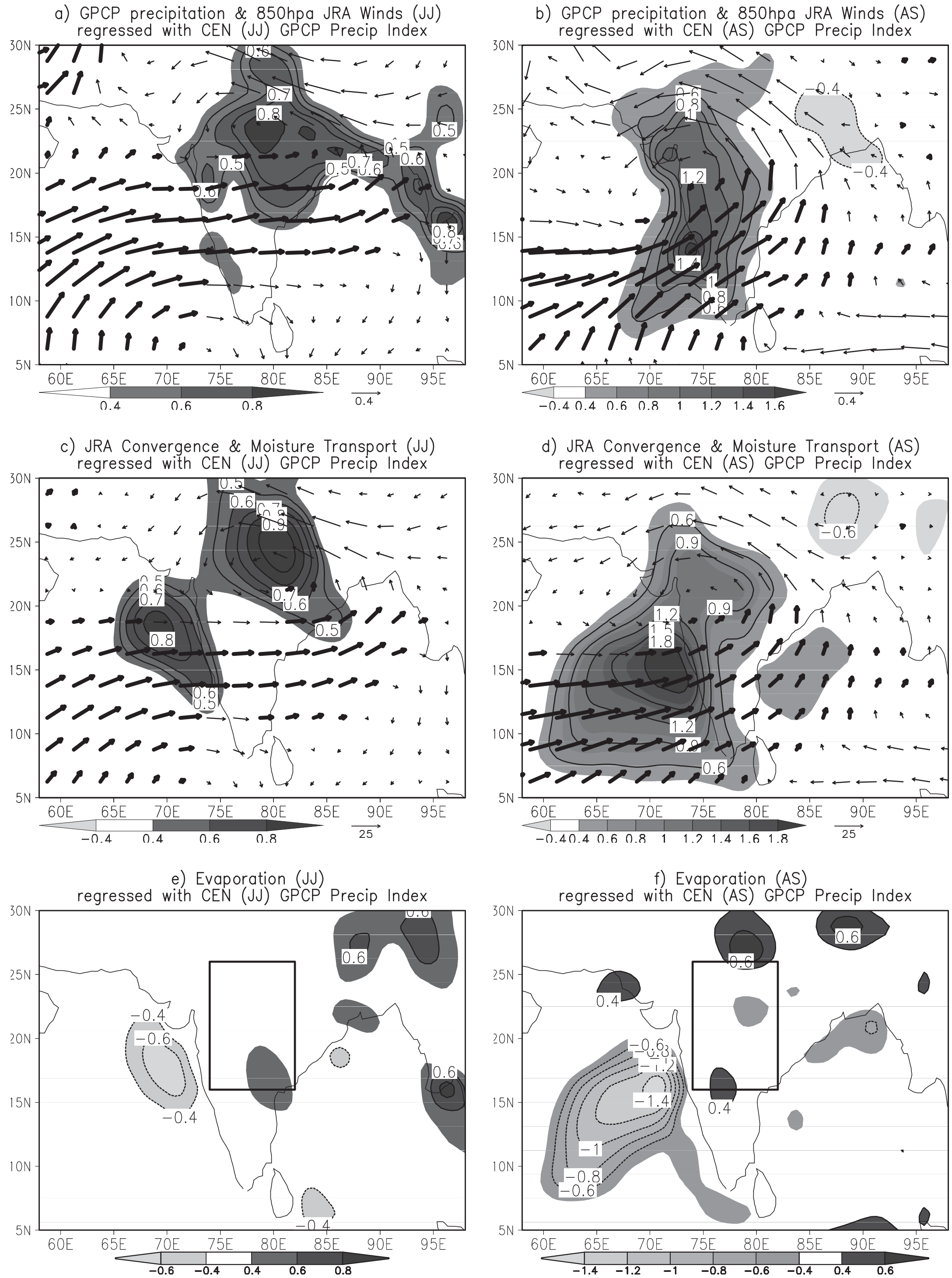

Fig. 11. As in Fig. 10, but for Central India (CEN) domain.

from the head Bay of Bengal sector is associated with the precipitation variability over the CEN region and the large scale cyclonic circulation is basically from the Bay of Bengal sector in early summer (Figs. 11a and 11c). During the late monsoon season (AS), the large-scale cyclonic circulation over the northwest and central parts of India enveloping peninsular India is strongly associated with precipitation variability over the CEN region. Active convergence over the Arabian Sea and cyclonic moisture circulation favour positive precipitation anomalies over central India (Figs. 11b and 11d). A similar picture evolves in the ERA-40 dataset (Figures not shown) for early and late summers and also in the NCEP/NCAR reanalysis in both summers (Figures not shown). Regressed pattern of evaporation reveals a significant but weak association of evaporation over south of central India both in early summer and in late summer (Figs. 11e and 11f). Thus, we can say that both ΔC and ΔE during early (JJ) summer months and only ΔC during late (AS) summer months play a role in the interannual variability of P over central India. We can also notice large negative regression values of E with the CEN domain precipitation over the Arabian Sea, which are unrealistic values, due to the overestimation of C over these grids (Figs. 11e and 11f).

GPCP precipitation and 850 hpa winds regressed with the NEI domain averaged GPCP precipitation for early summer (JJ) is shown in Fig. 12a and that for late summer (AS) is shown in Fig. 12b. During early summer, the NEI precipitation is largely associated with the NEI domain itself. Strong association over southeast of the domain and weak association with the central domain are evident from the regression map. During late summer (AS), the positive association is strong only over the southeast of the domain (stronger over the oceans), but no significant correlations are noticed over the west and northeast areas of the domain box (unlike in the case of early summer) and a significant negative association with NWI precipitation and the southwest coast of India are also seen (Fig. 12b). Large-scale convergence (C) and moisture transport regressed with the NEI domain averaged GPCP (P) for early summer (JJ) is shown in Fig. 12c. We notice that the convergence along the foot hills of Himalayas (northwest of the domain) is regressed positively with the precipitation index of the NEI domain. Though regression is weak over the domain box, the positive precipitation anomalies are coupled with the cyclonic circulations from the Bay of Bengal and the upper reaches of the climatological position of the monsoon trough, which is similar to the typical condition of monsoon break, where dry condition prevails over most part of the Indian subcontinent. The movement of the low level trough (monsoon trough) to foothills of the Himalayas causes break condition over the subcontinent (Raghavan 1973, Krishnamurti and Bhalme, 1976) and the northeast Indian (NEI) regions receive above normal rainfall. A typical break-like circulation brings positive precipitation anomalies over northeast India (NEI) during early summer (JJ) (Figs. 12a and 12c).

During the late monsoon season (AS) the cyclonic circulation is confined only to northeast India, strong divergent flux is noticed over the south Bay of Bengal and large-scale divergent flux encompasses most part of the Indian subcontinent showing a typical dry condition over the entire subcontinent. The positive precipitation anomalies over NEI are favoured by localized convergence and moisture transport from the northern Bay of Bengal (Figs. 12b and 12d). A similar picture is evidenced in the ERA-40 results and in the NCEP/NCAR reanalysis results, which suggest that precipitation over the NEI domain is inversely related to the land domains like NWI, CEN and PEN. However, one has to keep in mind that the representation of orography over this region in the reanalysis model is relatively poor due to the complex nature of the terrain, which may affect the calculated convergence (C) and the observed P may also have some errors. Both in early and late summer, evaporation also plays a key role in modulating the precipitation anomalies over NEI (Figs. 12e and 12f). A similar result can be seen in the ERA-40 dataset (Figures not shown) and the NCEP/NCAR dataset (Figures not shown).

Figures 13a and 13b show the GPCP precipitation and 850 hpa winds regressed with the BOB domain averaged GPCP precipitation for early and late summer, respectively. During early summer (JJ) (Fig. 13a), the regression pattern reveals that the precipitation anomalies over BOB are strongly associated with P over the head Bay of Bengal and along the Burma coast and no association with P over the central and south of the domain, whereas during late summer (AS) (Fig. 13b) the precipitation anomalies have profound effect on the entire BOB domain. The precipitation during early summer (JJ) is generally caused by the excessive evapo-

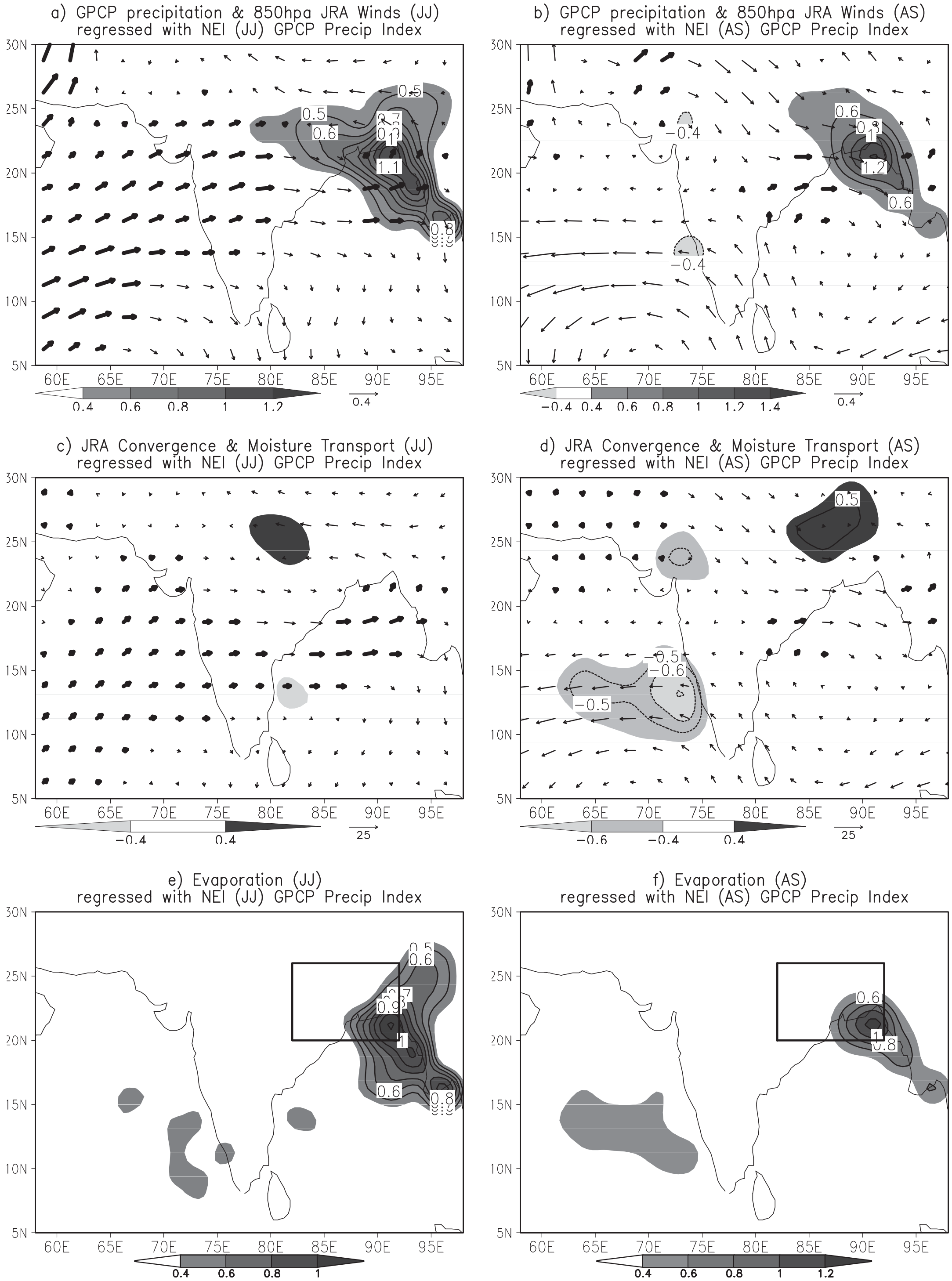

Fig. 12. As in Fig. 10, but for Northeast India (NEI) domain.

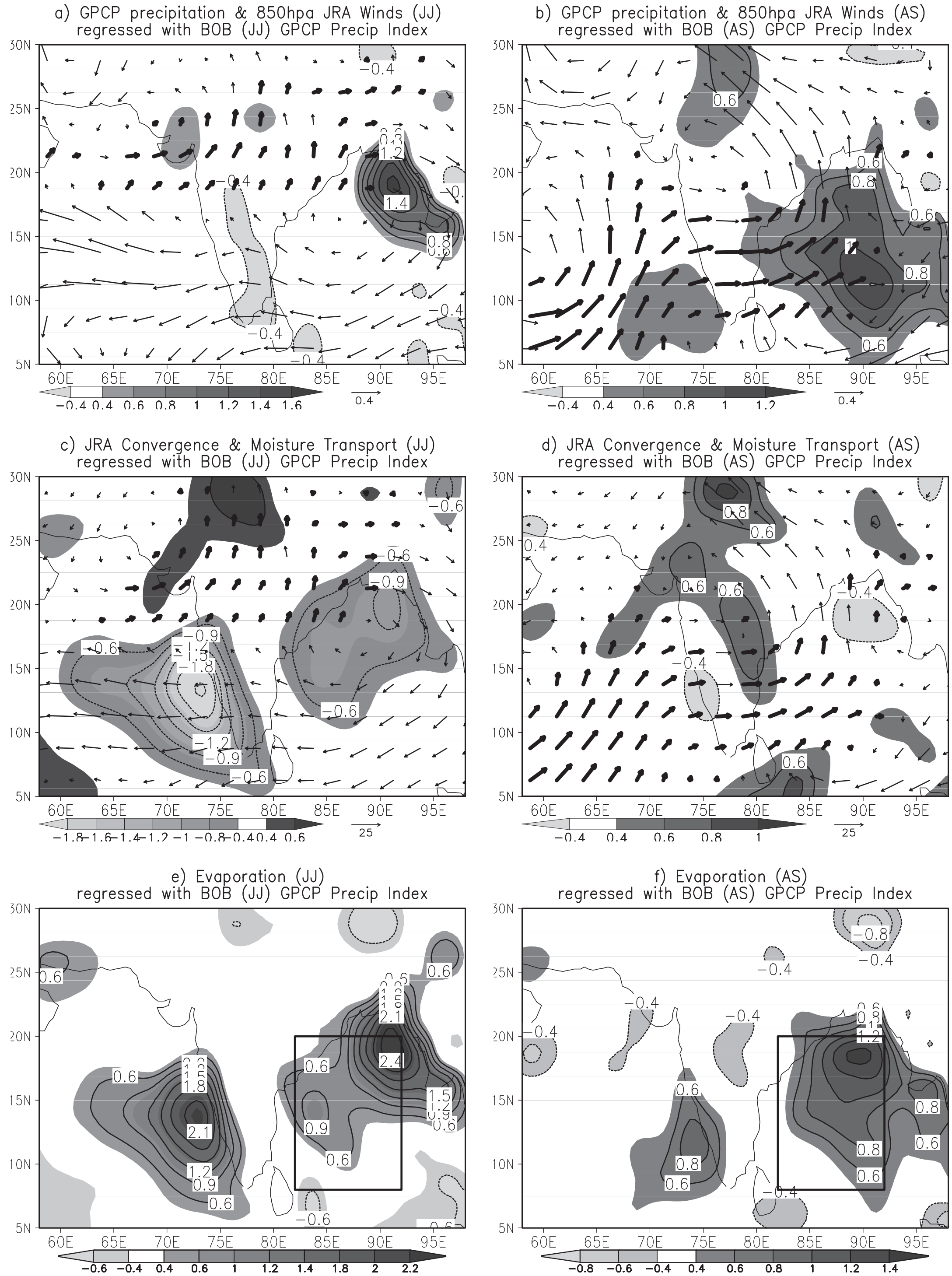

Fig. 13. As in Fig. 10, but for the Bay of Bengal (BOB) domain.

ration from the Bay of Bengal and strong divergence over the head Bay of Bengal transports moisture to the land region north of it, but strong divergence prevails over south peninsular India (Figs. 13a and 13c). During late summer (AS), the cyclonic circulation confined to the northern part of the Bay of Bengal sector and the strong moisture transport from Arabian sea coupled with higher evaporation over Bay of Bengal sector contributes to positive precipitation anomalies over the Bay of Bengal (Figs. 13b and 13d). From the regressed pattern of (E), the role evaporation is evident in both early and late summers over BOB to P variability (Figs. 13e and 13f).

8. Discussions

Thus the atmospheric water balance analysis has revealed that the early summer (JJ) and the late summer (AS) precipitation anomalies over South Asia show different features. The interannual variability of precipitation over central India and northwest India during early and late summers represents the interannual variability of precipitation over the entire Indian subcontinent. From the regression patterns of P, C and E, the precipitation variability especially over NEI is negatively related to other domains like NWI, CEN and PEN over the subcontinent during the late summer season (AS), as can be seen from the fact that the regression pattern of moisture convergence and moisture flux vector for NWI and CEN (Figs. 10d and 11d) are quite similar, whereas over NEI it is different (Fig. 12d). The interannual variability of precipitation over northwest India is influenced by large-scale moisture convergence for both early and late summers and the interannual variability of precipitation over central India is influenced by both the large-scale moisture convergence and the local evaporation for both early and late summers. However, over northeast India the surface conditions during early and late summers may also partly play a role in modulating the precipitation anomalies, since the convergence is poorly correlated with precipitation in all the reanalysis datasets and the CC between P and E is strong and a moderate amount of evaporation is also found over the land. However, one has to keep in mind that the representation of orography over this region in the reanalysis model is relatively poor due to the complex nature of the terrain, which may affect the calculated C and the observed P may also have some errors, but the relative role of land surface hydrological processes can not be ruled out and further studies are required to understand the role of land surface processes in modulating the precipitation anomalies over the NEI region.

A probable interaction between land and atmosphere over the CEN and NEI domains cannot be ruled out during the summer monsoon season due to the role of evaporation over these regions. Though evaporation is obtained as a residual from observed P and calculated C, we believe that the evaporation obtained as a residual from the water balance can at least partly explain the land-atmospheric interaction with some limitations better than evaporation obtained directly from reanalysis datasets. Recently, using ensembles of GCM models, Koster et al. (2005) showed that soil moisture hot spots (the regions where precipitation is sensitive to soil moisture anomaly) exist over some relatively dry monsoon regions. The land-atmospheric interaction over the domains (CEN, NEI) is crucial in understanding the soil moisture impact on precipitation. The stronger role of evaporation (ΔE) to precipitation (ΔP) as observed during early summer over CEN and during late summer over NEI shows some surface hydrological processes responsible for precipitation anomalies over these regions. It is also consistent with the previous studies such as those of Yoshimura et al. (2004) that the origin of land evaporation (around 36%) is responsible for precipitation over the Calcutta region (NEI domain) during July 1998 using coloured moisture analysis. As the evaporation is very much controlled by the amount of precipitation over land and the accuracy of precipitation is also important in this method, so further studies are needed to confirm such interactions. Also, Roads and Betts (2000) have studied the surface water and energy budgets for Mississippi River basin using NCEP/NCAR and ECMWF reanalyses, highlighted the limitations of both the reanalyses in depicting the surface water and energy budgets and recommended that further developments be needed in the current models.

The atmospheric water balance analysis based on the JRA-25 reanalysis dataset is reliable as the P and C correlations are the highest over land domains (especially over CEN) among the reanalysis datasets. Contrastive features are evident between land and oceanic regions. Especially the BOB domain precipitation is very much controlled by higher evaporation and so, the SST over the BOB domain is crucial for controlling precipitation variability over not only BOB, in addition to the influence on the majority of land domains. Warmer (Colder) SST's over BOB can alter the convergence and evaporation through stronger (weaker) convection over BOB and thereby it can influence the other domains substantially.

During early summer season (JJ), the precipitation over BOB is significantly correlated with the south-westerlies of 850 hpa wind circulation and vertically integrated moisture transport over the CEN domain (Figs. 13a and 13c) and during late season (AS), the precipitation over BOB is significantly correlated with the south-westerlies of 850 hpa wind circulation and vertically integrated moisture transport over the PEN domain (Figs. 13b and 13d) shows that the precipitation variability over the BOB region very much controls the precipitation variability over the domains like CEN and PEN. The reliability of precipitation over the oceans (BOB) and the calculated convergence (C) over the oceans (BOB) are, however, less reliable due to lack of sufficient observations. Caution may be needed for P and C correlation over BOB, since those from the three reanalyses data show considerably large differences (as shown in Table 1). As we can say, P is a more frequently observed meteorological variable compared to C and E. Among P, C and E, E is the less observed variable and to some extent C can be deduced to some accuracy, therefore a good correlation between P and C indicates the reliability of the data to some extent. However, the results from the JRA-25 reanalysis dataset particularly for land domains are consistent in the water balance studies over South Asia.

9. Conclusions

We investigated the space-time characteristics of atmospheric water balance components over South Asia in detail using selected sub domains from the available model and observed datasets and summarize our results as follows.

a) JJAS based precipitation anomalies only partially explain the interannual variations of Indian monsoon rainfall, since the large time-space differences are noticed between early summer (JJ) and late summer (AS) anomalies. Therefore, the sub-seasonal (JJ and AS) based water balance analysis helped us to explain the difference between the precipitation anomalies of sub-seasons and over the different spatial domains of South Asia.

b) The contribution of convergence and evaporation to the seasonal mean precipitation over the CEN domain for early summer (JJ) and late summer (AS) are different, suggesting that the mechanism of precipitation generation during early and late summers are basically different. The different structure of P variability over CEN for the early and late monsoon season implies that the modulating component of precipitation for early and late summers is not the same. The changes in large-scale convergence affect P variability in the late summer season compared to the early season. Similarly the surface condition during the early summer season very much affect the P variability compared to late summer over the CEN domain.

c) The interannual variability of precipitation over the whole Indian subcontinent measured by AISMR is closely related mainly to the precipitation variability over northwest India and central India. Though the regional differences of the Indian monsoon rainfall variabilities have been discussed in many preceding papers, in this paper we have shown the regional differences in the Indian monsoon rainfall variabilities and explained the variabilities with P, C and E relationship using the atmospheric water balance method. During early summer, the large-scale convergence over the Bay of Bengal sector and during late summer the large-scale convergence over the Arabian Sea sector have the potential of modulating the monsoon for early and late summer, respectively, on interannual timescales.

d) The precipitation variability over northwest and central India is quite different from that over northeast India. It is evident from the atmospheric water balance that the processes causing anomalies over NEI is different from those over CEN, NWI. Therefore, the northeast India (NEI) regional monsoon variability is independent of the interannual variability over the domains like NWI, CEN and PEN of the Indian subcontinent. There exists a strong inverse relationship between the NEI domain and the domains like NWI, CEN and PEN over the Indian subcontinent during the late summer period.

e) On the interannual time scales, the NEI domain precipitation anomalies are not directly influenced by large-scale convergence both in early and late summers, whereas the evaporation is likely to play at least partly a role in modulating the anomalies over NEI. These results suggest that some surface hydrological processes are responsible for modulating the monsoon over the NEI domain during the summer season. Still, this is a tentative result, as the accuracy of computed C and observed P over this region has known limitations. Thus by dividing the summer monsoon season (JJAS) into early summer (JJ) and late summer (AS), the interannual variability of water budget components for the early and late summer monsoon period have revealed different characteristics of E, P and C relationships among different sub domains.

Acknowledgment

Authors would like to thank Drs. Fujinami, Hori, Takahashi, Abe, Ichikawa and Mr. Kanamori for their helpful comments during this research work. Authors would also like to thank Drs. K. Onogi, N. Yamazaki, K. Takahashi and Kamahori of JMA for their helpful comments. VP was supported by Monbukagakusho scholarship from the ministry of Education, Culture, Sports, Science and Technology. Authors would also like to thank the three anonymous reviewers for their helpful comments, which helped us immensely in improving the paper. We also acknowledge many centers for providing datasets. JRA-25 dataset obtained from the website (http://jra.kishou.go.jp/) archived by JMA, CRIEP. ERA-40 dataset obtained from the website (http://data.ecmwf.int/data/). NCEP/NCAR reanalysis data obtained from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at (http://www.cdc.noaa.gov/) and VASClimO dataset from (http://www.deutscherwetterdienst.de/). VASClimO is an activity of the German Weather Service (http://www.dwd.de/de/FundE/Klima/KLIS/prod/KSB/archiv.htm). Monthly AISMR index is obtained from (www.tropmet.res.in). The diagrams used for this study have been prepared using the free software packages like GrADS, XMGRACE and computational work done on the Fedora Core 2 operating system environment.

References

Adler, R. F., G. J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, and E. Nelkin, 2003: The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). *J. Hydrometeor.*, **4**, 1147–1167.

Ailikun, B., and T. Yasunari, 2001: ENSO and Asian summer monsoon: persistence and transitivity in the seasonal march. *J. Meteor. Soc. Japan*, **79**, 145–159.

Beck, C., J. Grieser, and B. Rudolf, 2005: A new monthly precipitation climatology for the global land areas for the period 1951 to 2000. *Climate Status Report*, **2004**, 181–190.

Dhar, O. N., and P. R. Rakhecha, 1983: Forecasting northeast monsoon rainfall over Tamil Nadu, India. *Mon. Wea. Rev.*, **111**, 109–112.

Fukutomi, Y., H. Igarashi, K. Masuda, and T. Yasunari, 2003: Interannual variability of summer water balance components in three major river basins of northern Eurasia. *J. Hydrometeor.*, **4**, 283–296.

Graversen, R. G., E. Kallen, M. Tjernstrom, and H. Kornich, 2007: Atmospheric mass-transport inconsistencies in the ERA-40 reanalysis. *Quart. J. Roy. Meteor. Soc.*, **133**, 673–680.

Hagemann, S., K. Arpe, and L. Bengtsson, 2005: Validation of the hydrological cycle of ERA40. *ERA-40 Project Report Series*, **24**, 42 pp.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kawamura, R., K. Uemura, and R. Suppiah, 2005: On the recent change of the Indian summer monsoon-ENSO Relationship. *SOLA*, **1**, 201–204.

Koster, R. D., P. A. Dirmeyer, Z. Guo, G. Bonan, E. Chan, P. Cox, C. T. Gordon, S. Kanae, E. Kowalczyk, D. Lawrence, P. Liu, C. -H. Lu, S. Malyshev, B. McAvaney, K. Mitchell, D. Mocko, T. Oki, K. Oleson, A. Pitman, Y. C. Sud, C. M. Taylor, D. Verseghy, R. Vasic, Y. Xue, and T. Yamada, 2004: Regions of Strong Coupling Between Soil Moisture and Precipitation. *Science*, **305**, 1138–40.

Krishnamurti, T. N., and H. N. Bhalme, 1976: Oscillations of a monsoon system. Part I, Observational aspects. *J. Atmos. Sci.*, **33**, 1937–1954.

Marengo, J. A., 2005: Characteristics and spatio-temporal variability of the Amazon River Basin water budget. *Clim. Dyn.*, **24**, 11–22.

Oki, T., K. Musiake, H. Matsuyama, and K. Masuda, 1995: Global atmospheric water balance and runoff from large river basins. *Hydrol. Processes*, **9**, 655–678.

Onogi, K., J. Tsutsui, H. Koide, M. Sakamoto, S. Kobayashi, H. Hatsushika, T. Matsumoto, N. Yamazaki, H. Kamahori, K. Takahashi, S. Kadokura, K. Wada, K. Kato, R. Oyama, T. Ose, N. Mannoji, and R. Taira, 2007: The JRA-25 Reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.

Pant, G. B., and K. Rupa Kumar, 1997: *Climates of South Asia*. John Wiley & Sons, Chichester, 320 pp.

Parthasarathy, B., A. A. Munot, and D. R. Kothawale, 1995: All India monthly and seasonal rainfall series: 1871–1993. *Theor. Appl. Climatol.*, **49**, 217–224.

Peixoto, J. P., and A. H. Oort, 1992: Physics of Climate. *Amer. Inst. Phys.*, 520 pp.

Raghavan, K., 1973: Break Monsoon over India. *Mon. Wea. Rev.*, **101**, 33–43.

Roads, J. O., and A. Betts, 2000: NCEP-NCAR & ECMWF Reanalysis surface water and energy budgets for the Mississippi River Basin. *J. Hydrometeor.*, **1**, 88–94.

Trenberth, K. E., 1991: Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses. *J. Climate*, **4**, 707–722.

Trenberth, K. E., and C. J. Guillemot, 1998: Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR reanalyses. *Clim. Dyn.*, **14**, 213–231.

Trenberth, K. E., 1999: Atmospheric moisture recycling: Role of advection and local evaporation. *J. Climate*, **12**, 1368–1381.

Trenberth, K. E., J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated water vapor. *Clim. Dyn.*, **24**, 741–758.

Uppala, S. M., P. W. Kallberg, A. J. Simmons, U. Andrae, V. da Costa Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Holm, B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. McNally, J. -F. Mahfouf, J. J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Sterl, K. E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, and J. Woollen, 2005: The ERA-40 reanalysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.

Yoshimura, K., T. Oki, N. Ohte, and S. Kanae, 2004: Colored moisture analysis estimates of variations in 1998 Asian monsoon water sources. *J. Meteor. Soc. Japan*, **82**, 1315–1329.