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Temporal and Spatial Variability of Precipitation and Evaporation over the Tropical Ocean

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Abstract: Temporal and spatial variability of precipitation (P), evaporation (E), and moisture balance (P-E; precipitation minus evaporation) has been investigated over the tropical ocean during the period from January 1998 to July 2001. Our data were analyzed by the EOF method using the satellite P and E observations made by the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) and the Special Sensor Microwave/Imager (SSM/I). This analysis has been performed for two three-year periods as follow; The first period which includes the El Niño in early 1998 ranges from January 1998 to December 2000, and the second period which includes the La Niña events in the early 1999 and 2000 (without El Niño) ranges from August 1998 to July 2001. The areas of maxima and high variability in the precipitation and in the P-E were displaced from the tropical western Pacific and the ITCZ during the La Niña to the tropical middle Pacific during the El Niño, consistent with those in previous P studies. Their variations near the Korean Peninsula seem to exhibit a weakly positive correlation with that in the tropical Pacific during the El Niño. The evaporation, out of phase with the precipitation, was reduced in the tropical western Pacific due to humid condition in boreal summer, but intensified in the Kuroshio and Gulf currents due to windy condition in winter. The P-E variability was determined mainly by the precipitation of which the variability was more localized but higher by 2-3 times than that of evaporation. Except for the ITCZ (0-10°N), evaporation was found to dominate precipitation by ~2 mm/day over the tropical Pacific. Annual and seasonal variations of P, E, and P-E were discussed.

Keywords : moisture balance, precipitation, evaporation, P-E, EOF, El Niño, TRMM, SSM/I

Introduction

It is important to monitor variability of freshwater factors, for instances, precipitation (P), evaporation (E), and river discharge (R) which can directly affect human habitat, in order to understand the basic aspects of climate change and water circulation (Trenberth, 1992). In particular, as the atmosphere over tropical oceans contains a large amount of water vapor, the release/influx of latent heat through the processes of precipitation and evaporation is a fundamental driving force for atmospheric general circulation. It is thus found to be closely related with the interannual variation of energy/water in climate system, such as the El Niño event (Peixoto and Oort, 1992).

The freshwater flux ($F = P - E + R$) at the ocean surface is also important from the viewpoint of air-sea interaction because it determines surface salinity (Wells, 1997). Furthermore, temporal and spatial variability of precipitation and evaporation has become human concerns to efficiently manage water resources, and to prepare for the lack of water resources in the future.

There have been previous studies that used satellite observations for the distribution and variation of precipitation (e.g., Spencer, 1993; Huffman *et al.*, 1995, 1997; Adler *et al.*, 2001; Yoo *et al.*, 2002). The moisture balance (i.e., P-E or P minus E) has been analyzed for limited areas due to the shortage and uncertainty of observed data, and thus only a few detailed analyses are available over the globe (e.g., Baumgartner and Reichel, 1975; Yoo and Carton, 1990). Thus, satellite observations are essential to the global analysis for the freshwater budget.

The purpose of this study is to investigate temporal and spatial variability of P, E, and P-E over the tropical ocean with the help of Empirical Orthogonal Function (EOF) analyses (Kutzbach, 1967;

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Wilks, 1995), using satellite-observed data of precipitation and evaporation for two three-year periods which include the El Niño in early 1998 and a few La Niña phenomena. In addition, we have examined seasonal and annual moisture balance over the tropical Pacific Ocean in terms of zonal average.

Data and Method

The precipitation data used in this study is Tropical Rainfall Measuring Mission (TRMM) Gridded Products (3A25) in a spatial grid of $0.5^{\circ} \times 0.5^{\circ}$, observed by Precipitation Radar (PR), onboard the TRMM satellite (e.g., Kummerow *et al.*, 1998). The TRMM data are available for the period from November 1997 to the present over the latitude belt of about 39°N-39°S. The PR also helps TMI (TRMM Microwave Imager) radiometer onboard the satellite estimate precipitation simultaneously.

In this study, the TRMM precipitation has been compared and analyzed for the two three-year periods of 36 months individually to examine its sensitivity to El Niño/La Niña phenomena. In other words, the first period (P1) which includes the 1998 El Niño ranges from January 1998 to December 2000. The second period (P2) which includes a few La Niña events without the El Niño ranges from August 1998 to July 2001. The main purpose of this analysis is to address how the El Niño/La Niña events have affected the moisture balance through the variability of precipitation and evaporation.

The evaporation data, derived by the method of Chou *et al.* (1997) and from satellite observation of the Special Sensor Microwave/Imager (SSM/I; Kidder and Vonder Haar, 1995) radiometer (January 1998 to December 2000) are analyzed in relation with the precipitation to estimate the variability of P-E. Chou *et al.* (1997) have estimated evaporation (or latent heat fluxes) by combining the datasets of the surface humidity and winds of SSM/I, National Centers for Environmental Prediction sea surface temperatures (SSTs), and European Center for Medium-Range Weather Forecasts (SSTs minus 2 m temperatures). The evaporation data, available in the latitude belt of about 60°N-60°S, have been arranged in a grid of longitude $3^{\circ} \times$ latitude 2° and used in the EOF analysis. The EOF has been performed on monthly mean values and their anomalies of the TRMM precipitation, the SSM/I evaporation, and the P-E. The EOF method has been described in detail in the previous studies of Kutzbach (1967), Wilks (1995), and Yoo *et al.* (1998).

EOF Analysis: P, E, and P-E

Mode 1 of Monthly Average

In the analyses of monthly mean precipitation during each of the two study periods, the first mode values explain 35.6% (P1) and 36.3% (P2) of total variance (Figs. 1a and 4a). The typical annual cycle in which the rainfall near the Korean Peninsula increases in summer and decreases in winter was seen to be dominant during the two periods. In the Atlantic, maximum rainfall occurs in summer in the region north of the equator, called the Inter-Tropical Convergence Zone (ITCZ) of the Atlantic (Gruber, 1972). For the P1, the precipitation during the El Niño in early 1998 substantially increased over the tropical middle Pacific, while it was reduced in the ITCZ at ~10°N of the Pacific (Fig. 1a).

For the P2 when the El Niño did not occur, the precipitation in boreal summer increased in the ITCZ at ~10°N of the Pacific and Atlantic oceans (Fig. 4a). However, the precipitation variability over the middle Pacific south of the equator, as seen for the P1 (Fig. 1a), was not distinct during a few La Niña events in the early 1999 and 2000.

From the EOF of monthly mean evaporation, the first mode explains 45.4% of total variance, and the evaporation variations between the Northern and Southern Hemisphere in the mode show the negative correlation with each other (Fig. 1b). The

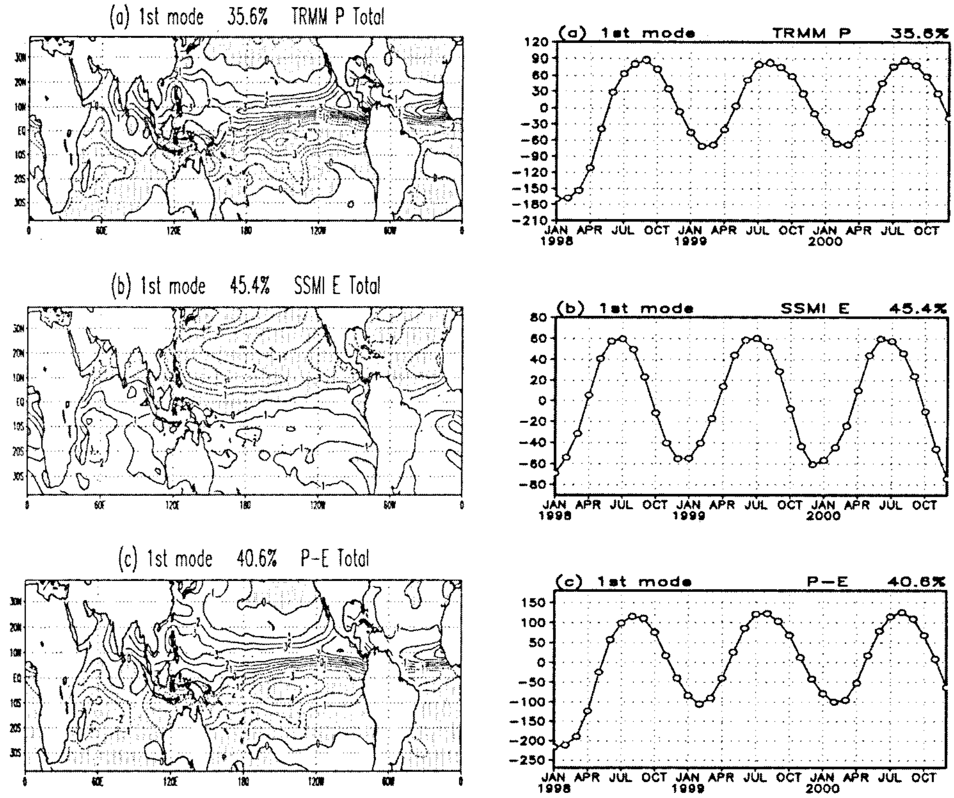

Fig. 1. The EOF mode 1 of the covariance matrix in left panel and corresponding principal component time series in right panel of monthly mean (a) precipitation of TRMM, (b) evaporation of SSM/I, and (c) P-E over the tropical ocean of 37.5S-38.5N during the period from January 1998 to December 2000.

annual cycle in evaporation (45.4%) is stronger by ~10% than that in precipitation (35.6%) (Figs. 1a and 1b). This means that the variability of precipitation is affected more by regional climatic factors than that of evaporation which is governed more by solar cycle. Together with the corresponding time series, the evaporation in the Northern Hemisphere is minimized in July, and maximized in December. It decreases in the warmpool of tropical western Pacific in rainy summer. It is because atmospheric humidity, generally out of phase with evaporation, is higher during the rainy period than during the dry period. In addition, the evaporation in winter is higher near the eastern coast of Japan because the Kuroshio Current releases an enormous amount of water vapor under strong windy condition. Overall, the annual cycle in which evaporation decreases in summer and increases in winter prevails in the Northern Hemisphere.

The first mode for P-E indicates 40.6% of total variance (Fig. 1c). By and large, the Northern and Southern Hemispheres are anticorrelated in the variations of P-E, showing north-south gradients of variation. Similarly to the precipitation case, the P-E annual cycle in the Northern Hemisphere follows the pattern in which precipitation increases in summer and decreases in winter (see also Fig. 1a). The P-E value significantly increases over the tropical middle Pacific during the El Niño. However, as mentioned earlier, since the evaporation in the Gulf stream and the Kuroshio Current is enhanced in winter, the P-E in the season is considerably reduced in the warm western boundary currents compared to that in the other areas. Additionally in

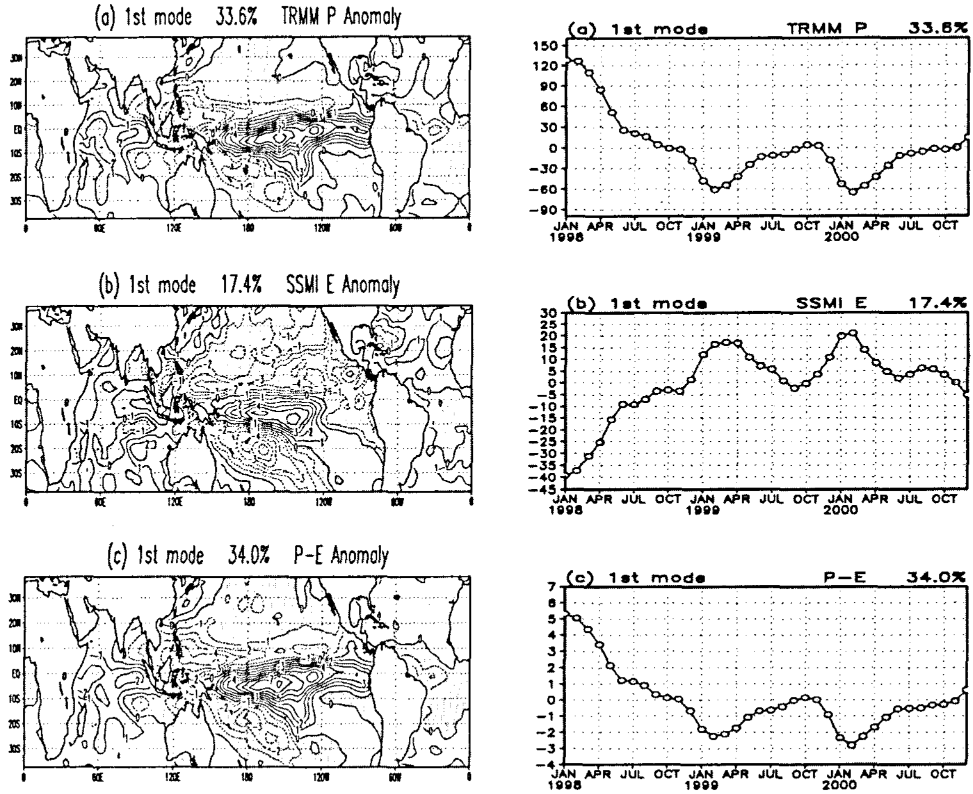

Fig. 2. Same as Fig. 1 except for the anomaly.

the ITCZ boundaries at 0-10°N, the spatial gradient of P-E is relatively high by the meridional movement of seasonal rain bands.

Mode 1 of Anomaly

The first mode of precipitation anomalies over the tropical ocean explains 33.6% of total variance during the P1 period and 10.2% during the P2, respectively (Figs. 2a and 4b). This suggests that the El Niño in the tropical ocean influences the precipitation variability about three times more than the La Niña. During the El Niño event of the P1, precipitation increased in the regions of the tropical middle Pacific, the western Indian Ocean, and near the Korean Peninsula (Fig. 2a). In comparison with precipitation variability of the two periods, the areas of its maxima and high variability in the tropics were displaced from the western Pacific during the P2 (La Niña or non-El Niño) to the middle Pacific during the P1 (El Niño) (Figs. 2a and 4b). The precipitation for the P2 was intensified in the warmpool near the Indonesia during the La Niña in January-February 1999 (Fig. 4b). This result was consistent with those in previous studies including the El Niño phenomena of other periods (e.g., Rasmusson and Carpenter, 1982; Lau and Chan, 1986; Philander, 1990; Kummerow *et al.*, 2001).

The first mode of evaporation anomalies explains 17.4% of total variance (Fig. 2b). The evaporation during the El Niño in early 1998 is clearly reduced over the tropical middle Pacific south of the equator. This is because the evaporation in the region decreases due to more rainy and humid atmospheric conditions during the El Niño. On the other hand, the evaporation notably increases during the La Niña periods in January-April in 1999 and January-March 2000.

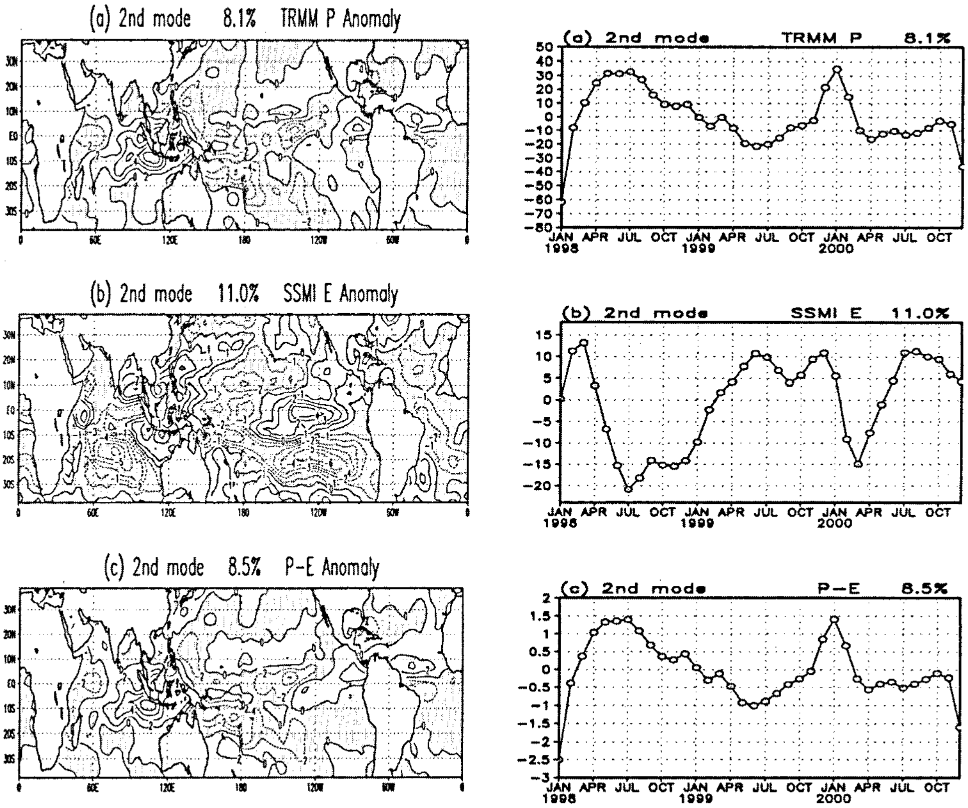

Fig. 3. Same as Fig. 1 except for mode 2.

The first mode of P-E anomalies shows 34% of total variance (Fig. 2c). The P-E over the tropical middle Pacific is enhanced remarkably during the El Niño in early 1998, but reduced during the La Niña in early 1999 and early 2000. The P-E value during the El Niño is also reinforced over the western Indian Ocean and near the Korean Peninsula. The P-E variability in the ITCZ and the South Pacific Convergence Zone (SPCZ) exhibits negative correlation with that over the tropical middle Pacific. This P-E pattern in this mode for the anomalies is similar to that of precipitation. The P-E increment in the warmpool during the La Niña in two consecutive February between 1999 and 2000 is related to both increased precipitation and decreased evaporation during the same period.

Mode 2 of Anomaly

The second mode of precipitation anomalies during the P1 explains 8.1% of total variance, and shows the enhanced precipitation over the ocean southwest of the Indonesia during the La Niña in January 2000 (Fig. 3a). Evaporation anomalies in the mode explain 11% of total variance, and indicate the north-south dipole pattern, centered at (130°W, 10°S) over the tropical eastern Pacific (Fig. 3b). In this region, the evaporation decreased south of the equator during La Niña periods in July-December 1998 and January-March 2000. The same mode of P-E anomalies explains 8.5% of total variance (Fig. 3c). The P-E over the Indian Ocean, located at (100°E, 10°S) south of the equator, decreased during the El Niño in January 1998, and increased during the La Niña in January 2000. However, the high variability was not conspicuous during the La Niña in early 1999, and the cause need to be examined further.

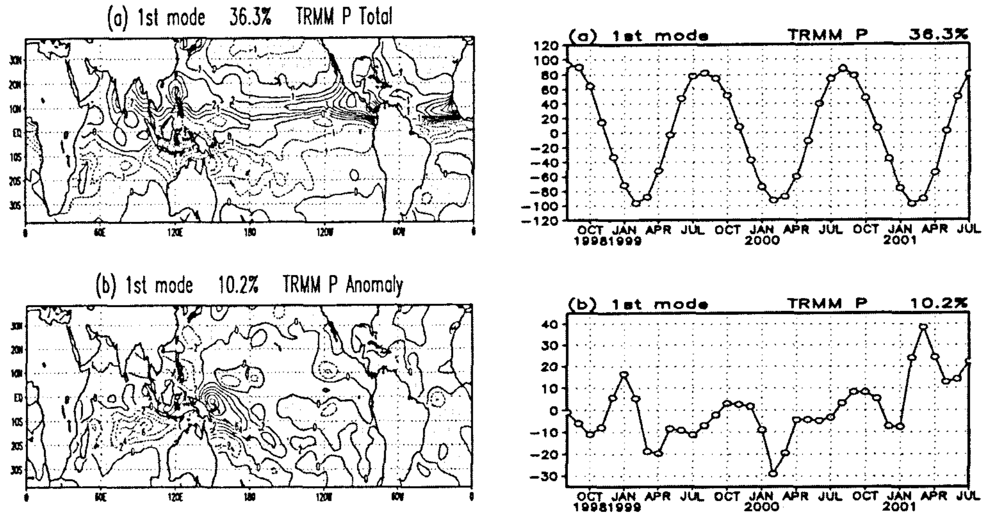

Fig. 4. The EOF mode 1 of the covariance matrix in left panel and corresponding principal component time series in right panel of (a) monthly mean precipitation, and (b) its anomaly of TRMM over the tropical ocean of 37.5S-38.5N during the period from August 1998 to July 2001.

Zonal average of P, E, and P-E

Fig. 5 shows climatological seasonal and annual zonal-averages of the TRMM precipitation, the SSM/I evaporation, and the P-E over the tropical Pacific Ocean during January 1998 to December 2000. The precipitation (solid line) and the P-E (dotted line) increased at 8-10°N of the ITCZ in summer and fall, and at 5-10°S of the SPCZ in spring and winter (Figs. 5a-d). However, the maximum (6 mm/day) of annual precipitation at 7-8°N in the ITCZ is higher than that (4 mm/day) at 5°S in the SPCZ (Fig. 5e).

On the other hand, the evaporation (dashed line) has maxima (5-7 mm/day) in the subtropics (10-20°N or 10-20°S) of the trade-wind regions, and minima (2-4 mm/day) in the ITCZ (0-10°N) (Fig. 5). It is interesting to note that the annual average of evaporation has a local minimum in the equatorial upwelling region, and a north-south symmetric pattern on an axis of the equator. Based on maximum precipitation, the SPCZ is intensified and located at 5°S in boreal spring and at ~11°S in winter. In addition, the ITCZ has the maximum precipitation at ~9°N in boreal summer, and at ~10°N in fall. In annual average, precipitation exceeds evaporation over the 0-12°N region, while evaporation exceeds precipitation over the subtropics (Fig. 5e). Annual averages of the P-E have maximum (2 mm/day) at 7°N, and minima (–3 mm/day) at 18°N and 17°S. Since the evaporation value generally dominates the precipitation over the tropical Pacific Ocean, the oceans play an important role as a moisture source to provide water vapor to the land and the high latitude ocean.

Conclusion

The moisture balance components of precipitation, evaporation, and P-E during two three-year periods, derived from recent satellite observations of TRMM and SSM/I, have been analyzed by the EOF analysis in order to interannually examine their temporal and spatial variability. During the El Niño period in the early 1998, the precipitation increased over the tropical middle Pacific, the western Indian Ocean, consistent with that of Kummerow *et al.* (2001), and near the Korean Peninsula. The variation of precipitation near the Korean Peninsula for this period seems to be

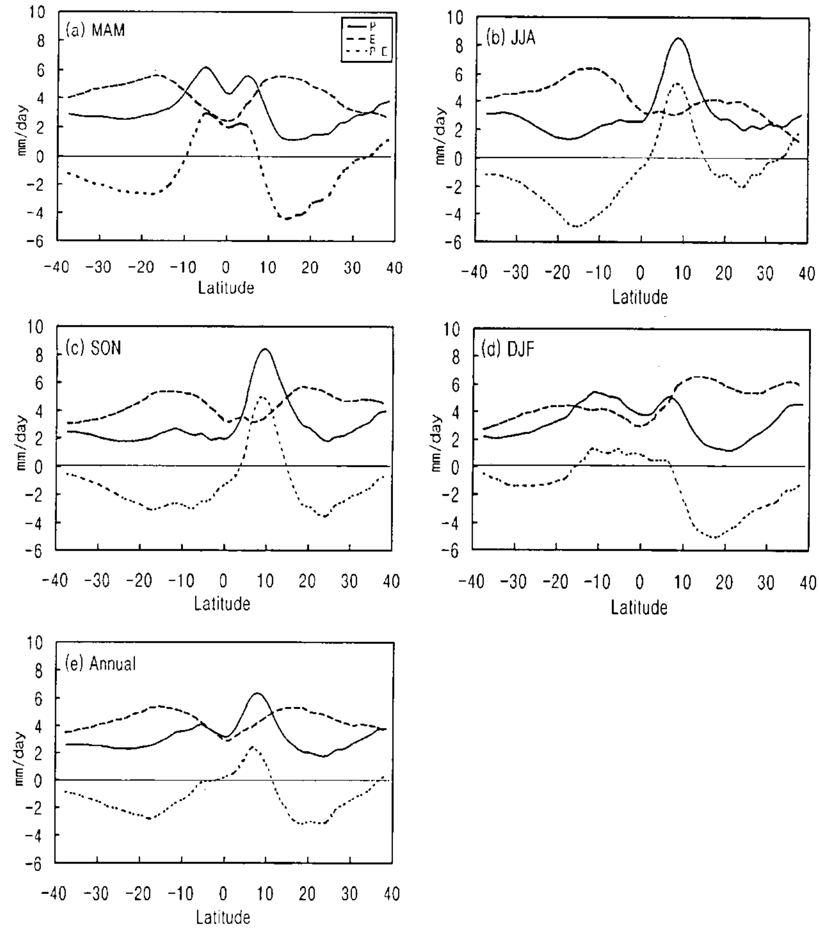

Fig. 5. Climatological zonal averages of the TRMM precipitation (solid line), the SSM/I evaporation (dashed line), and the P-E (dotted line) over the tropical Pacific Ocean for (a) spring (March-May), (b) summer (June-August), (c) fall (September-November), (d) winter (December-February), and (e) annual during the period from January 1998 to December 2000. Negative values in the ordinate of figures stand for the latitude of the Southern Hemisphere.

weakly but positively correlated with that over the tropical middle Pacific. In the meantime, during the La Niña in the early 1999 and 2000 (or non-El Niño period), it was enhanced in the IPCZ, the SPCZ, and the tropical western Pacific.

The evaporation in the warmpool of the tropical western Pacific decreased due to relatively high humid condition in the rainy season of boreal summer. It was also intensified in winter in the Kuroshio and Gulf warm currents where a large amount of water vapor was released from the ocean surface into the atmosphere under windy condition. The evaporation over the tropical middle Pacific south of the equator decreased during the El Niño, but increased during the La Niña. Consequently the variability of the precipitation and evaporation over the tropical Pacific was generally out of phase, inducing their negative correlation.

The P-E value increased over the tropical middle Pacific south of the equator, the western Indian Ocean, and near the Korean Peninsula during the El Niño, while it decreased during the La Niña. The P-E variability is affected more strongly by that of precipitation, rather than evaporation. The spatial variability in precipitation over the tropical ocean is higher by 2-3 times and localized more than that in evaporation.

Since the river discharge over the tropical ocean corresponds to less than 10% of evaporation (Yoo and Carton, 1990), it dose not substantially influence the freshwater budget. Except for the ITCZ and SPCZ regions, evaporation dominates precipitation over the tropical Pacific Ocean, which is a moisture source for the atmosphere over the land and the high latitude ocean.

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