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Soil moisture variability and its possible impact on the atmosphere: A case in Sri Lanka

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Abstract

Time series analyses of soil moisture, rainfall, air temperature and other hydrometeorological components observed at inland area of Sri Lanka in 1994 were carried out. Auto-correlation analysis gives a time scale from 10 to 30 days as persistency of soil moisture anomaly, which is considerably small relative to that under mid-latitude temperate climate and is shorter than that for atmospheric temperature. Two dominant periodicities are detected from spectral analysis: 45-60-day period (especially for large rainfall and soil moisture at all depths) and 22.5-30-day period (for small rainfall and shallow soil moisture). The two intraseasonal variations are also detected for satellite-remote-sensed outgoing longwave radiation (OLR) over and around Sri Lanka. Band-pass filtered OLR anomaly for the former periodicity propagates from around Sri Lanka to the west and is strengthened through the process of its westward propagation. On the other hand, OLR anomaly for the latter periodic component has its origin at east ocean-region and propagates westward to Sri Lanka. For the 45-60-day period, band-pass filtered anomaly propagates from rainfall to soil moisture, soil temperature, wet-bulb temperature and back to rainfall, indicating a feedback loop. In contrast, propagation of anomaly through hydrometeorological variables is not found for the 22.5-30-day period. These statistical results indicate that external forcing causes the latter periodic and also that the former periodicity is introduced by an enhancement of the latter variation once in its two cycles due to negative feedback between soil moisture and rainfall. The selective enhancement against different periodic variations appears to be associated with characteristic time-scale of the soil moisture persistence.

Key words: Soil moisture, Rainfall, Feedback mechanism, Time series analysis, Sri Lanka.

1. Introduction

Improvement of predictability in hydrological system is an important issue for reducing societal vulnerability to natural hazard such as drought and flood. Entekhabi (2001) stated that the following four points should be understood more clearly in predictability research: 1) remote and local sources of variability, 2) propagation of uncertainty and variability in hydrologic system, 3) characteristics of memories, pathways, and feedbacks in hydrological system, and 4) intrinsic and model-derived limits to prediction.

Soil moisture is a key factor being local source of rainfall variability over land as well as sea surface

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temperature (SST) being remote source (e.g., Atlas et al., 1993; Koster and Suarez, 1995; Giorgi et al., 1996). Many researchers have investigated the effects of soil moisture conditions on rainfall variability mainly using numerical models (e.g., Walker and Rowntree, 1977; Shukla and Mintz, 1982; Rowntree and Bolton, 1983; Yeh et al., 1984; Oglesby and Erickson, 1989; Oglesby, 1991; Koster and Suarez, 1996; Paegle et al., 1996). Characteristics of soil moisture variability and its impact on surface meteorological conditions (e.g., average or maximum air temperature) have also been investigated mainly using model-derived soil moisture data (e.g., Georgakakos et al, 1995; Cayan and Georgakakos, 1995; Huang et al, 1996). These modeling studies have clarified quantitatively that soil moisture can give a persistence (i.e., acting as a memory) in hydrological system variability, and that dry (wet) anomaly of soil moisture induces and/or amplifies drought (flood) conditions. Giorgi et al. (1996) also suggested the existence of two possible but opposite feedback mechanisms, that is, positive and negative feedbacks. On the one hand, anomalous wet soil conditions can produce an increase in evaporation, which provides additional moisture source for convective storm systems, leading to a increase in rainfall. On the other hand, anomalous dry soil conditions may provide for increased sensible heat flux, which contributes greater buoyancy to the lower atmosphere, enhancing convective systems and producing more rainfall. The former processes drive the positive feedback between soil moisture and rainfall, and the negative feedback consists of the latter processes, although it is expected that the relative contribution of the two feedback mechanisms change depending on geographical conditions or any other factors.

Unfortunately, there is no research, except for those of Vinnikov and Yeserkepova (1991), Hollinger and Isard (1994), and Findell and Eltahir (1997), on soil moisture-rainfall feedback purely based on direct observations. In addition, regions focused in those studies are limited geographically to mid- or high-latitude continental interiors. In this paper, we present a case study based on direct observations from Sri Lanka, which is a tropical island with spatial extent of approximately 65,000 km^2 between the latitudes from 6°N to 10°N and the longitudes from 80°E to 82°E. In contrast to continental interiors, the negative feedback may dominate in the subjected area because of abundant atmospheric moisture supplied from warm ocean surface. We intend to confirm whether any signals of the soil moisture-rainfall feedback can be detected only from actually observed data. Because it is difficult to isolate the causal relationship between soil moisture and rainfall or other hydrometeorological components when we use real data, we focus on statistical characteristics (e.g., persistence of anomaly, periodicity of variation, and lag-correlation among variables) of temporal variability in soil moisture and other variables. Statistical procedures should help in extracting specific causal relationship hidden by complex land-ocean-atmosphere interactions.

The next section gives a brief description of study area. Section 3 mentions data used and methods of analytical procedures. In section 4 we show some of the results of local variabilities of soil moisture and other hydrometeorological components at one site, and in section 5 we present relationships between the local variabilities and large scale variations in rainfall and convective activity. Final considerations are presented in section 6.

2. Study Area

Sri Lanka is situated off the southeastern end of the Indian peninsula within the northern Indian Ocean facing the Bay of Bengal in the northeastern side and the Gulf of Mannar in the northwestern side. Topographically, mountainous highland and moderate plateau occupy the inland area of the southern half of the island (Fig. 1). Altitude of the highest point is 2518 m.

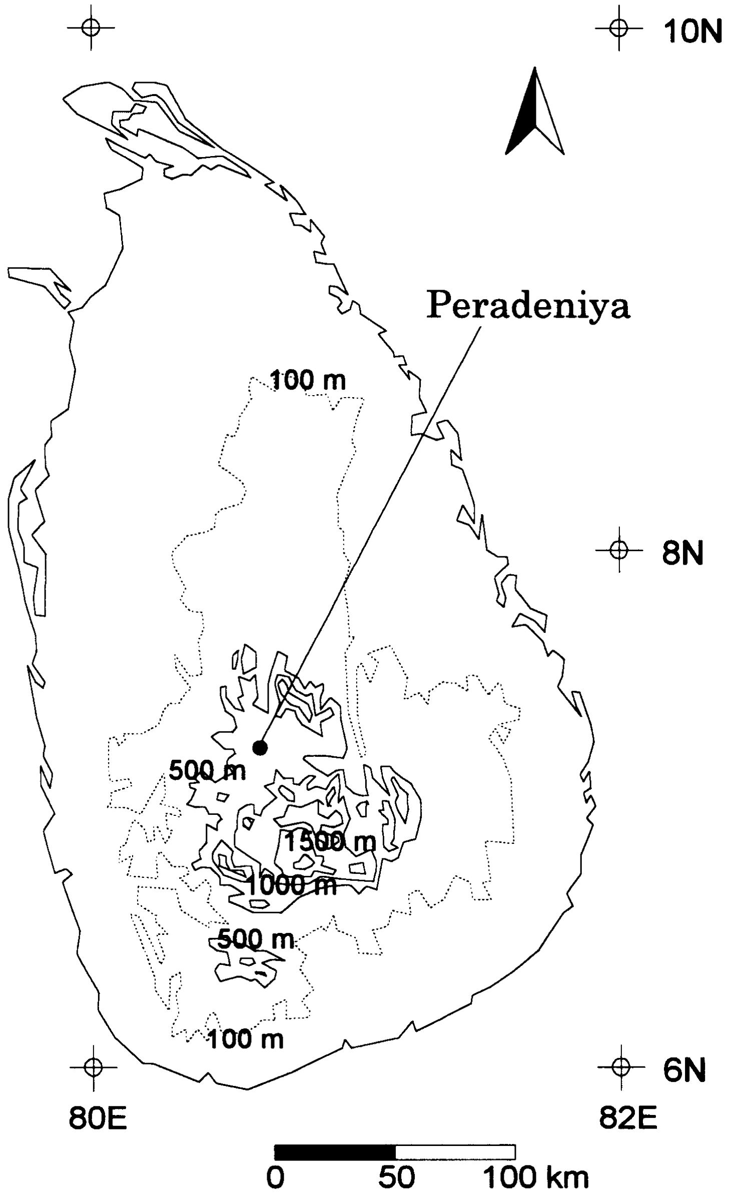

Fig.1. Map of Sri Lanka and location of hydrometeorological observation site (Peradeniya).

Generally, seasonal variation of rainfall in Sri Lanka is affected by meridional migration of the intertropical convergence zone (ITCZ) and Asian monsoon circulation, and can be divided into four stages (Suppiah, 1988): (a) the first intermonsoon season characterized by the northward migration of the ITCZ from March to April, (b) the southwest monsoon season from May to September, (c) the second intermonsoon season characterized by southward migration of the ITCZ from October to November, (d) the northeast monsoon season from December to February. Although the long-term mean monthly rainfall is much in the two intermonsoon seasons rather than in the two monsoon seasons, the dominance of this seasonal pattern is different among locations or year-by-year.

3. Materials and method

3.1 Data

Although several datasets from different sources are used in the present study, the period of all data available is one year of 1994. Thus, the present study covers only the period. Although the length of the period may not be appropriate for hydroclimatological study, we suppose it would be enough for investigating the negative feedback between soil moisture and rainfall because its time scale is expected to be seasonal or shorter. Of course, the result for 1994 is not always representative over long-term period. Nevertheless, those should be meaningful as a case study.

Daily soil tension data at 7 different depths in Peradeniya (see Fig. 1) were obtained by Shimada et al. (1997) and were published in the data book of "Hydrological study data in Sri Lanka" (Tase et al., 1995) together with the descriptions of soil physical properties. The soil tension observations were carried out at grassland in the campus of the University of Peradeniya. We also carried out to convert the tension (ψ) values into volumetric water content (θ) using the following van Genuchten's equation (van Genuchten, 1980):

$$\theta = \theta_r + \frac{\theta_{sat} - \theta_r}{\left[1 + (-\alpha\psi)^n\right]^m}$$

where, θ_r is the residual water content, θ_{sat} the saturated water content, and α, n and m ($=1-1/n$) are the empirical parameters. The values of θ_r and the three empirical parameters were obtained by non-linear fitting of measured soil moisture characteristic curves for each depth-zone.

Hydrometeorological observation data provided from Gunnaruwa Plant Research Center, just within one kilometer from soil moisture observation site, includes daily rainfall, dry- and wet-bulb temperatures, soil temperature (5 cm depth), and wind speed. Data of temperatures are instantaneous value at 0830 LST, and wind speed is daily mean value. Period for rainfall and wind speed measurements is 0830-0830 LST.

In addition to the data for Peradeniya, daily rainfall data for other 6 stations in Sri Lanka is used for investigating the spatial coherence of rainfall variability. The data are being provided as "Global Surface Summary of the Day" (http://www.ncdc.noaa.gov/cgi-bin/res40.pl) from National Climatic Data Center (NCDC). The daily averaged outgoing longwave radiation (OLR) data on a 2.5° grid from National Oceanic and Atmospheric Administration (NOAA's) satellites (Gruber and Krueger, 1984) were also used in order to infer the relationship between Sri Lanka rainfall and large-scale convective activities.

Table 1 summarizes variables used in the present analysis and the number of the data. In evaluating the statistical results, it should be noted that a lot of data missing exists for some variables.

3.2 Method of analysis

To reveal the persistence of variations and the causal relationship among variables, auto-correlation and cross-correlation analyses were performed, respectively. The values of correlation coefficient implying statistically significance at 5 % level was obtained by t-test. The value changes slightly with lag-time since the data number also varies due to data missing.

The spectral analysis using the Fast Fourier Transform (FFT) with the Hunning window was applied to determine the periodicity of variations. The band-pass filtering process was also applied for evaluating the features of the periodic variability for each frequency band. The missing data were replaced by annual mean

Table 1. Summary of the data used in the present analysis.

Variable	Location	No. of data
Soil moisture (28 cm depth)	Peradeniya	352
Soil moisture (60 cm depth)	Peradeniya	352
Soil moisture (95 cm depth)	Peradeniya	352
Soil moisture (125 cm depth)	Peradeniya	337
Soil moisture (150 cm depth)	Peradeniya	352
Soil moisture (175 cm depth)	Peradeniya	341
Soil moisture (250 cm depth)	Peradeniya	329
Air temperature	Peradeniya	289
Wet-bulb temperature	Peradeniya	289
Soil temperature	Peradeniya	289
Wind speed	Peradeniya	253
Rainfall	Peradeniya	282
Rainfall	Anuradhapura	209
Rainfall	Puttalam	181
Rainfall	Katunayake	257
Rainfall	Hambantota	190
Rainfall	Nuwara Eliya	191
Rainfall	Trincomalee	201
Outgoing longwave radiation (OLR)	Globe (2.5° × 2.5°)	365

value for each variable in advance of the spectral analysis and the band-pass filtering. Although this interpolation procedure minimizes distortion in calculating statistical outputs, some part of information lost due to missing data cannot be restored.

4. local variabilities of soil moisture and hydrometeorological components at Peradeniya

4.1 Time series

To give a general view of soil water dynamics firstly, the time-depth cross section of hydraulic potential is shown in Fig. 2. The use of hydraulic potential instead of matric potential or volumetric water content has an advantage indicating the direction of soil moisture movement though it should be noted that soil water flux is not in proportional to the hydraulic gradient because of dependence of hydraulic conductivity upon soil moisture content. Fig. 2 indicates that there are repetitions of wetting and drying and that the direction of water flux in a zone shallower than 125 cm in depth turns over keeping pace with the wetting-drying cycle. In contrast, the direction of water flux in a deeper zone is constantly downward. During the driest periods from DOY (day of year) 60 to DOY 100 and from DOY 140 to DOY 150, soil pF value at a depth of 28 cm reaches down to 2.9, and even during the other period it decreases to 2.5. These values of soil pF are in level of suppressing transpiration from grass.

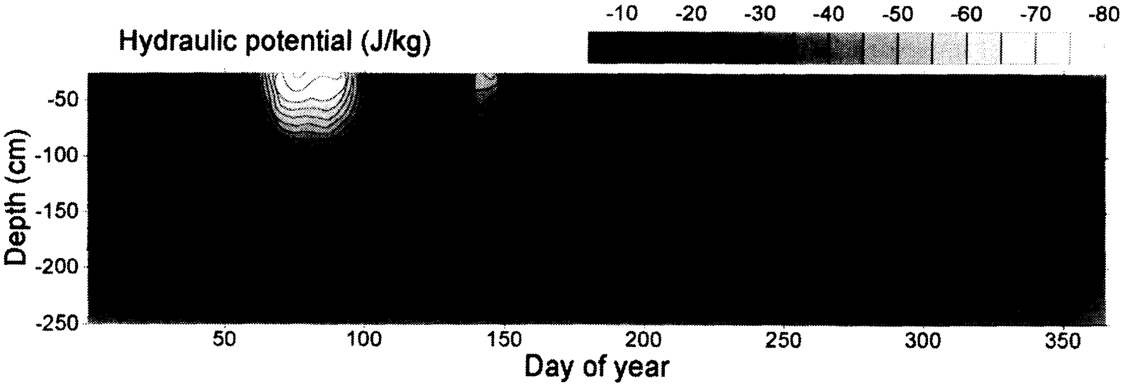

Fig.2. Time-depth cross section of hydraulic potential.

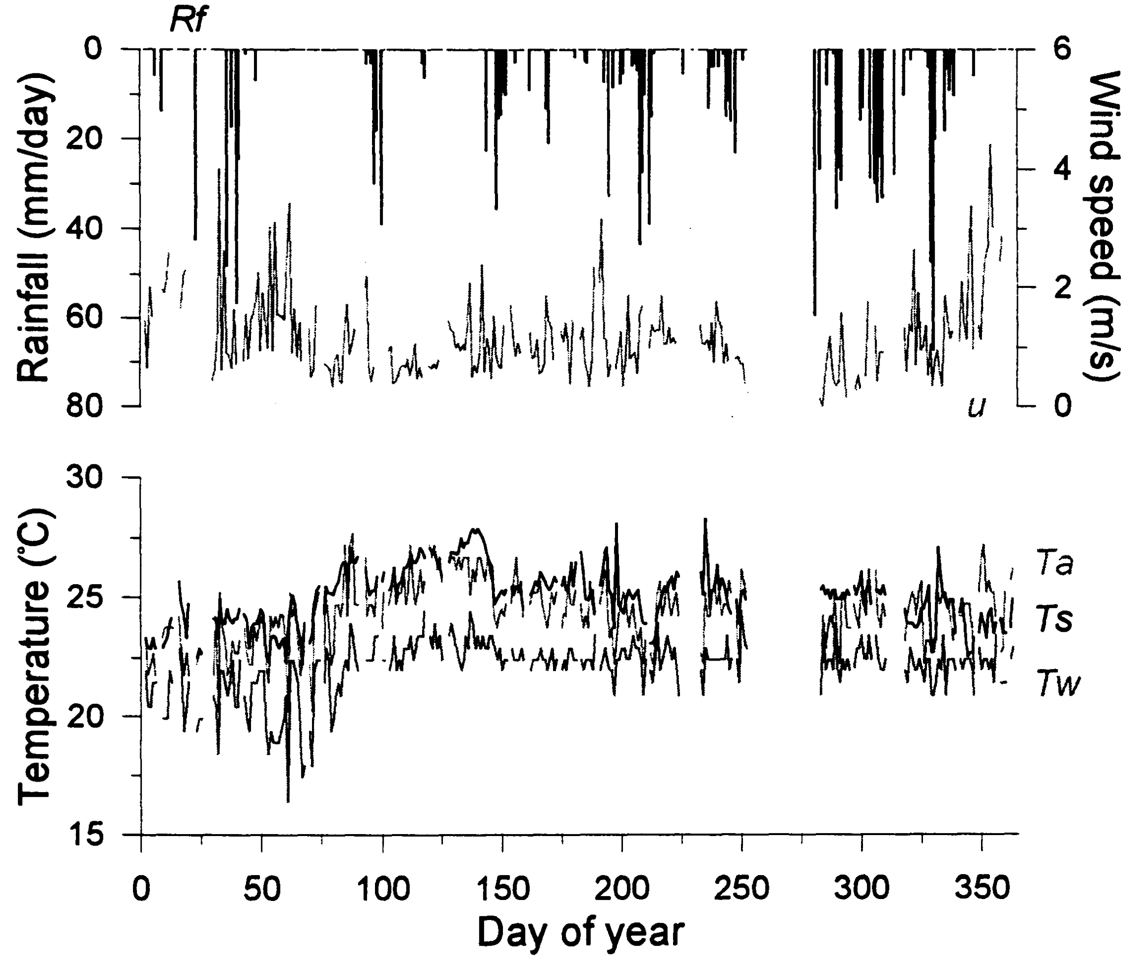

Fig.3. Time series of hydrometeorological components: rainfall (*Rf*), wind speed (*u*), air temperature (*Ta*), wet-bulb temperature (*Tw*) and soil temperature (*Ts*).

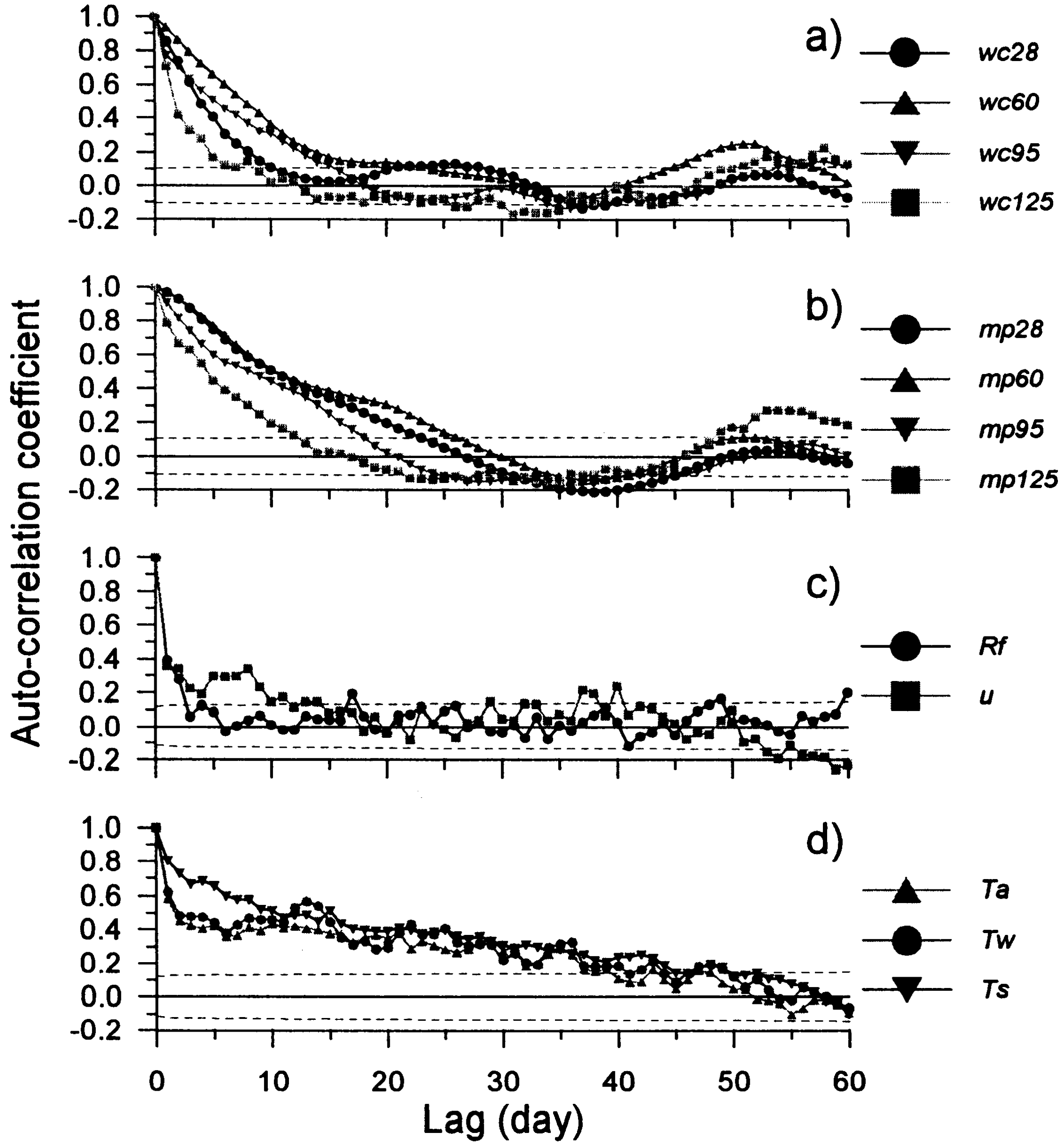

Fig.4. Auto-correlation functions for a) volumetric soil-water content (*wc*) at four depths (28, 65, 95 and 125 cm), b) matric potential (*mp*) at same depths, c) rainfall and wind speed, and d) air temperature, wet-bulb temperature and soil temperature. Dashed line denotes the values of correlation coefficient implying statistically significance at 5 % level (t-test).

Time series of hydrometeorological components are presented in Fig. 3. Rainfall is very little during a period from DOY 50 to DOY 90 (approximately corresponding to the first intermonsoon season) and much during a period from DOY 280 to DOY 310 (corresponding to the second intermonsoon season). This seasonal pattern is not consistent with the normal pattern as mentioned in section 2. As well as the seasonal variation, intraseasonal and quasi-periodical variation can be seen in large rainfall event with amount more than 30 mm/day. Wind speed appears to be relatively large in winter and small in summer. Annual variations of air temperature, wet-bulb temperature and soil temperature seem to be all alike, and ranges of those are less than 10°C. Wet-bulb temperature has a minimum in the beginning of the first intermonsoon season (i.e., DOY 60) and increases gradually during the season. There are several, sudden depletion in soil temperature in response to large rainfall events (e.g., DOYs 100, 150, 210 and 250). Such a tendency is relatively weak for air temperature and wet-bulb temperature.

4.2 Temporal coherence

Fig.4 shows the auto-correlation functions for volumetric soil-water content, matric potential and other hydrometeorological components. The persistency of anomaly, which is defined as a time taken for the auto-correlation function decaying from one to zero, has a scale of approximately 10-30 days in all depths. Attempting to calculate the decay time scale of soil water content based on the first-order Markov process (Vinnikov and Yeserkepova, 1991), the values ranging from 3 to 10 days are obtained. Although the persistency is slightly longer in matric potential than in volumetric water content, these values are likely too small in comparison to the representative values of mid-latitude soil moisture of 1.5 to 2.0 months (Robock et al., 2000).

We can find two peaks around a 26-day lag and a 52-day lag for water content at the 28 cm depth. The latter peak is a common feature for all depths and for both water content and matric potential. On the contrary, the former peak is clearly found only in shallower zone for water content.

The persistency of rainfall anomaly is very little and has a time scale of 5 days. For wind speed, the value is small too although it is difficult to determine the value accurately because of existence of a peak at around 8-day lag. In contrast, temporal coherence for air temperature, wet-bulb temperature and soil temperature are relatively high and the persistency reaches approximately two months. Auto-correlation coefficient is slightly larger for soil temperature than for the other two temperatures, particularly in a small lag-domain (within 10-day lag). It can be also pointed out that there is a moderate peak at around 13-day lag for only wet-bulb temperature.

As for a case under mid-latitude temperate climate, Georgakakos et al. (1995) have shown that the temporal scale of soil moisture anomaly is longer than that of air temperature. The result of the present study is opposite to the above, indicating that the interrelationship of temporal coherence between soil moisture and atmospheric variables is different depending on climatic situation.

4.3 Periodicity

In this subsection we investigate periodicity of variations in soil moisture and other hydrometeorological components because auto-correlation functions for those variables indicate that there are some periodic variations.

Fig. 5 shows power spectra of soil moisture and hydrometeorological components, standardized by their respective total powers. For both water content and matric potential, we can find two distinct spectral peaks at around 45-60-day and 22.5-30-day periodic bands (Fig. 5a, b). For convenience, hereinafter variation with the

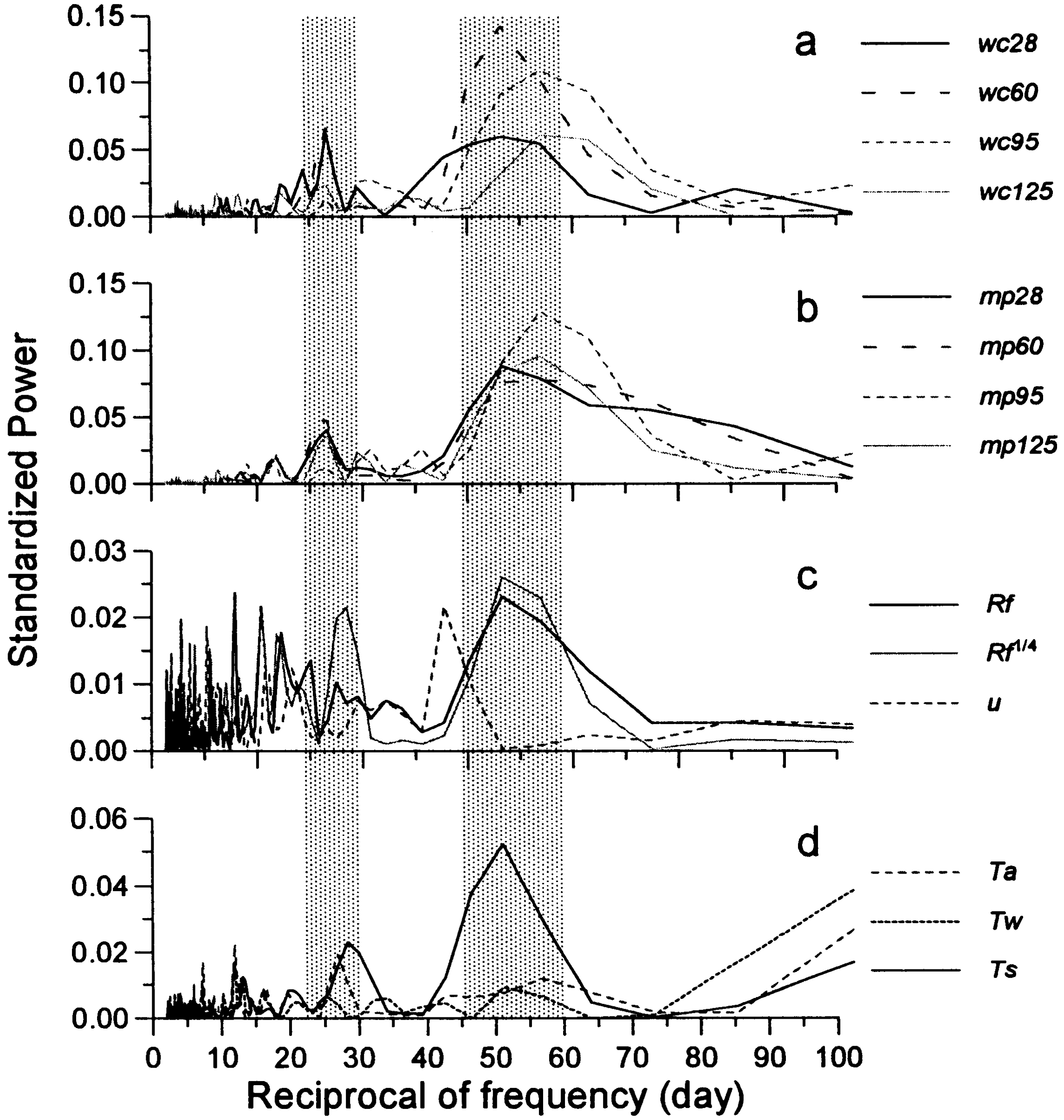

Fig.5. Power spectra of a) water content, b) matric potential, c) rainfall and wind speed, and d) air temperature, we-bulb temperature and soil temperature. Spectra are normalized by their respective total powers.

former periodicity is referred to as the first intraseasonal variation (ISV-1) and the latter as the second one (ISV-2). Relative dominance of the ISV-2 against the ISV-1 is decreasing with depth, and at a depth of 95 cm the ISV-2 is not significant. For the rainfall variability (Fig. 5c), short-term periodicities within 20-day period are relatively dominant as compared to soil moisture variability. The ISV-1 is also exhibited as well as in soil moisture although the ISV-2 cannot be clearly found. The power spectra of rainfall would be more strongly affected by large rainfall events. To emphasize the rainfall variability relating with small events, power spectrum of biquadratic root of rainfall is added in Fig. 5c. For this spectrum the ISV-2 becomes clear in contrast to the original spectrum. This indicates that the ISV-2 is related to relatively small rainfall events. The results for soil moisture variability noted above suggests that the anomaly relating to small rainfall events cannot propagate to deeper soil layers.

For wind speed, relatively short-term periodicities are dominant, and the ISV-2 is not seen (Fig. 5c). Although there is a spectral peak around 40-day period, this period is apparently shorter than the ISV-1 appeared in soil moisture. Power spectrum of soil temperature is very much similar in predominant periodicity to that of soil moisture, that is, both the ISV-1 and ISV-2 can be clearly seen (Fig. 5d). On the other hand, the two ISVs are not clear for air temperature, showing dominance of short-term periodicities and seasonal variation larger than 90-day period. For wet-bulb temperature the ISV-2 is dominant as well as short-term fluctuations (e.g., 7 and 11-day periods) although the ISV-1 is considerably weak. As far as the relative dominance of the first and second ISVs is concerned, the spectral characteristic of wet-bulb temperature is fully opposite to that of rainfall.

4.4 Causal relationship

Fig.6 shows the cross-correlation function between rainfall and soil moisture. Positive lags designate that soil moisture lags rainfall. The maximum of the cross-correlation function occurs on a positive lag (3-13 days) indicating that rainfall anomaly introduces soil moisture anomaly with a few to ten days lag. From peaks at around -45 and +55-day lags, we can see that the relationship between soil moisture and rainfall is strongly affected by the ISV-1 (45-60-day period). The effect of the ISV-2 (22.5-30-day period) on the function is also seen for the depth of 28 cm although it is not clear for the deeper depths. Negative peak occurs on approximately -10 and +50-day lags. The statistical significance of those negative peaks, however, is less than that of the positive peaks. These results indicate that rainfall induces soil moisture variation though it is not always suggested that soil moisture anomaly affects rainfall variation.

Because of multiple periodic variations it is difficult to draw out causal relationships between soil moisture and rainfall or other hydrometeorological components by means of simple cross-correlation technique. There-

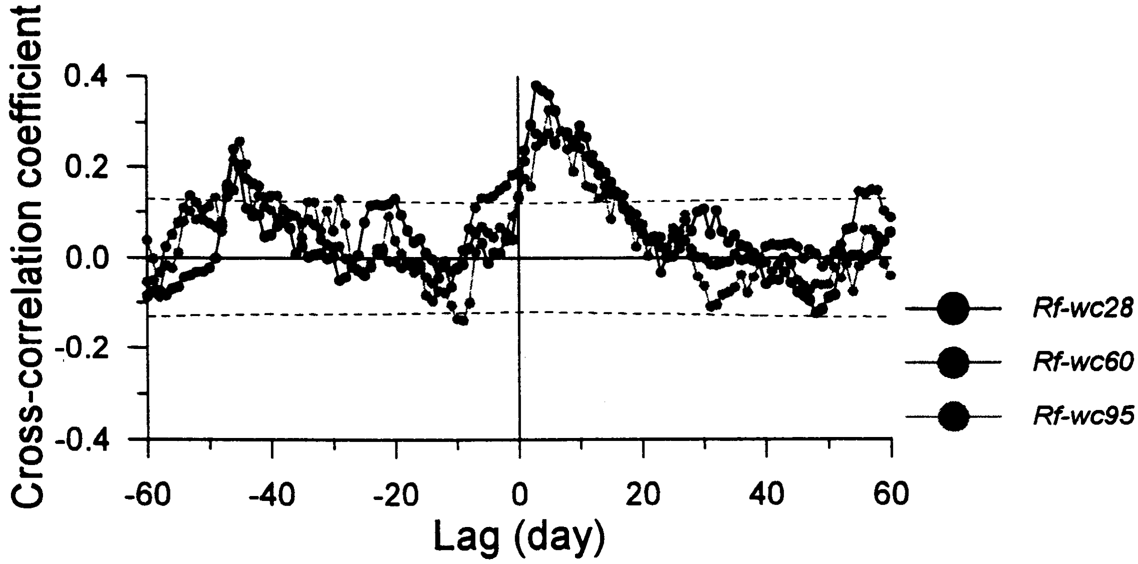

Fig.6. Cross-correlation functions between rainfall and water content at three depths (28, 60 and 95 cm). Positive lags designate that soil moisture lags rainfall, and negative lags designate that rainfall lags soil moisture. Dashed line is same as in Fig.4.

fore, the cross-correlation analysis is applied to band-pass filtered data. We focus particularly two periodic bands: the ISV-1 (45-60-day period) and the ISV-2 (22.5-30-day period). Fig. 7 shows the cross-correlation functions between rainfall and soil moisture or other variables. (Only the top column of the figure shows auto-correlation function of rainfall.) From Fig.7-1 for the ISV-1, we can see a propagation of anomaly from rainfall to soil moisture, soil temperature, wet-bulb temperature, and back to rainfall. An increase (decrease) in soil temperature associated with low (high) soil-moisture anomaly indicates decreased (increased) evapotranspiration and increased (decreased) sensible heating of the lower atmosphere. The wet-bulb temperature is a variable related with the convective available potential energy (CAPE) particularly in the tropics (Williams and Renno, 1993; Eltahir and Pal, 1996). Since in a tropical island there exists abundant water vapor supplied from the surrounding ocean, enhanced sensible heating of the lower atmosphere would result in increases of wet-bulb temperature and convective rainfall. Thus, the propagation of anomaly shown in Fig.7-1 suggests a possible feedback mechanism between soil moisture and rainfall.

In contrast to the ISV-1, feedback loop linking soil moisture and rainfall is not realized for the ISV-2 (Fig.7-2). Soil moisture anomaly does not induce soil temperature anomaly and succeeding wet-bulb temperature anomaly. The reason for the discontinuity of the loop can be probably explained in terms of the time scale of persistency of soil moisture anomaly. As seen in Fig.4, the persistency is approximately from 10 to 30 days. Thus, the soil-moisture anomaly cannot develop sufficiently for affecting soil temperature in the cycle of the 22.5-30-day period. Therefore, these results support a possibility of the feedback for the ISV-1 but reject for the ISV-2.

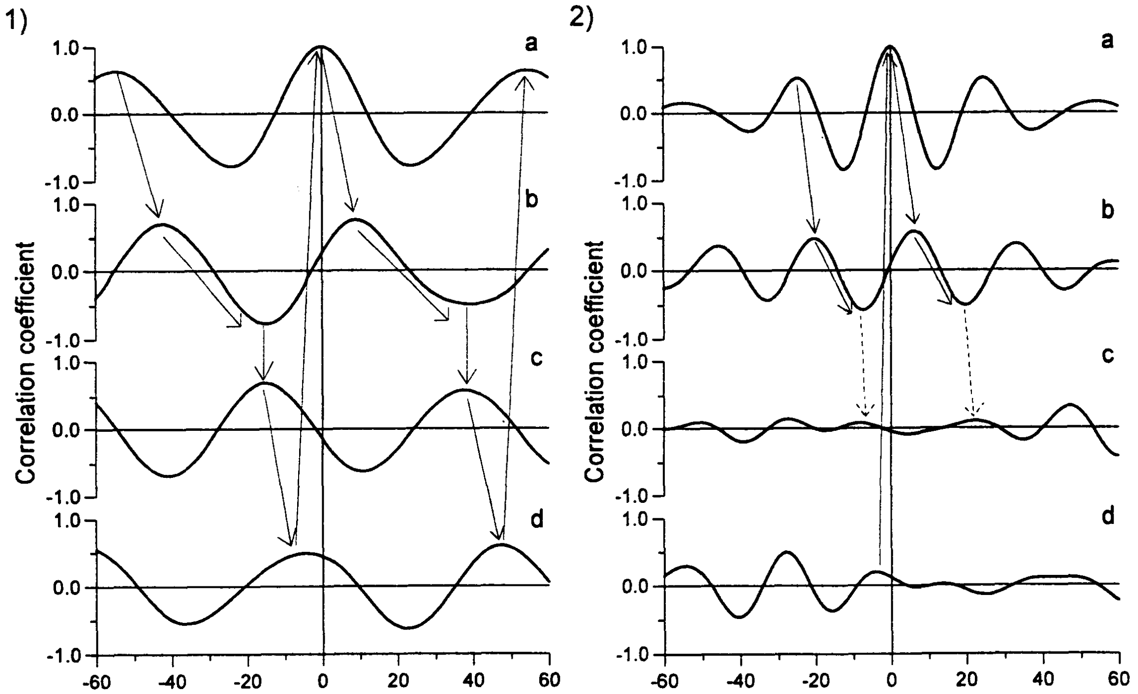

Fig.7. 1) Cross-correlation functions between rainfall and b) soil water content (28 cm depth), c) soil temperature and d) wet-bulb temperature, obtained using 45-60-day band-pass filtered data. Only the top column (a) shows auto-correlation function for rainfall. Arrows indicate propagation of anomaly. 2) Same as in 1) but using 22.5-30-day band-pass filtered data.

5. Large-scale variations of rainfall and convective activity and those relations to local variability

5.1 Spatial coherence of rainfall variability

To confirm spatial extent of the variability of hydrometeorological components appeared in Peradeniya, spatial coherence of rainfall variability is investigated with a special interest of its spectral characteristics.

Fig. 8 shows the power spectra of rainfall at different stations spread out over Sri Lanka. Spectrum for Nuwara Eliya is considerably similar to that for Peradeniya in the following three points: (1) existence of high frequency fluctuations, (2) predominance of the ISV-1, and (3) less significance of the ISV-2. Although spectral peaks are shifted more or less probably due to missing data, the ISV-1 can be found for almost all stations and is very dominant in inland or northeast regions (i.e., Nuwara Eliya, Anuradhapura and Trincomalee) but less dominant in a south coastal region (i.e., Hambantota). If we consider a spectral peak at 30-day period for Trincomalee and at 22.5-day period for Hambantota are shifted due to missing data, the ISV-2 is more dominant in coastal regions than in interiors. Consequently, both the ISVs-1 and -2 can be found almost all over Sri Lanka although those dominances are different depending on geographical conditions.

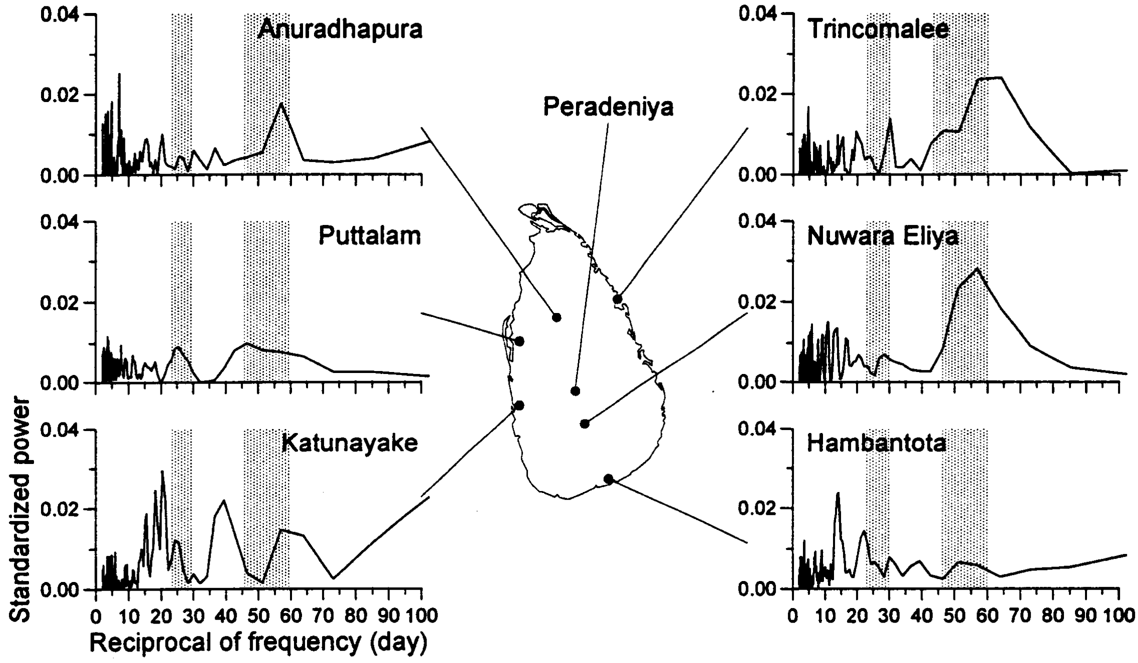

Fig.8. Power spectra of rainfall at different stations over Sri Lanka. Spectra are normalized as in Fig.6.

Besides the two ISVs mentioned above, a clear oscillation with 40-day period, which is equal to the predominant periodicity appeared in wind speed spectrum (Fig. 5c), can be seen for Katunayake. It can be also pointed out that biweekly and/or 20-day-period fluctuations are very dominant in southwest coastal regions. Periodicity of rainfall in coastal regions appears to be highly variable.

5.2 Large scale convective activity

The deeper convective clouds develop, the lower the cloud top temperature is. Therefore, convective activities in the tropics can be well investigated by satellite observed OLR (e.g., Nakazawa, 1986; Hendon and

Glick, 1997; Fink and Speth, 1997). Fig. 9 shows the spatial distribution map of correlation coefficient between rainfall at Peradeniya and OLR on a 2.5° grid. Daily rainfall at Peradeniya has negative correlation with OLR over and around Sri Lanka, and the closest correlation (r = -0.36) is found at the nearest grid point (7.5°N, 80°E).

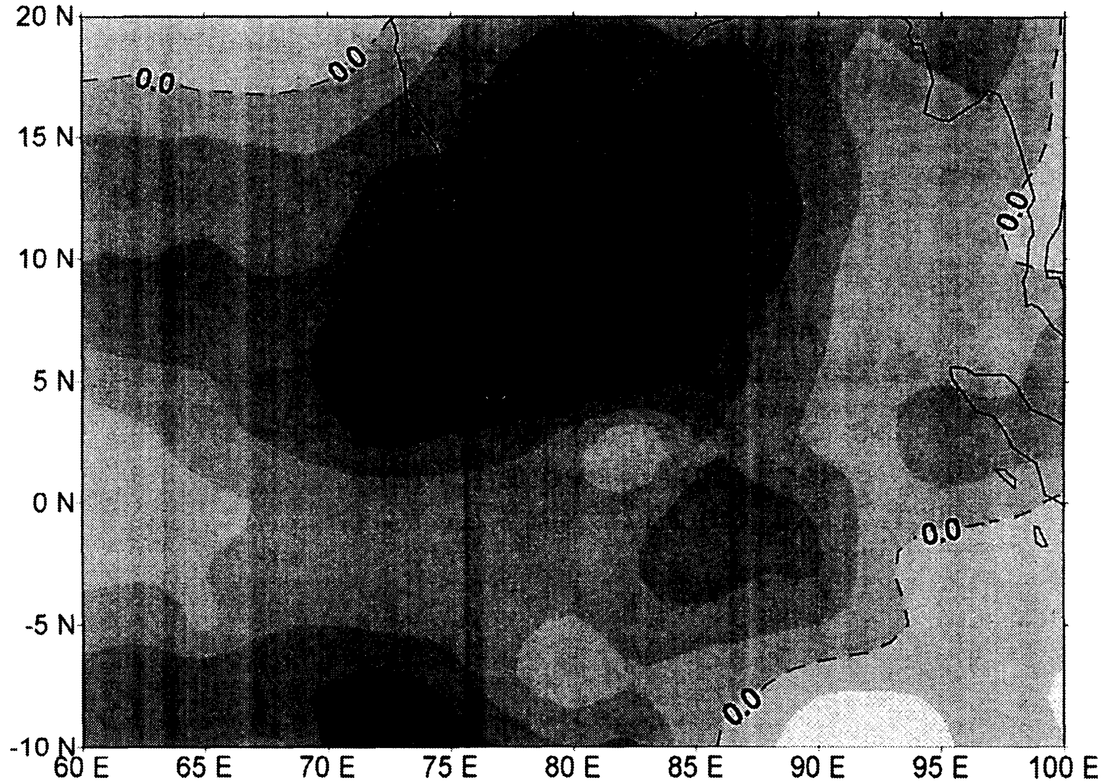

Fig.9. Spatial distribution of correlation coefficient between rainfall at Peradeniya and OLR on a 2.5° grid.

Fig. 10 shows power spectrum of OLR at the grid point. Spectral characteristics are similar to those of Peradeniya rainfall and soil moisture, that is, we can see the ISVs-1 and -2. In the figure power spectra at other grid points around Sri Lanka are also shown. The ISV-1 is more predominant at the westward but is less significant at the three other directions. The ISV-2 is found at all the direction and is most clearly at the eastward. We can also find that there are several dominant periodicities other than the two ISVs, including 10-day (at the southward), 16-day (the northward), 30-40-day (at the southward and eastward), and 75-day (at the westward) periods.

To reveal the origin of the two ISVs in OLR, we assess the movement and temporal evolution of the convective anomaly using band-pass filters. Since Fig. 10 shows that the ISV-1 is predominant at the westward of Sri Lanka and the ISV-2 is dominant at the eastward, zonal (i.e., east-west direction) propagation of the phase of band-pass-filtered OLR is focused. Fig. 11 displays the time-longitude cross section of cross-correlation coefficient between OLR at the point (7.5°N, 80°E) nearest to Peradeniya and OLR at gird points along 7.5°N. Negative lag means that OLR over Sri Lanka lags those at the other locations. For the ISV-1 (Fig. 11a) westward propagation of OLR anomaly can be seen clearly, particularly at a zone from 82.5°E to 65°E. In addition, the OLR anomaly over Sri Lanka appears to be not associated with that over the east of 87.5°E. On the other hand,

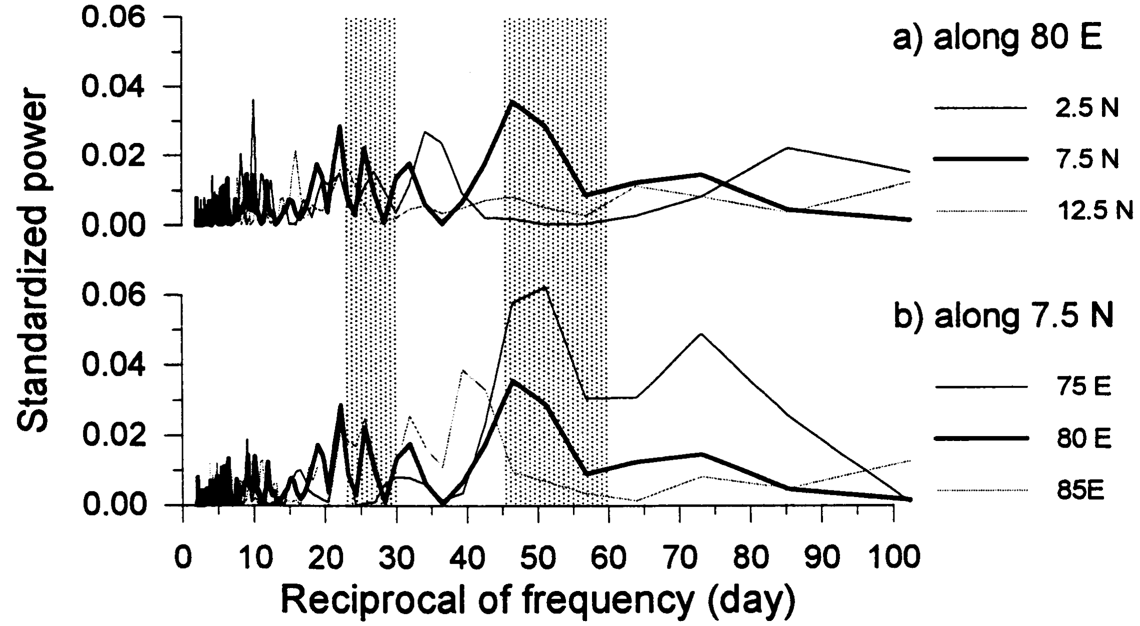

Fig.10. Power spectra of OLR at (7.5°N, 80°E; thick line) and around Sri Lanka.

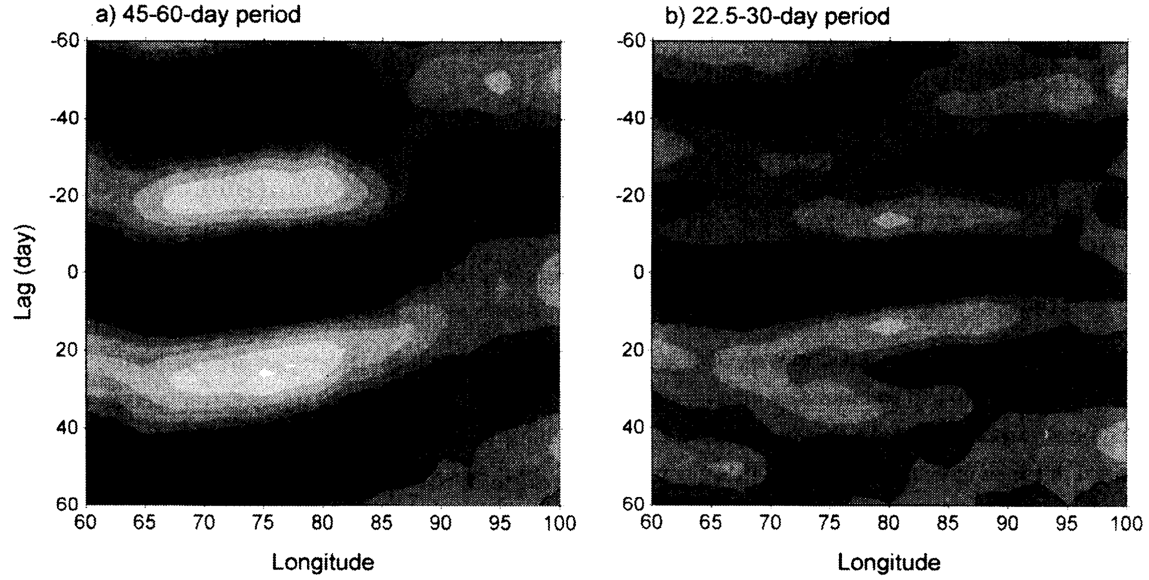

Fig.11. Time-longitude cross section of cross-correlation coefficient between OLR at Sri Lanka (7.5°N, 80°E) and OLR at gird points along 7.5°N, obtained using a) 45-60-day band-pass filtered data and b) 22.5-30-day band-pass filtered data. Dashed line denotes correlation coefficient r = 0, and solid line denotes r = 0.6.

for the ISV-2 (Fig. 11b) westward propagation of OLR anomaly is clear as well as for the ISV-1, but at a zone between 87.5°E and 72.5°E. These results indicate that the ISV-2 component in OLR variation has its origin in east ocean-region. Furthermore, we must reject a possibility that the ISV-1 component takes its origin from the westward; nevertheless the maximum dominance of the ISV-1 of OLR is seen at west ocean-region. It should be reasonable to consider that the ISV-1 component is strengthened through the process of its westward propagation.

It is well known that in the tropics there exists intraseasonal variation called as Madden-Julian oscillation (MJO) with eastward or northward propagation of convective anomaly (e.g., Madden and Julian, 1971, 1972; Yasunari, 1979, 1980). However, the direction of propagation of convective anomaly is different between the MJO and the two ISVs found in the present study. According to an analysis of Ohfuchi (2000), the MJO activity in 1994 was in the lowest level throughout a period of 1980-1997. Thus, the two ISVs in the present study is considered to be independent of MJO-like variations at least in 1994.

6. Discussion and concluding remarks

The time scale of the persistency of soil moisture anomaly was obtained from direct observation data (section 4.2). The scale is from 10 to 30 days and is very small relative to that for mid-latitude continental regions. In addition, the persistency of soil moisture anomaly is shorter than that of air temperature and wet-bulb temperature. This is opposite to the result from a case under mid-latitude temperate climate and suggests that in the humid tropics the persistency of atmospheric temperature is affected more strongly by external conditions such as SST than by internal condition, namely, soil moisture.

As another feature in the tropic, it was found that intraseasonal variations are dominated in soil moisture, rainfall, and other hydrometeorological components (section 4.3). There were the following two characteristic periodicities: 45-60-day period (ISV-1) and 22.5-30-day period (ISV-2). The former is associated with large rainfall events and is seen in soil moisture variation for all depths. In contrast, the latter is related to small rainfall events and soil moisture anomaly cannot propagate into the deeper depths.

The ISV-2 was dominant in convective activity over east ocean-region, and convective anomaly associated with ISV-2 propagates from the east to Sri Lanka (section 5.2). These facts indicate that external forcing causes the ISV-2 observed within Sri Lanka (sections 4 and 5.1). On the other hand, the ISV-1 was very predominant in west ocean-region but convective anomaly propagates from east to west, that is, the ISV-1 component of convective anomaly over Sri Lanka is strengthened through a process of its westward propagation (Fig. 11b) and its origin seems to be located at around Sri Lanka. These observational facts suggest a hypothesis that the ISV-1 is caused or reinforced by internal feedback mechanisms such as soil moisture-rainfall feedback rather than by external forcing.

Cross-correlation analysis for band-pass filtered (45-60-day period) data showed a propagation of anomaly from rainfall to soil moisture, soil temperature, wet-bulb temperature, and back to rainfall. As mentioned in section 4.4, negative correlation between soil moisture and soil temperature indicates a change in surface energy balance including sensible heat flux from land surfaces to the lower atmosphere. In addition, anomaly of wet-bulb temperature leading rainfall anomaly is a measure of anomalous CAPE triggering convective rainfall. In a tropical island there exists abundant water vapor supplied from the surrounding ocean. Therefore, enhanced sensible heating of the lower atmosphere would result in increase of wet-bulb temperature and convective rainfall. Thus, these results support the negative feedback between soil moisture and rainfall.

Finally, we mention the relationship between the ISV-1 and the ISV-2. The period of the ISV-1 is just twice that of the ISV-2, that is, large rainfall event seems to be induced once in two cycles of the ISV-2. The existence of the ISV-2 of convective activity over the surrounding ocean may help to supply water vapor from ocean surfaces to interiors of Sri Lanka. However, as seen in Fig. 7, soil-moisture anomaly cannot affect soil temperature in a time scale of the ISV-2 but can do in its twice time scale, which exceeds the soil moisture persistency

(10-30 days). Thus, it can be inferred that the soil moisture-rainfall feedback weakens the ISV-2 and reinforces the ISV-1. It remains unknown whether the soil moisture-rainfall feedback and its periodicity can be maintained without any external forcing. Further investigations including numerical modeling of regional climate are required to reveal this point.

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