Statistical and long-term characteristics of Southern Oscillation

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Abstract There are many research papers on the relationship between Southern Oscillation (SO) and hydro-meteorological phenomena. However, the properties of the barometric data from which Southern Oscillation Index (SOI) is derived and general statistical and long-term characteristics of SO have unexpectedly not been published, as far as the authors know. In this study, statistical characteristics of SO and the long-term variation characteristics of SO are presented. Firstly, the availability of the monthly mean sea level pressure data at Tahiti and Darwin, the statistics of the monthly pressure data, and the correlations between Tahiti and Darwin pressure anomalies are presented. In this paper, uniquely long-term continuous monthly mean sea level pressure data are used for the analyses. In this study, correlation between Tahiti and Darwin pressure deviations is defined as Southern Oscillation Intensity (SO Intensity). The long-term variation SO Intensity was investigated in detail. Secondly, the long-term variation of SOI was studied. Finally, the characteristics of SOI, including frequency analysis of SOI by magnitude and by month (January-December), and duration properties of SOI by run analysis are discussed.

Key words: SO, SOI, SO Intensity, statistical characteristics, long-term variation

INTRODUCTION

El Niño is the condition in which sea surface temperature rises 1 to 2°C (sometimes 2 to 5°C) above normal in the eastern and central equatorial Pacific Ocean. It lasts typically 12-18 months, and occurs irregularly at the interval of 2-7 years. In the opposite La Niña condition, the temperature is lower than normal. Southern Oscillation (SO) is an atmospheric see-saw phenomenon in tropical Pacific sea level pressure between the eastern and western hemispheres associated with the El Niño and La Niña oceanographic features (Sakurai, 1998; Japanese Study Group for Climate Impact & Application, 1999). The oscillation can be measured by a simple index, the Southern Oscillation Index (SOI) (Kawamura et al., 1998) which is used by NOAA (National Oceanic and Atmospheric Administration) to judge whether the El Niño and La Niña events occurring (Japanese Study Group for Climate Impact & Application, 1999). The features are known collectively as the El Niño Southern Oscillation (ENSO) phenomenon.

The impacts of ENSO on climate are widespread and extend far beyond the tropical Pacific, a phenomenon known as teleconnection (Sakurai, 1998; Japanese Study Group for Climate Impact &

Application, 1999). There are many reports of abnormal weather conditions worldwide considered caused by ENSO. These abnormal weather conditions and climatic change are considered to raise concerns about e.g., stable water resources management. As the result, qualitative and quantitative analyses of SO and its influence on local hydro-meteorological phenomena have become a very important research task.

There are many research papers on the relationship between SOI and hydro-meteorological phenomena (e.g., Ropelewski and Halpert, 1987; Halpert and Ropelewski, 1992; Uvo et al., 1998; Yoshino, 1999). The authors have described the chaotic characteristics of SOI (Kawamura et al., 1998) and the correlation between SOI and precipitation and temperature data in Fukuoka, Japan (Kawamura et al., 2000a; 2000b; 2001). However, the properties of the barometric data from which SOI is derived (i.e. mean sea level pressure data at Tahiti and Darwin) and general statistical and long-term characteristics of SO have unexpectedly not been published, as far as the authors know.

We have published autocorrelation and spectral characteristics of SOI (Kawamura et al., 1998), so that in this study, other statistical characteristics of SO and the long-term variation characteristics of SO are presented. Firstly, the availability of the monthly mean sea level pressure data at Tahiti and Darwin, the statistics of the monthly pressure data are presented. In this paper, uniquely long-term continuous monthly mean sea level pressure data at Tahiti and Darwin since 1866 are used for the all analyses. Secondly, the correlations between Tahiti and Darwin pressure anomalies are presented. Especially, in this study, correlation between Tahiti and Darwin pressure deviations is defined as Southern Oscillation Intensity (SO Intensity). The long-term variation SO Intensity is investigated in detail. Then, the long-term variation of SOI is studied. Finally, the characteristics of SOI, including frequency analysis of SOI by magnitude and by month (January-December), and duration properties of SOI by run analysis are discussed. These characteristics of SOI have not investigated in detail as far as the authors know. We expect that these characteristics will offer useful background information when using SO for other analyses.

LONG-TERM VARIATION OF MSLP AS THE BASE OF SO

Availability of the pressure data at Tahiti and Darwin

SO phenomenon is expressed using the monthly mean sea level pressure (MSLP) data at Papeete, Tahiti (149.6°W, 17.5°S.) and Darwin, Australia (130.9°E, 12.4°S). Those MSLP pressure data since 1882 are available through web cites such as NOAA Network Information Center [http://www.nnic.noaa.gov/ data/indices/]. Totally 102 months missing values exist for the Tahiti pressure data as shown in Table 1. However, Ropelewski and Jones (1987) infilled all missing values using newly found old pressure data in Tahiti. Furthermore, by supplementing and interpolating the data of Tahiti before 1882, they completed the pressure time series since 1866. Allan et al. (1991) also infilled the pressure data in Darwin before 1882 by using the older records and by correlation with data from other observation stations. As the result, the pressure data in Darwin are also complete since 1866. As the result, in this study, we use the long monthly MSLP data of 135 years (1620 months) from January 1866 to December 2000 at Tahiti and Darwin, acknowledging that the reliability of the pre-1935 pressure data may be slightly less than the later data (Ropelewski and Jones, 1987).

Table 1. MSLP data missing periods at Tahiti.

Missing Period		Missing
From	To	Months
Sep 1892	Dec 1895	40
Mar 1906	May 1906	3
Dec 1906	Aug 1908	21
Apr 1914	Sep 1914	6
Nov 1914	Oct 1915	12
Mar 1921	Jun 1921	4
Jun 1927	Aug 1927	3
Aug 1931	Aug 1932	13
	Total	102

Characteristics of MSLP data

Figure 1 shows the mean values and their standard deviations of monthly MSLP for each month (January-December) at Tahiti and Darwin for 135 years data. The mean values of MSLP are higher in the summer season of northern hemisphere and lower in the winter season for both sites. The difference between the highest and the lowest mean values is 6.8 hPa at Darwin, which is about twice as much as that (3.7 hPa) at Tahiti. The standard deviations are larger in January-March and smaller in April-June for both sites. Figure 2 shows the average values, their standard deviations, maximum and minimum values of MSLP difference between Tahiti and Darwin for each month (January-December). From the figure, the average values of MSLP differences are positive for all months, but they are close to zero in the northern hemisphere summer. The mean minus standard deviation values are negative in June and July. The minimum values are negative for all months.

SO Intensity

Deviation time series from the average MSLP of each month (January-December) are shown in Figure 3 for the last 30 years. From this figure, we can see a clear tendency that when the pressure

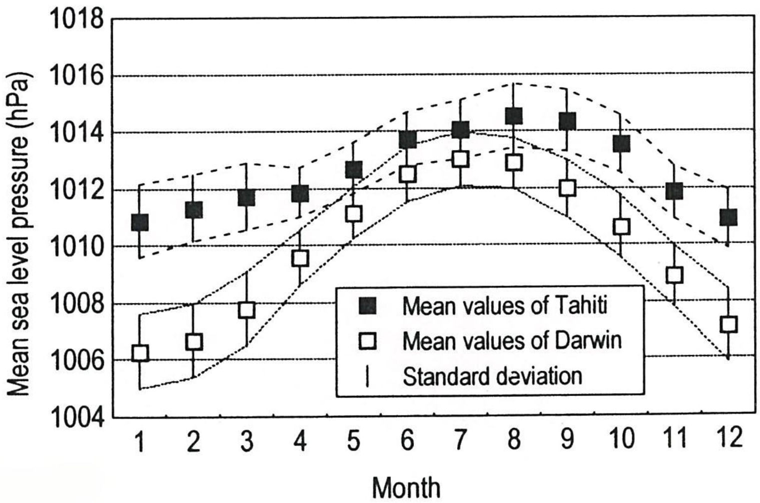

Figure 1. The mean values and their standard deviations of monthly MSLP for each month (January-December) at Tahiti and Darwin for 134 years data.

deviations rise above the monthly averages at Tahiti, the pressure deviations at Darwin fall below the monthly averages, and vice versa. This famous phenomenon was discovered by Sir Gilbert Walker early in the 20th century, and it was named Southern Oscillation. Figure 4 shows the scatter plots for Figure 3, i.e., the relationship between pressure deviations from the average MSLP at Tahiti and Darwin. From this figure, we can obtain the cross-correlation coefficient of -0.40 for the most recent

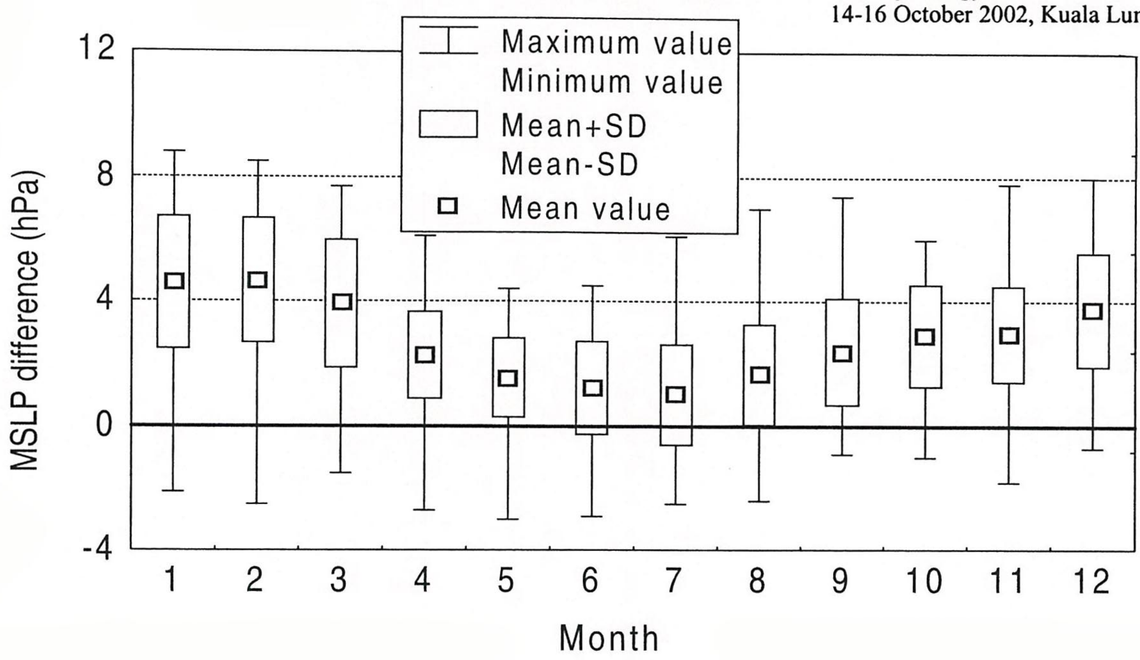

Figure 2. Average values, standard deviations, maximum and minimum values of MSLP difference between Tahiti and Darwin for each month (January-December).

30 years. The correlation is not so high as we expect. For the whole series, the correlation coefficient of pressure deviations was -0.26 which is even smaller (Kawamura et. al., 1992). However, note that the significant level of those correlation coefficients is extremely high because of the large number of the data. In other words, when the statistical hypothesis test is executed, the null hypothesis of "correlation coefficient = 0" is easily rejected at the significant level of 0.001%. In this study, the cross-correlation between Tahiti and Darwin pressure deviations is named Southern Oscillation Intensity (SO Intensity).

Long-term tendency of SO Intensity

Figure 5 shows 30-year moving time series of SO Intensity. Thick line indicates no lag time between Tahiti and Darwin pressure deviation data. In this figure, for example, the recent 30-year (1971-2000) SO Intensity of -0.40 (Figure 4) is plotted at year 2000 of x-axis in the thick line. The thin and broken lines indicate one month lagged SO intensity in Tahiti and Darwin, respectively. The reason for using 30-year moving series is that World Meteorological Organization (WMO) defines the normal value as the average of past 30 years. The significant level of all SO Intensity values in Figure 5 maintains at least 1 %. From Figure 5, we can see a very clear tendency in which the SO Intensity has become almost consistently stronger since before 1900. Especially, the tendency is dominant since the middle of 1970s when it is said the dominant climatic change called as ENSO shift occurred (Zhang et al., 1997; Chao et al., 2000). From Figure 5, we can also see the tendency in which until the mid-1920s the SO Intensity is bigger for the case of one month lagged in Tahiti, but after that time the one has become bigger for Darwin one month lagged.

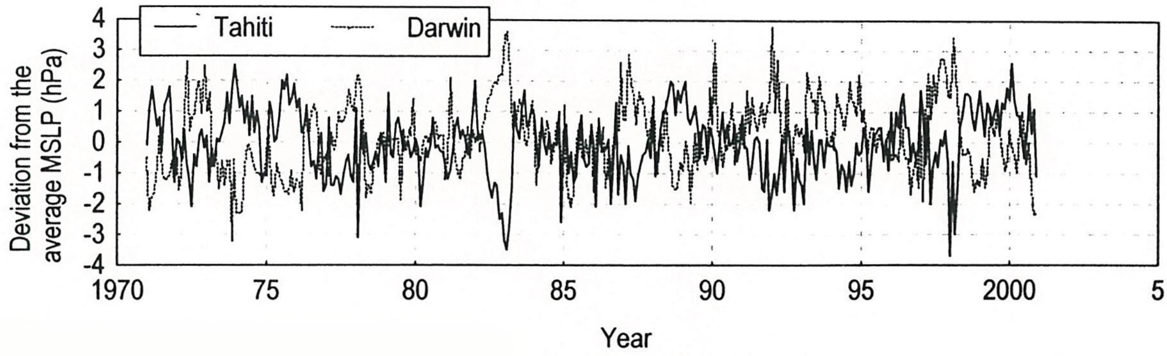

Figure 3. Deviation time series from the average MSLP for the recent 30 years.

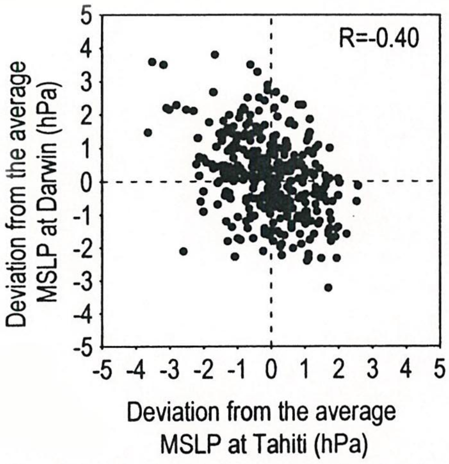

Figure 4. Scatter plots for Figure 3.

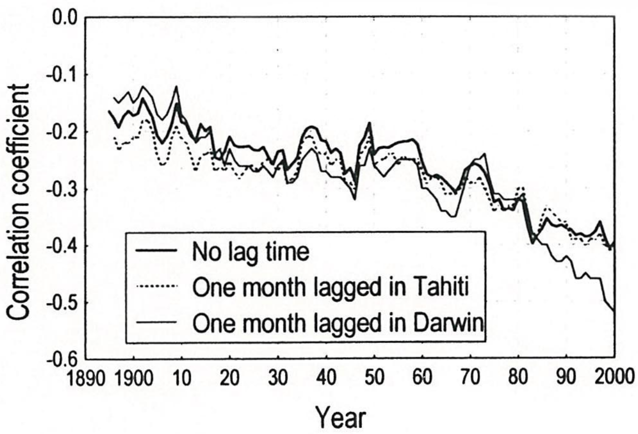

Figure 5. 30-year moving time series of SO Intensity.

Long-term variation of pressure deviation

Figure 6 shows 30-year moving average time series of pressure deviation from the average MSLP of each month (January-December) at Tahiti and Darwin. From this figure, at Tahiti the pressure deviation of about 0.1(hPa) around 1900 decreased to about zero value in 1930s. Then it fluctuated around zero until around 1980, and after that it decreased again to around -0.1(hPa) in the 1990s. On the whole, the pressure deviation at Tahiti tends to decrease consistently. On the other hand, although the pressure deviation at Darwin had been fluctuating, it generally had been decreasing until the mid-1970s. However, it drastically changed to dominant increasing tendencies in the middle of 1970s. As the results we can say that the increasing tendency of SO Intensity after 1980 in Figure 5 has been caused by the dominant increasing tendency of pressure deviation at Darwin after the mid-1970s.

STATISTICAL AND LONG-TERM CHARACTERISTICS OF SOI

Long-term variation of SOI

Two commonly used methods to compute the SOI from the MSLP data at Tahiti and Darwin are Troup's method and the Climate Prediction Center's method. The difference between two methods is very small as pointed out by McBride and Nicholls (1983), Ropelewski and Jones (1987) and Kawamura et al. (1998). In this study, we use Troup's method (Troup, 1965). The $SOI(y,m)$ in year y, month m (m=January to December) is calculated by the following equation;

$$SOI(y,m) = [\{P_T(y,m)-P_D(y,m)\}-M_{30}(m)]/S_{30}(m) \qquad (1)$$

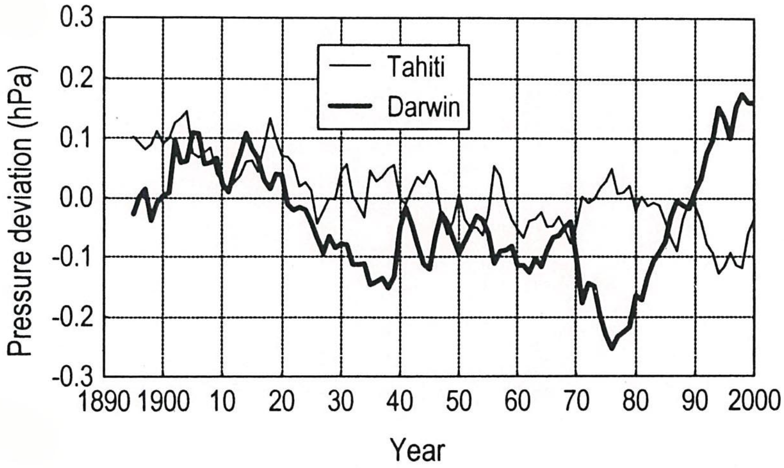

Figure 6. 30-year moving average time series of pressure deviation.

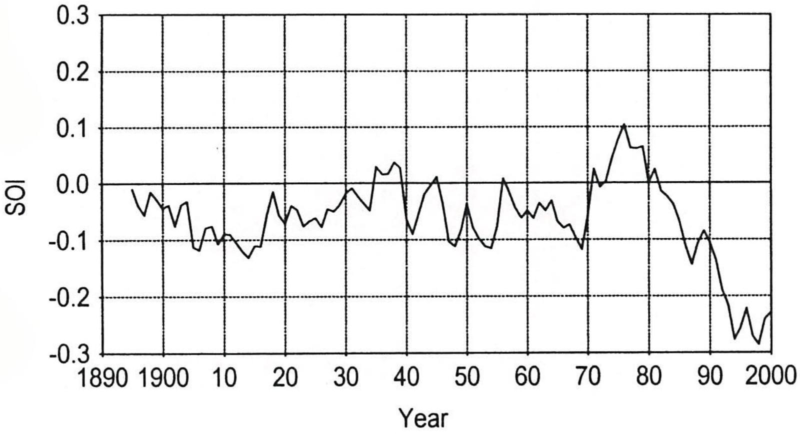

Figure 7. 30-year moving average time series of SOI.

Here, $P_T(y,m)$, $P_D(y,m)$ = MSLP (hPa) at Tahiti and Darwin, respectively ; $M_{30}(m)$, $S_{30}(m)$ = the mean value (hPa) and its standard deviation (hPa) of MSLP difference between Tahiti and Darwin (cf. Fig.2) for the base period of 30 years (usually 1951-1980). As is indicated in Eq. 1, SOI is expressed as the MSLP difference series between Tahiti and Darwin which is normalized to mean zero and a standard deviation of one. Note that a standard deviation of 10 is also commonly used. Generally, El Niño conditions occur when the SOI is less than -1, and La Niña conditions when the SOI is more than 1. Strong El Niño/La Niña conditions prevail when the SOI absolute value exceeds 2.

Figure 7 shows 30-year moving average time series of SOI. From this figure, on the whole SOI time series sways to the negative side. The values had been fluctuating between -0.1 and 0 until around 1970. After SOI time series sways to the positive side for the short time in 1970s, it drastically changed into decreasing tendency and has reached recently around -0.3. In other words, recently the SOI values greatly sway to the negative ones resulting in putting into dominant El Niño tendency. In fact, we have had very strong El Niño events in 1982/83 and 1997/98 as is well known.

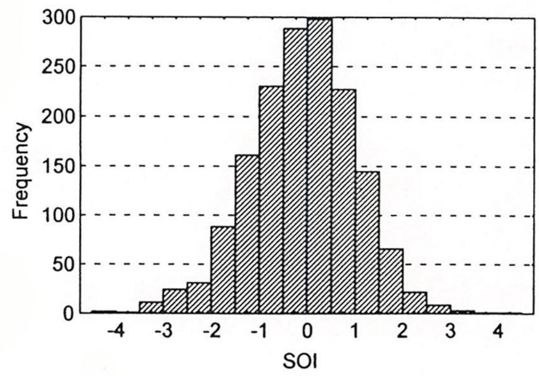

Figure 8. Histogram of original SOI time series.

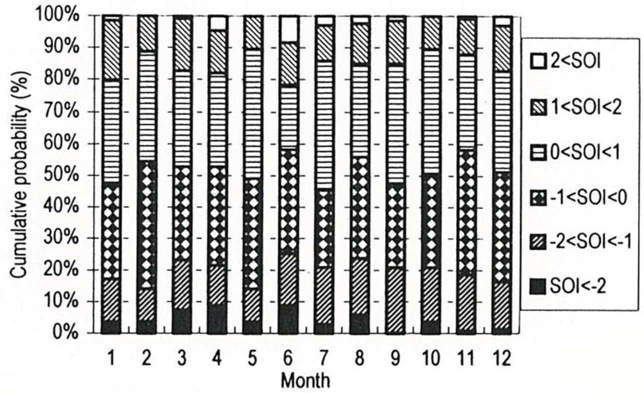

Figure 9. Cumulative frequency of SOI classified into six categories.

Frequency characteristics of SOI

There are several papers in which SOI values are classified into some categories according to their magnitudes, and the relationship between the categorized SOI and hydro-meteorological elements are studied (e.g., Moss et al., 1994; McKerchar et al., 1998; Kawamura et al., 2000a, 2000b, 2001). In this section, as the base of those researches, frequency analysis of classified SOI is studied. Figure 8 shows the histogram SOI data of 1620 months. It looks normally distributed as expected. However, frequencies of the negative values are larger than those of positive values except for the case that the absolute values are less than 0.5. For example, the frequency less than -2 is 69, while the frequency more than 2 is 35, i.e., El Niño tendencies occur more frequently than La Niña tendencies. The tendency becomes more dominant when the SOI time series is smoothed (Kawamura et al., 2002).

Figure 9 shows cumulative frequency of SOI classified into six categories for each month (January-December) during the past 135 years. From this figure, in spite of the small variation of the frequency of each category from month to month, it may be seen that El Niño and La Niña could occur in any month. However for June the frequencies of more than 2 and less than -2 are extremely high compared with those of other months. Also, the frequencies of more than 1 and less than –1 are much higher, whereas the ratio between -1 and 1 is very low.

Duration properties of SOI time series

In order to investigate the duration properties of SOI, run analysis of the time series is carried out. Figure 10 shows the histogram of positive run length (La Niña side) and negative run length (El Niño side). Positive run length is defined by the number of consecutive months in which the positive values of SOI continue, and similarly, negative run length is for the negative values. From Figure 10, both positive and negative run length have the biggest frequency at one month, and the frequency decreases drastically with the increase of run length. The average of positive run length is 3.4 months, and 3.7 months for negative run length. The longest negative run length of 33 months is from August 1939 to April 1942. The negative run length for the large-scale El Niño event covering spring 1982 to summer 1983 is 13 months, and 14 months for another large-scale El Niño event covering spring 1997 to summer 1998.

Next, the duration analysis is carried out for the case in which the absolute value of SOI is more than 1, which means how many months SOI time series is continuously above one or below minus one. The result is shown in Figure 11. From this figure, the biggest run length is 14 months of negative side, which corresponds to the 1997/1998 El Niño event. The

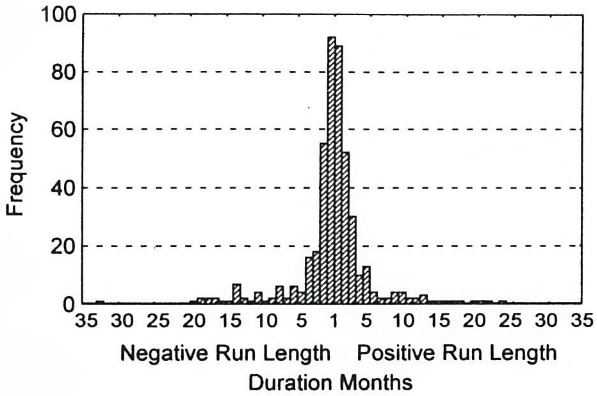

Figure 10. Histogram of positive and negative run length for SOI

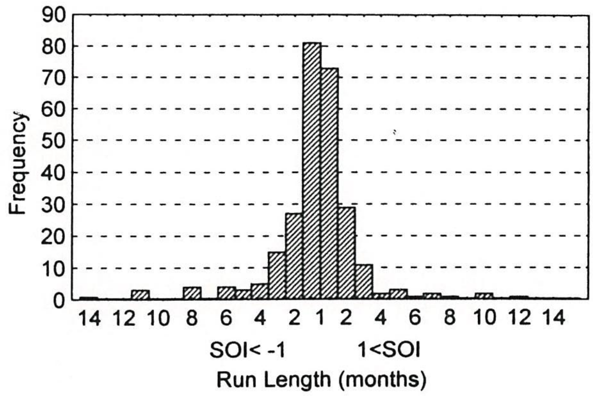

Figure 11. Histogram of duration analysis result for the case in which the absolute value of SOI is more than 1.

biggest positive one is 12 months which corresponds to the 1917 La Niña event. Average run lengths are 2.0 and 2.2 months for positive and negative, respectively, in which El Niño side tends to be a bit longer. The similar duration analysis was also carried out for the case in which the absolute value of SOI is more than 2 and for 5 months moving average SOI time series. Please refer to the results by Kawamura et al. (2002).

CONCLUSIONS

In this paper, the statistical and long-term characteristics of SO are presented. Firstly, the availability of the monthly mean sea level pressure data at Tahiti and Darwin, the statistics of the monthly pressure data are presented. Secondly, The long-term variation SO Intensity is investigated in detail. Then, the long-term variation of SOI is studied. Finally, the characteristics of SOI including frequency analysis and duration properties are discussed. The main conclusions obtained from this study are as follows;

- The consecutive SOI data are available since January 1866. The pre-1935 data may be slightly less reliable.
- The average values of MSLP difference between Tahiti and Darwin are positive for all months, but they are close to zero in the northern hemisphere summer season.
- SO Intensity has been an obvious increasing tendency since before 1900 and for the recent years it is about -0.4.
- SOI has changed into remarkable decreasing tendency since the late 1970s, which corresponds to the drastic increasing tendency of pressure deviation at Darwin.
- The occurrences of SOI more than 2 and less than -2 are remarkably high in June compared with other months, and occurrences between -1 and 1 are relatively low.
- Both positive and negative run length of SOI time series have the biggest frequency at one month, and the frequency decreases drastically with the increase of run length. Negative run length is longer than positive run length on average.

We expect the results, which are statistical and long-term characteristics of SO, will contribute useful background information when using SO for other analyses.

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