Nonlinear Multivariable Analysis of SOI, Precipitation, and Temperature in Fukuoka, Japan

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ABSTRACT: Global climate variations are expected to affect local hydro-meteorological variables like precipitation and temperature. The Southern Oscillation (SO) is one of the major driving forces that give impact on regional and local climatic variation. The relationships between SO and local climate variation are, however, characterized by strong nonlinear variation patterns. In this paper, the nonlinear dynamic relationship between the Southern Oscillation Index (SOI), precipitation, and temperature in Fukuoka, Japan, is investigated using by a nonlinear multivariable approach. This approach is based on the joint variation of these variables in the phase space. The joint phase-space variation of SOI, precipitation, and temperature is studied with the primary objective to obtain a better understanding of the dynamical evolution of local hydro-meteorological variables affected by global atmospheric-oceanic phenomena.

1 INTRODUCTION

Global climatic variation and warming are expected to result in significant changes in local and regional climate. It is especially local temperature and precipitation patterns that are expected to significantly deviate from the present-day levels in case of a significant future global warming. The Southern Oscillation Index (SOI) is an easily quantifiable climatic parameter that can be used to measure the strength of the atmospheric signal in local and regional climatic data. The SOI is defined as the normalized difference in surface pressure between Papeete at Tahiti in central Pacific Ocean and Darwin in northern Australia. The SOI quantifies the inter-annual atmospheric seesaw phenomenon called Southern Oscillation (SO). Quantitative links between the SOI and observed local climatic and other geophysical variables are important to establish because they can be used as early indicators of near-term extreme weather or long-term effects on available water resources (e.g., Chiew et al., 1998).

Finding quantitative links between the SOI and local climatic variables, however, is hampered by the strong nonlinearities involved when studying relationships between joint atmosphere-ocean-land surface data. Recently, Kawamura et al. (2000) showed that categorization of extreme SOI and displays corresponding elevated values of temperature and precipitation. This type of relationship, however, is not easily distinguished using simple linear statistics. Consequently, there are needs to develop methods that can display complicated nonlinear relationships among several variables simultaneously.

In this paper we investigate nonlinear relationships between SOI, temperature, and precipitation at Fukuka, Japan, using a multivariable dynamical approach. Our main interest is focused towards simultaneous temporal variation in the span between 10-100 years. The approach involves investigation of the dynamical variational pattern in phase space after standardization and nonlinear smoothing. In the first parts of the paper we outline the data treatment and methodology. After this follow analyses using joint phase space trajectories. We close with a summary and discussion of practical implications.

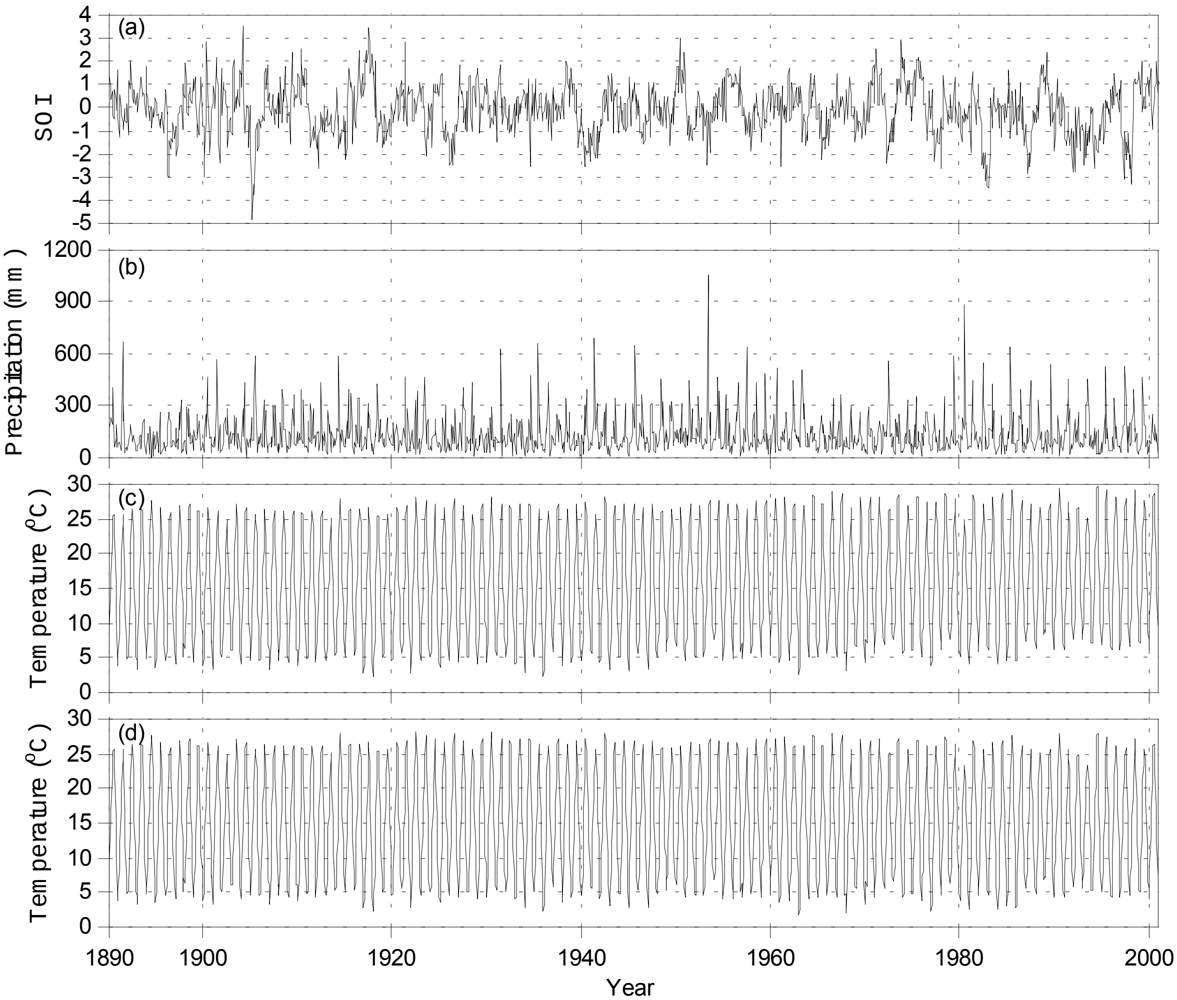

Fig. 1. Time series plots of raw monthly (a) SOI, (b) precipitation, (c) temperature, and (d) trend-removed temperature

2 DATA USED

Monthly time series of SOI, precipitation, and temperature were used to investigate joint phase space relationships. The SOI data were calculated using the monthly mean sea level pressure (MSLP) at Papeete, Tahiti (149.6°W, 17.5°S) in central Pacific Ocean and Darwin (130.9°E, 12.4°S) in northern Australia. The MSLP data starting from 1882 are available through web sites such as NOAA Network Information Center. However, in the present study, we used the MSLP data from 1866 augmented by Ropelewski and Jones (1987), and Allan et al., (1991). Two commonly used methods to compute SOI from mean sea level pressure at Tahiti and Darwin are Troup's method and the Climate Prediction Centre's method. The difference between the two methods is very small as pointed out by McBride and Nicholls (1983), Ropelewski and Jones (1987), and Kawamura et al. (1998; 2001). Therefore, in the present study, only the values for the Troup's SOI time series are used. Troup's method (Troup, 1965; McBride and Nicholls, 1983) first takes the difference between pressures at Tahiti and Darwin. Then the difference series is normalized to a mean of zero and a standard deviation of one by subtracting the monthly mean values and dividing the monthly standard deviations using a base period (usually 1951 – 1980) for the computation of the mean and standard deviation. This normalized time series is defined as Troup's SOI and used for the present study (Fig. 1 (a)).

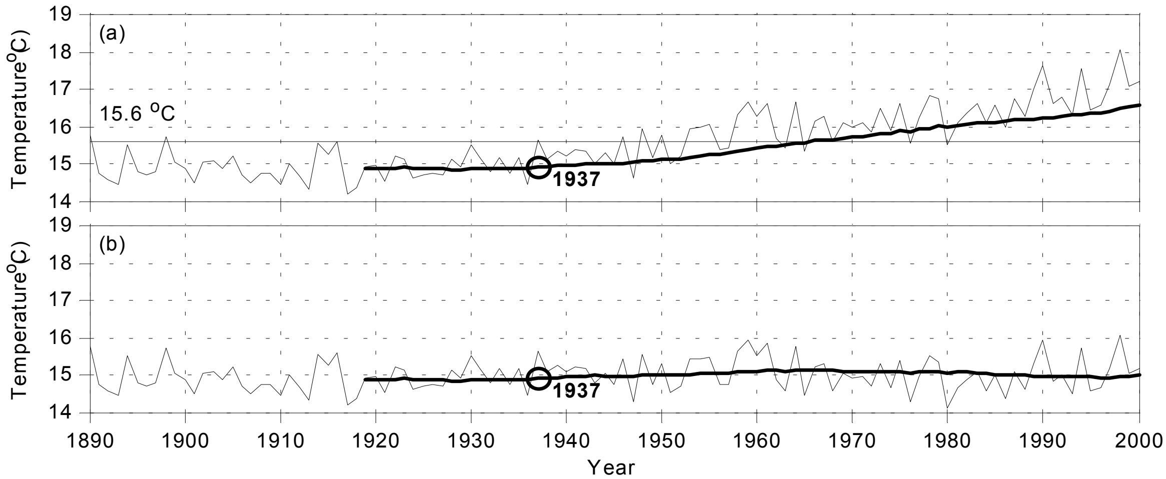

Fig. 2. Trend-removal from temperature data since 1937: (a) annual mean temperature and its thirty-year moving average and (b) annual mean temperature and its thirty-year moving average after linear trend was removed.

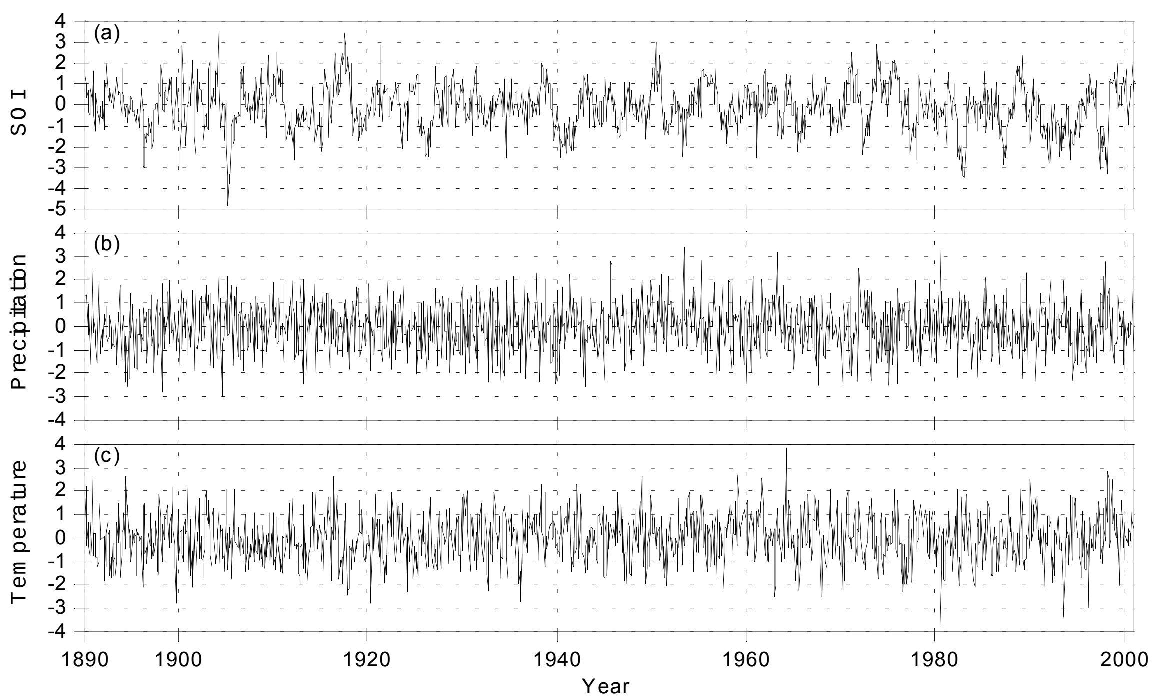

Fig. 3. Normally standardized data for (a) SOI, (b) precipitation, and (c) temperature.

Monthly precipitation and temperature data at Fukuoka, Japan, were selected because of long and well-established observations. The annual mean for precipitation here is 1627 mm, while the annual mean temperature is 15.6°C. The time series plots are shown in Fig. 1 (b) and (c). The monthly temperature data, however, display clear positive linear trend from about 1937. Therefore, mean annual values and thirty-year moving averages were calculated to remove the trend (see Fig. 2). It is likely that this linear trend is an effect of urbanization. Therefore, the trend was removed.

3 DATA TRANSFORMATION

The SOI data were used directly without transformation due to its already normal distribution (Fig. 3 (a)). However, the precipitation and temperature data display positive skewness and annual periodicity (e.g., Jin et al., 2002a; 2002b). Therefore, the data were normalized and standardized to remove deterministic components, i.e., seasonality and annual periodicity (Salas, 1993). The monthly precipitation data were normalized by a cubic root transformation. The normalized precipitation was then standardized to a mean of zero and standard deviation of one (Fig. 3 (b). The temperature data were similarly standardized to a mean of zero and standard deviation of one (Fig. 3(c); e.g., Jin, 2004).

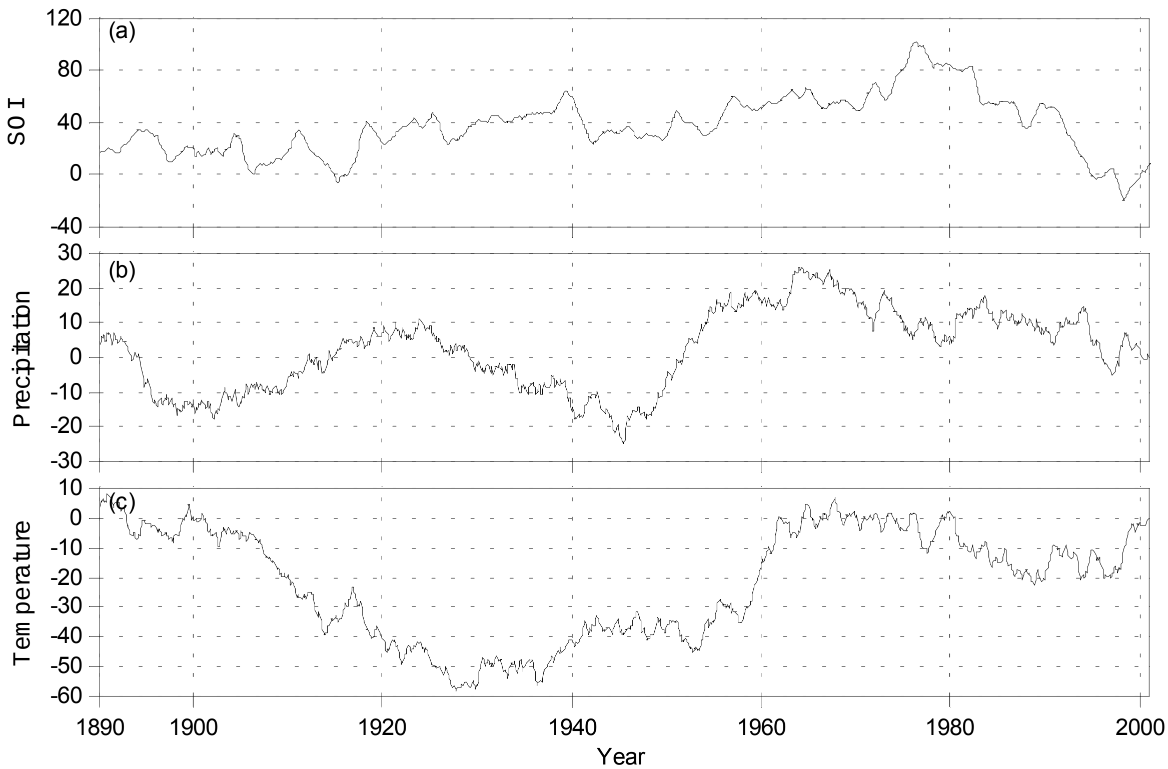

Fig. 4. Accumulated deviations from mean for (a) SOI, (b) precipitation, and (c) temperature.

The next procedure was to calculate accumulated deviations from mean for all time series. This was done in order to display general quasi-periodical characteristics in time domain. The resulting time series are shown in Fig. 4(a)-(c). Generally, observed time series data contain a substantial amount of noise. Therefore, the data need to be cleaned by a noise reduction scheme (e.g., Grassberger et al., 1991). Moving average and low-pass filter are commonly used methods for noise reduction. In the present study, however, we used a nonlinear noise reduction scheme specifically developed for deterministic dynamics studies proposed by Schreiber (1993). The general idea of the nonlinear smoothing is to replace each coordinate in the time series $\{x_i\}$, i=1,…, T, by an average value over a suitable

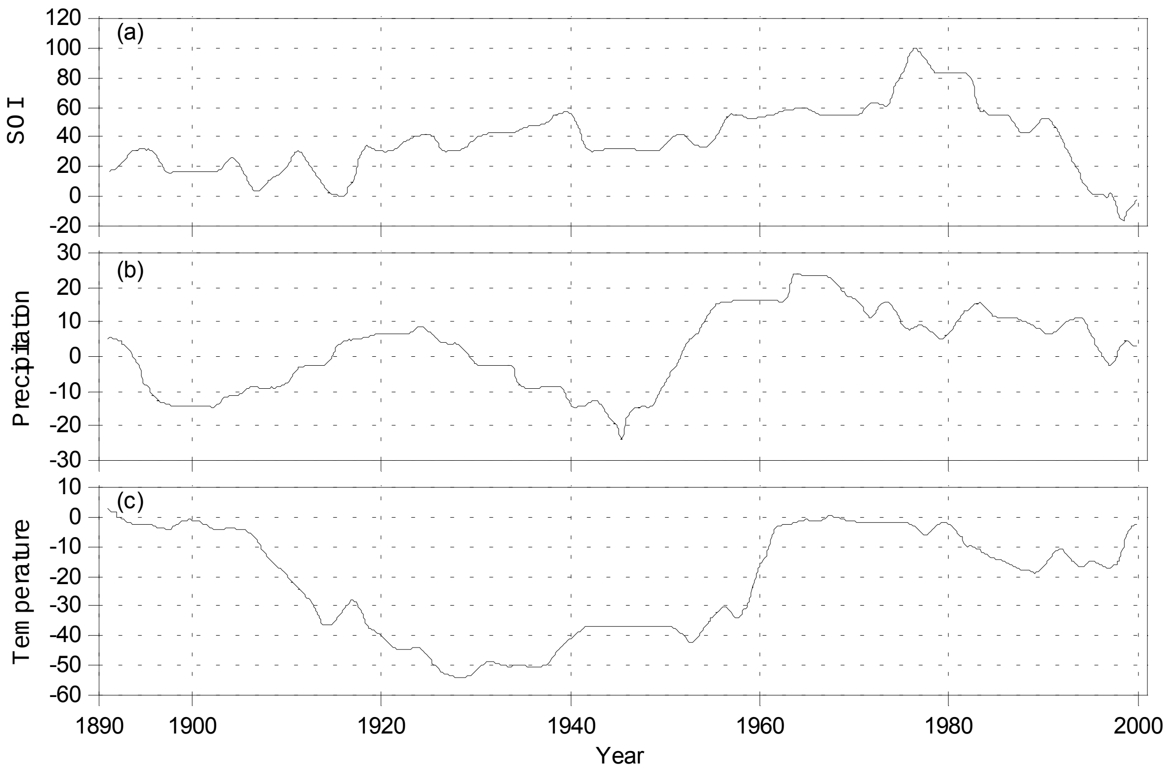

Fig. 5. Noise-reduced monthly time series for (a) SOI, (b) precipitation, and (c) temperature.

neighborhood in the phase space. The neighborhoods are defined in a phase space reconstructed by delay coordinates. To define the neighborhoods, first fix the positive integers *k* and *l*, and construct embedding vectors X_i.

$$X_i = [x_{i-k},..., x_{i+l}] \tag{1}$$

A radius η is chosen for the neighborhoods. For each coordinate in X_i find the set Ω_i^η of all neighbors X_j for which

$$\sup\{|x_{j-k} - x_{i-k}|,...,|x_{j+l} - x_{i+l}|\} \equiv \|X_j - x_i\|_{\sup} \pi \eta \tag{2}$$

where the symbol "sup" denotes the highest value of the elements. Consequently, the present coordinate x_i is replaced by its mean value in Ω_i^η:

$$x_i^{corr} = \frac{1}{|\Omega_i^\eta|} \sum_{\Omega_i^\eta} x_j \tag{3}$$

Here, k and l were both selected to 12 months. As a result, the first and last 12 months of the monthly time series were not noise-reduced, and the unchanged periods were neglected in the following analysis. The time series plots for the resulting noise-reduced monthly time series are shown in Fig. 5(a)-(c).

4 PHASE SPACE ANALYSES

Dissipative dynamical systems exhibiting chaotic behavior generally display strange attractors in the phase space (Grassberger and Procaccia, 1983). The attractor can be examined in the phase space by using the method of time-delay coordinates. For this, time series are plotted versus the same series but with a time delay on the other axes. In mathematical terms, let $\{x(t)\}$ be a discrete sample time series. A state space vector X_t is constructed, or embedded from m consecutive values of the time series into a phase space whose coordinates are described by

$$X_t = [x(t), x(t+\tau), ..., x(t+(m-1)\tau)] \tag{4}$$

where τ is the delay time, and the dimension m of the vector is known as the embedding dimension. Following Eq. (4), a new time series of the state space vector $X_1, X_2, ..., X_N$ is generated. Each vector X_t describes a point in an m-dimensional phase space. Thus, the sequence of these vectors defines a trajectory in time.

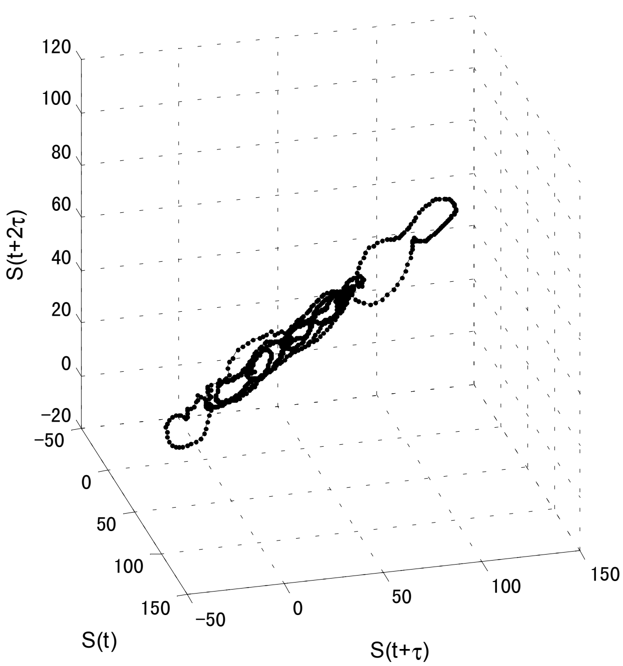

Fig. 6. Phase space plot for SOI with delay time τ = four months.

Figure 6-8 show phase space trajectories for for SOI, precipitation, and temperature, respectively, as previously defined. The generated time series for the state space vectors are connected with straight lines to indicate the continuous time evolution, even though the transition values between one space vector and the next are not known. For all variables, the delay time τ was selected to four months.

If a time series contain chaotic properties, the state vector X_t will be attracted to a particular region in the phase space known as the strange attractor (see e.g., Jinno et al., 1995; Berndtsson et al., 1994). The attractor may, however, be completely concealed if the time series contain noise. Therefore, it is important to clean the time series before any type of analysis.

The phase space plots of SOI, precipitation, and temperature as seen in Fig. 6-8 appear to display regions of recurring visits in time domain. These may indicate the region which could hold a strange attractor. Due to the rather short time series, however, the number of recurring visits in phase is also rather small and it is therefore difficult to make an exhaustive analysis.

Corresponding plots for joint phase space plots are shown in Fig. 9. As seen from the figure the phase space trajectories for these relationships are much more complicated and do not display any obvious relationships. Consequently, if relationships exist, they are highly nonlinear. The diagrams can, however, be used to show similarities between different co-evolving climatic variables and driving climatic indicator such as the SOI. For precipitation and temperature it can be seen that years that represent a local minimum and/or maximum in the cumulative time series diagrams (Fig. 5) is clearly displayed in the joint phase space diagrams. Examples of such situations are the years 1945, 1963, 1976, and 1998 for precipitation. Corresponding years for temperature are 1890,

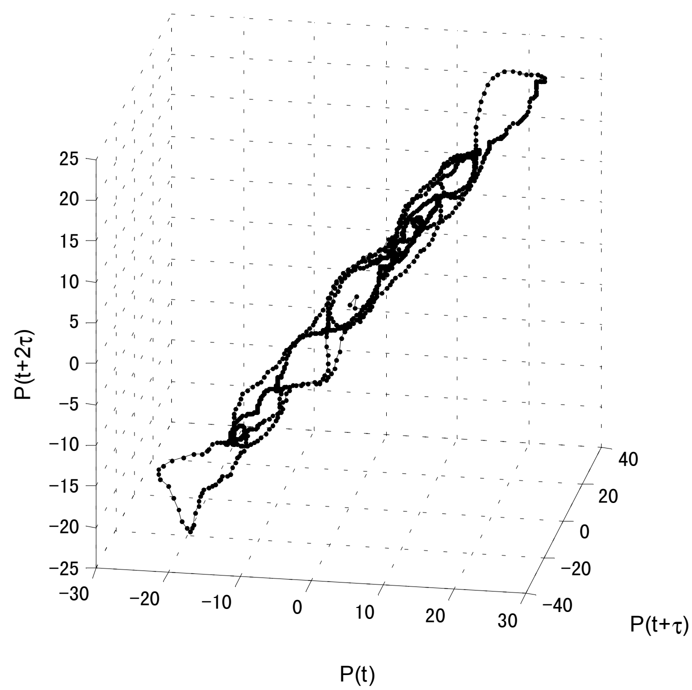

Fig. 7. Phase space plot for precipitation with delay time τ = four months.

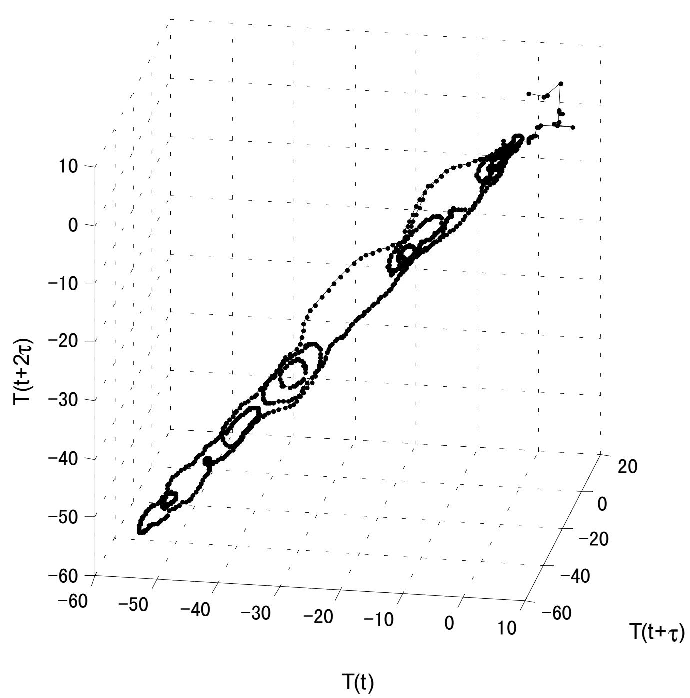

Fig. 8. Phase space plot for temperature with delay time τ = four months.

1928, 1976, and 1998. For these years SOI displayed maximum for 1976 and minimum for 1998. For the years 1890, 1928, 1945, and 1963, SOI displayed intermediate values. When comparing joint precipitation and temperature phase space trajectories, 1890 and 1963 were years when both variables displayed large maxima and 1928 and 1945 large minima.

In a similar way, phase space plots can be drawn for all three variables jointly. Figure 10 shows this for all the three investigated time series. Again, the plot shows an extreme variation and no obvious structure. This may partly be due to that time series are relatively short and consequently do not cover many quasi-periodical trajectories in the phase space. However, the figure still shows the extreme nonlinearities at hand and the complicated three-dimensional structure among the three interrelated variables.

5 CONCLUSIONS

In the paper we outlined a methodology to investigate joint phase space characteristics of several climatological variables by using ideas from dynamical systems theory. The data used were firstly treated in a number of ways. The time series were treated for trends and non-normal distributions. After linear trend removal for temperature and normalization by cubic transformation for precipitation, both time series were standardized to zero mean and standard deviation of one. Consequently, hereafter we can say that the series are jointly homogeneous. After this the accumulated deviations from the mean were calculated for all three time series. Finally, the time series were noise reduced using an especially designed nonlinear filter.

The results from the analyses displayed rather clear phase space trajectories when treating the time series individually. However, when plotting phase space trajectories for several joint time series complicated relationships appear to emerge. It can thus be said that the joint relationships between the three investi-

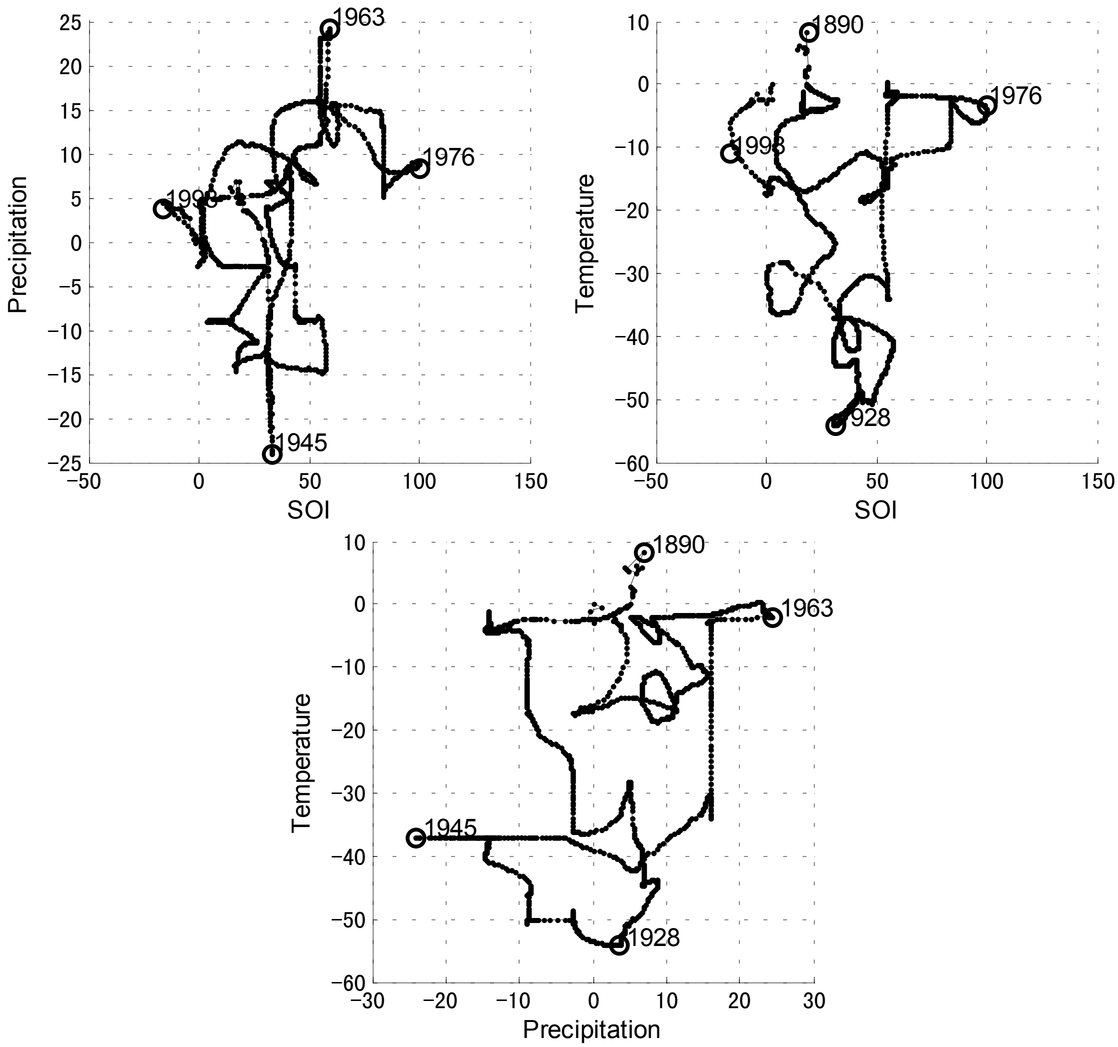

Fig. 9. Joint phase space plots of SOI, precipitation, and temperature ($\tau = 0$).

gated variables are complex with no obvious linear relationships. The metho-dology presented herein, however, may serve as a basis for preliminary analysis of deterministic dynamics of several jointly interrelated variables. Because of the importance that SOI has as a driving ocean-atmosphere climatic force, it is important to investigate quantitative links between the SOI and observed local climatic and other geophysical variables. These may then be used as early indicators of near-term extreme weather or long-term effects on available water resources. Consequently, there are needs to develop methods that can display complicated nonlinear relationships among several variables simultaneously. In this respect, the outlined methodology in this paper may be used as a first step towards this objective.

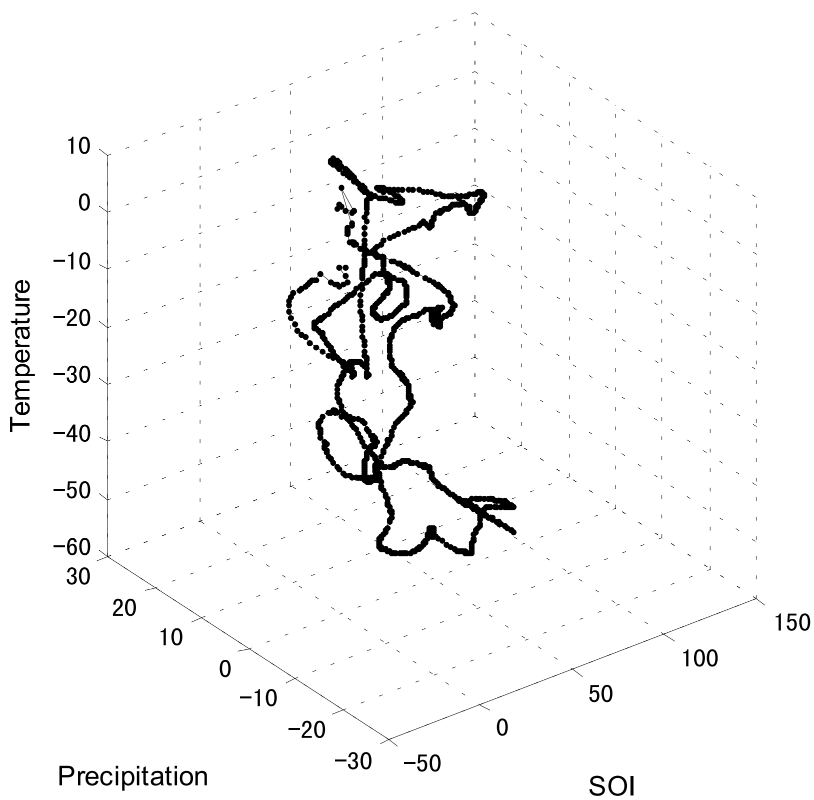

Fig. 10. Joint three-variable phase space plot for SOI, precipitation, and temperature.

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