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CHAPTER 17

Diagnosis of Climate and Weather

Koji Nishiyama

17.1 Introduction

For the last decade, there are increasing concerns regarding global warming and associated future climate as well as recent climate change and weather situations that have caused serious damages (e.g., extremely high or low temperature, serious flood, draught with water stress) to human life and ecosystems. Therefore, it is important to diagnose ‘past and future’ climate changes and weather situations. However, too many meteorological information composing climate and weather situations makes it difficult to extract and interpret significant signals related to serious disasters.

So far, for the extraction of the significant signals, the analysis of the Empirical Orthogonal Function (EOF), which is basically the same as the Principle Component Analysis (PCA) based on linear orthogonal transform among many meteorological variables, has been the most widely used and developed as a conventional method for pattern recognition. For the last decade, unlike the EOF linear analysis, non-linear pattern recognition technique called a self-organizing map (SOM), which is a kind of unsupervised artificial neural networks (ANNs) technique, has also been applied to meteorological studies. The technique is one of useful information tools for classifying visually interpreting high-dimensional complicated climate and weather data.

In such a context, the main topic of this chapter is how to apply the SOM analysis to the diagnosis of climate and weather. The first part of this chapter explains the SOM methodology for identifying high-dimensional complicated weather situations to easily-recognizable patterns, by showing an example of synoptic weather causing heavy rainfall in the Kyushu Islands of Japan, and relates these weather patterns to independent local variable (heavy rainfall frequency) in a specific target area. The second part of this chapter introduces fundamental studies on future climate change caused by global warming, motivated by the Intergovernmental Panel on Climate Change (IPCC), and explains how to apply SOM to the analysis of such future climate change studies.

17.2 Methods for Signal Extraction

EOF and SOM. In the field of climate meteorology, in order to extract globally significant signals related to disasters such as drought, flood, and extremely high temperature, from high-dimensional meteorological variables (e.g., spatial and temporal distribution such as geo-potential height, sea surface temperature, surface pressure), the analysis of the EOF (Preisendorfer 1988) has been the most widely used and developed as a conventional method for pattern recognition. The analysis is basically equivalent to the Principle Component Analysis (PCA), which mathematically determines a new coordinate system consisting of principle components by conducting an orthogonal linear transformation of a set of correlated variables into uncorrelated variables so that variance among variables can be the greatest. Therefore, the EOF analysis has contributed largely to the extraction of a set of globally dominant climate and teleconnection modes with large variance, affecting the past and anticipated climate change. For example, the Pacific Decadal Oscillation (PDO) index (Mantua et al. 1997; Zhang et al. 1997) and Arctic Oscillation (AO) index (Thompson and Wallace 1998) are derived as the leading principal components of monthly SST and 1000 hPa height anomalies north of 20N, respectively. However, there is a shortcoming that the assumption of linearity and orthogonality imposed by EOF, making it difficult to interpret physical meanings of patterns obtained from principal components. There is no guarantee that the EOF patterns have physical meanings, as pointed by Dommenget and Latif (2002). Moreover, even if principal components obtained are mathematically independent from each other, there is no guarantee they are physically independent actually.

On the other hand, unlike the EOF based on the linear constraint, non-linear pattern recognition technique called a SOM, which is a kind of unsupervised artificial neural networks (ANNs) technique in the field of information science, was developed by Kohonen (1995). The SOM provides useful information for helping the interpretation of non-linear complicated features by classifying a set of high-dimensional data into the units (patterns) arranged regularly on a two-dimensional space that can be *easily* and *visually* recognized by '*human eye*' although there is a shortcoming that the number of patterns must be arbitrarily determined in advance. The results obtained by the SOM training show that, in each unit, similar input samples are classified after the SOM training, and the similarities and dissimilarity between the units can be visually recognized by the Euclidean distance between them on the two-dimensional space, as explained in Section 117.3. Moreover, the analysis of the SOM has no cumbersome process equivalent to careful consideration on physical meanings of principal components obtained by the EOF. Owing to such a powerful ability, in the last decade, the SOM has been widely used in many research fields (e.g., various engineering areas, physics, biology, ecological science, medical science, economic science) that require pattern recognition. For example, Nikkilä et al. (2002) applied the SOM to the analysis and visualization of gene expression, and Park et al. (2003) applied it to the recognition of aquatic insect species richness in running water. Since the development of the SOM, it has also been applied to the field of climate and synoptic meteorology, as shown in the next section.

Application of SOM to Meteorology. The SOM methodology available for the analysis of synoptic meteorology is introduced by Hewitson and Crane (2002). The first step of the analyses is to conduct the pattern recognition of high-dimensional synoptic situations (e.g., spatial distribution of geo-potential height, wind, temperature, moisture). The next step is to construct visualized relationships on the two-dimensional SOM space between formed patterns and independent local variables (e.g., extreme high and low temperature, strong wind, heavy rainfall frequency) observed in a specific target area. The final step is to investigate the frequency of synoptic patterns, the frequency of the independent local variable(s) per each synoptic pattern, temporal variability in the frequency per each synoptic pattern, and so on. For example, Hope et al. (2006) investigated temporal variability of synoptic situations and the decrease in precipitation accompanying the decrease in the frequency of troughs in southwest Western Australia. Cavazos (1999) conducted the classification of winter large-scale atmospheric circulation and humidity fields related to extreme rainfall events in northeastern Mexico and southeastern Texas. Nishiyama et al. (2007) extracted synoptic situations related to the occurrence of heavy rainfall in western Japan. Cassano et al. (2006a) extracted synoptic patterns in the western Arctic associated with extreme events at Barrow, Alaska, USA. Crimins (2006) conducted the analysis on synoptic situations related to extreme fire-weather in the southwest United States.

On the other hand, in the analysis of climate, the features of decadal climate change and associated teleconnection patterns were investigated by visualizing spatial climate patterns using the SOM methodology. For example, Johnson et al. (2008) provided the continuum properties of the Northern Hemisphere teleconnection patterns related to climate shift characterized by the North Atlantic Oscillation (NAO). Leloup et al. (2007) demonstrated that the SOM methodology provides the potential ability to classify the ENSO phase and to enhance the understanding of seasonal and decadal variability of ENSO.

The SOM was also applied for evaluating the ability of climate models to reproduce past significant climate modes through inter-comparison among climate models by visualizing the performance of each model. Leloup et al. (2008) assessed the ability of 23 climate models (IPCC-AR4/CMIP3) to reproduce spatial SST variability related to ENSO in the twentieth century. Tennant (2003) assessed the ability of three atmospheric general circulation models (AGCMs) to reproduce daily circulation patterns by comparing these model results with each other. Such analyses are useful for identifying adequate and poor performance of each model.

17.3 Principle of SOM

As shown in Figure. 17.1, the basic structure of SOM consists of two-dimensional arrangement (hereafter named, map) of the units. It takes a hexagonal form, having the same distance between neighboring units. Each unit has a reference vector $m_i(t)$, which is updated through the training process of the SOM. After training, the updated reference vector represents common features among the input data classified into each unit. The reference vector m_i (t) has the same dimension as the input vector x (t). Prior to the SOM training, the reference vector elements are initialized on a random basis, and the input vector elements are normalized to values between 0 and 1 using the maximum and minimum in each element.

The first step is to calculate the Euclidean distance between an input vector $\boldsymbol{x}(t)$ and all the reference vectors $\boldsymbol{m}_i(t)$ and, subsequently, to find the 'winner' unit c with the reference vector closest to the input vector, as shown by Eq. 17.1 and the top panel of Figure 17.1. The 'winner' unit c is called the best matching unit (BMU).

$$c = arg\,\min_i \left\{ \left\| \boldsymbol{x}(t) - \boldsymbol{m}_i(t) \right\| \right\} \qquad \text{(Eq. 17.1)}$$

The next step is to update all the reference vectors against the presentation of the input vector according to Eqs.17.2 and 17.3.

$$\boldsymbol{m}_i(t+1) = \boldsymbol{m}_i(t) + h_{ci}\left(t, \left\| \boldsymbol{r}_c - \boldsymbol{r}_i \right\|\right) \left[\boldsymbol{x}(t) - \boldsymbol{m}_i(t) \right] \qquad \text{(Eq. 17.2)}$$

$$h_{ci}\left(t, \left\| \boldsymbol{r}_c - \boldsymbol{r}_i \right\|\right) = \alpha(t) \cdot \exp\left(-\frac{\left\| \boldsymbol{r}_c - \boldsymbol{r}_i \right\|^2}{2\sigma^2(t)} \right) \qquad \text{(Eq. 17.3)}$$

The modification of the reference vectors is represented by the second term on the right hand in Eq. 17.2 and depends on the neighborhood function $h_{ci}(t, \| \boldsymbol{r}_{\mathrm{c}} - \boldsymbol{r}_{\mathrm{i}} \|)$. This neighborhood function takes a Gaussian form, decreasing with the distance from the BMU, as shown by Eq. 17.3. Therefore, the reference vectors in units closer to the BMU are more strongly modified. Moreover, the neighborhood function decreases with the iteration step t. The rate is governed by a monotonic decrease with the iteration step t according to the decreasing of both the learning-rate $\alpha(t)$ and the width of the neighborhood function $\sigma(t)$ with the iteration step. Consequently, the modification of the reference vectors decreases with the iteration step. To keep the stability of the SOM training, the series of computation procedures from Eqs. 17.1–17.3 needs to be repeated as many times as possible, as shown by Kohonen (1995).

As a result of the SOM training, similar input samples are classified into an identical unit on the map. In other words, each unit on the map can be interpreted as the assembly of similar input samples with a reference vector, which shows representative features among these input samples. Moreover, the neighboring units in the map are similar to each other while distant units are dissimilar on the map, as shown in the bottom panel of Figure 17.1. Therefore, the SOM provides visually recognizable information for interpreting non-linear complicated features.

17.4 Classification of Synoptic Field Patterns Using SOM

The objective of this section is to a) visualize high-dimensionally complicated synoptic fields using the SOM algorithm, and b) extract synoptic field patterns related

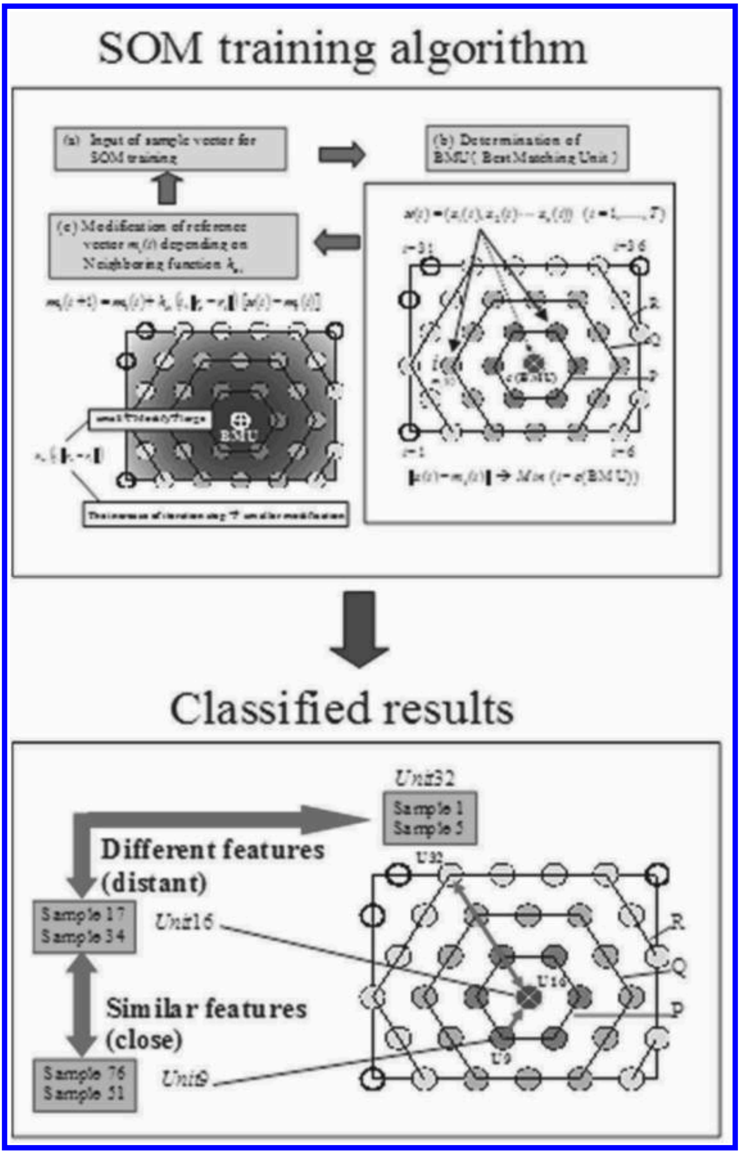

Figure 17.1. Flowchart of the SOM training (top) and the interpretation of classified pattern results on the SOM map (bottom)

to heavy rainfall in western Japan, showing an example of the application of the SOM to meteorology (climate science and weather science). The example of the application is based on Nishiyama et al. (2007), which conducted pattern classification analysis