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Climate variability and its effects on regional hydrology: a case study for the Baltic Sea drainage basin

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Abstract: As climate models can be used to reproduce historical climates, the outcomes can be used to put climate extremes in to a proper historical perspective. This also allows investigation of nonlinear properties of hydrologic processes (e.g. precipitation, runoff) to better understand regional hydrologic dynamics. To this end, the present study uses results from a so-called 'paleosimulation' (i.e. simulation of climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available) covering the Baltic Sea drainage basin and the surrounding areas. Time series of annual temperature, precipitation, and runoff are simulated to study their dynamic characteristics. Three different simulation periods between years 1000 and 1929 are considered: 1000–1199, 1551–1749, and 1751–1929; these three periods represent a warm, a cool, and an intermediate climate episode, respectively. Both linear (autocorrelation function) and nonlinear (phase space reconstruction) methods are employed. The autocorrelation function is a normalized measure of the linear correlation among successive values in a time series, while the basic idea behind the phase space reconstruction is that the past history of a single variable contains important information about the dynamics of the multivariable system.

The 30-year average for all the three variables seems to follow a quasi-periodic behavior. An increasing trend is noted for temperature and precipitation during the later periods, but no such pronounced trend is evident for runoff. There is a general linear correlation between annual temperature and precipitation equal to 0.53, and between precipitation and runoff equal to 0.77; however, the correlation between temperature and runoff is as low as 0.30. The annual temperature series has one significant autocorrelation coefficient (lag 1 year), but precipitation and runoff series have no significant coefficients. Significant and slowly decreasing autocorrelation may be an indication of chaotic dynamics and temporal persistence that could be related to fractals. Due to the small autocorrelation, further analyses are carried out using serial time series (i.e. the simulated data are assumed continuous in time). The 30-year moving average for these serial time series reveals linear correlations between the variables; the cross-correlation between temperature and precipitation is 0.88, between precipitation and runoff is 0.83, and between temperature and runoff is 0.52.

For these serial time series, phase space reconstruction is carried out to investigate the possible presence of attractors. Univariate (temperature, precipitation and runoff, independently) as well as multivariate (temperature-precipitation, temperature-runoff, precipitation-runoff) reconstructions are performed. For reconstruction, a delay time value of 5 years is considered for the univariate cases, while two delay time values (0 and 5 years) are considered for the multivariate cases. The results generally indicate clear attractors for all the variables and combinations, suggesting nonlinear relationships between temperature, precipitation, and runoff. These relationships could be exploited in prediction schemes, in both univariate and multivariate senses. Such an analysis would contribute to a better understanding of regional runoff dynamics due to climate effects. This is especially important for the Baltic Basin, since transport of nutrients, for example, are strongly correlated to the runoff conditions.

Keywords: *Regional hydrology; Baltic sea; climate; temperature; precipitation; runoff; nonlinearity; chaos*

1. INTRODUCTION

Generally speaking, catchment runoff determines water availability for the society. At the same time, runoff is also strongly correlated to (and, more specifically, affects) mass transport of environmental pollutants. From a near-future climate change perspective, it is the regional water balance and runoff that are of main interest. Consequently, much of recent research efforts has been focused on understanding rainfall-runoff dynamics at a regional scale (e.g. the entire Baltic Basin). Understanding the rainfall-runoff process also means understanding of the climatic forcing, especially if climatic interactions are warranted. For Scandinavia and the Baltic, the North Atlantic Oscillation (NAO) is of major importance for precipitation conditions, especially winter precipitation (e.g. Uvo and Berndtsson, 2002; Uvo, 2003). Since the Earth's atmosphere is generally considered to be part of a chaotic system (Lorenz, 1963; Shukla, 1998), it is reasonable to believe that sub-systems of the atmosphere, such as the NAO, will also be chaotic; indeed, studies in recent years have found this to be true (e.g. Morton, 1998). According to this theory, it is impossible to predict the exact time evolution of the NAO, or for that matter major precipitation patterns, beyond a few weeks into the future. Consequently, rainfall-runoff processes will also, at a regional scale where NAO is essential, follow chaotic characteristics, which mean that long-term predictions of climate and runoff become impossible. Repeated short-term forecasts, however, are possible based on information about the chaotic system. The science that deals with the properties of chaotic systems and their identification and prediction is put under the umbrella of dynamical systems theory.

Progress in dynamical systems theory related to regional-scale hydrologic processes that can be related to climatic variations has been hampered due to the non-availability of records of long-term runoff or other water balance components at the regional scale. Another problem is that runoff from small-scale catchments, for example, is often contaminated by noise or local climate-related variations. Large-scale basins, however, provide a great advantage in this context, since the integrated runoff from large basins effectively filters out small-scale variations and leaves a large-scale climatic imprint. Consequently, runoff at large scales provides insights to regional climatic variability and can be vital for understanding long-term climatic patterns. To our knowledge, only one example to this type of study exists in the literature: the Great Salt Lake (GSL). Studying the biweekly volume series of the GSL using nonlinear dynamical tools, Sangoyomi et al. (1996) found evidence of structure in the recurrence patterns of climatic variations that drive hydrologic dynamics in the western US, which were then used by Abarbanel et al. (1996) to predict water level variations with a horizon in the order of a few years.

The objective of the present study is to combine recently acquired knowledge from regional-scale modeling of runoff from the Baltic Basin in the time scale of the last millennium with tools within dynamical systems theory, towards better understanding of regional-scale hydrologic variations driven by climate. Specifically, 'paleosimulation' covering the Baltic Sea drainage basin and the surrounding areas is performed to obtain annual temperature, precipitation, and runoff records for three periods between years 1000 and 1929 (1000-1199, 1551-1749, 1751-1929), which are then analyzed using nonlinear tools.

2. STUDY AREA AND METHODS

The Baltic Sea is the largest brackish water body on Earth and is, thus, of great international importance as well as concern. The drainage basin of the Baltic spans 14 countries and 85 million people, a majority of them living in big cities like St. Petersburg, Copenhagen, Helsinki, Tallinn, Riga, Vilnius, Warsaw, and Stockholm. In recent years, the Baltic has experienced large-scale water quality degradation, affected not only by the runoff from the surrounding drainage areas but also, more critically, by the so-called Major Baltic Inflows (MBIs) that freshen the Baltic Sea water with influx of saline and oxygen-rich water from the North Sea depending on specific sequences of winds and atmospheric pressure (Matthäus and Schinke, 1994; Lass and Matthäus, 1996). These short-lived freshening episodes (about one–three weeks) may be related to NAO and, thus, to chaotic properties of the atmosphere. If runoffs from surrounding drainage basins and MBIs into the Baltic Sea follow chaotic characteristics, then systematic investigation of these processes based on dynamical systems theory may provide insights as to how the water quality in the basin may change in time. This may, in turn, help explain the potential precarious future situation of marine ecosystems in the Baltic.

The analyses carried out herein use the reconstructed temperature, precipitation, and runoff records during the last millennium, after the study by Graham et al. (2008). In Graham et al. (2008), temperature and precipitation were simulated by the coupled atmosphere-ocean global climate model ECHO-G (Legutke and Voss, 1999), and these data were downscaled using the regional climate model RCA3 (Kjellström et al., 2005) coupled with the FLAKE lake model (Mironov, 2007). The well-known conceptual HBV (Hydrologiska Byråns Vattenbalansavdelning) hydrologic model (e.g. Lindström et al., 1997) was used to reconstruct river flow to the Baltic Sea. Graham (1999) calibrated the HBV model for the period 1980-1986 to simulate total runoff to the basin and verified the model for 1986-1994. Subsequently, the model has also been used to predict the effects of future climate (Graham, 2004; Graham et al., 2007). Figure 1 shows the Baltic Basin area that was considered in these studies. Precipitation and runoff analyses focused on the Bothnian Bay, the Bothnian Sea, the Gulf of Finland, and the Gulf of Riga (also shown in the figure). In the present study, three simulation periods are considered: 1000-1199, 1551-1749, and 1751-1929, representing a warm, a cool, and an intermediate climate episode.

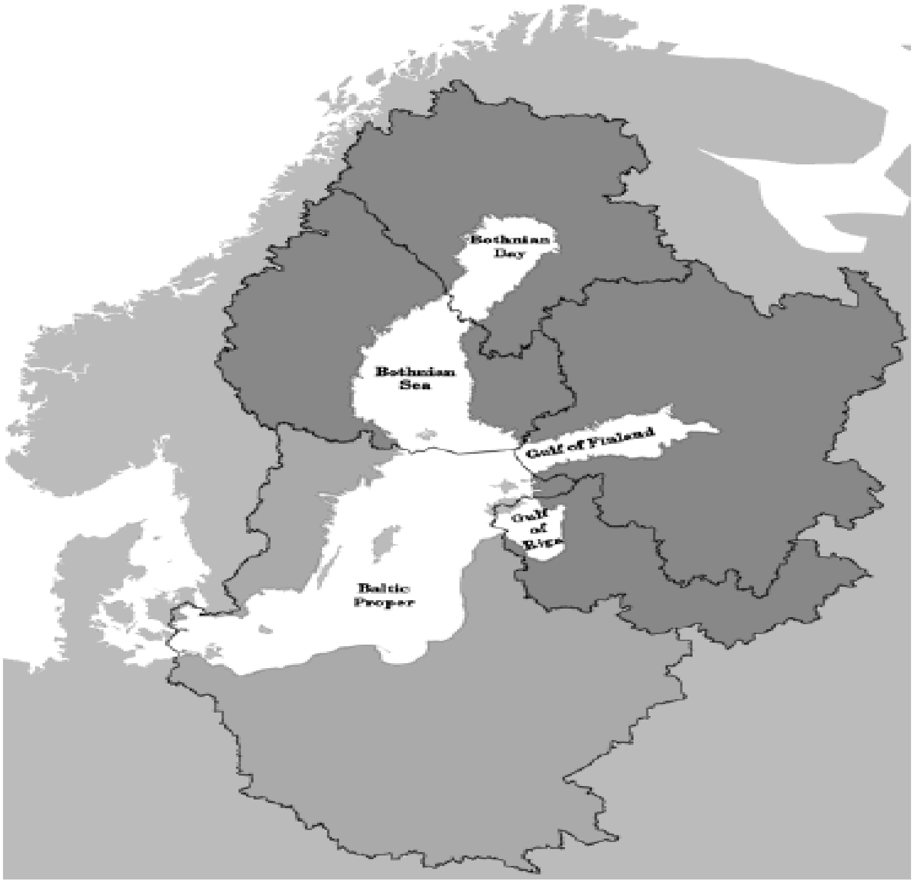

Figure 1. Principal Baltic Sea drainage basins used in the analyses. The Baltic Proper is shown in lighter grey as it was not included in this study [after Graham et al. (2008)].

3. CHAOTIC DYNAMIC SYSTEMS AND REGIONAL HYDROLOGY

Lorenz (1963) was the first to point out possible chaotic characteristics of atmosphere and climate. A major breakthrough in chaos research came when several independent researchers proposed methods to use empirical time series to evaluate the dimension of the attractor in the system underlying such series (Packard et al., 1981; Takens, 1981; Grassberger and Procaccia, 1983). The dimension of the attractor is a way to mathematically characterize the ‘complexity’ of the system’s evolution. A series of investigations conducted subsequently on various climatic data reported presence of low-dimensional attractors (e.g. Nicolis and Nicolis, 1984; Tsonis and Elsner, 1988). These results, however, did not lack criticisms and responses (e.g. Grassberger, 1986; Lorenz, 1991; Sivakumar et al., 2002), since many of these earlier studies involved rather short and noisy time series and often used only one method to identity chaos. Sivakumar (2000) discusses these issues with particular reference to hydrologic time series, while a review of chaos studies in the much broader spectrum of geophysics is presented by Sivakumar (2004).

Despite the controversies, there has been continued interest in chaos studies in climate. Most of these studies, however, have dealt with different observables from global, regional, or local climatic characteristics, and studies on regional hydrology and chaos are almost non-existent. An exception to this is the study by Abarbanel et al. (1996) that, following up on the study by Sangoyomi et al. (1996), used biweekly data of the GSL volume and reported that the regional climate appears governed by an approximately three-dimensional attractor. The biweekly data allowed reasonable predictions up to a few years ahead.

Based on these results, a hypothesis for the present study, on regional climate change impacts on runoff, may be presented as follows. A drainage basin may effectively act as an indicator to display historical climatic states (e.g. Abarbanel et al., 1996). To do so, some pre-requisites need to be fulfilled. First, the drainage basin must be large enough to average out small-scale variations and local climatic influences. Second, depending on the input-output ratio of water in the basin given by E/Q (where E is evaporation and Q is runoff), different basins may display different climatic influences. For example, the GSL has no outflow and, hence, the water level displays an accumulated effect due to climate. For the Baltic Basin, however, the E/Q ratio is lower since there is a significant outflow. This means, in other words, that departures from the accumulated mean outflow would indicate major climatic effects on the basin. With these observations, Figure 2 shows a general hypothesis on the possibilities to reveal chaos in regional climatic impact for runoff from drainage basins. The case for the GSL is plotted in the figure beside the one for the hypothetically included Baltic Basin (note the difference in the E/Q ratio between the two).

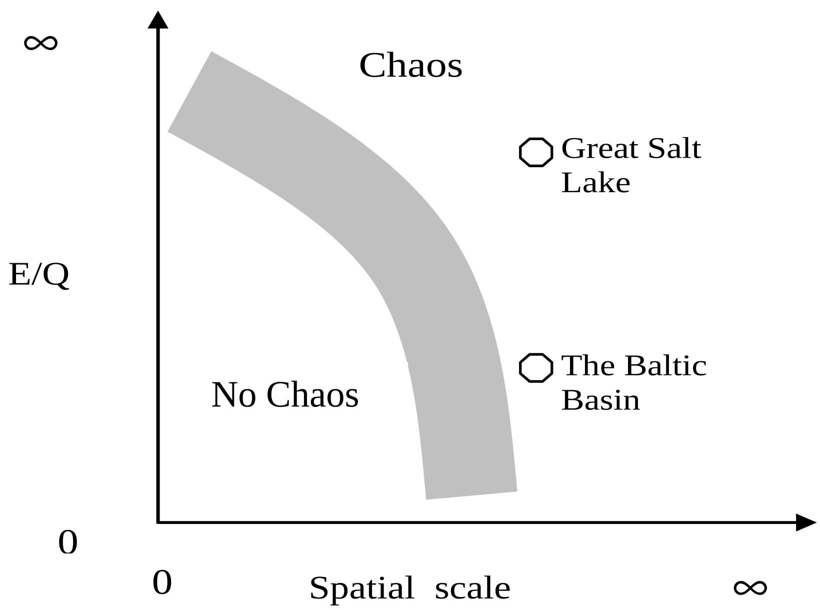

Figure 2. Hypothetical relationship between E/Q (evaporation divided by runoff) and spatial scale for drainage basins and possibility to find chaos.

4. ANALYSES AND RESULTS

Figure 3 shows (bottom to top) the simulated annual temperature, precipitation, and runoff series for the periods 1000–1199, 1551–1749, and 1751–1929, following the methodology described in Section 2. A large variation is obvious for each of the three variables. However, from the 30-year average (shown in the figure with thick lines), each of these variables also appears to follow a quasi-periodic behavior. While an increasing trend is noticeable for temperature and precipitation during the later periods, no pronounced linear trend is evident for runoff. There is a general linear correlation between annual temperature and precipitation equal to 0.53, and between precipitation and runoff equal to 0.77; however, the correlation between temperature and runoff is as low as 0.30.

Figure 4 shows the autocorrelation functions for the above three variables. As seen, annual temperature has one significant coefficient (lag 1 year), but precipitation and runoff have non-significant coefficients. Significant and slowly decreasing autocorrelation may be one indication of chaotic dynamics and also temporal persistence that may be related to fractals. Due to the small autocorrelation, further analyses are carried out using serial time series, which means that the simulated data are assumed continuous in time. The 30-year moving average for these serial time series reveals linear correlations between the variables (figures not shown due to space constraints). The cross-correlation between temperature and precipitation is 0.88, between precipitation and runoff is 0.83, and between temperature and runoff is 0.52. These time series are further used in a nonlinear analysis to investigate the possible presence of attractors.

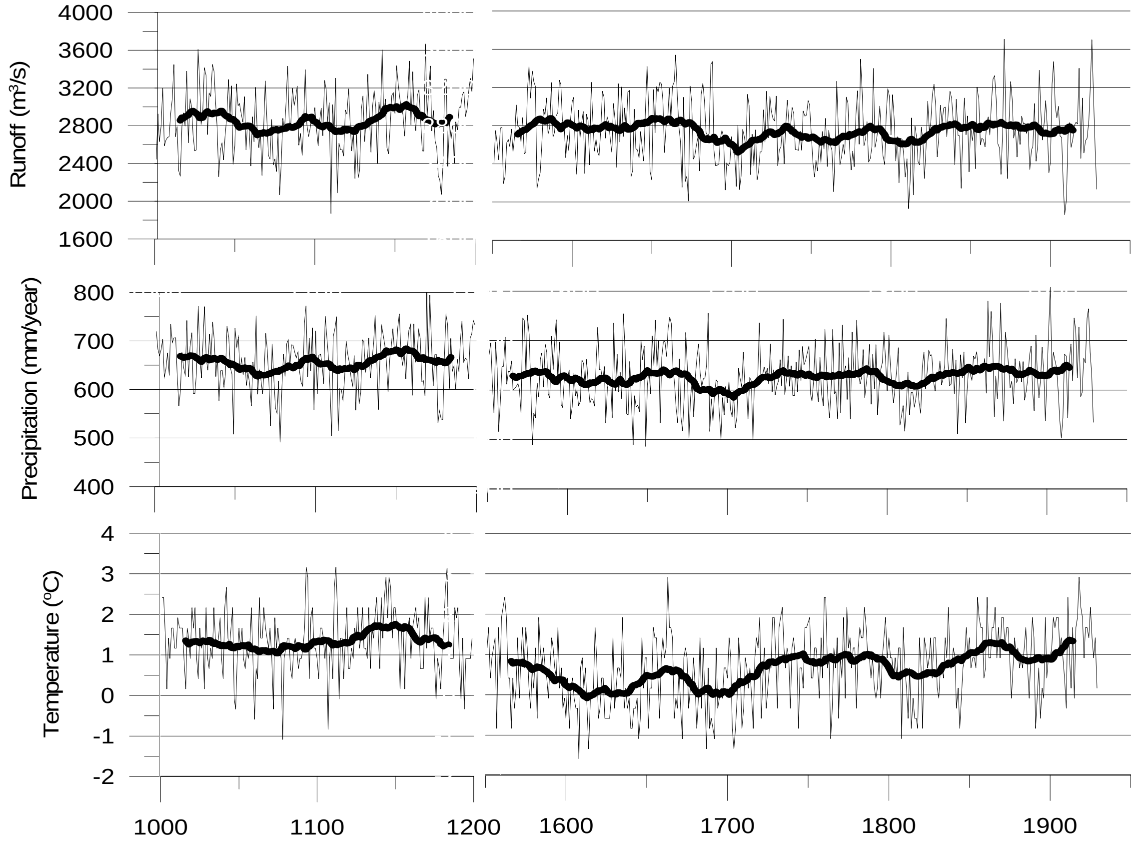

Figure 3. Simulated annual temperature, precipitation, and runoff to the Baltic Sea basin.

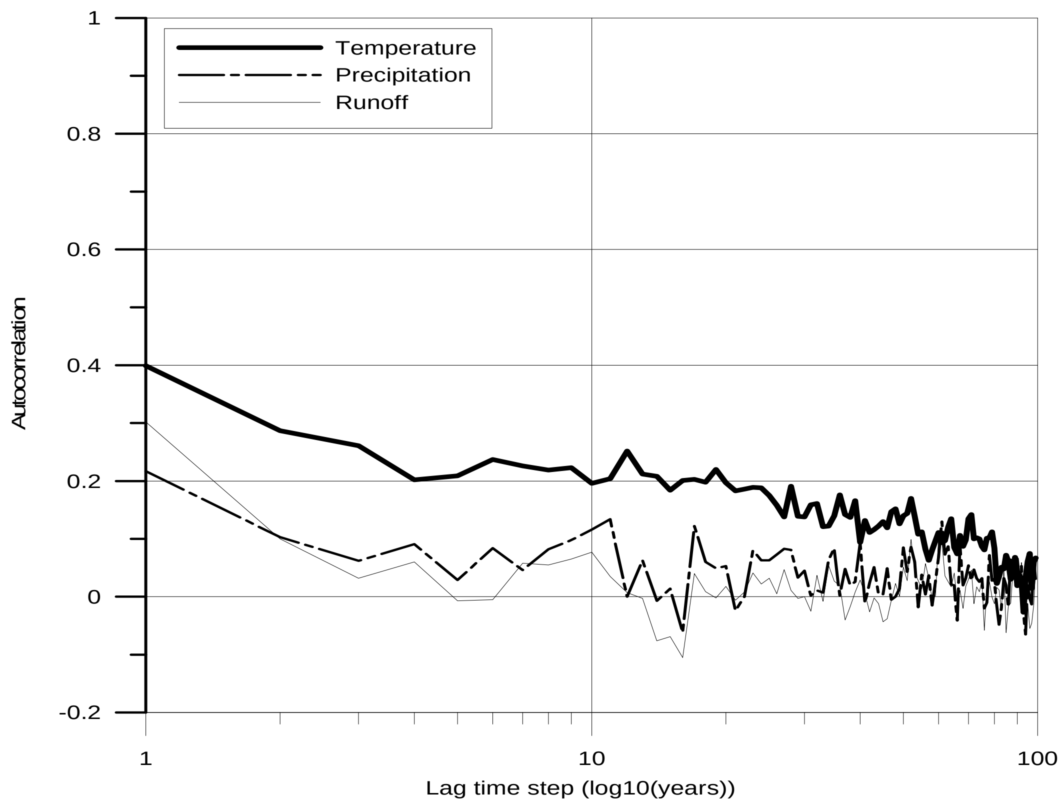

Figure 4. Autocorrelation of simulated annual temperature, precipitation, and runoff.

Figure 5 shows, for example, the attractors for the different variables with a 5-year time lag. The general procedure to evaluate the attractor is to perform a phase space (also called state space) reconstruction. The idea behind the phase space reconstruction is that the past history contains information about unobserved state variables that may be used to define a state at the present time (Packard et al., 1980). The reconstruction procedure is motivated due to the unknown properties of the dynamical system under consideration, such as relevant variables and their total number. The phase space characteristics of the attractor provide reliable information on the system's temporal properties and how well prediction may be performed.

The first column of graphs in Figure 5 shows nonlinear properties of possible attractors for univariate cases. For all three variables, it appears that a rather clear attractor is at hand for a time lag of 5 years. The second column of graphs shows possible attractors for a multivariate case but with no time lag. The graphs show the nonlinear dependence between the different variables. Possible attractors emerge in this case too, though not as clear as in the previous case. The third column of graphs displays possible multivariate attractors with a time lag of 5 years. Here also emerge possible attractors that have a clear nonlinear dependence in time. In essence, there are nonlinear relationships between temperature, precipitation, and runoff and time lag that could be exploited in prediction schemes.

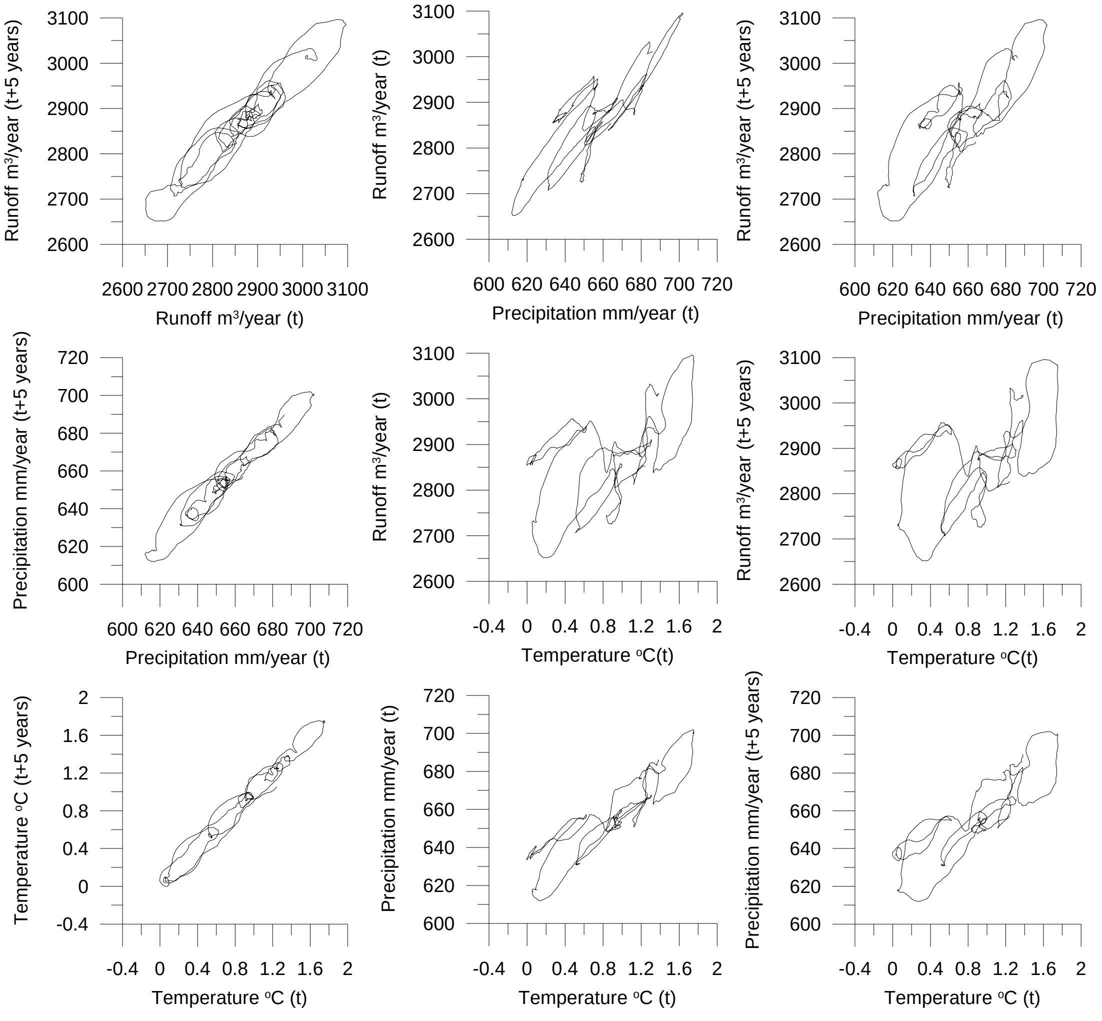

Figure 5. Attractor reconstruction for different combinations of variables.

5. CONCLUSION

We investigated the properties of simulated time series of annual temperature, precipitation, and runoff for the Baltic Basin for three different periods during the last millennium. It was shown that, while linear correlation between the three series is present, the series are also correlated in a nonlinear way, as expressed by the possible attractors in the phase space diagrams. These relationships may be utilized in simple autoregressive moving average schemes (or in others) for prediction purposes. However, a more tempting possibility would be to further investigate the above nonlinear properties in order to exploit prediction possibilities for both univariate and multivariate cases. Studies in this direction, involving application of additional and more sophisticated nonlinear techniques (e.g., correlation dimension, false nearest neighbors, Lyapunov exponents), are underway. Such an analysis would certainly contribute to a better understanding of regional runoff dynamics due to climate effects. This is especially important for the Baltic Basin, since transport of, for example, nutrients, is strongly correlated to runoff conditions.

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