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DYNAMIC CHARACTERISTICS OF TEMPERATURE, PRECIPITATION AND RUNOFF TO THE BALTIC SEA DURING THE PAST MILLENNIUM

by RONNY BERNDTSSON[1], BELLIE SIVAKUMAR[2], JONAS OLSSON[3], and L. PHIL GRAHAM[3]
1 Department of Water Resources Engineering & Center for Middle Eastern Studies, Lund University, Lund, Sweden
e-mail: Ronny.Berndtsson@tvrl.lth.se
2 Department of Land, Air and Water Resources, University of California, Davis, USA
3 Research and Development, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

Abstract

The present study used results from a 'paleosimulation' covering the Baltic Sea basin and the surrounding areas to investigate chaotic properties of temperature, precipitation, and runoff. Three periods between years 1000 and 1929 (1000–1199, 1551–1749, and 1751–1929), representing a warm, a cool, and an intermediate climate episode, respectively, were studied. Time series of annual temperature, precipitation, and runoff were analyzed using phase space reconstruction (both univariate and multivariate) to investigate their dynamic and chaotic nature. The phase spaces for these variables display more or less clear attractors, suggesting possible nonlinear determinism in the underlying dynamics. This property may be exploited for pattern recognition and more accurate short-term predictions, which would contribute to a better understanding of regional runoff dynamics due to climate effects.

Key words – Baltic Sea; regional hydrology; temperature; precipitation; runoff; nonlinearity; chaos

Sammanfattning

Föreliggande studie använde resultat från en s k paleosimulering för Östersjön med omgivande avrinningsområde för att undersöka kaos i temperatur, nederbörd och avrinning. Tre perioder mellan 1000 och 1929 (1000–1199, 1551–1749 och 1751–1929), representerade en varm, en kall och intermediär klimatperiod. Tidsserier för årlig temperatur, nederbörd och avrinning analyserades med hjälp av fasrumsanalys för att undersöka kaotiska och dynamiska egenskaper hos tidsserierna. Analysen visade att alla tre variablerna innehåller mer eller mindre tydliga attraktorer som indikerar att tidsdynamiken kan beskrivas av kaosteori. Resultatet kan användas för att görs korttidsförutsägningar av hydrologiska variabler genom inverkan av klimatet.

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 climatic change perspective, it is the regional water balance and runoff that are of main interest. Consequently, much of recent research efforts have been focused on understanding the rainfall-runoff dynamics at a regional scale, such as the entire Baltic Basin (e.g. Graham and Jacob, 2000). Understanding rainfall-runoff process also means understanding of the climatic forcing, especially if climatic interactions are warranted. For Scandinavia and the Baltic, it has been shown that the North Atlantic Oscillation (NAO) is of major importance for precipitation conditions, especially winter precipitation (e.g. Uvo and Berndtsson, 2002; Uvo, 2003). Because 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 Earth's atmosphere, such as the NAO, would also be chaotic. The NAO, defined as the difference in air pressure between Iceland and the Azores, and its related index (NAOI) are perhaps the most important climatic anomalies for the Northern Hemisphere (e.g., Wallace and Gutzler, 1981). According to this, the NAO provides a potential precipitation predictor for especially northern Europe. Indeed, studies in recent years have found this to be true (e.g. Morton, 1998). The chaotic theory states that the time evolution of a chaotic variable is completely deterministic, however, due to unknown boundary conditions it is impossible to predict the exact time evolution of, e.g., the NAO, or for that matter major precipitation patterns, beyond a few weeks into the future. Consequently, rainfall-runoff processes would 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 dynamic systems theory (e.g. Abarbanel, 1996).

Progress in dynamic systems theory (DST) related to regional-scale hydrologic processes that can be related to climatic variations has thus far been hampered due largely to the non-availability of records of long-term runoff or other water balance components at the regional scale. Another inter-related problem is that runoff from small-scale catchments is often contaminated by 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, thus, can be crucial for understanding the long-term major climatic patterns. To our knowledge, only one example to this type of study exists in the scientific literature: the Great Salt Lake (GSL). Studying the biweekly volume time series of the GSL using nonlinear dynamic tools, Sangoyomi et al. (1996) found evidence of structure in the recurrence patterns of climatic fluctuations that drive the hydrologic dynamics of the western United States, which were then utilized by Abarbanel et al. (1996) to predict water level variations with a horizon in the order of a few years. The Great Salt Lake is an example of a large hydrological system where small-scale variations are evened out. Consequently, similar large hydrological systems such as the Baltic Basin may display similar chaotic properties.

The objective of the present study is to combine recently acquired knowledge from regional-scale modeling of runoff from the Baltic Basin with analyses tools within DST in the time scale of the last millennium, towards better understanding of the regional-scale hydrologic variations driven by climate. More specifically, '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 is performed to obtain annual temperature, precipitation, and runoff records for three different periods between years 1000 and 1929 (i.e. 1000–1199, 1551–1749, and 1751–1929), which are then analyzed using a nonlinear tool. The nonlinear tool is called phase-space reconstruction or investigation of the multi-dimensional strange attractor (e.g. Packard et al., 1980; Takens, 1981). The rest of the paper is organized as follows. First, a brief description of the Baltic Basin is provided. Next, the DST and its applications to regional hydrology are introduced. Then, analyses of reconstructed temperature, precipitation, and runoff are presented. Finally, some practical implications of the present results are highlighted.

Study Area

The Baltic Sea is the largest brackish water body on Earth and, consequently, 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 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 atmosphere 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 DST may provide insights as to how the water quality of the Baltic Basin may possibly change in time. This may, in turn, help explain the potential precarious future situation of marine ecosystems in the Baltic.

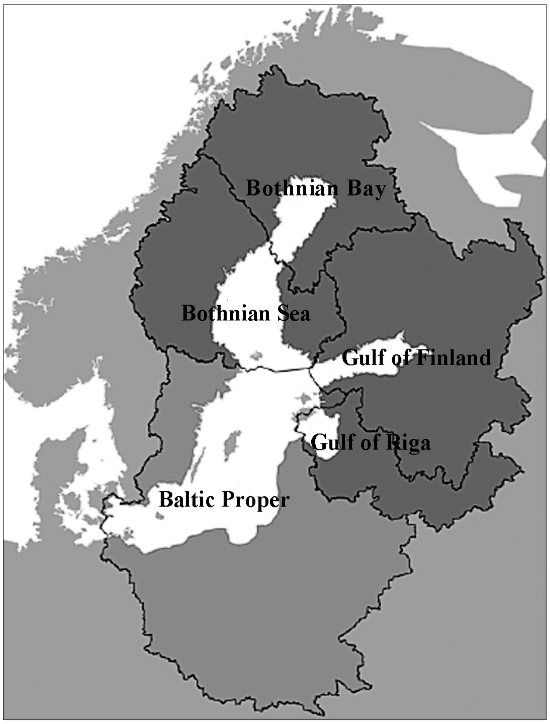

Figure 1. *Principal Baltic Sea drainage basins used in the analyses. The Baltic Proper is shown in lighter grey as it was not included in this study, after Graham et al. (2008).*

Methods

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; Min et al., 2005), and the data were then 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.

The global climate model ECHO-G (Legutke and Voss, 1999, Min et al., 2005) is constituted by the atmospheric model ECHAM4 (Roeckner et al., 1999) that is coupled to the ocean model HOPE-G (Wolff et al., 1997). The horizontal grid resolution of ECHO-G is about 3.75° for the atmosphere layer and 2.8° for the ocean layer with increasing resolution of 0.5° at the equator (20–100 km). The simulation used here is described in González-Rouco et al. (2003) and von Storch et al. (2004). It is based on reconstructed forcing from three major external variables based on ice core data: (i) annual global concentrations of CO_2 and CH_4, (ii) volcanic radiative forcing, and (iii) solar radiative forcing. These estimates were combined in ECHO-G with historical sunspot observations (after around 1700).

The RCA3 model has a horizontal resolution of 0.5°. The model was evaluated in a boundary experiment with data from the period 1961–1999 (Uppala et al., 2005; Kjellström et al., 2005). They showed that the model could reproduce European as well as Swedish climate in a reasonable way (Moberg et al., 2006).

Graham (1999) calibrated the HBV model for the period 1980–1986 to simulate total river flow from the Baltic Sea drainage basin and then verified the model from 1986–1994 with reasonably good results. A Nash-Sutcliffe efficiency R^2 (Nash and Sutcliffe, 1970) of 0.84 for total daily river flow to the Baltic Sea in an independent verification period (1986–1994) was achieved. Subsequently, the model has also been used to predict the effects of future climate (Graham, 2004; Graham et al., 2007). 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 were considered: 1000–1199, 1551–1749, and 1751–1929. These three periods represent a warm, a cool, and an intermediate climate episode, respectively.

Chaotic Dynamic Systems and Regional Hydrology

Lorenz (1963) was one of 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., 1980; 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 on various climatic data reported presence of low-dimensional attractors (e.g. Nicolis and Nicolis, 1984; Fraedrich, 1986; Essex et al., 1987; Tsonis and Elsner, 1988; Rodriguez-Iturbe et al., 1989; Jayawardena and Lai, 1994; Sivakumar et al., 2001; Nordstrom et al., 2005). These results, however, did not lack criticisms and responses (e.g. Grassberger, 1986; Osborne and Provenzale, 1989; Lorenz, 1991; Sivakumar et al., 2002; Sivakumar, 2005), because many of these (earlier) studies involved rather short (few hundred data points) and noisy time series and often used only one method (correlation dimension) to identity chaos. Sivakumar (2000, 2009) discuss-

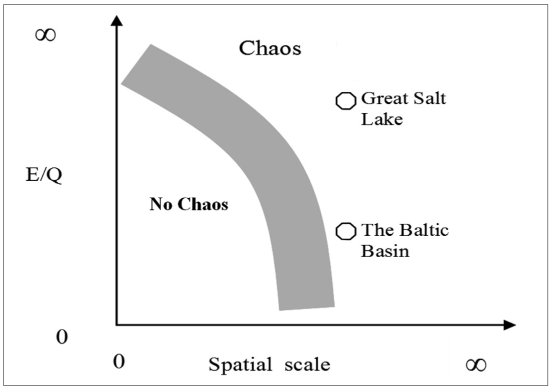

Figure 2. *Hypothetical relationship between* E/Q *(evaporation divided by runoff) and spatial scale for drainage basins and possibility to find chaos.*

es such studies and issues with particular reference to hydrologic time series, while a review of chaos studies in the broader spectrum of geophysics is presented by Sivakumar (2004).

Despite the above controversies, there has been a great interest, in recent years, in chaos studies in climate. Most of these studies, however, have dealt with different observables from local climatic characteristics, and studies on regional hydrology and chaos are still rare. An exception to the latter is the study by Abarbanel et al. (1996) that, following up on the study by Sangoyomi et al. (1996), used biweekly data of the Great Salt Lake volume and reported that the regional climate appears governed by an approximately three-dimensional attractor. The attractor dimensionality and phase-space characteristics are ways to describe the variation in time. A low-dimensional attractor means a more complex temporal variation as compared to a high-dimensional attractor The phase-space characteristics of the attractor thus indicate the temporal properties of the system and also how well prediction may be performed for future times. A quantitative estimate of the system´s predictability is the Lyapunov exponent. It measures the system´s speed of divergence of trajectories from nearby initial conditions (Abarbanel 1996; Rodriguez-Iturbe et al. 1989). In the case of Sangoyomi et al. (1996), the biweekly data allowed reasonable predictions up to a few years ahead for the Great Salt Lake. In a similar way, investigation of a possible attractor for the Baltic Sea may indicate to what extent predictions can be made for future times. However, based on the comparison between the Great Salt lake and the Baltic Basin, both of which represent regional hydrological systems, 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,

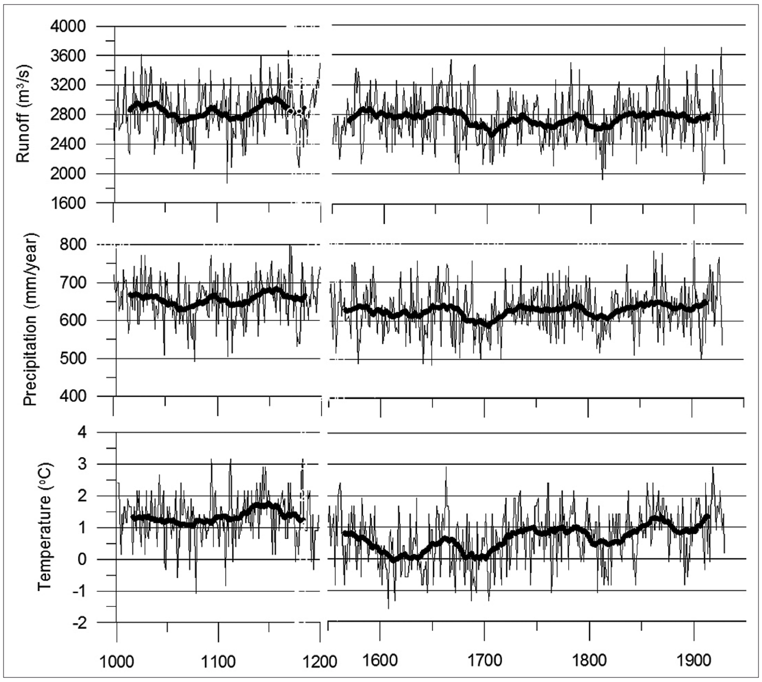

Figure 3. *Simulated annual temperature, precipitation, and runoff from areas delineated in Figure 1. Thick line shows 30-year average.*

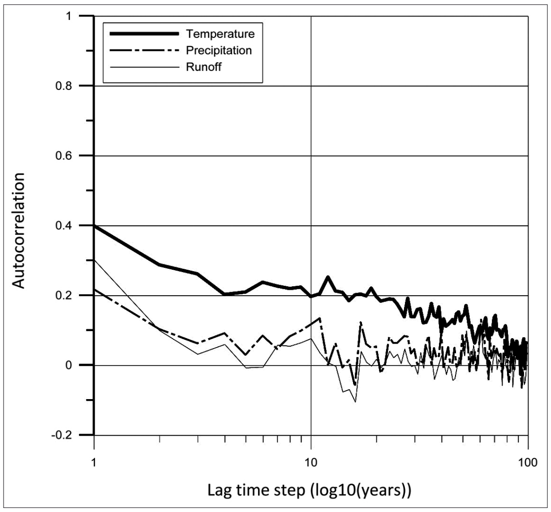

Figure 4. *Autocorrelation of simulated annual temperature, precipitation, and runoff according to Figure 3.*

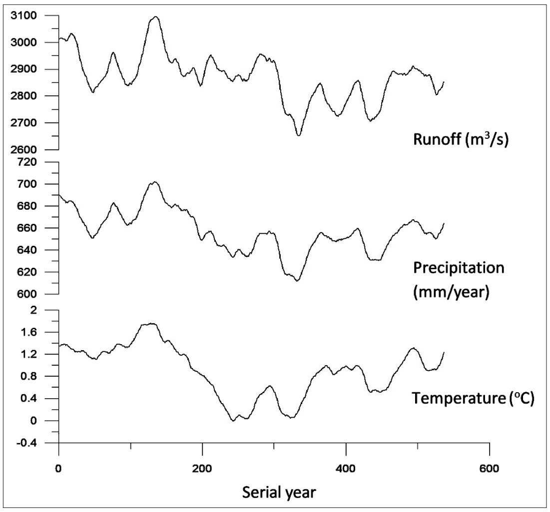

Figure 5. *Serial 30-year moving average time series used in attractor analyses.*

however, some pre-requisites need to be fulfilled. Firstly, the drainage basin must be large enough to average out small-scale variations and local climatic influences. Secondly, 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 (see Figure 2). For example, the Great Salt Lake 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 as 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 regarding possibilities to reveal chaos in regional climatic impact for runoff from drainage basins. The case for the Great Salt Lake 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).

Analyses and Results

Figure 3 shows (top to bottom) the simulated runoff, precipitation, and annual temperature time series for the periods 1000–1199, 1551–1749, and 1751–1929. According to the 30-year average (shown in the figure with thick lines), all three variables appear to follow a quasi-periodical behavior. Also, while an increasing trend is noticeable for temperature and precipitation during the later periods, no 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.

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 has non-significant coefficients. Significant and slowly decreasing autocorrelation may be one indication of chaotic dynamics (e.g. Abarbanel et al., 1996) and also temporal persistence that may be related to fractals (e.g. Rodriguez-Iturbe et al., 1989). Due to the small autocorrelation, however, further analyses are carried out using serial time series, which means that the simulated data are assumed continuous in time. Figure 5 presents the 30-year moving average for these serial time series. It reveals an obvious linear correlation between the variables. The cross-correlation between temperature and precipitation is 0.88 and precipitation and runoff is 0.83. The cross-correlation 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 6 shows these possible attractors for the different variables and with a 5-year time lag. The general procedure to evaluate the attractor is to perform a phase space (sometimes called state space) reconstruction. The basic idea behind the phase space reconstruction is that the past (and future of the) time series contain information about unobserved state variables that may be used to define a state at the present time (e.g. Packard et al., 1980). The procedure of phase space reconstruction is

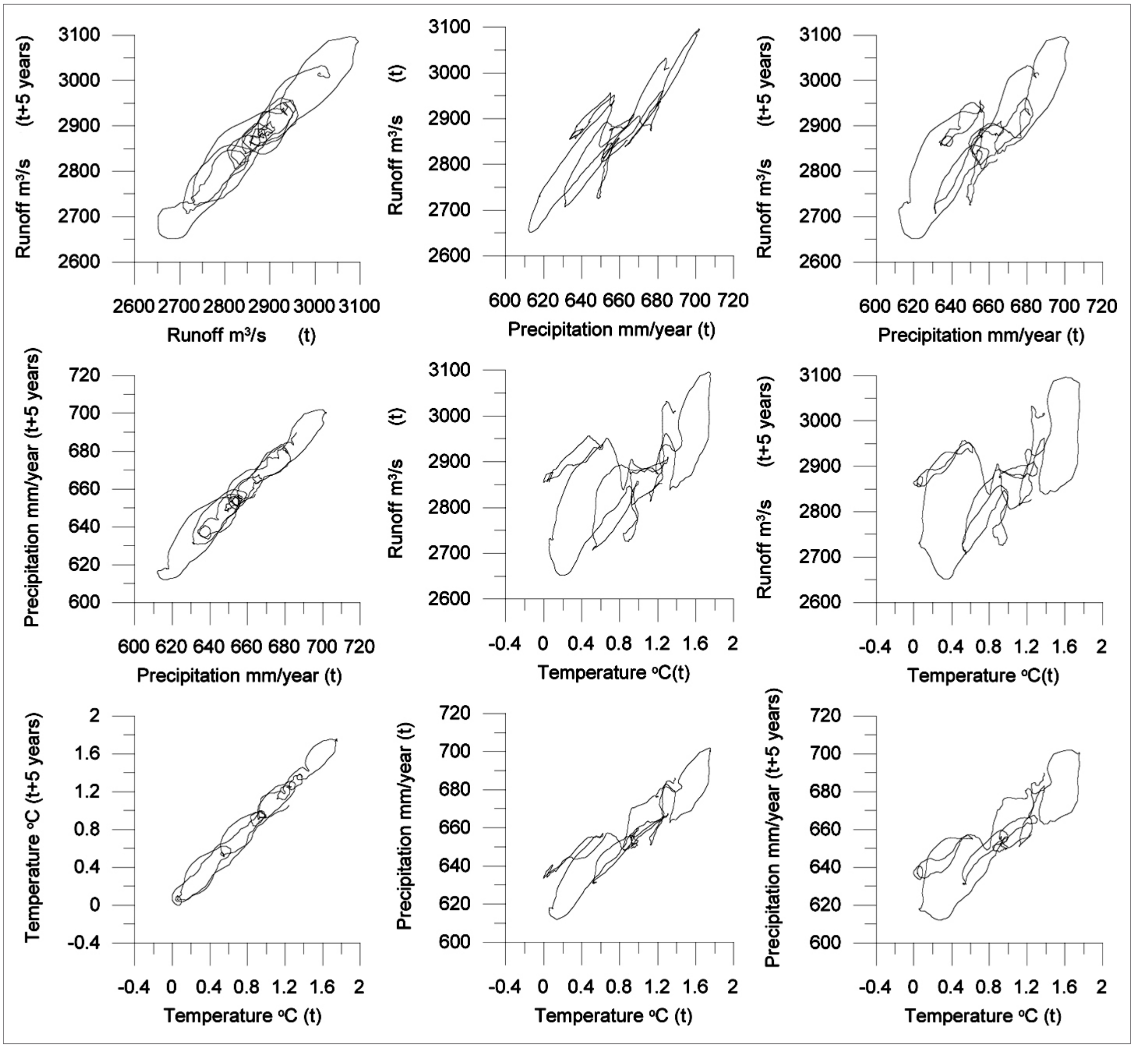

Figure 6. *Attractor reconstruction for different combinations of variables and a time horizon of 5 years.*

motivated due to the unknown properties of the dynamic system under consideration, such as relevant variables and their total number. The phase space characteristics of the attractor provide reliable information on the temporal properties of the system and how well prediction may be performed.

The first column of graphs in Figure 6 shows nonlinear properties of possible attractors for univariate cases. For all the 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, consequently, show the nonlinear dependence between the different variables with no time lag. Possible attractors emerge in this case too, though not as clear as in the previous case. The third column of graphs displays multivariate possible attractors with a time lag of 5 years. Here also emerge possible attractors that have a clear nonlinear dependence in time. To summarize, there appears to be nonlinear relationships between temperature, precipitation, and runoff and time lag that could be exploited in prediction schemes.

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 correlations between the three series are 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 for obtaining further information on the nonlinear dynamic nature of the system(s) governing these variables and also for pattern recognition and prediction purposes. Studies in this direction, involving application of additional and more sophisticated nonlinear techniques (e.g. correlation dimension, false nearest neighbours, Lyapunov exponents), are underway, details of which will be reported elsewhere. 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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