A Conceptual Model of Abrupt Shifts in the Biosphere-Climate System

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Abstract

Time series analysis of global temperature and ~70 other global and local parameters indicates the presence of abrupt shifts between stationary states. The concept of non-linear systems, which undoubtedly include the "biosphere-climate" system, makes the threshold response to gradually increasing influence factor (the increase in greenhouse gas concentrations) quite expectable. Quasi-stable regimes taking place between the shifts presume the existence of some regulation mechanism which can maintain global temperature near constant in the presence of changing externalforcing.Some authors suggest regulation of surface temperatures by clouds.Understanding the nature of such shifts and stationary regimes between them at qualitative concepts can be achieved by using conceptual small-scale models. In the paper some phenomenological extension of Lorenz-84 Model devoted to low order description of atmospheric circulation accounting possible clouds feedback was considered. It was shown the model itself is able to reduce the effect of forcing changes. Involving clouds feedback increases the resistance of the model to external disturbances.

Keywords: climate shifts, multiple equilibria in climate, staircase-like climate dynamics

1. Introduction

In accordance with linear representation of climate system gradual increasing of climate forcing due to growth of green-house gases atmospheric concentration has to lead to gradual growth of global temperature. Detection of abrupt climatic shifts shared by quasistationary periods (Belolipetsky, 2014; Belolipetsky *et al*., 2015; Hare, Mantua, 2000; Reid *et al*., 2001; Reid *et al*., 2016; Tian *et al*., 2008) corresponds much more closely to the idea about biosphere-climate system (BCS) as an essentially non-linear system. Accepting the non-linearity of BCS makes multistable states of it expectable, but the mechanism of the multistability is under the question. This question is of great importance since the time of an another shift is difficult to predict, and in addition, there is a chance that the next stationary temperature level can significantly impair the quality of life of the significant part of human population. Four possible mechanisms of multistability characterized by more than two stable states were mentioned early (Bartsev *et al*., 2017) and two of them (coupled bistable systems and transitions between attractors of chaotic or near chaotic natural oscillator) were considered. Natural oscillators possessing several attractors seem to be more appropriate versions since they simultaneously demonstrate variability typical to weather (Garay, Indig, 2015; Lorenz, 1984, 2006; Vallis, 1986). It was shown that transitions between attractors of Lorenz-84 Model (Freire *et al*., 2008) can be interpreted as abrupt climatic shifts. The paper is devoted to testing the stability stationary states of the model against to external forcing changes and possible influence of cloud feedback.

2. Materials and methods

Lorenz-84 Model was used as basic low order model of atmospheric circulation (Lorenz, 1984, 2006). In the paper (van Veen, 2003) detailed inference of the model from the initial spatially distributed equations was given. Lorenz-84 model was obtained via accepting a number of simplifying assumptions in particular intermediate six dimensional model was reduced to a linearisation of the invariant manifold about the Hadley state. Hadley state describes a strong jet in the upper layer, rising air at the south boundary and sinking air at the north boundary. The link between a Galerkin truncation of a quasi-geostrophic baroclinic model and the Lorenz-84 model made by (van Veen, 2003) justifies the use of the latter in conceptual studies of atmosphere and climate dynamics.

The model consists of three equations:

$$\begin{aligned}\frac{dx}{dt} &= -y^2 - z^2 - ax + aF\\ \frac{dy}{dt} &= xy - y - bxz + G\\ \frac{dz}{dt} &= bxy + xz - z,\end{aligned} \qquad (1)$$

Here x represents the deviation of pole ward temperature gradient or the intensity of the symmetric globe-encircling westerly wind current from ones of the Hadley state, y and z represent the cosine and sine phases of a sequence of eddies which are large-scale and superposed. The variables y and z are the strengths of cosine and sine phases of a chain of superposed waves transporting heat poleward. The terms in b represent displacement of the waves due to interaction with the westerly wind. The coefficient *a*, if less than 1, allows the westerly wind current to damp less rapidly than the waves. *F* and *G* are thermal forcings: *F* represents the symmetric cross-latitude heating contrast and *G* accounts for the asymmetric heating contrast between oceans and continents. Investigating the behavior of atmospheric circulation model at periodic forcing imitating (for example) daily cycle was conducted by Lakshmi and Vasundhara (2012). Accounting the influence of clouds to the model properties can be phenomenologically accomplished via extending expressions for *F* and *G* terms:

$$F(t,x,y) = F_0(A\cos(\omega t)+1)(1-\alpha W(x,y))$$

$$G(t) = G_0(A\cos(\omega t)+1) \qquad (2)$$

where α is albedo caused by clouds; *W(x, y)* – total cloud fraction.

Formula for *W(x, y)* was built via simplification dependencies presented in (Abbot, Tziperman, 2008):

$$W(x,y) = th(\sigma x)(1+\rho y).$$

Negative values of *th(x)* function describes the case of low clouds, which promote increasing of temperature of lower layer of initial model by van Veen (2003).

For calculations and plotting, SciLab 5.4 was used.

3. Results

Computer experiments showed that on the background of irregular dynamics (Fig 1, Fig 2) the model demonstrates an ability to prevent essential increasing amplitude of the variables variability at significant increasing temperature forcing (Fig.3, 1A, 1B). This result can be considered as preliminary answer to the question on the mechanism of quasi stability between shifts. As can be seen from Fig.3 clouds decrease the variability of temperature operating as some amplifier of atmospheric circulation stability. The appearance of bimodal distributions after increasing thermal forcing can be explained by decreasing variability and the appearance of preferred trajectories (Fig.2).

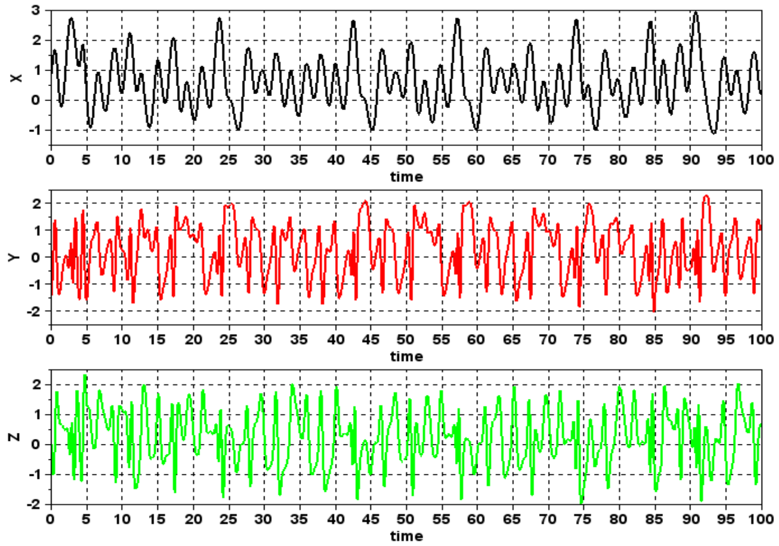

Figure 1. Typical dynamics of the model (a=0.25; b=4; F_0=8; G_0=1.2; A=1; ω=3; α=0; σ=2; ρ=0.1).

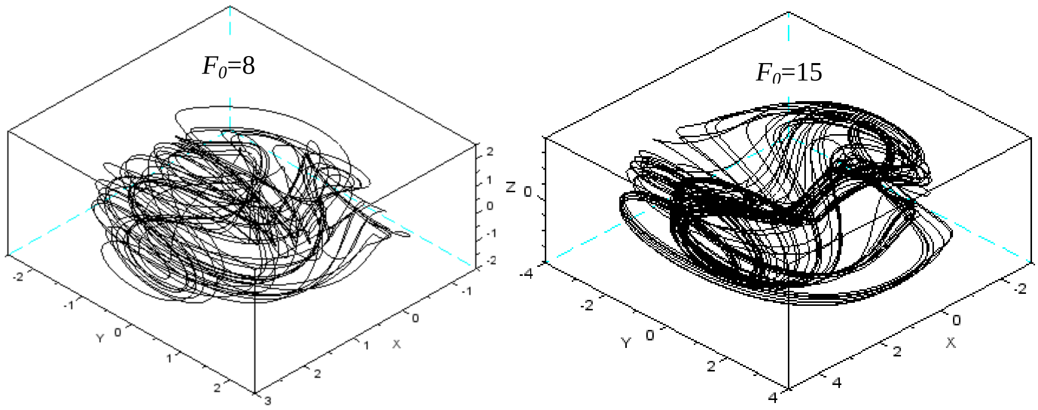

Figure 2. Phase trajectories of the model under different forcing values (a=0.25; b=4; G_0=1.2; A=1; ω=3; α=0; σ=2; ρ=0.1).

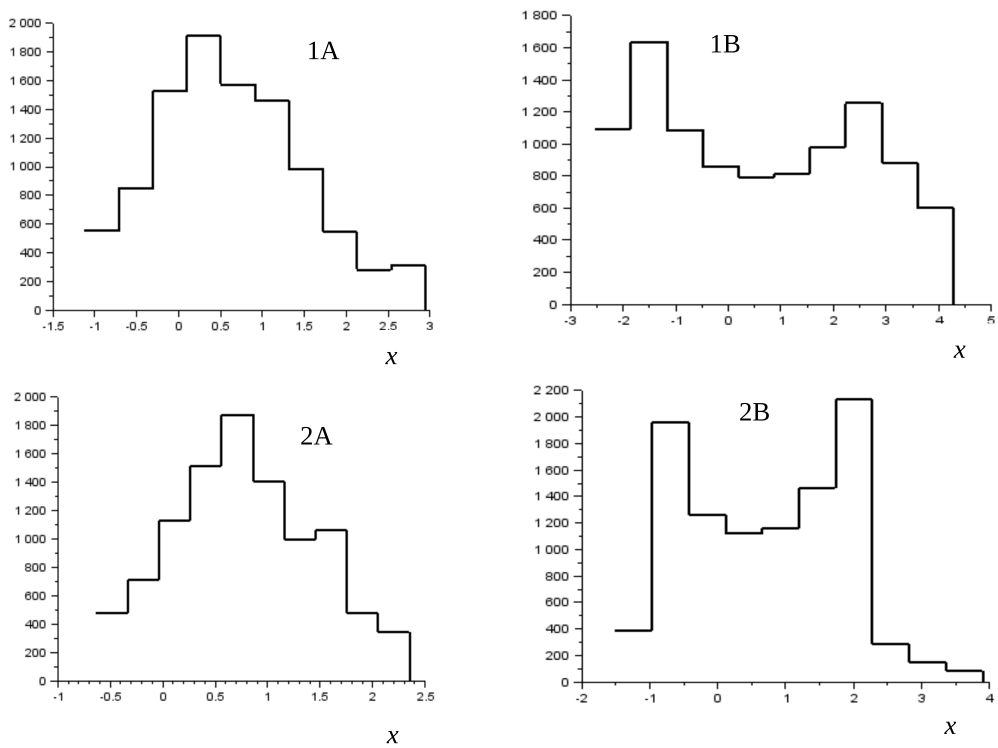

Figure 3. Reaction of the model to the forcing increasing and clouds influence (case A - F_0=8, B - F_0=15; case 1 - α=0, 2 - α=0.25).

4. Discussion and conclusions

Simple low order model of atmospheric circulation manifested an ability to keep values of variables inside relatively small operation ranges despite significant changes of forcing. Involving clouds increased effect of stabilization. This result is quite expectable from any more or less adequate model since on the background of very variable weather our climate looks like more or less unchanging givenness. However, detected abrupt shifts require to combine in one concept stability and variability of climate. Low order models give a possibility to come to this concept by successive approximations. Simplicity of the models makes this approximation visible.

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