Multistable states in the biosphere-climate system: towards conceptual models

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Abstract. Forecasting response of the biosphere and regional ecosystems to observed and expected climate change is the fundamental problem with obvious practical significance. Fundamental non-linearity of the climate system and biosphere makes feasible implementing multiple states and threshold processes in the biosphere-climate system (BCS) in response to gradually increasing influence factor (greenhouse gas concentrations growth). Really time series analysis of global temperature and other global and local parameters indicates the presence of abrupt transitions between stationary states. Identification of the switching mechanisms using general circulation models of the atmosphere and the ocean is associated with the obvious difficulties due to their complexity. Understanding the nature of such switches at qualitative level can be achieved by using a conceptual small-scale models. Some variants of possible mechanisms capable of generating these shifts and simultaneously supporting quasi-stationary periods between them are discussed.

1. Introduction

Prediction of the biosphere and regional ecosystems reaction to observed and anticipated climate change under different scenarios of anthropogenic influence is a fundamental problem which is of obvious practical value. This prediction of the state of "biosphere-climate" system (BCS) is complicated by its fundamental non-linearity that can produce multiple steady states of the system and the threshold switching between these states.

A good example of the manifestation of non-linear properties of the BCS is so-called "pause" or "hiatus" of global temperature rise which is interpreted as a result of the transition of the climate system to another state [1]. Moreover it was observed [2], [3] that Earth temperatures on both local and global scales exhibit sharp shifts at 1976/1977, 1987/1988 and 1997/1998 years. These shifts are more or less visible on the background of natural climate variability. Changes of atmospheric [4], [5], hydrological [6], [7] and ecological [8], [9], [10] parameters were observed together with temperature shifts.

These fast shifts between stationary states cause particular attention since the time of 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.

There are two points of view on these environmental shifts. The first one is the shifts are the result of superposition of natural oscillations and continuous anthropogenic warming [11], [12]. The second
one is that these shifts are the manifestations of the properties of the climate system itself. They are not simply acceleration of temperature rise, caused by coincidence of various processes, but these shifts represent some structural changes in climate system masked by variability.

According to the first point of view there are no special mechanisms of shifts, and since they are the result of natural oscillations superposition, they do not need special attention. Accepting the second point of view and accounting that the most portion of observed recent warming is caused by the shifts we come to importance of the phenomenon investigation. In this case mechanics of shifts on the one hand and processes producing quasi-stationary periods (like recent temperature pause) on the other hand are to be in the focus of our attention.

The cessation of global temperature growth observed in the past 13 years contradicts the prediction based on the IPCC (Intergovernmental Panel on Climate Change) models of general atmosphere and ocean circulation [1]. The absence of a direct relationship between the growing concentration of green-house gases in the atmosphere and the global temperature can be interpreted as a manifestation of the own dynamics of the Earth's climate system. So prediction of abrupt changes seems to be very serious challenge to investigators in comparison with the prediction of gradual dynamics since nonlinearity plays key role in the shifts origin.

Climate and biosphere indices are highly variable in space and in time. Commonly used technique for identifying patterns of variability in climate science is empirical orthogonal function (EOF) analysis [15]. Conceptually, EOF analysis determines a spatio-temporal pattern of variability that accounts for the maximum covariance between the field anomaly time series at all pairs of grid points in the data. Each EOF pattern is associated with corresponding principal component (PC) of time series [16], which describes the temporal evolution of the EOF pattern. The PC time series may be obtained by projecting the EOF pattern onto the original anomaly field at each time step so as to find the sign and amplitude of the pattern at any given time.

Early studies [13], [14], [15] on short and long timescales global temperature variability and trends showed that first principal component (PC1) of global sea surface temperature (SST) is almost the same as various ENSO (El Nino South Oscillation) indexes (Nino3.4, SOI, MEI). Linear adjustment on ENSO by means of subtracting PC1 projection from surface temperature anomalies revealed that residual temperature dynamics looks like staircase dynamics [13], [14]. After this adjustment 1976/1977 shift almost disappeared, that suggests its relation to ENSO. In contrast 1987/1988 and 1997/1998 shifts, which were previously detected in many regional processes, became obviously visible in global temperature anomalies (Fig. 1).

![Fig. 1. Residual annual average temperature variations. (1)](image1)

Average annual global temperature anomaly, (2) approximation by the model step function.
Verification of these results [13], [14] on satellite-based temperature datasets and consideration of potential mechanisms of the shifts can serve as an additional argument in favor of physical reality of global climate structural shifts.

2. Abrupt climate shifts and observations

In this study we considered three global satellite-based temperature datasets - NCEP OI v2, UAH MSU v5.6 and RSS MSU v3.3. Satellite-based measurements period starts approximately at 1980 year. These measurements have some advantages over surface measurements e.g. better spatial coverage and less discrepancies between each other if compare to the surface ones. Since we are interested in the dynamics of climate and due to calculation convenience, all the datasets considered not as absolute values but as anomalies.

As was mentioned above application of EOF technique to detrended sea surface temperatures (HadSST3) data revealed [13], [14], [15] the leading EOF of monthly SST anomalies over the globe is the ENSO mode. These mode is persistent in most of climate datasets with global coverage. The major ENSO indexes are nearly identical to the PC1 time series obtained from SST and temperature of lower troposphere (TLT) fields. Correlation coefficients between them is near 0.9.

In this study we used first principal components of detrended NCEP OI SST, tropical UAH MSU TLT and RSS MSU TLT in order to account ENSO influence on corresponding field. Then linear projections of PC1 time series on corresponding fields were subtracted from initial fields. This procedure allows to adjust for main ENSO effects. All the datasets were achieved and manipulated at Climate Explorer site (climexp.knmi.nl).

Major features of the global atmospheric circulation, averaged over timescales longer than a month or two, are largely determined by (SST). The dynamics of global SST monthly mean temperature anomalies adjusted for linear ENSO effects shows three major perturbation events during 1980-2015 period. One event is associated with well-known Pinatubo eruption at 1991 [17]. Other evident events having outstanding amplitude are 1987/1988 and 1997/1998 shifts (Fig. 2). On the figure the contribution of volcanoes is not accounted in the SST graph since estimations of aerosols effect are very uncertain. Aerosols curve is shown for illustration of possible cause of SST steady state deviations.

All time-series have short-term fluctuations, which we consider as noise. In contrast to them 1987 and 1997 shifts and 1991 Pinatubo eruption produced more significant changes. Linear fit to constant temperature during 1980-1987 and 1998-2015 is quite good for all considered data, and Fig. 2 is shown as a typical example. And it seems that during 1988-1997 years temperatures will also be near constant after adjustment for Pinatubo eruption. It is seen in ENSO adjusted datasets that in the periods before, between, and after the shifts warming was absent or very small. In other words during 24 years of total 36 years of satellite measurements there were no warming if ENSO variability removed.
Fig. 2. Adjusted for ENSO NCEP OI v2 global SST, major perturbation events and quasi-stationary periods.

On the graph: (1) El Chichon eruption; (2) - Pinatubo eruption.

As a result, our analysis indicates that the dynamics of satellite-based temperature anomalies can be interpreted as stationary periods partitioned by sharp steps with superimposed ENSO variability on them. Thus the results of the study the temporal dynamics of reanalysis, SST and TLT data are in agreement with previous results on the which is additional argument in favor of physical reality of global climate structural 1987/1988 and 1997/1998 shifts.

The synthesis of satellite-based global temperature datasets and widely used EOF analysis conducted in the present study has provided robust evidence that previously found staircase signal [15] is a real climate signal. Forcing from anthropogenic greenhouse gases continuously rose from 1980 to 2015. From the other hand our analysis suggests that most of warming occurred during 1987/1988 and 1997/1998 events. Thus 1987/1988 and 1997/1998 shifts are outstanding events which underlying physical mechanics remain unresolved.

3. On possible mechanisms of abrupt climate shifts

Understanding that gradual global temperature changes can hardly be expected due to natural variability modulating the gradually increasing concentration of anthropogenic greenhouse is presented in literature [18]. Breach of graduality in the form of abrupt shifts can be attributed to the superposition of natural oscillations and monotonic trends however long-lasting quasi-stationary periods rise some doubts on this issue.

Let's consider possible mechanisms capable of generating these shifts and simultaneously supporting quasi-stationary periods between them. There are several pure versions: 1) there is some yet unknown parameter of biosphere-climate system possessing multiple (not less than three) stable stationary states, and observed stochastic-like variability is of external nature; 2) there is a set of more simple bistable systems and each shift is a manifestation of switch of only one system (variability is also of external nature); 3) variability is an inherent property of the system which is chaotic or near chaotic oscillator (the simplest classical example is Lorenz system) and shifts are transitions between attractors; 4) there is a system of interconnected (coupled) oscillators and shifts are transitions between attractors of this super system.

To these variants we can add spatial coordinate for example a set of bistable systems can be considered as spatially distributed systems of similar nature, or as locally combined system of different nature. Later some of them will be considered. In addition nobody can exclude from the consideration some mixed cases, which makes the system more complex.

Let's consider the first case. Formally three quasi-stable states correspond to the existence of at least five stationary states of considered parameter of BCS. And if we presume possibilities of new shifts then we have to assume the existence of additional stationary states, what corresponds to the existence of the number of roots of function describing time derivative of the parameter. Literature searching for BCS parameter possessing such property was unsuccessful.

Completely another situation is with the second case. Many papers describing models and observation data on bistable indices can be found. Some of them are listed here just for instance: bistable regime is possible due to interactions between SST anomaly and thermocline depth anomaly [19]; between SST anomaly and salinity [20], [21]; between vegetation and monsoon precipitation [22]; between sea level pressure and eddy heat flux [3]; between CO2 and convection [23]; temperature and soil moisture [24]; between temperature gradient and precipitation [25]. However all these examples consider only bistable systems and each of them can not describe two shifts observed. Possible way to explain the phenomenon is in presuming similar bistable systems located in different Earth's regions, which are autonomous and due to different thresholds of switching undergoes transitions at different time moments. However statistical analyses does not support this versions, no well-marked distinct spatial anomalies were detected yet.
An alternative idea, that each observed shift is the result of state transition in one of feedback interconnected systems including listed above. Observations support this version since found 1987/1988 and 1997/1998 shifts have different physical mechanics. So 1987/1988 shift is associated with expansion of Hadley cell and a pole ward broadening and intensification of the Ferrel cell [3]. McLean [4] observed 7 percents reduction in total cloud cover followed by 1987 shift till 1997 shift. These features were not observed after 1997/1998 shift. Also in reanalysis parameters revealing these shifts [14] looks different. The shift of 1987/1988 is more sharp than 1997/1998 shift in global average meridional wind at 300 mb and in tropical near surface vertical wind speed.

Local manifestations of these shifts are also very different. In the southwestern Japan sea 1987/1988 shift is seen in sharp rise of winter temperatures and 1997/1998 shift is seen in summer temperature rise [6]. According to Chavez and coworkers [5] 1987/1988 shift is associated with maximum of Pacific Decadal Oscillation warm phase and 1997/1998 shift with transition to cold phase.

To illustrate possible interrelation between two bistable systems producing two shifts let’s consider two pairs of parameters: SST anomaly and thermocline depth anomaly [19] and SST difference anomaly and salinity [20]. The first system can be described by the following model

\[
\frac{dT_E}{dt} = RT_E + \gamma h_w - \epsilon_s (h_w + bT_E)^3
\]

\[
\frac{dh_w}{dt} = -rh_w - abT_E,
\]

where \(h_w\) denotes the thermocline depth anomaly in the western Pacific; \(T_E\) denotes the SST anomaly, averaged over the central to eastern equatorial Pacific; \(b\) is coupling coefficient between the wind stress and SST anomalies; \(\gamma\) is thermocline feedback coefficients; \(r\) collectively represents the damping of the upper ocean system through mixing; \(\alpha\) - coupling coefficient between wind forcing and zonally integrated wind stress; \(R\) collectively describes the positive feedback hypothesis of the tropical ocean-atmospheric interaction; \(\epsilon_s\) coefficient describes a nonlinear dependence of subsurface temperature on the thermocline depth.

The second system is finally described by only one equation on normalized salinity obtained after normalizing and limiting transition due to estimating temperature difference as fast variable [20]:

\[
\frac{dy}{dt} = -[1 + \mu^2(y - 1)^2]y + p_0 + p(t),
\]

where the parameter \(\mu\) corresponds to the ratio of diffusive timescale; \(p_0\) and \(p(t)\) denotes constant and stochastic components of fresh water flux depending on the difference between evaporation and precipitation.

One of possible interactions among these systems is the influence of temperature on the precipitation and consequently on fresh water flux, in its turn salinity affects thermocline depth via changes in mixing intensity. So GHG forcing can initialize changes in thermocline depth backward causing temperature change which in turn causes salinity changes affecting thermocline and temperature. An illustrative model of mentioned system interrelations can be described as:

\[
\frac{dF}{dt} = F + (\sigma - \epsilon)T_E - \epsilon T_E^3 + Rd(t)
\]

\[
\frac{dy}{dt} = p - y - \mu^2(y - 1)^2 + Rd(t)
\]

\[
\frac{dp}{dt} = k_1(p + kT_E - P)
\]

\[
\frac{dT_E}{dt} = F + (\sigma - \epsilon)T_E - \epsilon T_E^3 + Rd(t)
\]
where $P_0$ denotes some constant level of precipitation; $k_2$ denotes the influence of temperature to cloud formation and precipitation; $k_1$ represents time scale of precipitation formation; $Rud(t)$ imitate external stochastic influence.

The dynamics of this system at increasing forcing is shown on Fig. 3.

![Fig. 3. Dynamics of "temperature-thermocline-salinity-temperature" model demonstrating two temperature shifts causing by thermocline and salinity transitions.](image)

The abundance of potentially bistable systems is some kind of challenge for researchers since selecting and predicting actual interactions capable of initiating the next climate shift can not be conducted analytically and require huge amount simulations of uncertain credibility due to our uncertainty concerning what interaction is actual now and what will be the next one.

Let’s return to the list of possible mechanism of multiple shifts. Third case presumes that observed climate variability is an inherent property of the system and observed shifts are manifestations of transitions over a set of attractors belonging chaotic or near chaotic oscillator responsible for this variability. The most probable candidate to this role is ENSO.

ENSO originates in the tropical Pacific through interactions between the ocean and the atmosphere, but its environmental impacts are felt worldwide. While air-sea interactions responsible for ENSO are centered over the equatorial Pacific Ocean, changes in tropical precipitation from deep convection associated with ENSO influence the global atmospheric circulation [19]. There are mathematical models of ENSO [26], [27] and atmospheric general circulation [28] based on some modifications of classic Lorenz model:

$$\frac{dx}{dt} = \sigma(y - x)$$
$$\frac{dy}{dt} = r x - y - xz$$
$$\frac{dz}{dt} = xy - bz,$$

Vallis [26] used the following transformation
\[ x \rightarrow -x \]
\[ y \rightarrow -\frac{C}{B} y \]
\[ z \rightarrow -\frac{C}{B} z + 1 \]

and obtained a model for El Nino:
\[
\begin{align*}
\frac{dx}{dt} &= By - C(x + p) \\
\frac{dy}{dt} &= xz - y \\
\frac{dz}{dt} &= -xy - z + 1,
\end{align*}
\]

where variable \( x \) represents velocity of the westeast ocean current; variable \( y \sim (T_E - T_W) \) where \( T_E \) and \( T_W \) are averaged temperatures of the upper ocean layer in the western and eastern Pacific; \( z \sim (T_E + T_W - 2T_d) \), where \( T_d \) is deep ocean temperature under the thermocline and is taken as a constant. The ocean current is driven by the surface wind which, in turn, is generated by the temperature gradient.

Very interesting properties of another modification of Lorenz model named Lorenz84 were discovered [28]:
\[
\begin{align*}
\frac{dx}{dt} &= -y^2 - z^2 - ax + aF \\
\frac{dy}{dt} &= xy - y - bxz + G \\
\frac{dz}{dt} &= bxy + xz - z,
\end{align*}
\]

where \( x \) represents the intensity of the symmetric globe encircling westerly wind current, and also the poleward temperature gradient, which is assumed to be in permanent equilibrium with it. The variables \( y \) and \( z \) represent the cosine and sine phases of a chain of superposed large-scale eddies, which transport heat poleward at a rate proportional to the square of their amplitude. The constant terms \( aF \) and \( G \) in the model represent symmetric and asymmetric thermal forcing.

This model demonstrates that there are areas of parametric space where four stable attractors coexist in phase space. So this is a rather nontrivial low-order system and it can be complex, useful tool for investigating problems of climate dynamics in a simple setting. A striking result is that the final climate scenario crucially depends on subtle and minute tuning of parameters.

In the context of this model the shifts can be the result of the model transitions from one attractor to another. Fig. 4 demonstrates the coexistence of two attractors corresponding to periodic solutions.
Fig. 4. Two attractors of Lorez84 model.

However addition of relatively weak external periodic forcing makes the behavior of the system hardly predictable (Fig. 5).

Fig. 5. Dynamics of Lorenz84 model under weak periodic external forcing.

Short impacts can switch the system from one attractor to another (Fig. 6). Certainly this example looks very simple however our objective is to consider potential mechanisms of shifts without claim to an accurate description.

Fig. 6. Response of Lorenz84 model to weak shot impact.

Investigating of the fourth version of potential mechanism of the shifts generations (system of coupled stochastic or near stochastic oscillators) and mixed variants of all these mechanisms including spatial distribution of oscillators are extremely interesting area and many pictures of complex dynamics can be obtained [29], [30], [31].

4. Conclusions
Principal feasibility of complex regimes in BCS including abrupt shifts is not in doubt. We hardly will be able to know all about interactions and exact values of BCS indices. However predicting expected time of abrupt shifts by means small-scale conceptual models involving key variables and parameters seems to be rather possible.

The analysis conducted in this paper demonstrates sizable set of potential mechanisms capable of providing multi stable dynamics of BCS. In this context the primary objective is to reveal some rules and constrains (for instance mass and energy conservation lows), which reduce the set of possible combinations of multi stable systems or/and oscillators.

Further statistical searching for interactions between different global and local BCS variables for detecting key variables for conceptual mathematical model combined with parallel testing of different variants of the model are expected to provide consistent and explainable representation of shift generating mechanics.

Acknowledgments. This work was supported by grant RFBR−KKFN No 15−41−04300 and Complex Program of SB RAS No II.2. No 0360−2015−0002.

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