DIAGNOSIS OF TRANSITION PROCESSES IN THE OCEAN-ATMOSPHERE SYSTEM

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Abstract: Transition processes between different situations in the "ocean-atmosphere" system are studied by means of the methods of sequential analysis. Instability indicator is introduced to be used as the generalized characteristics of the state for this system. The indicator is evaluated based on the data obtained from the TAO/TRITON&PIRATA system of anchored buys and other meteorological stations located in tropical zone of the World Ocean. It is shown that the combination of sequential and cluster analysis with the percolation model allows the detection of tropical hurricane 1-2 days in advance of its initiation

Keywords: Ocean-atmosphere system, Instability indicator

1.INTRODUCTION

There is no doubt that the investigation of the "ocean-atmosphere" system (OAS) is necessary to understand the global climate changes and to assess the consequences of the anthropogenic influences on these changes. A wide series of open questions related to the inventory of the environmental disasters and their prediction are displayed among the important problems of climate change. The tropical hurricanes (the intensity and frequency of which grow during last years) are the most important and less predicted environmental disasters. Tropical hurricanes bring significant economic losses and fatalities [1]. Hurricanes are mainly formed above the tropical ocean and affect with regularity the eastern and near-equatorial regions. Tropical hurricanes are mostly originating from the northern and southern Pacific Ocean, the Bay of Bengal, above the Arabian Sea, the southern part of Indian Ocean, near the coasts of the Madagascar, off-shore of north-western Australia and the tropical sector of Atlantic Ocean. An extent of damage from tropical hurricanes is determined by numerous factors. The most important factors are the positional geographic relationship and the available lands.

Significant losses from tropical hurricanes have been observed over the Caribbean Basin and the states of the south-eastern coast of the U.S.A [2]. Therefore, the problems of hurricane prediction are studied in the frame of numerous International and U.S. national Programs of climate change. Particularly, NOAA is developing the three-level monitoring system of OAS that includes ground-based meteorological stations, flying and satellite remote sensing systems, and anchored buoys. Coordination and analysis of information flows within this system are realized by means of the network from 10 centers for the observation of tropical cyclones. These centers are managed by U.S. National Hurricane Center [3]. However, the efficiency of these centers in hurricanes prediction is low, since the precision of these predictions does not exceed 35% [4,5]. The most developed infrastructure for the hurricanes prediction sector is concentrated in the Miami Tropical Prediction Center. According to the prediction of this center, the tropical Atlantic generated about 15 tropical hurricanes in 2007. In reality only 6 hurricanes have taken place and none from them reached the level of hurricane Katrina.

The basic difficulty to achieve high level of hurricane prediction lies in the time-dependent character of the OAS processes. The main problems are connected with the fact that the evolution of atmospheric processes is chaotic, with special spatial-temporal characteristics not always well parametrized. The existing climate models consider different processes in the OAS and contain high level noise. That is why, a useful signal extraction in this situation needs the elaboration of new nonstandard algorithms for the processing of the monitored data, which are free from the conditions of stationarity and are oriented to the parametrization of evolutionary mechanisms of the OAS element interactions [6,7]. In this regard recent studies [8,9] revealed the role of the existing non-stationarities in the spatio-temporal evolution of the global column ozone suggesting that this atmospheric parameter exhibits long range dependence (long memory) [10,11].

This paper develops one of these algorithms that is based on the combined use of sequential - cluster analysis and percolation theory.

2.THE MONITORING DATA

The Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS) deliver numerous archive and operative data about different environmental characteristics on a global basis. Tropical Atmosphere Ocean/TRIangle Trans-Ocean buoy Network & Pilot Research moored Array in the Tropical Atlantic (TAO/TRITON&PIRATA) is one of efficient sub-system of these systems. Namely, the data of this sub-system are the most precise and informative.

Table 1 describes the data that are employed in this study. More precisely this data set is based on the archived data of the TAO/TRITON&PIRATA system for the months of hurricane activity. The basic goal of the data processing is to search for the procedure and the criterion to determine with high probability the time at which the hurricane arises. The tropical moored buoys that deliver numerous data about different meteorological and geophysical characteristics of the OAS are located in the Pacific and Atlantic Oceans. The most densely spaced meteorological stations are in tropical sector of the Atlantic Ocean near the U.S. State of Florida. An assessment of the algorithm that is proposed in this paper is accomplished by means of choice of such meteorological stations that are located close to the aquatory, where severe hurricane is registered by the existing monitoring systems. To this end, the standard meteorological data of the following meteorological stations of the U.S. National Data Buoy Center were used:

(1) Station FWYF1 (25°35’25’’N 80°05’48’’W), Fowey Rocks.

(2) Station MLRF1 (25°00’36’’N 80°22’48’’W), Molasses Reef.

(3) Station SPGF1 (26°42’16’’N 78°59’40’’W), the Islands of the Bahamas.

(4) Station SMKF1 (24°37′36′N, 81°06′36″W), Sombrero Key.

(5) Station 51003 (19°22′N, 160°82′), Southwest of Honolulu, Hawaii.

3. PERCOLATION PROCEDURE

Let us consider the cubic grid $\Xi_d = \{\Xi_{i_1,...,i_d}\}$ of dimension *d* with side *h* in the phase space of meteorological parameters enumerated in the Table 1. Data flow from the system TAO/TRITON&PIRATA does not restricted in the time and is characterized by the data entry $\bar{x} = \{x_i; i = 1,...,10\}$ with regularity of one hour. Restricted time interval *T* is chosen with the successive moments $\{t_j; j=1,\dots,N\}$ when data on the meteorological situation in the previously surveyed site of OAS are delivered. In the course of time the cells $\Xi_{i_1,...,i_d}$ in which a point $\{x_1^*(t_j),...,x_d^*(t_j)\}$ is hit are colored. Here the value $x_i^*(t_j)$ is measured magnitude of *i*th parameter in the time $t_j \in T$. Following to the percolation theory [12-14] we are forming the clusters combining the interfacing colored cells into unique chain. A part of colored cells l, relative volume$m$ of the cluster space, and distribution of the clusters by the size are assessed.

Cluster space structure depends on the interval *T* the choice of which is determined by specific character of given task. As it follows from the data processing, parameters l and m can achieve their asymptotic levels l^* and m^* when the observations are realized during long time. Under this consideration the character of such transition between different phase states of the OAS reflects the objective laws of hurricane beginning. Consequently, a calculation of percolation cluster parameters for different environmental conditions of the OAS functioning gives a possibility to construct the decision making rule to assess the moment of the phase transition in the OAS dynamics. In other words,

empirical estimation of critical levels l^* and m^* as well as evaluation of cluster size distribution in the moment of the OAS phase transition permit to determine the time of phase space disruption. It is particularly important to detect the OAS outcome from its background state. In this case the process of approach of λ and μ to l^* and m^*, respectively, corresponds to the hurricane beginning.

According to [10] an average cluster size *S* (number of colored cells) and correlation length ξ (linear size of the cluster) are approximated with the following functions

$$S(l) \approx \left| l - l^* \right|^{-g},\ x(l) \approx \left| l - l^* \right|^{-n}, \tag{1}$$

where parameters γ and ν depend on the cluster space dimension *d* and in special case are determined by empirically. Functions *S* and ξ are sharply increasing with the forthcoming of the hurricane beginning.

4. RANDOM WALK ON THE PERCOLATION CLUSTER

The use of TAO/TRITON&PIRATA data in the monitoring regime with the employment of percolation model is equivalent to the scheme of the point $\{x_i\}$ walk within the sites of Ξ_d. In the case d=2 (plane x_9, x_2), as it is follows from Figure 1, the random walk of point $\{x_i\}$ in $\Xi_2(x_9,x_2)$ is a function of changing meteorological situation that is characterized by the transition from the background to the state when tropical hurricane takes place. Really, the existence of tropical hurricane within the time period *T* is characterized by double percolation transition of point $\{x_9,x_2\}$ in the line of η between zones Ξ_2^1 and Ξ_2^3. An analysis of the point $\{x_9,x_2\}$ motion connects with the assessment of probability characteristics for the drift of its projection on the direction η. Deviation of this projection from some initial point *A* chosen, for example, thus its characteristics x_2 and x_9 is maximal and minimal, respectively, represent the sum Σ_ν of random number of the components.

According to [11] a distribution of the normalized moments $\tau = \nu / E\nu$ of reliable occurrence of the point *A* to Ξ_2^3 is described by the Wald's distribution function:

$$p_h = P(t < y) = W_c(y) = \int_0^y w_c(z)dz, \tag{2}$$

where

$$w_c(z) = \sqrt{\frac{c}{2p}} z^{-\frac{3}{2}} \exp\left[-\frac{c}{2}\left(z + z^{-1} - 2\right)\right],\ c = (\mathrm{E}n)^2 (Dn)^{-1},$$

$E\nu$ is the average value of time during which point A was walking prior to its reliable entry to the zone Ξ_2^3, $D\nu$ is the dispersion of parameter ν.

As it follows from [6] the Wald's distribution function can be assessed with the following correlation:

$$W_c(y) = \Phi\left[(y-1)(c/y)^{1/2}\right] + \Phi\left[-(y+1)(c/y)^{1/2}\right]\exp\{2c\}$$

where $$\Phi(x) = \frac{1}{2p}\int_{-\infty}^{x} \exp\left\{-t^2/2\right\}dt \quad (3)$$

By definition in [12] an average number N_t of colored sites in the percolation cluster after numerous steps t of the point A walking and under the absence of critical transitions equals:

$$< N_t > = t^{\frac{-q}{2}},$$

where parameter $\theta \in [1.29\text{-}2.84]$ is evaluated in each case by means of modeling procedure.

An analysis of the percolation transition

The distribution structure of zones in the plane Ξ_2 (Figure 1) has specific elements bounded by the zone Ξ_2^2 in which the event was arising but it did not detected. When $(x_9, x_2) \in \Xi_2^1$ the meteorological situation was characterized as the background up to August 20, 2005. Hurricane Katrina recorded on the morning of August 23 by Landsat above south-eastern sector of the Island of Bahamas and after that it received the first category by the Saffir-Simpson scale. Moving to the Gulf of Mexico in direction to the New Orleans, Louisiana, it achieved the category 5 on the morning of August 28 and then its power was slowly decreased up to the appearance at August 31. An analysis of meteorological data shows that first signs of the environmental instability began to originate on August 20. Consequently, interval between August 20 and 23 can be considered as the uncertainty zone. Namely, it is necessary to search the indicators of environmental instability within this zone. Undoubtedly, size of Δ and the structure of zone Ξ_2^2 depends on the hurricane category dynamics. Searching such dependency is one of important task solution of which permit to forecast the hurricane origin and prognosis of its category.

Figure 2 represents percolation cluster that was formed in the region of the Bahamas on August of 2005 hurricane season. It is seen that both percolation cluster sections have the zones of transition to the infinite cluster but are distinguished by the structural characteristics of the percolation cluster. Section (x_2,x_9) has the following parameters: l^*=0.2, m^* = 0.87 and S=7.08. Section (x_{10},x_8) is characterized by the parameters l^*=0.5, m^* = 0.94 and S=22.5. Zone of the phase transition is defined in each case by the geometric reduction of the way between two zones of basic cluster each of which correspond to one state of the environment. It is evident that moment of this reduction formation corresponds to the hurricane origin.

Calculation of the hurricane origin probability depends on the dynamics of cluster space structure. If p is the portion of colored sites of percolation cluster that critical level of probability p^* is determined by the following conditions:

(1) $p < p^*$ - if the grouping the cells leads to the null cluster that hurricane does not expected;

(2) $p > p^*$ - if grouping the cells leads to the filled cluster that hurricane is expected.

To formalize the detection procedure of hurricane beginning it is introduced the algorithm for the assessment of OAS instability $I_m(t)$ [13,14]:

$$I_m(t) = \frac{1}{s(T-N)}\sum_{j=K}^{M}\sum_{i=1}^{s} b_i a_i(t_j) \quad (4)$$

where N is the length of time observational range; m is the moment of observational range beginning; s is the number of registered parameters of OAS; β_i is the weight coefficient for the i-th characteristic; K=l+T(m-1); M=mT-N; l is the time beginning for the $I_m(t)$ calculation;

$$a_i(t_j) = \begin{cases} 1 \text{ when } \Delta x_i(t_j)\cdot\Delta x_i(t_{j-1}) \le 0; \\ 0 \text{ when } \Delta x_i(t_j)\cdot\Delta x_i(t_{j-1}) > 0 \end{cases}$$

where $\Delta x_i = \bar{x}_i - x_i$; $\bar{x}_i(N) = \frac{1}{N}\sum_{j=1}^{N} x_i(t_j)$.

An indicator of the OAS instability $I_m(t)$ characterizes the changeability of current average value of the vector $\{x_i\}$. Figure 3 explains the calculation procedure for the OAS instability indicator. As it is seen to use traditional statistics for the meteorological data processing it is necessary to assess the quasi-stationary time interval. Analysis of the one-dimensional distributions for selected meteorological parameters measured by TAO/TRITON&PIRATA showed that this interval equals 7 hours. Figure 4 gives example of $I_m(t)$ calculation for the case of hurricane Katrina. One can see that the approach of the hurricane origin is accompanied by the $I_m(t)$ increasing. Under this consideration three regions of $I_m(t)$ take place:

(1) the region of background characteristics when the OAS parameter variations during restricted time interval is changed in the limits of statistical stability;

(2) the region of the uncertainty, where probability of the hurricane beginning exceeds the level 0.5; and

(3) the region of the hurricane existing where velocity of changes of all parameters $\{x_i\}$ achieves maximal values.

The control of the $I_m(t)$ dynamics in the case of Figure 1 with the sequential analysis shows that in the zone Ξ_2^1 En=17, $D\nu \to 0$ and $W_c(x) \to 0$. At this time in the zone Ξ_2^3 En=9,

$D\nu \rightarrow 5$, $x=\nu/D\nu \rightarrow 1.35$, $c \rightarrow 16$ and $W_{16}(1.35) \rightarrow 0.912$. The latter explains the result represented in the Figure 4. In other words, processing from verbal reasoning to a quantitative estimation of the $I_m(t)$ dynamics, we introduce a generalized calibrated scale Ξ, for which we postulate the presence of relationships of the type $\Xi_1<\Xi_2$, $\Xi_1>\Xi_2$ or $\Xi_1=\Xi_2$. It means that there always exists a value of $I_m(t)=\rho$ which determines when the OAS phase transition of a given type can be expected. As a result, the magnitude $\theta=|I_m(t)-\rho|$ determines the expected time interval before the phase transition occurs.

The region of the sharp increase in the derivative of $I_m(t)$ corresponds with the OAS phase transition. Consequently, tracing for the meteorological situation and synchronous calculation of instability indicator under its comparison with cluster space structure gives a possibility to detect the moment of OAS transition from background state to the hurricane origin. Figure 4 shows that introduced instability indicator could detect hurricane Katrina beginning at least 31 hours before its registration by Landsat. Figure 5 describes the $I_m(t)$ within the 2005 hurricane season. Behaviour of the $I_m(t)$ is identical to the registered hurricane series. Such result is justified by results given in Figure 6 for the case of tropical hurricane Flossie that formed in the eastern sector of the Pacific Ocean on August 8 and reached Hawaii on August 15, 2007. One can see that probabilities of the OAS transition between its phase positions are more 0.7. Therefore, indicator $I_m(t)$ reflects the OAS phase structure with high reliability and can be used to predict the hurricane beginning.

5. CONCLUSION

An analysis of observational data characterizing the OAS dynamics in tropical sector of the World Ocean shows that differentiation of the OAS phases by means of transitions in the meteorological percolation cluster allows the division of zones with different levels of the OAS instability. To achieve the more reliable agreement between the OAS state and parametrical space of meteorological percolation cluster it is necessary to establish the algorithm for the calculation of critical level of renormalisation probability p^* taking into consideration the procedure of renormalisation group transformations for more than two dimension. Only in this case that the real-space renormalisation process can make more precise the moment of $I_m(t)$ transition from background zone Ξ_2^1 to the signal zone Ξ_2^3 (Figure 1).

Thus the following conclusions are drawn:

(1) An application of percolation procedure gives a possibility to detect the time moment when the OAS switches its phase state from the background position to the state with high level of environmental instability.

(2) An introduced indicator of the OAS instability allows the detection of the hurricane beginning before its registration by existing monitoring systems.

(3) An increase of the precision of proposed algorithm is possible with the optimization of parametrical structure in the indicator $I_m(t)$.

It is evident that the solution of the problem for a reliable prediction of the hurricane beginning requires the development of an efficient information technology which must be used in the environmental monitoring systems. This technology should include sections responsible for planning of measurements, development of algorithms for complex processing of data from different sources, and relevant risk assessment. The main difficulty on this way lies in the spatial and temporal heterogeneity of existing information given by means of different observational systems. An overcoming of this heterogeneity can be accomplished by using the algorithms of the space-temporal interpolation [1,7].

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Table 1. The list of environmental characteristics that uses for the detection of tropical hurricane beginning.

Meteorological parameter measuring by means of the TAO/TRITON&PIRATA system	Parameter identifier	Parameter characteristic
Ocean surface temperature, °C	x_1	Temperature is measured on the depths 1.0 m or 1.5 m depending on the buoy station type with precision ±0.003°C - ±0.02°C.
Wind speed (m/s) and its direction (in degrees on clockwise from northern direction)	x_2, x_3	Wind parameters are measured on the altitude 3.5m. Wind speed is measured with precision 3%. In direction it is determined with precision 5.0°-7.8°.
Precipitation (mm/h)	x_4	Precipitation are registered every 10 minutes on the altitude 3.5 m with precision ±0.4 mm/h.
Sea water density ($\mathrm{kg\,m}^3$)	x_5	Water density is calculated as function of its salinity.
Depth of the isotherm 20°C	x_6	Depth of isotherm is calculated on the base of vertical temperature distribution by means of linear interpolation with the step 20 m by depth.
Water temperature of fixed depths $\{h_i\}$, °C	$x_7(h_i)$	Water temperature is measured up to 750 m on the fixed horizons with the precision ±0.02°C.
Relative humidity of atmospheric air, %	x_8	Air humidity is measured on the latitude 2.2 m above the sea level with precision ±2.7 %.
Atmospheric pressure, atm.	x_9	Atmospheric pressure is fixed with the precision ±0.01% on the latitude 3m above the sea level.
Atmospheric temperature, °C	x_{10}	Atmospheric temperature is measured on the latitude 2.2 m with the precision ±0.2°C.
Sea water salinity, $^{o}/_{oo}$	x_{11}	Salinity is assessed by the data on the water temperature and its conductivity with the precision ±0.02 $^{o}/_{oo}$.

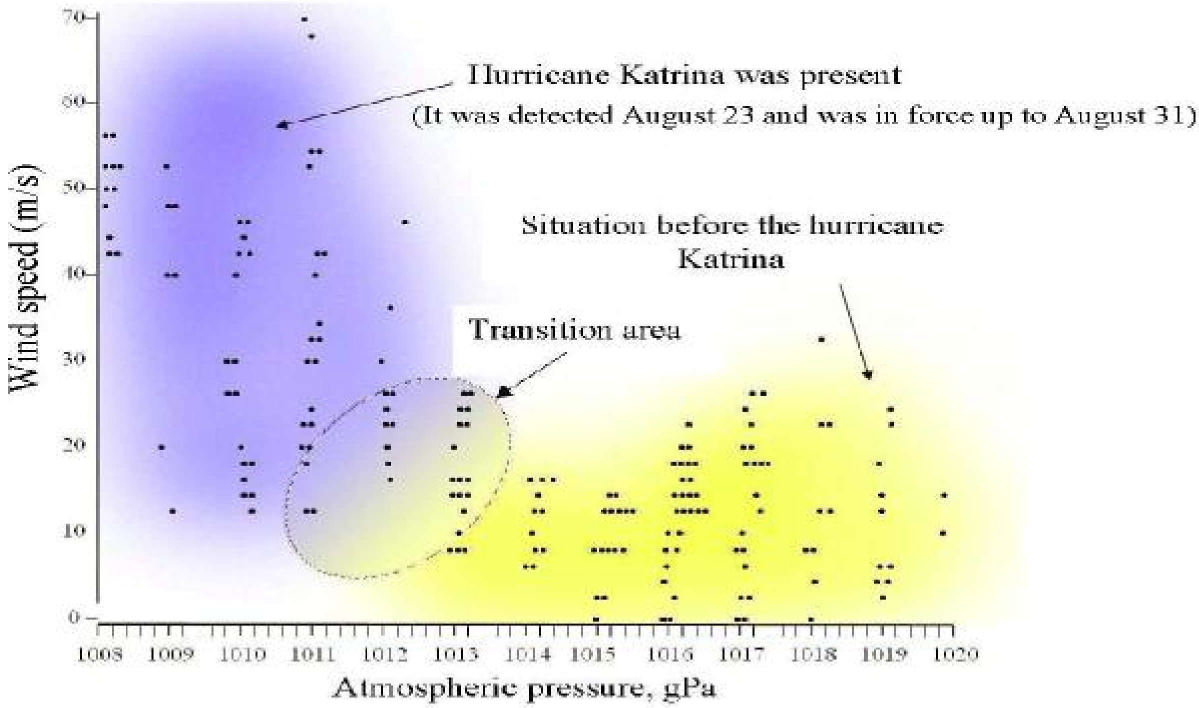


Fig. 1. Cluster structure of meteorological situation that taken place during August of 2005 in the region of the Islands of Bahamas by the data of Meteorological Station No. SPGF1 (26°42'16" N 78°59'40" W). Phase-plane portrait of the percolation transition of meteorological situation before, during and after the hurricane Katrina

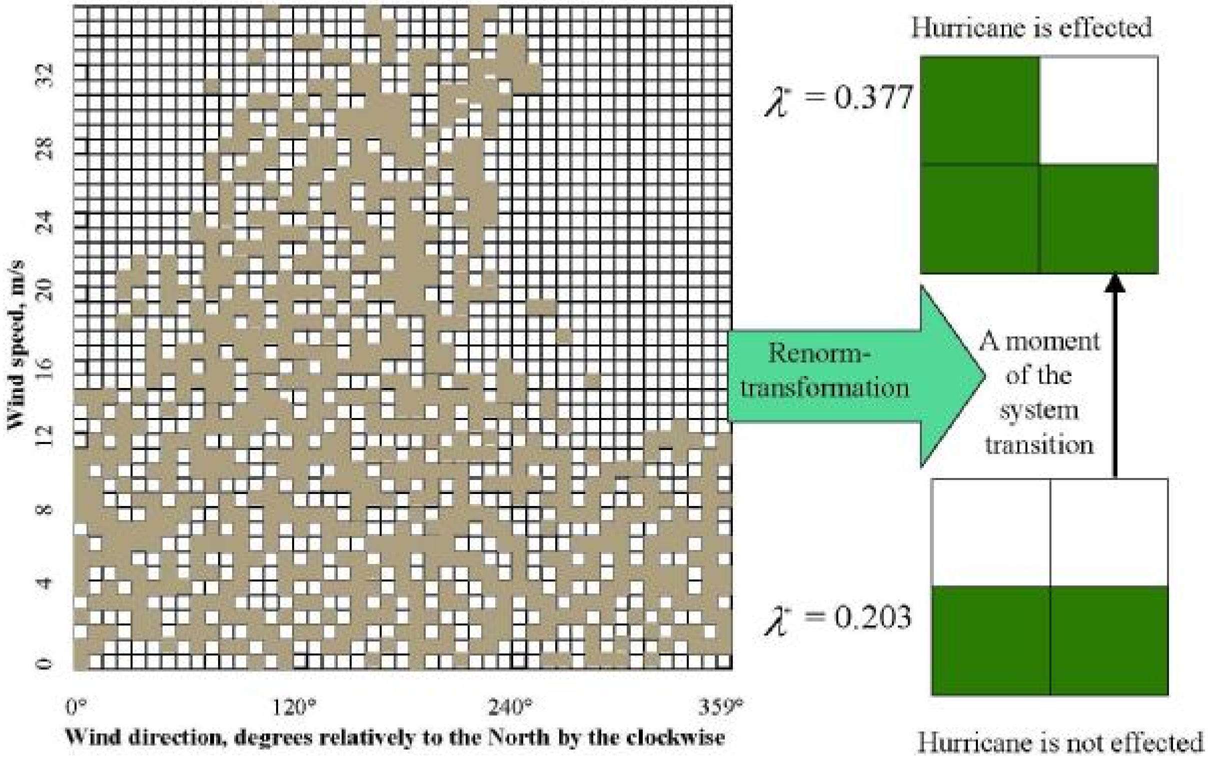
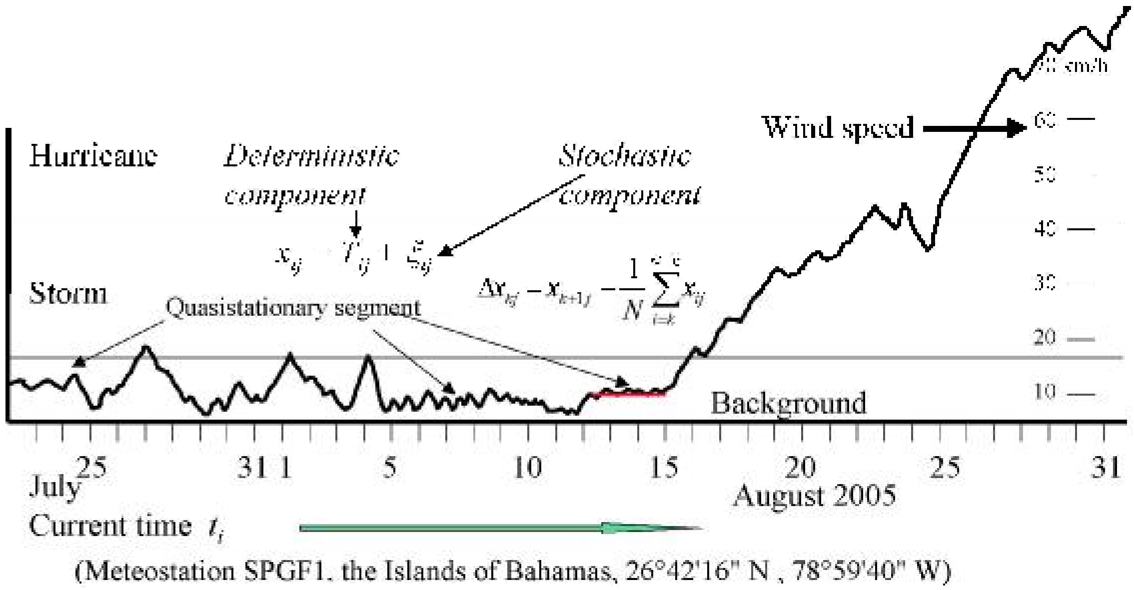


Fig. 2. Principal scheme of the percolation transition in the OAS phase situations between background and hurricane presence states during August of 2005. Data of meteorological station No. smkf1 (24°37′36″N, 81°06′36″W) were used.



Quasistationarity interval

$$|\Delta x_{ij}| \le 3\left(1+\frac{1}{N}\right)^{\frac{1}{2}}\sigma_j$$

Month	2003	2004	2005	2006
January	16 h	12 h	9 h	13 h
July	8 h	**7 h**	8 h	9 h
October	14 h	11 h	12 h	?

Fig. 3. Model of the OAS instability.

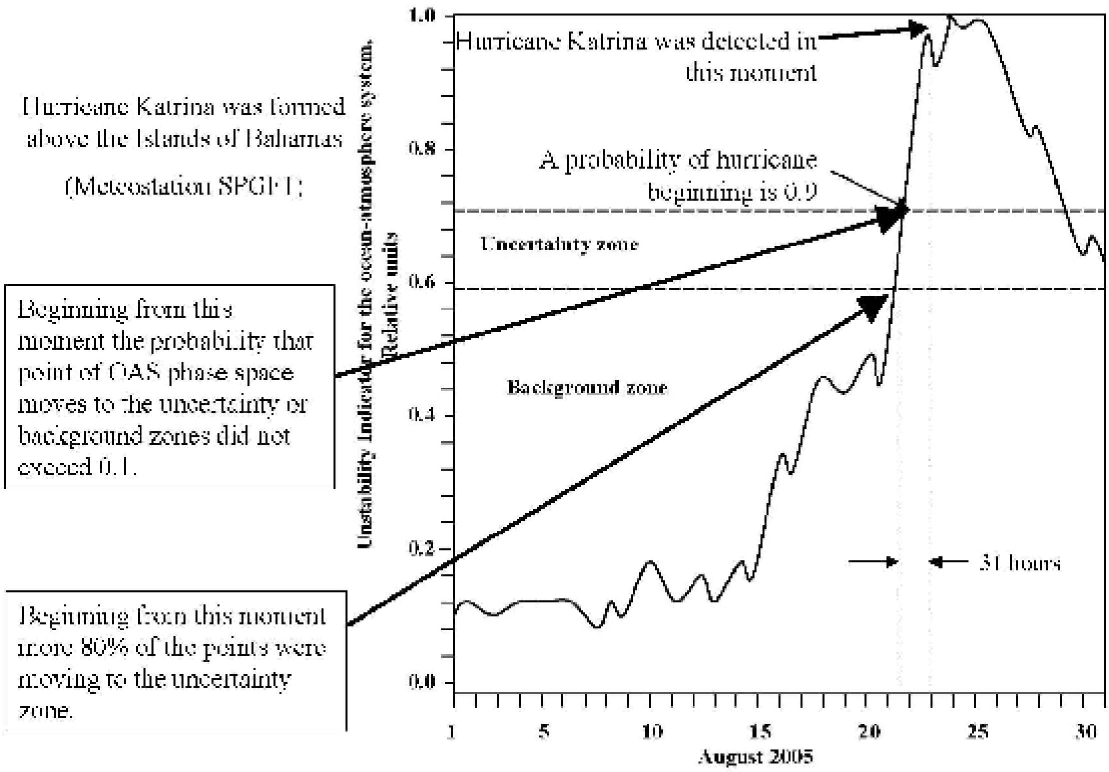


Fig. 4. Dynamics of the OAS indicator instability assessed by the meteorological data from stations FWYF1 (25°35'25''N, 80°05'48''W); MLRF1 (25°00'36''N, 80°22'48''W) and SPGF1 (26°42'16''N, 78°59'40''W).

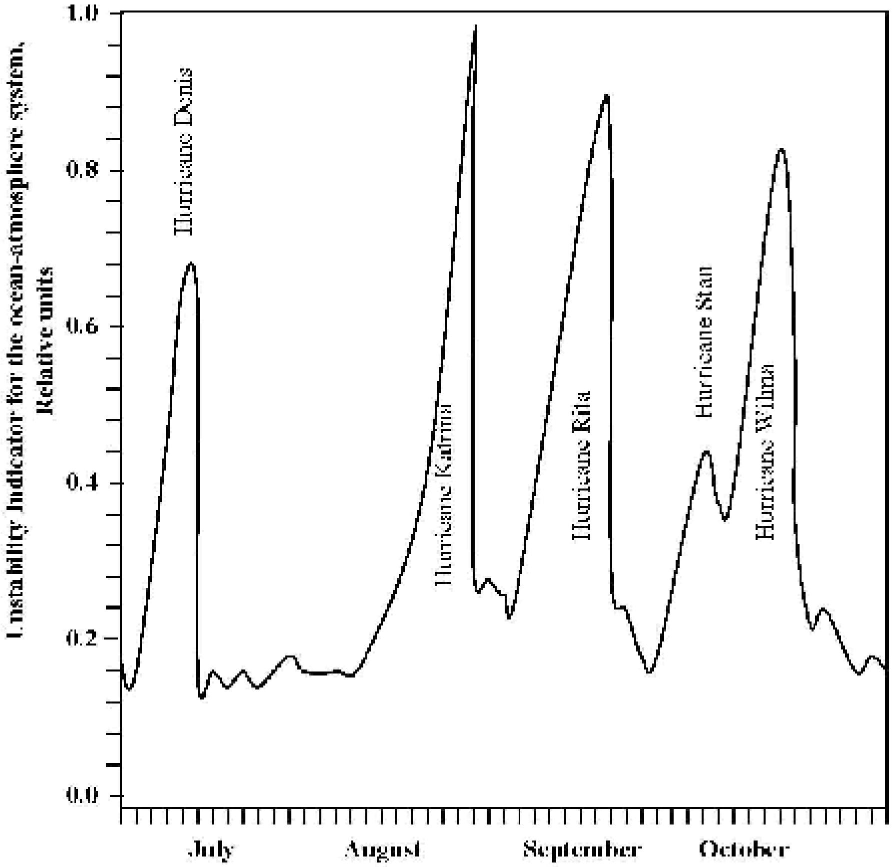


Fig. 5. Dynamics of the OAS instability indicator calculated for the 2005 tropical hurricane season basing on the Meteorological Station No. smkf1 (24°37′36′N, 81°06′36″W).

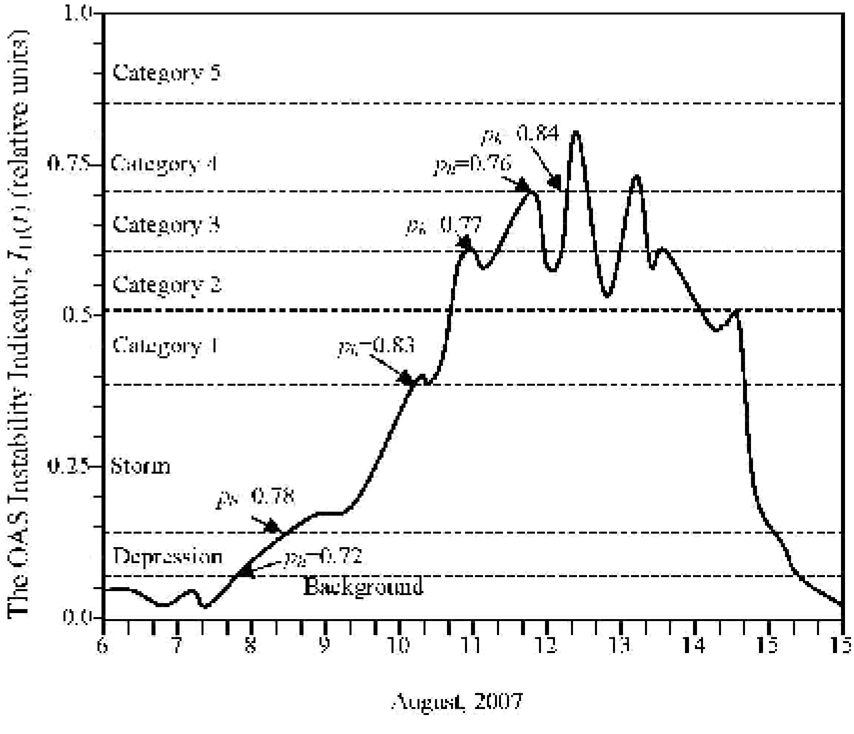


Fig. 6. Dynamics of the OAS instability indicator for the case of tropical hurricane Flossie that take place on the August 8-15, 2007. Data of meteorological station No. 51003 (19°22′N, 160°82′) were used to assess the $I_m(t)$ (m=11).