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Hurricane genesis modelling based on the relationship between solar activity and hurricanes II

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ABSTRACT

This research presents improved results on modelling relationship between the flow of charged particles that are coming from the Sun and hurricanes. For establishing eventual link, the methods of Big Data, such as Adaptive Neuro Fuzzy Inference System (ANFIS), Parallel Calculations, Fractal analysis etc., are applied. The parameters of solar activity were used as model input data, while data on hurricane phenomenon were used as model output, and both of these on daily level for May–October in period 1999–2013. The nonlinear R/S analysis was conducted to determine the degree of randomness for time series of input and output parameters. The time lag of 0–10 days was taken into account in the research. It led to growing input parameters up to 99. The problem of finding hidden dependencies in large databases refers to the problems of Data Mining. The ANFIS with Sugeno function of zero order was selected as a method of output fuzzy system. The "brute-force attack" method was used to find the most significant factors from all data. To do this, more than 3 million ANFIS models were tested on Computer Cluster using Parallel Calculation. Within the experiments, eight input factors were calculated as a base for building the final ANFIS models. These models can predict up to 39% of the hurricanes. This means, if causal link exists, approximately every third penetration of charged particles from coronary hole(s) or/and from the energetic region(s) toward the Earth precede the hurricanes.

1. Introduction

The basic topic in this study is the relation between indicators of solar activity and atmospheric motions in terms of hurricane phenomenon. Even still without precise and exactly interpretation of physical mechanisms that can explain appearance and prediction of hurricanes, there is a several studies which highlighted correlation between changes in solar energy input and atmospheric processes. Usually, opposite to the classical meteorology and climatology, these studies show that disturbances in solar activity affect terrestrial climate and, stratospheric and troposphere air movements as well as meridional and zonal energy exchange. Landscheidt (2003) gives detailed list of papers where the link Sun-atmospheric processes is proved.

Energy received from the Sun is not constant and these variations correlate with stratospheric and tropospheric parameters with meaning that solar influence on Earth's climate should not be considered as non-zero (Tsiropoula, 2003, Radovanović et al., 2014a). Some studies, such as Rozanov et al. (2012), suggest that the energetic particles which coming from Sun affect atmospheric chemical composition and, consequently, atmospheric dynamics and climate. Voiculescu et al. (2013) found statistically significant relation between low cloud cover at middle-high latitudes and interplanetary electric field indicating solar-driven mechanism on climate. Stressing the complexity in solar impact assessment, Georgieva et al. (2012) showed that toroidal field-related solar activity decreases the zonality of wintertime atmospheric circulation at all levels in atmosphere, while poloidal field-related solar activity act conversely.

It is expected that propagation of solar energy input across

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geomagnetic field and atmosphere has the horizontal and vertical component with different regional implications. Lockwood et al. (2010) pointed out that the mechanisms through the Sun impacts terrestrial climate have top-down direction and long term drift in solar UV radiance correlates with stratospheric and tropospheric temperature and wind with regional variation impacts. Gomes et al. (2012) suggest that sudden inflows of protons, depending on the angle of incidence of the main stream can be directly connected with the hurricanes. More recently Pazos et al. (2015) found correlation between tropical cyclogenesis precursors and Dst geomagnetic index with a note that geomagnetic activity and tropical cyclones might be modulated by the influence of geomagnetic activity on the vertical wind shear.

Boberg and Lundstedt (2003) showed strong correlation between electric field strength of solar wind and pressure variation in stratosphere and troposphere while the tropospheric pressure influence is concentrated to an area in the northern Atlantic which coincides with the action centers of North Atlantic Oscillation. Veretenenko and Orgustov (2012) revealed the impact of solar activity and galactic cosmic rays on pressure variations in the lower troposphere with strong latitudinal and regional differences and specific features of baric systems formed in different regions. Furthermore, duration of elementary synoptic processes is in relation with character of solar and galactic cosmic rays (Artamonova and Veretenenko, 2013). Solar proton events (>90 MeV) are accompanied with intensification of cyclonic circulation at middle latitudes, mainly over oceans, in period October–March and April–September for North and South hemisphere, respectively (Veretenenko and Thejll, 2013).

Important topic is exploring time delay between different solar events (flares, coronal mass ejections, and eruptive prominences) and atmospheric responses. Gabis and Troshichev (2000) concluded that influence of short-term changes in solar activity (Forbush decrease and proton events followed by increase of solar UV radiance) on baric field perturbation is the most evident in stratosphere (30 mbar level) with impact on meridional and zonal circulation realized within 5–7 days before the key date. Furthermore, fluctuation of baric fields in troposphere (500 hPa) is connected with internal atmosphere dynamic, while troposphere cyclonic activity is in relation with changes in meridional circulation in stratosphere. Analysing the short-term variation in galactic cosmic rays, Artamonova and Veretenenko (2014), found delay period of 3–4 (4–5) days for tropospheric pressure field variation in extratropical latitudes of North (South) hemisphere after the event onset.

In our previous study (Vyklyuk et al., 2016), the relations between the flow of charged particles from Sun and hurricane were examined by applying correlation analysis, Hurst index and ANFIS model. Under computational limitations (technical requirements for power computers machines), the analysis of time lag is restricted up to 3 days and results showed that models can predict 22–26% of the hurricanes. Now, we improved previous results and analysis of 10 days lag and larger prediction ability of model is presented in this study. The paper is organized under sections; used data and model description are presented in the part Materials and methods, while the main results are contained in Results and Discussion section, and key finding in Conclusion.

2. Materials and methods

The improved modelling in this analysis is performed on the same data input as in previous study; indicators of solar activity (proton and electron flows of various energy levels as well as solar wind features) and hurricanes parameters on daily level for May–October in period 1999–2013. Model's predictions are based on input and output data. The first are presented as: X_1 is protons flow >1 *MeV*; X_2 is protons flow >10 *MeV*; X_3 is protons flow >100 *MeV*; X_4 is electrons flow >0.6 *MeV*; X_5 is electrons flow >2 *MeV*; X_6 is index F10.7 (the measure of the noise level generated by the Sun at a wavelength of 10.7 *cm* at the Earth's orbit); X_7 is solar wind speed; X_8 is density of the solar wind particles; X_9 is the solar wind temperature.

The factors X_1-X_6 represent mean daily values and data are taken from internet source ftp.swpc.noaa.gov/pub/warehouse. The factors X_7-X_8 are expressed as daily maximum from the mean hourly values. The source for these datasets was http://umtof.umd.edu/pm/crn/. The factor X_9 presents the mean daily values and data were taken from http://www.srl.caltech.edu/cgi-bin/dib/rundibviewswel2/ACE/ASC/DATA/level2/swepam?swepam_data_1day.hdf.

Model outputs are data about hurricane phenomenon. For each hurricane in research period we use data about year, month, day, and hour when it appear, geographical position (altitude and longitude) at which hurricane is recorded, as well as the speed it had at a certain moment and place. The time resolution of the data is 6 h. Atmospheric process was defined by Saffir-Simson scale, i.e. system with air pressure below 980 mb and wind speed above 64 knots is treated as hurricane. The number of hurricanes in the Atlantic (H_a), East Pacific (H_e), West Pacific (H_w) and total hurricanes (H_t) are taken to be the output variables in this study. The data are retrieved from http://weather.unisys.com/hurricane/.

The pre-processing of data is based on filling gaps in time series and testing seasonal and cyclic dependence. Except in the case of the parameter X_9, when the share of missing data is 10%, in all other cases it is not more than 2% (Vyklyuk et al., 2016). The maximum-likelihood estimation (MLE) was used for estimation of missing data (Little and Rubin, 2002). Time realizations of observed parameters showed no cyclic and seasonal dependence, except in case of X_6 parameter. Using additive model (Soltani et al., 2010), decomposition of time series for X_6 parameter is done (Vyklyuk et al., 2016).

Due to the lack of linear dependence between input and output parameters, it is necessary to apply non-linear methods. Earlier researches showed that application of Data Mining in analysis of hidden dependencies in large databases is useful, and R/S analysis and ANFIS modelling show the best results in similar studies (Radovanović et al., 2014b, 2015).

The normalization of time series was done and R/S analysis (Lenskiy and Seol, 2012; Mitra, 2012) was performed in order to determine the degree of randomness for time series, i.e. fractal dimensions and Hurst index. Based on these, the stochastic degree of time series and availability of long-terminal correlation (long-terminal memory) were calculated (Table 1). According to obtained values, the following conclusions stand out (Vyklyuk et al., 2016): the Hurst index has value of 0.5 for X_1, H_w and H_t suggesting that these parameters describe some stochastic processes; X_2, X_3, H_a and H_e are characterized as antipersistent while all others are persistent; the similarity of the fractal dimensions for X_7 and X_9 means existence of the same rules of changing for such time series with scaling.

All aforementioned steps were made to ensure a good selection of the analysed variables for the next phases of the research.

As was shown in previous paper, modelling of solar activity–hurricane phenomenon is related to problem of Data Mining and the best approach in this case is based on the models of hybrid neural

Table 1
The Hurst index and fractal dimensions for model input and output time series (Vyklyuk et al., 2016).

Factor		Hurst index (H)	Fractal dimension (D = 2-H)
>1 MeV Proton	X_1	0.52	1.48
>10 MeV Proton	X_2	0.43	1.57
>100 MeV Proton	X_3	0.4	1.6
>0.6 MeV Electron	X_4	0.94	1.06
>2 MeV Electron	X_5	0.72	1.28
SolFlux 10.7 *cm*	X_6	0.71	1.29
Speed	X_7	0.84	1.16
Np	X_8	0.96	1.04
Temp	X_9	0.84	1.16
Atlantic	H_a	0.41	1.59
East Pacific	H_e	0.33	1.67
West Pacific	H_w	0.54	1.46
Total hurricanes	H_t	0.5	1.5

networks ANFIS. For solving this task, we used the same settings like in previous paper: the number of terms for each linguistic variable X_i was three; each term was described by Gauss membership function; the Sugeno function of zero order was selected as a method of output fuzzy system due to a lot of time for training. Also, the hybrid method that integrates back-propagation method with the least squares method was used as a method of learning.

As we shown, concerning physical processes of interaction between solar activity and the processes of hurricane origin, the existence of time delay (lag) between these processes can be assumed. Now, we increased the time lag from 3 days to 10 days long. In this case the number of input fields will increase 11 times (9 × 11 = 99) and the problem is reduced to finding the dependence in the form $M : X_1^{lag=0} \times \cdots \times X_9^{lag=10} \rightarrow H$. For this task (taking into account the lag), training sets in the form of corteges, the following is created:

$$Tr_a = \left\{ \langle \overline{x}_{1,j}^{0}, \ldots, \overline{x}_{9,j}^{10}, h_j^a \rangle_{j=\overline{1,n}} \right\} \quad (1)$$

$$Tr_e = \left\{ \langle \overline{x}_{1,j}^{0}, \ldots, \overline{x}_{9,j}^{10}, h_j^e \rangle_{j=\overline{1,n}} \right\} \quad (2)$$

$$Tr_w = \left\{ \langle \overline{x}_{1,j}^{0}, \ldots, \overline{x}_{9,j}^{10}, h_j^w \rangle_{j=\overline{1,n}} \right\} \quad (3)$$

$$Tr_t = \left\{ \langle \overline{x}_{1,j}^{0}, \ldots, \overline{x}_{9,j}^{10}, h_j^t \rangle_{j=\overline{1,n}} \right\} \quad (4)$$

where$\overline{x}_{i,j}^{l}$ – normalized components of X_i time series and can be calculated as $x_{i,j}^{-l} = \frac{x_{i,j}^{l} - \min(X_i)}{\max(X_i) - \min(X_i)}$, upper index means lag, n – size (number of records) of training set (after lag transformation it had 2610 records), l – lag.

Of course, the largest number of computer capacities cannot allow creating such a complex neural network that contains 99 input fields and one output, with training set size of 2610 records. Therefore, we must find the most significant factors from all data using "brute-force attack" method (Vyklyuk et al., 2016). For do it we tested all possible combinations of ANFIS models containing 4 input factors from 99. According to the probability theory, the number of these models is defined as:

$$C_n^m = \frac{n!}{m!(n-m)!} = 3\ 764\ 376 \quad (5)$$

The optimum value of m is determined according to the criterion that concerns the number of input factors/time relation. The evaluation was

Table 2
Results of the search of key factors.

H_t		H_a		H_e		H_w	
Input factor	Time lag	Input factor	Time lag	Input factor	Time lag	Input factor	Time lag
Speed	Lag 10	Speed	Lag 10	Np	Lag 10	SolFlux 10.7 *cm*	Lag 10
SolFlux 10.7 *cm*	Lag 9	SolFlux 10.7 *cm*	Lag 9	Np	Lag 6	SolFlux 10.7 *cm*	Lag 9
SolFlux 10.7 *cm*	Lag 5	SolFlux 10.7 *cm*	Lag 5	Np	Lag 5	Speed	Lag 8
SolFlux 10.7 *cm*	Lag 3	SolFlux 10.7 *cm*	Lag 3	Temp	Lag 5	Np	Lag 6
Speed	Lag 3	Speed	Lag 3	Speed	Lag 4	Np	Lag 4
Temp	Lag 2	Temp	Lag 2	Speed	Lag 3	SolFlux 10.7 *cm*	Lag 2
SolFlux 10.7 *cm*	Lag 1	SolFlux 10.7 *cm*	Lag 1	Temp	Lag 3	Temp	Lag 2
SolFlux 10.7 *cm*	Lag 0	SolFlux 10.7 *cm*	Lag 0	Temp	Lag 1	SolFlux 10.7 *cm*	Lag 1

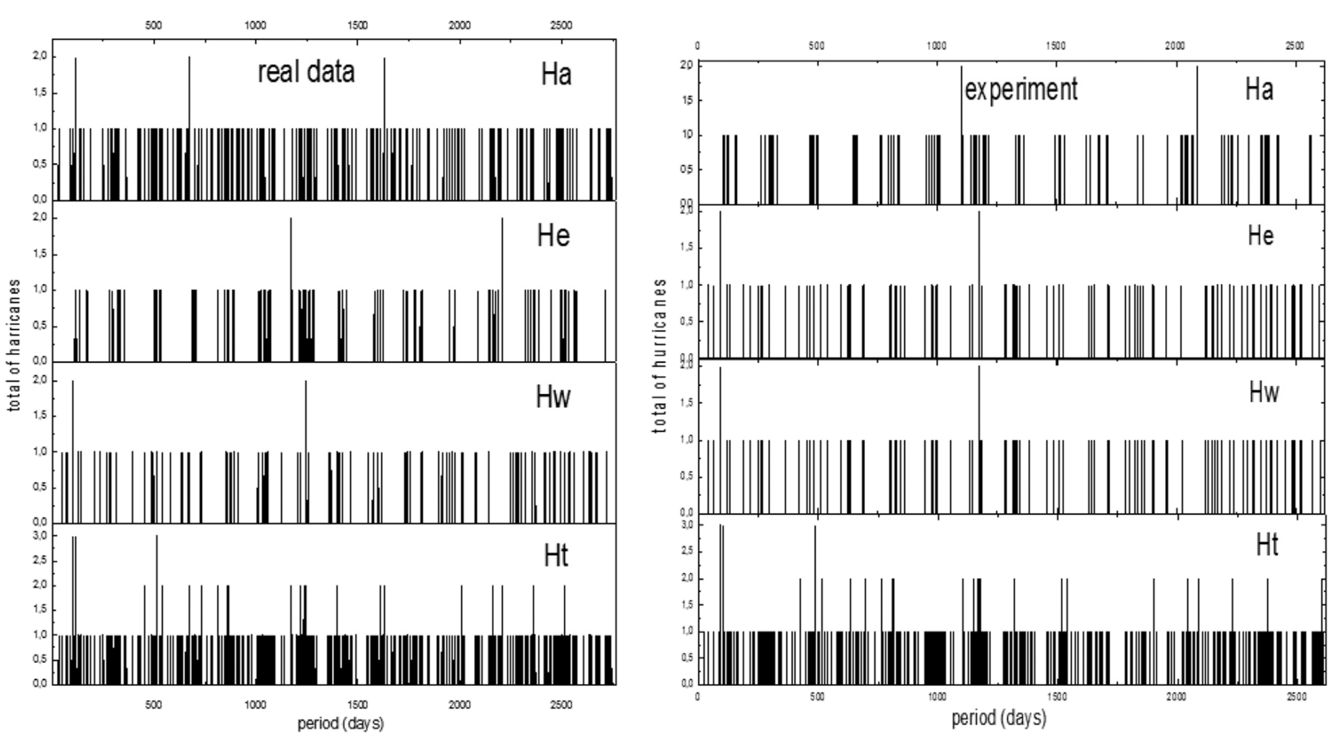

Fig. 1. Comparison of simulation results with real data series of Atlantic (H_a), East Pacific (H_e), West Pacific (H_w), and total hurricanes (H_t) under experiment.

done using approximately time of training for 100 epochs ANFIS models. Because each ANFIS model was independent on each other, the parallel calculation on computer cluster was used. It allows reduced the calculation time is inversely proportional to number of cluster core workers. For do it the cluster Kyiv Politechik Institute (**Sites:** 44 nodes with two Quad-core Intel Xeon E5440 @ 2.83 Ghz processors and 8 GB of RAM; 68 nodes with two Dual-core Intel Xeon 5160 @ 3.00 Ghz processors and 4 GB of RAM; **Capacity:** 7, peak linpack TFlops TFlops 5.7) was used.

To find functional dependence we prepared experiment that consists from next steps: building and training using parallel calculations on computer cluster 3 764 376 ANFIS models that contain all possible combinations of 4 input factors according to (5); estimation of accuracy of ANFIS models by mean-square error; selecting the "key" factors i.e. ANFIS models which have the least mean square errors and to build data set from "key" factors; building and training one final ANFIS model based on the "key" factors, and sensitivity analysis.

3. Results and discussion

Looking for the key factors under the parallel calculation arrays of separate datasets (that included all combinations from 4 input fields) for each testing ANFIS models were formed. After that, these arrays were distributed between cores of computer cluster. It led to decreasing of learning time proportionally to the numbers of working cores. This has enabled to determine the most important factors (Table 2). According to Table 2, the factors that characterize energy protons do not affect the activity of the occurrence of hurricanes. The last step of the experiment is to build and explore ANFIS model containing 6 or more additional factors. Because computer power does not allow us to investigate a model that contains more than 8 input factors, the ANFIS model which contains 6 factors was constructed, trained and investigated.

Using obtained experimental results, the various key fields for each output field were analysed for the adequacy and accuracy of the models. Also, it should analyse false peaks and difference in the amplitudes. Simulation results are presented in Fig. 1. As can be seen from the figures, graphs have many joint peaks. The large number of peaks requires a computer analysis with a special Python program which we developed for this purpose.

It is evident that some of the hurricanes can be caused by the solar activity. Some of the peaks in the model graph correspond to the peaks in the graph of real hurricanes by position and amplitude. This indicates the adequacy of models. To check the accuracy, the comparative analysis between a number of real hurricanes and calculated by models have been provided using created program. The results of computer calculations are shown in Table 3.

According the presented results in Table 3, the designed models can explain the existence of hurricanes or their absence from 90% to 98%. But the most important information is the forecasting of hurricanes. As it can be seen from the columns 5 and 6, models can predict not so big number of hurricanes. Totally, these models can predict "only" from 29% to 39% of hurricanes (columns 7 and 8). And only 1% of them will be false (columns 9 and 10). Small number of errors indicates the accuracy of the models. Also, results suggest that with concerning only solar factors and not others, the predicted number of hurricanes is up to 39%. It can be assumed that with including more factors this percentage will increase.

The next step is a sensitivity analysis. To do this, the values of all input factors were fixed to their averages and the dependence of the hurricane occurrence from sequential changes in each factor from min to max values has been analysed. The results of this analysis are presented in Fig. 2.

It is obvious that with decreasing intensity of factors characterizing solar activity from the mean, the number of hurricanes should decrease, or remains without change. This is clearly seen in all graphs. On the contrary, by increasing the values of the solar activity the number of hurricanes should increase, too. But some of factors impact on reverse

Table 3
Accuracy analysis of hurricanes prediction for ANFIS models[a].

Types of hurricanes	Dimension of time series	Number of coincidences with calculated by model (including days without hurricanes)		Total number of observed hurricanes	Number of calculated hurricane	Number of true calculated hurricane		Number of false calculated hurricane			Number of hurricanes that cannot be calculated	Mean-square error in amplitude
1	2	3	4	5	6	7	8	9	10	11	12	13
Ha	2610	2548	98%	100	39	39	39%	-	0%	61	61%	0.1566
He	2610	2545	98%	102	37	37	36%	-	0%	65	64%	0.1614
Hw	2610	2537	97%	102	30	30	29%	-	0%	72	71%	0.1706
Ht	2610	2357	90%	363	126	122	34%	4	1%	241	66%	0.3275

[a] **Types of hurricanes** – data for Atlantic (Ha), East Pacific (He), West Pacific (Hw) and total number hurricanes (Ht); **Dimension of time series** – the number of days for which all parameters are measured; **Number of coincidences with calculated by model (including days without hurricanes)** – the number of days for which the number of actual and calculated by model hurricanes are equal. This number includes the days without observed hurricanes and model also predicted the absence of hurricanes; **Total number of observed hurricanes –** number of real hurricanes, which was registered during the analysed period; **Number of calculated hurricane –** number of hurricanes calculated by model for analysed period; **Number of true calculated hurricane –** the number of correct forecasts made by using of the model. Days for which the calculated hurricane was equal zero was not considered**; Number of false calculated hurricane**– the number of false forecasts for the whole researched period; **Number of hurricanes that cannot be calculated –** number of real hurricanes that developed model could not predict; **Mean-square error in amplitude** – mean-square error between the time series of real hurricanes and calculated by model.

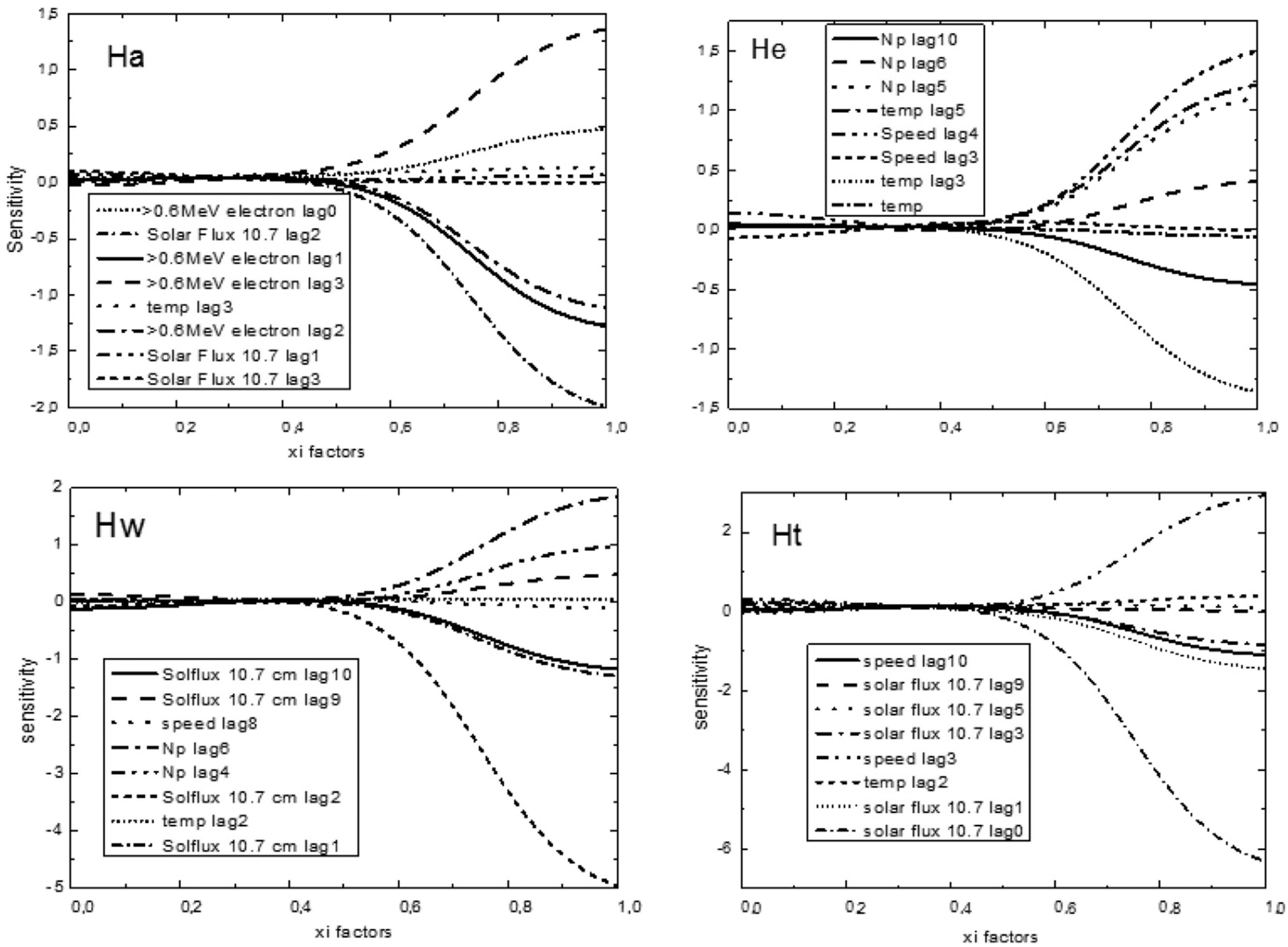

Fig. 2. Dependencies of hurricanes numbers for Atlantic (H_a), East Pacific (H_e), West Pacific (H_w), and total hurricanes (H_t) on sequential changes in each input factor.

way. It means that increasing of these factors lead to decreasing of hurricanes number.

According to H_t model, the most important factor is the Speed Lag = 3 and increasing of this factor leads to increasing of hurricanes number. The SolFlux 10.7 *cm* Lag = 9 is the strongest reverse factor; if it increases the number of hurricanes will decrease.

The model H_a shows weak exponential dependence on SolFlux 10.7 *cm* Lag = 0 and Lag = 3. The reverse factors are: SolFlux 10.7 *cm* Lag = 5 and Lag = 9 and Temp Lag = 2. It is very strange dependence that needs further physical investigations.

The number of H_e strongly depends on the Speed Lag = 2, temp Lag = 5 and Np Lag = 5. The reverse factor is temp Lag = 3.

The model H_w is strongly dependent on Np Lag = 4 and Lag = 6, SolFlux 10.7 *cm* Lag = 9. The most reverse factor is SolFlux 10.7 *cm* Lag = 2.

The potential theoretical (physical) explanation of the mechanism that could explain the considered interaction in this paper was already presented by the authors: Radovanović et al. (2003), Mukherjee and Radovanović (2011), Gomes et al. (2012), Radovanović et al. (2013), Pérez-Peraza and Juárez-Zuñiga (2015) Mihajlović et al. (2016), Mihajlović (2017) etc.

In the space between the Sun and the Earth, the current field moves along the lines of the magnetic field of the Sun, and in the free atmosphere, along the lines of the resulting magnetic field of the Sun and Earth. Movement of charged particles creates a convection electric current, and the emergence of electric current causes the appearance of a magnetic field in the form of a shell that does not allow the particle to be scattered. The forces that occur in the electric fields are the result of the interaction of the convection electric current and the magnetic field. The strength and direction of the electromagnetic force are uniquely determined by the vector product:

$$df = Idl \times B \tag{6}$$

where I is the strength of the electric convection current, dl is the vector of the length of the current field, and B is the magnetic induction vector. On the basis of the relation (6) it can be concluded that in the current field the direction of positively charged particles (protons) is opposite to the direction of the negatively charged particles (electrons). The circulation of charged particles in the current field is done in a level that is vertical to the direction of motion of the current field. The movement of the current field, that is, the atmospheric river, is under the influence of the kinetic energy of the particles taken from the Sun. Moving of the particles creates a convection electric current that creates a magnetic field. The magnetic field has the role of a shell that does not allow the particles to be scattered. However, during movement through the atmosphere, there is a decrease in speed, due to friction and increasing resistance of the geomagnetic field, which causes a decrease in the power of the electric current. By reducing the electric power, the magnetic field strength decreases. In a certain moment, it comes to the breakdown of the magnetic shell, that is, the opening of the current fields, and the particles of corpuscular radiation of the Sun get into the free atmosphere. After the opening of the current field, it comes to the spatial selectivity depending on the electric load of particles. The electrons are moving to the right, and the protons are moving left of the direction of radial speed of the current field. After the opening of the current field, the particles of corpuscular radiation get into free atmosphere with a certain quantity of movements. With a decrease in height, magnetic induction B of the Earth increases, resulting in a decrease in the radius of the proton tube in accordance with the relation:

$$r = mv \sin\theta / qB \tag{7}$$

With the increasing penetration into the lower layers of the atmosphere, there is an increasing effect of the geomagnetic field, that is, the effect of the circulation vector of the geomagnetic field, and the proton tube receives a cyclone motion. The magnetic shell of tube does not allow the particles to scatter, so the density of the particles increases with decreasing radius.

The basic weakness of the proposed models lies in the fact that they cannot predict with certainty where and when the opening will occur, i.e. disappearing of the magnetic shield that covers the current field.

4. Conclusion

Comparing to the results from previous study, with time lag up to 3 days, the present analysis with 10 days lag estimation and four input factors (F10.7, solar wind speed, density of solar wind particles, and solar wind temperature) improves hurricane prediction from 22–26% to 29–39% Also, our results implies that the hurricanes in different world places depend on absolutely different factors of solar activity. It means that nature of origin these hurricanes differs from each other.

So far, literature has no precise answers to the question of mechanisms that can explain origin of the hurricanes. This also applies to the solar impact on atmospheric processes. It is expected that response on changes in solar emission has time delay, but there is no consensus about it in recent literature. Gabis and Troshichev (2000) estimated that lag on 5–10 days, while Baldwin and Dunkerton (2001) pointed out that stratospheric mean-flow variations induce circulations that penetrate into the lower troposphere with propagation which takes 15 and 50 days and is most pronounced during winter months. However, our research shows that with increasing of technical possibilities, powerful computers and large datasets, the knowledge of the observed processes can expand.

Global temperature rise and strong El Niño events during 2015 coincide with strong tropical cyclones worldwide with strong implication on growing coastal population (Shultz et al., 2015), stressing the importance of intensifying research in this area. In this sense, the next task is to expand our model in the future with extended number of parameters covering all period during the year. In addition, Krapivin et al. (2012) stressed that reliable prediction of tropical cyclone depends of development of suitable indicators that contain various interactive parameters of magnetosphere-ionosphere-thermosphere and the solar wind-magnetosphere coupling.

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