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RAPID INTENSIFICATION OF A TROPICAL HURRICANE AS SELF-ORGANIZED DEVELOPMENT OF OPEN DISSIPATIVE SYSTEM

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1. INTRODUCTION

According to review of forecast advisories for 2007 (UNISYS Weather: Data/Archive 2007) regular predictions have overlooked or significantly underestimated practically all cases of rapid intensification of tropical hurricanes (TH). Proper forecasting of TH rapid intensification still remains as a challenging problem (Webber 2005, Krishnamurti et al. 2005). It also is of essential interest the problem of clarification of potential influence of global warming (Trenberth 2005, Kerr 2005, Emanuel 2005).

A new approach, based at so-called equilibrium translation model (ETM) (Shekriladze 2004), links the phenomenon of rapid intensification to certain type of conformity of dynamical and thermal fields in the combined system TH-ocean-atmosphere (alignment effect). The same model leads to new insight into the problem of influence of global warming.

ETM considers TH as self-organized dissipative system internally geared to maximum intensification. Realization of this internal tendency depends on two external factors: heat inflow and dynamical influence of surrounding atmosphere. Besides, heat capacity of a sea upper layer is assumed as the main energy source for TH development. When environmental wind (main driver of TH) is found to be in tune with internal thermal driving field, TH gains "freedom to operate" and this huge natural heat engine becomes mostly efficient in terms of conversion of oceanic heat potential into cyclonic motion of atmosphere. Developing in such a self-organized manner TH intensifies rapidly.

The main outcome of ETM is disclosure of non-dimensional alignment number (N_{al}) incorporating main integral thermal and dynamical parameters of the system and serving as a criterion of aforementioned systemic conformity.

The key role of N_{al} in TH rapid intensification was confirmed by wide field data on the cases of rapid intensification observed in 2004-2005 (including tropical hurricanes Charley, Katrina and Wilma) (Shekriladze 2006a). Here the same is demonstrated through correlation of the field data on the cases observed in 2007.

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2. EQUILIBRIUM TRANSLATION MODEL

Certain initial conformity of dynamical and thermal environmental fields almost always holds in the zones of TH development. It is caused by formation of background sea surface temperature (SST) field by aerodynamic field.

Another level of conformity of environmental fields is formed by longitudinal SST jump induced by TH itself. TH translation necessarily leads to considerable lowering of SST on its rear. Besides, influence of this SST jump assumes prevailing significance.

Intensity of heat and mass transfer from a sea surface to TH is little affected by translation speed. Here main role is played by much stronger tangent winds (for instance, beginning from outer boundary with tangent velocity 17.5 ms^{-1} (34 knots)). In this connection reduction of translation speed (leading to prolonging of TH passage above given area of a sea surface) steps up the share of heat removed from upper ocean layer, and, vice versa, gathering of TH translation reduces cooling of the upper ocean layer mentioned, all other things being the same.

According ETM aforementioned inverse dependence introduces rather strong feedback into thermal driving mechanism. TH not only prefers to shift toward SST elevation direction, but it also tends to establish certain equilibrium between translation speed and integral heat flux (equilibrium translation).

Generation of thermal driving force depends from TH translation speed and hurricane thermal potential (HHP) (Leipper and Volgenau 1972). Besides, generation of the same driving force needs more slow translation of TH at higher value of HHP and vice-versa. ETM assumes that this inverse dependence causes roughly constant value of heat involvement factor (equal to the share of HHP removed by TH from an ocean through passage of given area) during equilibrium translation. The last supposition is supported by analysis of the field data on the cases of TH rapid intensification (Shekriladze 2006a).

3. MAIN EQUATIONS

Analysis of ETM in the second approximation (SAP) (Shekriladze 2006b) covers general case of TH of non-circular geometry (Fig. 1). The analysis is based at restricted number of TH parameters reflected in regular forecast advisories. In this connection TH radius at tangent wind velocities equal to 34 knot (17.5 m s^{-1}) is accepted as TH outer boundary.

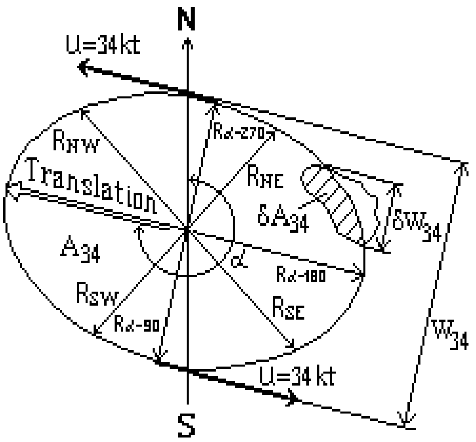

Fig.1. Scheme of translation of non-circular TH: A_{34} is area inside tangent velocity 34 knots (17.5 m s^{-1}); R_{NE}, R_{SE}, R_{SW} and R_{NW} are TH radii at tangent velocity 34 knots in Northeast, Southeast, Southwest and Northwest quadrants, respectively; α is TH translation azimuth; W_{34} is TH transverse width at tangent velocity 34 knots; δA_{34} is an area of land surface covered by A_{34}; δW_{34} is projection onto W_{34} of the part of the back boundary of A_{34} covered by land surface.

Integral heat flow (sensitive and latent) removed from left behind sea strip may be written in following form:

$$A_{34}q = C_i Q W_{34}\left(U_{bb} - U_{dr}\right) \qquad (1)$$

Here the nomenclature corresponds to Fig. 1; in addition, q is averaged inside A_{34} integral heat flux from sea surface to TH; Q is averaged inside A_{34} HHP; U_{bb} is translation speed of TH back boundary center; Production W_{34} (U_{bb}-U_{dr}), to a certain approximation, determines increment of cooled sea surface.

Based at analysis of the field data on number of cases of TH rapid intensification the value of heat involvement factor C_i is assumed as constant and equal in certain approximation to 1/19 for all cases of equilibrium translation.

Smooth (linear with the angle) distribution of intermediate TH radius is assumed through calculation of $R_{\alpha\text{-}180}$ and $R_{\alpha\text{-}270}$ serving further for determination of TH transverse width and back boundary center coordinates. The area A_{34} is determined as sum of the quadrants using aforementioned 4 values of TH radius.

Further, with regard to insignificance of sea surface drift, corresponding to value $C_i \approx 1/19$ condition of establishment of equilibrium translation is written:

$$N_{al} = \frac{\pi W_{34} U_{bb} Q}{2 A_{34} q} = \frac{U_{bb} Q}{q R_{ef}} \approx 30 \qquad (2)$$

Here R_{ef} is effective radius of TH:

$$R_{ef} = 2A_{34} / \pi W_{34} \qquad (3)$$

In addition, equations (2-3) are supplemented by a relation for average integral heat flux and correction factors on partial covering of land surface.

Empirical equation for average integral heat flux is developed based at three-zone model of heat transfer (Shekriladze 2006a) corresponding to tangent wind velocity zones according to regular forecast advisories:

$$q = [375(R_1^2 - R_2^2) + 600(R_2^2 - R_3^2) +$$
$$+1600(U_{max}/155)R_3^2]R_1^{-2}\ W\ m^{-2} \qquad (4)$$

Here R_1, R_2 and R_3 are average outer radii of first, second and third zones determined as a quarter of square root from sum of squares of corresponding radii in aforementioned four quadrants; U_{max} is maximum tangent wind velocity at given position in knots.

Characteristic for the first and second zones values 375Wm^{-2} and 600Wm^{-2} are determined through rounding the data recorded during rapid intensification of TH Opal (Shay et al. 2000). The value 1600 Wm^{-2} is determined through equating of arithmetic mean of 8 values of alignment number of super-typhoons Dianmu (2004) and Chaba (2004) at intensity 155 knots to 30.

Accounting of influence of land surface is carried out using correction factors (shares of δA_{34} and δW_{34}) through determination of alignment number. Besides, such a simple approach is applicable only if covered by TH land surface makes comparatively small part of A_{34}.

Finally, it should be noted also that assumption about decisive role of ocean upper layer heat potential naturally restricts applicability of ETM in the case of small TH radius when contribution of initial energy content of inflowing environmental air also may become valuable.

In addition the problem of determination of local transition speed of TH back boundary through discrete data specified in regular forecast advisory is once again reconsidered. A new aggregation procedure is developed using geographical coordinates of TH back boundary centre at current TH position and to the end of the first stage of TH further translation forecasted by the same regular forecast advisory. As a result only parameters presented in one forecast advisory are used through determination of N_{al}.

4. CORRELATION OF THE FIELD DATA

The main objective of correlation of the field data in the framework of equations (2-4) is verification of predicted by ETM linkage of TH development to alignment number. HHP maps (Goni and Trinanes 2007) are used as a basis for correlation. The results of correlation of four characteristic cases of TH development in different zones of the World Ocean during 2007 are presented in Figures 2-5.

TH Flossie, springing in equatorial zone of North East Pacific, passes almost strongly West in the zone with rather low HHP (40-30 kJ cm^{-2}). Previous regular forecasts predict its intensification only up to category 2. Nevertheless, Flossie rapidly intensifies to category 4. Further, despite forecasted by regular forecasts rather fast weakening, Flossie preserves high intensity during around 3 days (as HHP maps (Goni and Trinanes 2007) do not cover central part of North Pacific, the correlation does not include final part of Flossie's life cycle).

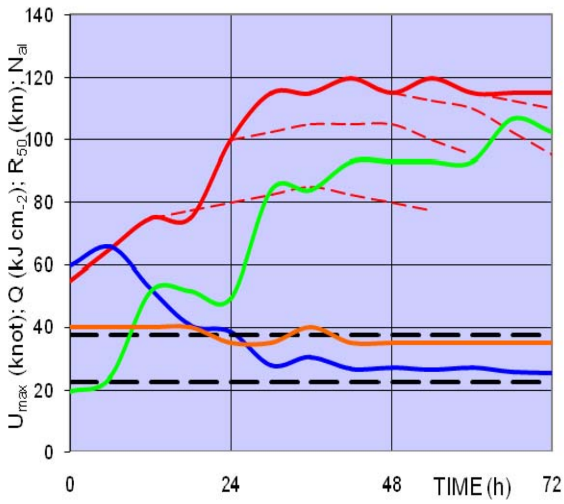

Fig. 2. Correlation of the field data on TH Flossie (North East Pacific, AUG 2007): red curve – U_{max}; red dotted curves – regular forecasts; orange curve – HHP; green curve – R_{50}; blue curve – N_{al} ; dotted horizontal lines - N_{al}=30±25%; the point 0 corresponds to 09:00 (UT) AUG 10 2007.

As is clear from the Fig. 2 contradictions between regular forecasts and real picture easily may be explained by TH self-organized development taking place under condition N_{al}=30±25%;.

It is reasonable to suppose that Flossie from the very beginning translated in equilibrium mode (influence of current value of R_{50} on N_{al} is considered below). Its long-term self-organized development has led to rapid intensification and achievement of maximum TH intensity possible at given rather low value of HHP (~40 kJ cm^{-2}). It seems likely that such a phenomenon was overlooked by numerical models used through preparation of regular forecasts in 2007.

In contrast to Flossie, TH Mitag, springing in equatorial zone of North West Pacific, passes North-West to Northern Philippines in the zone with quite high HHP (120-90 kJ cm^{-2}). Regular forecasts predict its intensification up to category 4. Nevertheless, Mitag intensifies only up to category 2.

As it clearly follows from the Fig. 2 poor development of Mitag in the zone with quite high

HHP easily may be explained by short-term realization of favorable mode of translation.

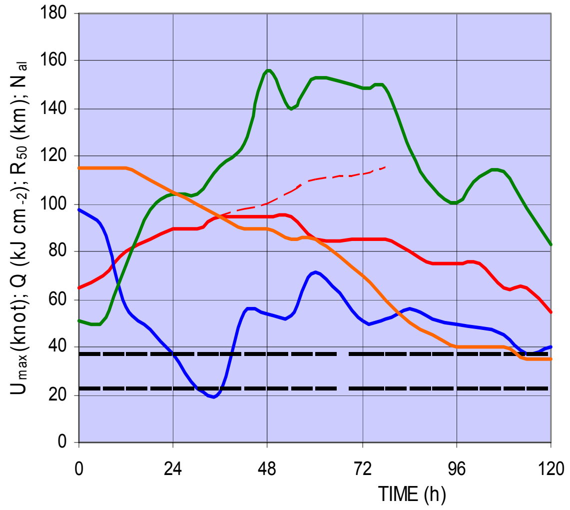

Fig. 3. Correlation of the field data on TH Mitag (North West Pacific, NOV 2007): red curve – U_{max}; red dotted curve – regular forecast; orange curve – HHP; green curve – $R_{50;}$ blue curve – N_{al} ; dotted horizontal lines - N_{al}=30±25%; the point 0 corresponds to 18:00 (UT) NOV 21 2007.

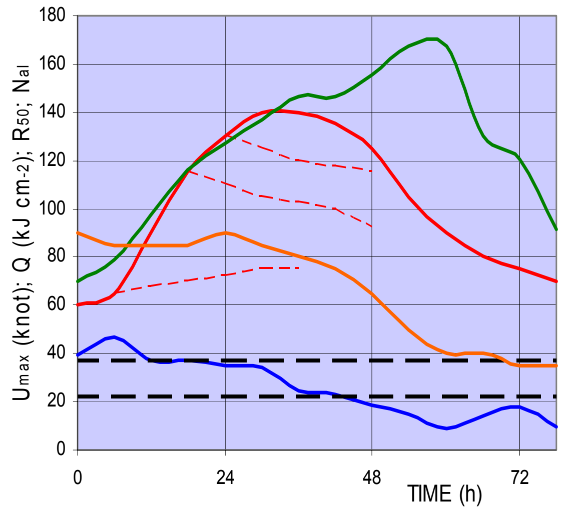

Fig. 4. Correlation of the field data on TH Gonu (North Indian, JUN 2007): red curve – U_{max}; red dotted curves – regular forecasts; orange curve – HHP; green curve – $R_{50;}$ blue curve – N_{al} ; dotted horizontal lines - N_{al}=30±25%; the point 0 corresponds to 06:00 (UT) JUN 3 2007.

Another TH Gonu (Fig. 4) represents an illustrative example of very rapid intensification (from TH of category 1 to category 5 during 24 hours) in the zone with rather high HHP (90-80 kJ cm^{-2}).

Gonu, springing in equatorial zone of North Indian, passes West-North. It rapidly intensifies translating under condition N_{al}=30±25%. Regular forecasts have fully overlooked Gonu's development persistently predicting its weakening even during rapid intensification. Further Gonu really weakens with transition to unfavorable mode of translation and significant lowering of HHP.

Presented here correlations should be examined also in the context of validity of the basic assumption about main role of oceanic heat inflow. According (Shekriladze 2006a) the assumption may lose force at small TH radii when initial energy content of inflowing environmental air also may become valuable. Inequality R_{50} > 80 - 100 is offered as rough condition of validity of the approach (such a validity really depends also on parameters of inflowing air that requires further analysis).

As it follows from the presented correlations the last condition is not obeyed at starting stages of TH development.

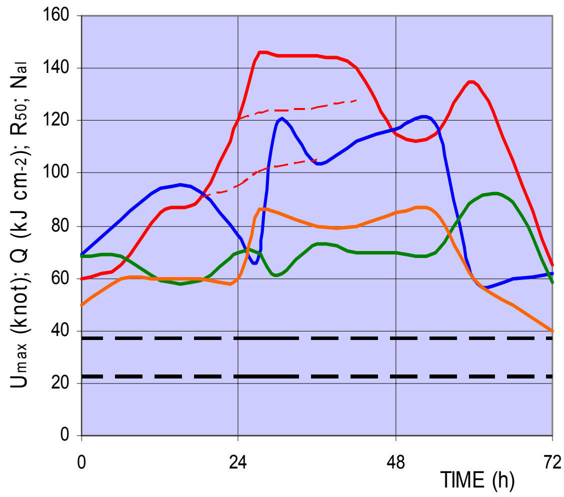

Fig. 5. Correlation of the field data on TH Felix (North West Atlantic, SEP 2007): red curve – U_{max}; red dotted curves – regular forecasts; orange curve – HHP; green curve – $R_{50;}$ blue curve – N_{al} ; dotted horizontal lines - N_{al}=30±25%; the point 0 corresponds to 21:00 (UT) SEP 01 2007.

At the same time in rear cases R_{50} remains small during all TH life cycle. TH Felix (Fig. 5) just represents such an example.

Felix, springing at east boundary of Caribbean Sea, passes almost strongly West to Nicaragua in the zone with moderate HHP (50-80 kJ cm^{-2}). Felix intensifies very rapidly from category 1 to category 5 during 24 hours. Further it re-intensifies once again prior to landfall.

As is seen from the Fig. 5, R_{50} remains small during all life cycle of Felix. In this connection, in general, Felix's development does not correspond to the equation (2). However, it should be noted also that the both stages of Felix's intensification are accompanied by rather fast changes of N_{al} towards the range 30±25%. The last circumstance makes prospective extension of ETM on small TH.

5. CONCLUDING REMARKS

The potential of qualitative physical models to disclose basic features of any subject matter is demonstrated once again, on this occasion, by the example of exclusively complex and powerful multi-scale natural phenomenon.

According to equilibrium translation model (ETM) self-organized development of a tropical hurricane (TH) under the condition N_{al}=30±25% leads to its maximum intensification (alignment effect). At that, achievable level of TH intensity is determined by hurricane heat potential (HHP) of a sea upper layer in given area.

Non-dimensional alignment number N_{al}, incorporating main integral parameters of combined system TH-ocean-atmosphere, gains the role of fundamental characteristic of TH development.

Limitations of the model are linked to lack of accounting of the role of initial energy content of environmental air inflow, most likely, valuable in the case of small TH.

Further investigation of the problem may contribute also in clarification of vital problem of potential influence of global climate changes on regional features of TH development.

As correlation of equilibrium translation speed with prevailing regional winds is decisive in context of TH development, in some cases reduction of HHP may lead even to promotion of TH development.

In this context, the most unwanted scenarios may be realized in the regions where long-term changes of HHP are accompanied by favorable for alignment effect transformation of correlation between equilibrium mode of TH translation and prevailing regional winds.

Comparative lowering of HHP in North Atlantic and North Pacific during 2006-2007 has shifted the condition N_{al}=30±25% towards rather high translation speeds. Against characteristic regional wind velocities the last circumstance has led to lowering of probability of alignment effect causing thereby reduction of seasonal number of powerful hurricanes.

In contrast to it, in North Indian comparative reduction of HHP has led to improvement of correlation between TH equilibrium translation and regional winds. As a result rather unusual for the region tropical cyclones of 4^{th} and 5^{th} category are observed during 2006-2007.

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