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CRITICAL ALIGNMEHT NUMBER AND MAXIMUM POTENTIAL INTENSITY OF TROPICAL HURRICANE

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1. INTRODUCTION

Characteristic scales of a tropical cyclone vary from the sizes of sprayed by wind water droplets to the sizes of lengthy spiral rainbands. Description of such a complex and multi-scale phenomenon requires accounting of great variety of interrelated irreversible thermo-hydrodynamic processes. That is why numerical methods of modeling in combination with wide field measurements become main instrument of research of TC phenomenon. By now this "great numerical attack" is in progress with certain achievements, for instance, in TC track forecasting (Webber 2005a, Chan and Li 2005, Pasad 2006, DeMaria 2007).

At the same time forecasting of TC intensity still remains as a challenging problem (Krishnamurti et al. 2005, Webber 2005b, Balling and Cerveny 2006, DeMaria et al. 2007, Zhou and Wang 2008). Despite permanent improvement of resolution of numerical models, even in 2008-2009, regular predictions have overlooked or significantly underestimated practically all cases of rapid intensification (UNISYS Weather 2003-2009).

Of special interest is the problem of potential influence of global climate change (Trenberth 2005, Kerr 2005, Emanuel 2005, Shepherd and Knutson 2007) that also may be linked to TC intensification phenomenon. In addition, it is left aside consideration potential of analysis at integral scales of the system COA.

Most likely all these challenges reflect rather typical contemporary problem with proper combination of numerical methods with adequate physical models.

A model of equilibrium translation (MET) (Shekriladze 2004; 2006a, 2008) bridges this gap linking TC development to conformity of dynamical and thermal fields of the system COA at integral scales.

According to the MET a TC always is influenced by certain internal thermal driving mechanism caused by thermal asymmetry at its outer boundary. As a result it tends to certain equilibrium between translation speed and intensity of heat removal from ocean upper layer. At the same time such an equilibrium translation is impossible without favoring by large-scale environmental wind that, as a rule, holds prevailing driving influence.

If internal tendency of a TC is found to be in tune with large-scale environmental wind, this huge natural heat engine gains "freedom to operate" and becomes mostly efficient in terms of conversion of oceanic heat into cyclonic motion of atmospheric air. As a result, the TC freely develops in self-organized manner and intensifies rapidly (alignment effect).

According to the MET, non-dimensional alignment number, incorporating integral thermal and dynamical parameters of the system COA, is the main characteristic of TC development.

In general case of a TC of non-circular geometry alignment number can be determined in the following manner (Shekriladze 2006a; 2006b; 2008):

$$N = \frac{U_{bb}Q}{qR_{ef}}, \qquad (1)$$

where U_{bb} is translation speed of the center of TC back boundary; Q is average initial hurricane heat potential (HHP) (according Leipper and Volgenau (1972)) fixed before entering of a TC in the given area; q is average integral heat flux (sensitive and latent) from sea surface to a TC;

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R_{ef} is effective radius of a TC (R_{ef} is equal to TC radius in the case of circular TC).

Another important problem, naturally linked to alignment effect, is assessment of maximum potential intensity (MPI) of a TC.

Alongside with theoretical studies (Emanuel 1986, 1988, 1991, 1995, 1999, Holland 1997, Persing and Montgomery 2003) semi-empirical and purely empirical approaches also have been developed (DeMaria and Kaplan 1994, Whitney and Hobgood 1997). Besides, quite robust theory (Emanuel 1996) is brought up to real time hurricane MPI maps. The theory establishes relationship between MPI and sea thermal parameters under acting TC.

Empirical approaches mainly assumed governing role of sea surface temperature (SST) although this concept has become the subject of rather wide discussion (Sun et al. 2006, Wada and Usui 2007, Shepherd and Knutson 2007).

At the same time, it is different matter assessment of MPI during forecasting procedures that cannot be made based on sea parameters under acting TC. Such an assessment can be performed only through using sea parameters fixed prior to entering of a TC in given area.

Discovery of alignment effect reveals some new dimensions of the problem of potential influence of global climate change on TC activity. It also gains certain significance possible interpretation of alignment effect as an emergent property of the system COA occurring at integral scales.

Abovementioned aspects of the problem are discussed below.

2. STARTING ASSUMPTIONS AND RELATIONSHIPS

According to the MET realization of internal tendency of a TC at intensification is linked to two external factors: heat inflow from an ocean and dynamical influence of surrounding atmosphere. Besides, oceanic heat inflow is assumed as the single energy source for TC development.

In general case internal driving mechanism of a TC is linked to longitudinal SST gradient induced by TC itself through considerable lowering of SST on its rear.

Intensity of heat and mass transfer from sea surface to a TC is little affected by translation speed. Here main role is played by much higher air tangent speeds (for instance, beginning from outer boundary at tangent wind speed 17.5 ms^{-1}).

In this connection slowing of translation, leading to prolonging of TC passage through the given area, steps up cooling of an ocean, and vice versa, gathering of translation reduces cooling, all other things being the same.

The inverse dependence introduces rather strong feedback into thermal driving mechanism. As a result a TC not only prefers to shift toward SST elevation, but it also tends to establish certain equilibrium between translation speed and integral heat flux. According to the central assumption of the MET corresponding so-called equilibrium translation roughly is linked to constancy of heat involvement factor that is equal to the share of initial HHP removed by a TC through full passage of given area (the assumption previously was confirmed by field data on TC Opal (1995) (Shekriladze 2006a)).

Development of a TC of non-circular geometry was considered in (Shekriladze 2006a) in the framework of the MET using HHP maps (Hurricane heat potential maps 2003-2009) and parameters specified in regular forecast advisories (UNISYS Weather 2003-2009). Full set of equations and description of calculation procedures are presented in (Shekriladze 2006a). The key relationships are reproduced below.

Taking in account minimum value of tangent wind indicated in regular advisories, outer boundary of a TC is accepted at tangent wind speed 34 knots (17.5 m s^{-1}).

Integral heat flux (sensitive and latent) removed by a TC from left behind sea strip, with regard to insignificance of sea drift, can be written in the following form:

$$A_{34}q = C_i Q W_{34} U_{bb}, \qquad (2)$$

where A_{34} is an area inside tangent wind 34 knots; C_i is heat involvement factor; W_{34} is transverse size of A_{34}; Production $W_{34}U_{bb}$, to a certain approximation, represents increment of cooled sea surface.

A condition of establishment of equilibrium translation mode was determined by critical alignment number (Shekriladze 2006a; 2008):

$$N_{cr} = \frac{U_{bb}Q}{qR_{ef}} = \frac{\pi W_{34} U_{bb} Q}{2A_{34}q} \approx 30, \qquad (3)$$

where R_{ef} is equal:

$$R_{ef} = 2A_{34} / \pi W_{34} \qquad (4)$$

In addition, equations (2-4) were supplemented by empirical equation for average heat flux from sea surface to a TC specifically fitted to equilibrium translation. The equation is based at three-zone model of heat transfer (Shekriladze 2006a, 2006b, 2008).

In connection with inverse negative relationship between translation speed and initial HHP (other things being the same) equilibrium translation is comparatively slow at high HHP and comparatively fast at low HHP. In this connection the area with high initial HHP undergoes more intensive cooling than the area with low initial HHP.

Reasoning from this circumstance it was assumed that, during equilibrium translation SST field under TH is roughly the same irrespective of initial value of HHP. Average integral heat flux was considered as single-valued function of tangent wind distribution and following empirical equation was offered (Shekriladze 2006a, 2006b, 2008):

$$q = [375\left(R_1^{\,2} - R_2^{\,2}\right) + 600\left(R_2^{\,2} - R_3^{\,2}\right) + \\ + 1600\left(U_{\max} / 155\right)R_3^{\,2}] / R_1^{\,2} \text{ W/m}^2, \qquad (5)$$

where R_1, R_2 and R_3 are average outer radii in meters of first (at tangent wind 34 knots), second (at tangent wind 50 knots) and third (at tangent wind 64 knots) zones according regular forecast advisories determined as a quarter of square root from sum of squares of corresponding radii in four quadrants; U_{max} is maximum tangent wind velocity in knots.

It also should be mentioned that calculation of alignment number through using the set of parameters specified in regular forecast advisories meets certain difficulties. However, in overwhelming majority of cases, accuracy of determination of the number turns out to be sufficient for reliable establishment of crucial role of alignment effect in TC development (Shekriladze 2006a, 2006b, 2008).

3. MAXIMUM POTENTIAL INTENSITY

The work performed by a TC during ideal thermodynamic cycle depends on heat removed from an ocean and efficiency of heat conversion. The latter, for its part, depends on SST field under acting TC and temperature of air outflow. In real cycle the efficiency additionally depends on other parameters of the system SOA. Besides, in the context of the MET, alignment number evidently claims to serve as generalized characteristic of such an additional influence.

As maximum intensity of a TC takes place at the same (critical) alignment number at any conditions, this number can be excluded from the number of influencing MPI variables. In addition, the same conclusion can be extended to the temperature of air outflow assuming rough uniformity of this parameter during life cycle of different TCs.

In such a framework, finally, SST and HHP fields under acting TC become the main variable parameters of upper oceanic layer that influences MPI.

At the same time, forecasting of SST field under acting TC based on SST field existed before entering of a TC in given sea area presents rather complicated problem.

The matter is that dynamical impact of acting TC leads to intensive vertical mixing of seawater with drastic transformation of initial SST field (Shay et al. 2000).

It is easy to verify that in such a situation resultant SST field mainly is dependent on initial HHP field (Shekriladze 2006a).

Finally, taking in account main provisions of the MET, following assumptions can be made:

- MPI can be achieved only through TC translation at critical alignment number;
- MPI should be considered as single-valued function of initial HHP.

In such a manner, the following functional relationship can be offered:

$$MPI = f\left(Q\right), \qquad (6)$$

Further, let to start with testing of validity of the aforementioned assumptions.

Among more than 160 tropical hurricanes observed during 2003-2009 Parma (2003), Chaba (2004), Dianmu (2004), Saomai (2006), Monica (2006), Flossie (2007), Rick (2009), and Nida (2009) stand out for maximum intensity at corresponding values of initial HHP.

Similar to previous works, during correlation of the field data in coordinates MPI – HHP, maximum intensity of a TC is equated with maximum sustained wind based on one-minute average according regular forecast advisories (UNISYS Weather 2003-2009).

As visual identification of low HHPs (less than 30 kJ cm^{-2}) through the maps is quite complicated task and is connected with significant error, hurricane Flossie and super typhoon Parma are not involved in the correlation.

Correlation of the field data on maximum intensities is presented in Fig. 1.

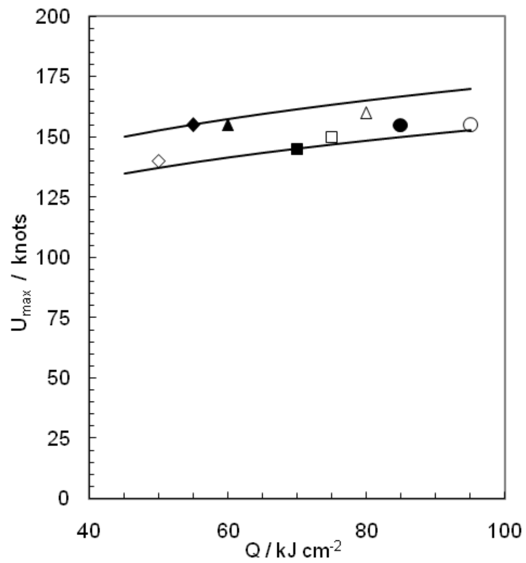

Fig. 1. Correlation of the field data on MPI: ◊ – Saomai ; ◆ – Monica; ▲ – Rick; ■ - Chaba; □ - Chaba; Δ – Nida; ● – Chaba; o – Dianmu; upper curve: equation (7); lower curve: 0.9 MPI

As may be inferred from the graph, dispersion of presented field data is ± 5 % within the belt corresponding to the law U_{max}~$Q^{1/6}$. Record-breaking intensities turn out to be a single-valued function of initial HHP.

Assuming that observed maximum intensities closely approach MPI and accepting cyclone Monica (155 knots at 55 kJ cm^{-2}) as a reference case, the following empirical equation can be offered:

$$MPI = 80Q^{1/6} \textit{ knots,} \qquad (7)$$

where a dimension of Q is kJ cm^{-2}**.**

The "sixth-root law" (7), determining MPI using initial HHP field, is valuable in terms of forecasting needs. It can be regarded as sufficiently accurate in the range Q=40÷100 kJ cm^{-2}.

Applicability of the equation (7) is restricted in the range of small diameters of a TC when basic assumption of the MET about overpowering role of HHP loses force and energy content of air inflow also becomes valuable.

Further, let to examine presented record-breaking cases in the particular context of evaluation of the role of alignment effect. Such a narrowed approach drastically simplifies analysis avoiding consideration of the roles of separate factors influencing TC development.

At the same time, efficiency of such an approach evidently depends on capability of alignment number to comprehend combined influence of full spectra of controlling TC development factors, such as seawater heat content, prevailing winds, intensity of air-sea interactions, wind shear, synoptic conditions, TC tracking peculiarities and others.

Calculation of U_{bb} using parameters specified in regular forecast advisories meets certain difficulties. The main source of the error is significant time lag between forecast advisories.

In the present study two values of U_{bb} were used. The mine value of U_{bb}, involved in N_1, has been determined as arithmetic mean of average translation speeds of the center of TC back boundary at two lengths, preceding and following the given position of a TC, using the procedure (Shekriladze 2006a).

The second (supplementary) value of U_{bb}, involved in N_2, has been determined using specified in regular forecast advisories translation speed of TC centre.

If the both values are roughly the same, it indicates roughly straight-forward translation of a TC with roughly constant sizes.

In such a case accuracy of the main value turns out to be sufficiently high. And, vice versa, disparity between these two values may reflect indirect and irregular character of TC translation at given length making questionable accuracy of the calculation.

Among selected cases the absolute record of intensity (160 knots) has been achieved by super typhoon Nida that emerged in tropical Western North Pacific in the zone with moderately high HHPs (70÷80 kJ cm^{-2}) in November 2009.

As may be inferred from Fig. 2, the zone of record-breaking intensity of super typhoon Nida is coincident with equilibrium mode of translation according to the condition (3). The stage of maximum intensity of Nida took place during its roughly uniform straight-forward translation with roughly constant sizes and coinciding N_1 and N_2.

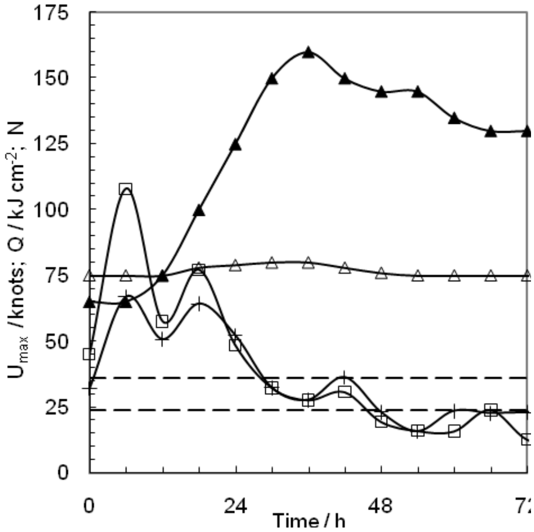

Fig. 2. Correlation of the field data on TC Nida: ▲ – maximum Tangent Wind: + – N_1; □ - N_2; Δ – initial HHP; dotted lines N=30±20%; the position 0 - 06:00 hour (UT) 24 NOV 2009

Cyclone Monica presents another outstanding case for very high maximum intensity at quite moderate initial HHP.

Monica emerged in tropical Western South Pacific in the zone with HHP 40÷50 kJ cm^{-2} in April 2006 (Fig. 3). In the Gulf of Carpentaria it intensified up to maximum intensity 155 knots just before landfall.

Accuracy of determination of alignment number is low in the case of Monica in connection with protracted time lags between forecast advisories. However, the stage of record-breaking intensity coincides with alignment effect (as the MET looses force beyond sea surface, alignment number becomes pointless at post-landfall stage).

Apart from Monica, during 2003-2009, three more TCs, hurricane Rick and super typhoons Dianmu and Chaba have achieved intensity 155 knots at more high initial HHPs. However, at corresponding initial HHP, each of them presents record-breaking case.

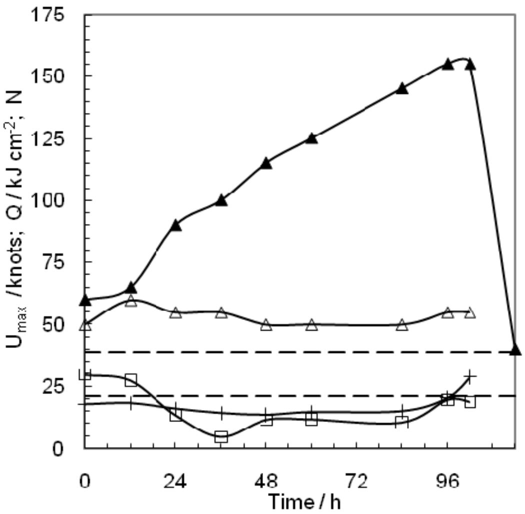

Fig. 3. Correlation of the field data on TC Monica: ▲ – maximum tangent wind; + – N_1; □ - N_2 ; Δ – initial HHP; dotted lines: N=30±30%; the position 0 - 00:00 hour (UT) 20 APR 2006

Hurricane Rick emerged in Eastern North Pacific in the zone with HHP 50÷60 kJ cm^{-2} in October 2009. Further it rapidly intensified up to maximum intensity 155 knots.

Correlation of the field data on TC Rick is presented in Fig. 4.

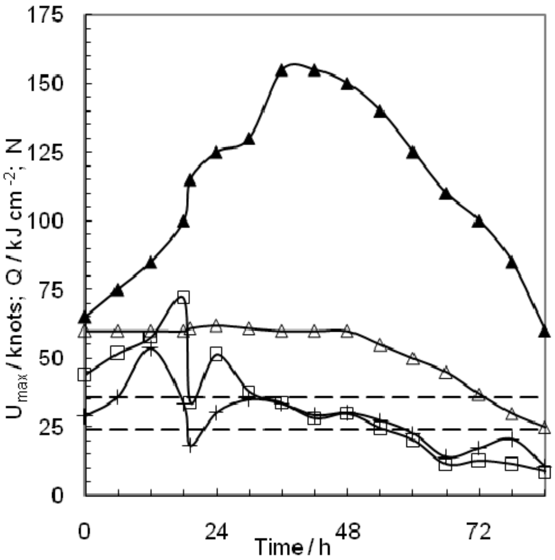

Fig. 4. Correlation of the field data on TC Rick: ▲ – maximum tangent wind; + – N_1; □ - N_2; Δ – initial HHP; dotted lines: N=30±20%; the position 0 - 15:00 hour (UT) 16 OCT 2009

As may be inferred from Fig. 4, the stage of maximum intensity of hurricane Rick coincides with equilibrium translation.

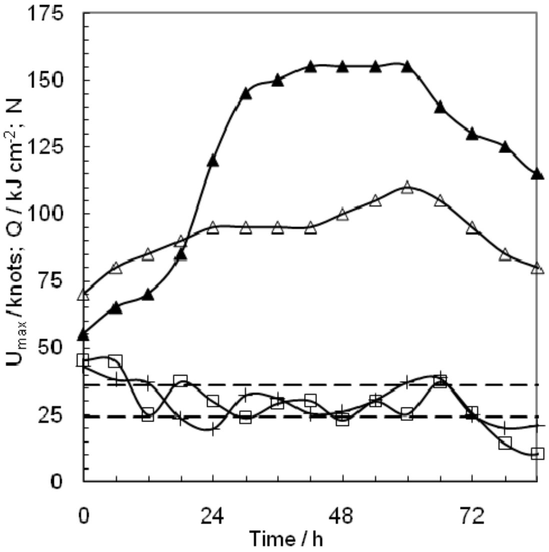

Fig. 5. Correlation of the field data on TC Dianmu: ▲ – maximum tangent wind; + – N_1; □ - N_2; Δ – initial HHP; dotted lines N=30±20%; the position 0 - 12:00 hour (UT) 14 JUN 2004

Super typhoon Dianmu (Fig. 5) emerged in the zone with HHP 70-80 kJ cm^{-2} in Western North Pacific in June 2004. Further it translated through the zone with moderately high HHP (90-110 kJ cm^{-2}). Dianmu rapidly intensified to 5th category up to maximum intensity 155 knots.

As follows from the graph, longstanding maximum intensity of super typhoon Dianmu coincides with equilibrium translation. Maximum intensities of Dianmu also took place during roughly uniform straight-forward translation with roughly coinciding N_1 and N_2.

Super typhoon Chaba (Fig. 6) emerged in the zone with rather high HHP (~110 kJ cm^{-2}) in tropical Western North Pacific in August 2004. Further it translated through the zone with HHP 100-70 kJ cm^{-2} and intensified up to 155 knots.

As distinct from other TCs, Chaba's life cycle additionally includes other stages with intensities 150 and 145 knots also representing maximums at corresponding values of initial HHP.

Another atypical peculiarity of Chaba is matching of equilibrium translation with tangible variations of translation speed, movement vector and outer radius. These circumstances evidently lower accuracy of determination of alignment number that apparently is manifested by swing of values of N_1 and N_2. Nevertheless, the correlation clearly exhibits coincidence of maximum intensities with alignment effect.

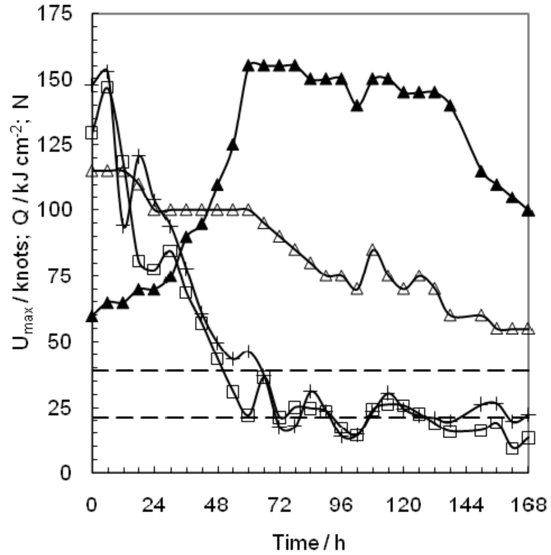

Fig. 6. Correlation of the field data on TC Chaba: ▲ – maximum tangent wind; + – N_1; □ - N_2; Δ – initial HHP; dotted lines N=30±30%; the position 0 - 06:00 hour (UT) 20 AUG 2004

Correlation of the field data on super typhoon Saomai is presented in Fig. 4.

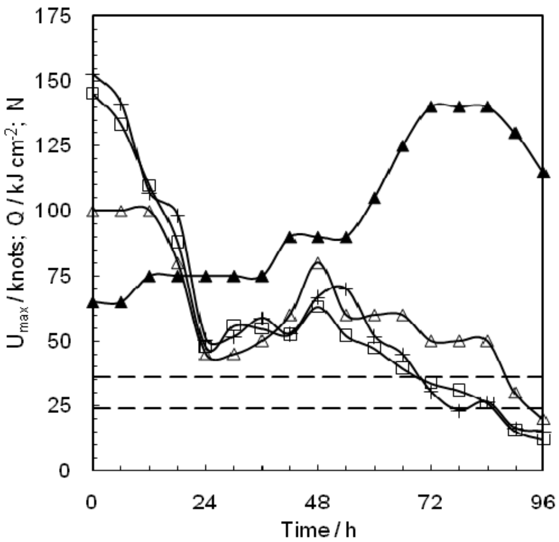

Fig. 7. Correlation of the field data on TC Saomai: ▲ – maximum tangent wind; + – N_1; □ - N_2; Δ – initial HHP; dotted lines N=30±20%; the position 0 - 12:00 hour (UT) 06 AUG 2006

Saomai emerged in the zone with rather high HHP (~100 kJ cm^{-2}) in tropical Western North Pacific in August 2006. Further it translated straight-forward at northwest through the zone with HHP 80-40 kJ cm^{-2}. Finally it achieved intensity 140 knots.

As follows from Fig. 7, intensification of Saomai clearly coincides with fast approaching to equilibrium translation at roughly coinciding N_1 and N_2.

Here also should be noted that regular advisories and HHP maps include only discrete field data represented in the figures by points. As regards to smoothed curves, they are of purely conventional character.

Summing up above correlations, we can say that the MET has received further support through demonstration of decisive role of alignment effect in achievement of MPI. Of special note is fundamental character of alignment number (Shekriladze 2004) that claims to comprehend combined influence of full spectra of factors controlling TC development.

In all considered cases attainment of critical alignment number or approaching to this value might serve as reliable harbinger of rapid intensification.

This conclusion additionally is supported by impressive cases of rapid intensification taking place even against lowering of initial HHP along TC's path.

For instance, in 2004, hurricane Charley intensified very rapidly through approaching South Florida with catastrophic consequences during landfall.

Charley's rapid intensification took place just through its translation above sea area with HHP lowering along the TC's path. Besides, corresponding regular advisory has forecasted Charley's rather fast weakening. In reality, before the rapid intensification, Charley passed on equilibrium translation (Shekriladze 2006a).

By the way, presented in Fig. 7 rapid intensification of super typhoon Saomai also took place against lowering of initial HHP along its path. Besides, this event also was preceded by regular advisories forecasting weakening of the TC.

In addition, it seems quite intriguing that existing numerical models give no indication on occurrence of specific conditions leading to explosive intensification of a TC.

Overlooking of alignment effect by these models motivates consideration of rapid intensification of a TC as an emergent property of the system COA that occurs at integral scales. Besides, similar property hardly may be revealed through low-scale modeling (Chalmers 2006).

Similar far-reaching inference, however, needs further detailed examination.

4. ALIGNMENT EFFECT AND POTENTIAL INFLUENCE OF CLIMATE CHANGE

Discovery of alignment effect opens new avenue of attack on vital problem of potential influence of global climate change on TC activity. Below an attempt is made to appraise potential influence of global climate change on TC activity in the light of the role of correspondence of equilibrium translation mode to prevailing regional winds.

According the MET the best conditioned development of a TC takes place at critical alignment number. And vice-versa, a degree of divergence of alignment number of real TC from critical value is a measure of worsening of conditions of its development.

In this context, it is not necessarily a case promotion of TC development by elevation of HHP although the latter remains as main energy source for TC development. Direct linking of promotion of TC development to HHP turns out to be unjustified simplification of the reality.

As shown below, alignment effect reveals more complex and ambiguous interrelations between thermal and hydrodynamic parameters of the system COA.

Necessity of matching of equilibrium translation with prevailing environmental winds rather strictly predetermines the range of TC translation speed favoring to alignment effect. As trade winds play the role of prevailing environmental wind in the main tropical regions, appropriate for alignment effect range of translation speed is 4÷6 m s^{-1}.

Proceeding from (3), following equation can be written for equilibrium translation speed (ETS):

$$U_{eq} = \frac{30qR_{ef}}{Q} \tag{8}$$

In such a manner, equation (8) once again demonstrates inverse dependence of TC equilibrium translation speed on initial HHP. The higher is HHP, the slower is equilibrium translation of a TC across given area (other things being the same).

Through further analysis, it is assumed that radii of overwhelming majority of TCs vary in the range 100÷400 km. Average heat flux 500 W m^{-2} from an ocean to a TC also is assumed. A set of curves reflecting dependence of ETS on initial HHP according equation (8) is plotted in Fig.8.

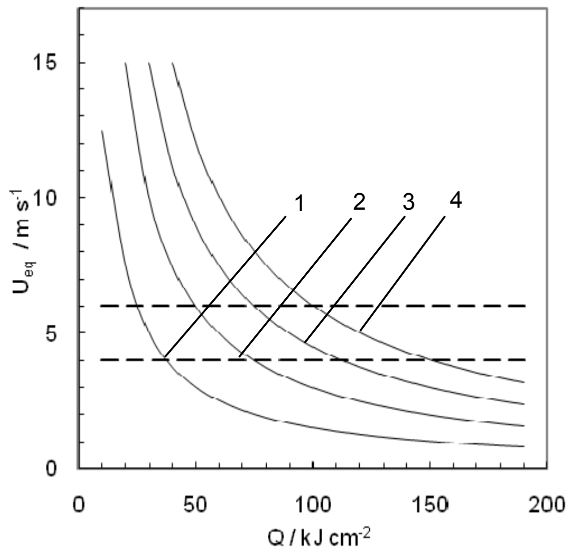

Fig. 8. Dependence of ETS on initial HHP according equation (8): 1 – U_{eq} at R_{ef}=100 km; 2 - U_{eq} at R_{ef}=200 km; 3 - U_{eq} at R_{ef}=300 km; 4 - U_{eq} at R_{ef}=400 km; dotted horizontal lines: characteristic range of trade wind speeds (4÷6 m s^{-1})

According presented curves, at very high HHP (150 kJ cm^{-2} and more), ETS falls significantly lower of characteristic range of trade wind speeds.

As large-scale environmental wind is main driver of a TC, this circumstance practically excludes establishment of equilibrium translation and, accordingly, promotion of TC development.

At the same time, alternatively, nearness of ETS and trade wind speeds is observed in the range of moderate and moderately high HHPs (40÷100 kJ cm^{-2}) that makes this range the best favorable to TC development.

As an impressive example of aforementioned ambiguous relationship between HHP and TC development may serve the most overheated zone of the world ocean – Western Equatorial Pacific. Despite the fact that spacious areas with HHP 150÷220 kJ cm^{-2} range there beyond 10° S, the zone is much less "productive" in terms of promotion of strong hurricanes than the zone of Western North Pacific with HHP in the range 0.4÷1.0 kJ cm^{-2}. By the way, this conclusion clearly is confirmed by the geographical distribution of considered TCs.

In such a manner, strange as it may seem, in some cases elevation of HHP, caused, for instance, by climate change, may lead even to hindering of TC development by mistuning of favorable thermo-hydrodynamic balance in the system COA. Otherwise, in some other cases, reduction of HHP may cause step up of TC development.

In the context of presented considerations the most unwanted scenarios may be realized in the regions where transformation of HHP field is tended at improvement of correlation between ETS and large-scale environmental wind through climate change.

Comparative lowering of HHP in North Atlantic and North Pacific during 2006-2008 shifted the condition of establishment of critical alignment number towards high translation speeds. Against slower regional winds, this circumstance led to lowering of probability of establishment of equilibrium translation causing thereby reduction of seasonal number of powerful hurricanes.

Besides, 2008 became the first year, among decades, that has passed without any tropical hurricane of 5th category.

5. CONCLUDING REMARKS

Basic character of the model of equilibrium translation once again is demonstrated, on this occasion, through analysis of development of the most intensive TCs selected among around 160 TCs observed worldwide during 2003-2009.

Linkage of rapid intensification of a TC to its self-organized development at critical alignment number (alignment effect) once again clearly is verified. Achieved by the TCs maximum intensities turn out to be single-valued function of initial HHP fixed prior to entering of a TC in given area. Corresponding empirical equation for maximum potential intensity of a TC adequately correlates related field data.

Once again is agreed fundamental character of alignment number, incorporating main integral parameters of the system COA and comprehending combined influence of full spectra of thermo-hydrodynamic factors controlling TC development.

The basis is formed for alternative approach to the problem of TC intensity forecasting through using of alignment number as reliable indicator of character of forthcoming development of the system COA.

Important role of alignment effect also is outlined in the context of clarification of potential influence of global climate change on TC activity.

It is established that thermal condition of upper oceanic layer influences TC development mainly through favoring (or hampering) establishment of TC equilibrium translation that depends on conformity of thermal and hydrodynamic fields. At the same time, intensity of a TC becomes single-valued function of initial HHP only consequent to approaching critical alignment number.

Correspondingly, influence of climate on TC activity mainly will be realized through change of preconditions for establishment of TC equilibrium translation. That is why, during 2003-2009, absolute record of TC intensity (160 knots) was set up at moderately high initial HPP (80 kJ cm^{-2}).

Overlooking of alignment effect by numerical models motivates consideration of rapid intensification of a TC as an emergent property of the system COA that occurs at integral scales and hardly can be revealed through low-scale modeling. Similar far-reaching inference, however, needs further detailed examination.

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