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Tropical Cyclone: Alignment Effect and Maximum Potential Intensity

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ABSTRACT. **The analysis of some major tropical cyclones (TC) has been performed in the framework of the so-called model of equilibrium translation (MET) in order to eliminate the contradiction between the available field data and thermodynamic theory of maximum potential intensity (MPI). According to the MET, TC is an open dissipative system internally aimed at intensification. When this inner focus comes into a certain harmony with large-scale environmental wind, TC becomes particularly effective in the conversion of oceanic heat into kinetic energy of cyclonic motion and rapidly intensifies (alignment effect). Dimensionless Shekriladze number, incorporating integral thermal and dynamical parameters of the system ocean-cyclone-atmosphere (SOCA) acquires the role of a predictor of the character of TC development, including rapid intensification. The MET reveals negative feedback between hurricane heat potential (HHP) and TC translation speed during the alignment effect, leading to a constant mean sea surface temperature (SST) under acting TC, regardless of the initial HPP. In such circumstances, the constancy of real maximum intensities of TCs recorded in field observations at HHPs, exceeding 50 kJ×cm^{-2}, is in agreement with the thermodynamic theory. In addition, the approximate analysis of the field data specified in the regular forecast advisories shows linkage of the alignment effect to the critical value of Shekriladze number around 35. However, this important outcome needs further confirmation by analysis of more detailed field data.** *© 2012 Bull. Georg. Natl. Acad. Sci.*

Key words: *tropical cyclone, Shekriladze number, maximum potential intensity, equilibrium translation.*

Tropical cyclone (TC) is an extremely complex multiscale phenomenon, the description of which requires accounting for a wide variety of interrelated irreversible thermo-hydrodynamic processes. That is why numerical models have become a major tool in the investigation of TC. Currently, this "great numerical attack" comes with certain achievements, such as TC track forecasting [1-3].

However, progress in forecasting TC intensity is much slower [3-4]. Besides, prediction of TC rapid intensification remains a particular challenge.

Another, important related problem is assessment of maximum potential intensity (MPI). Comparative analysis [5] reveals difficulties with interpretation of the existing field data by a known thermodynamic theory [6-7] considering TC as Carnot heat engine.

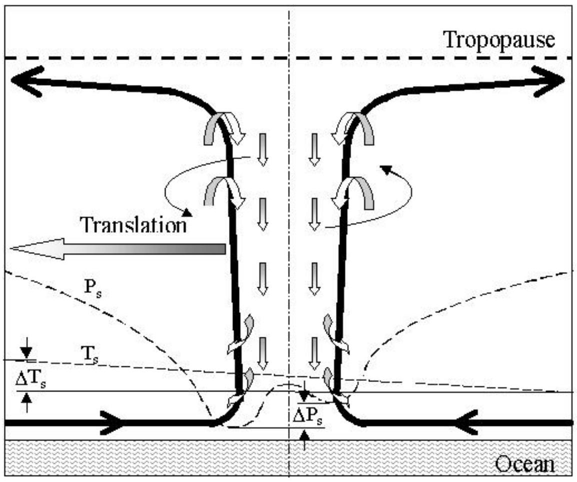

Fig. 1. Scheme of the internal thermal drive mechanism.

To some extent, all these challenges reflect a typical modern problem with proper combination of numerical methods with adequate physical models, including ignoring of the analysis at integral scales of the SOCA.

Model of equilibrium translation (MET) [8] attempts to bridge the gaps linking TC development to a degree of conformity dynamical and thermal fields of the SOCA. At that, dimensionless number, incorporating integral thermal and dynamical parameters of the SOCA [8] (named in [9] as Shekriladze number), acquires the role of the predictor of TC development, including the rapid intensification (alignment effect).

Below we consider the relationships between the alignment effect, MPI and the thermodynamic theory based on the analysis of 8 major TCs of more than 200 observed worldwide in 2003-2012.

Conceptual Basics of the Study

The MET considers sea upper layer as the only source of energy for the development of TC (the applicability of this approach is limited in the range of low HHPs and small diameters of TC, when energy of air inflow is also valuable). The MET also suggests that TC is always under the influence of a certain internal thermal drive mechanism caused by SST asymmetry at TC outer boundary.

Certain initial adaptation of dynamical and thermal fields always holds in the zones of TC development. In the main tropical zones background SST rise is oriented along the dominant environmental wind. In the area of trade winds, SST rise is of the order of $10^{-6}\,{}^0C\times m^{-1}$.

At the same time, the internal drive is mainly due to more significant longitudinal gradient of SST, induced by TC translation which inevitably leads to a cooling of sea upper layer and gradual reduction of SST in the rear. According to existing data the resultant SST gradient is of the order of $10^{-5}\,{}^0C\times m^{-1}$.

Further, aside from the fact that TC translation is mainly determined by large-scale environmental (steering) wind, the ideal case is considered in which TC moves only under the influence of the internal thermal drive mechanism.

According to the scheme (Fig. 1) SST jump (ΔT_s) results in more intense upstream in front of the eye wall cloud with a minimum air pressure. As eye wall cloud is a dynamic core of the whole system, a pressure drop between its front and rear (ΔP_s) can be assumed as a basis for the internal drive.

Heat and mass transfer from the sea to TC is only slightly dependent on TC translational speed. Here, the main role is played by much higher air tangent velocities. In this regard, slowdown of translation, resulting in the prolonging of the passage of the given sea area, intensifies the cooling of sea upper layer by TC, and on the contrary, the acceleration reduces cooling, all other things being the same.

This inverse dependence creates a rather strong negative feedback in the thermal drive mechanism: decrease of translational speed, along with increasing ΔT_s, leads to increased pressure drop ΔP_s, causing, in turn, TC acceleration. Conversely, increasing of the translational speed reduces ΔP_s, which is slowing down TC.

In such a manner, TC not only prefers to shift toward SST elevation, but it also tends to establish certain equilibrium between translational speed and heat inflow. Similar translation of TC is named as "equilibrium translation". Besides, it is equilibrium translation that is assumed to be a precondition for realization of the aforementioned internal tendency of TC (rapid intensification and achieving maximum intensity, that is, the so-called alignment effect).

ΔT_s and, accordingly, ΔP_s depend on TC intensity and HHP in a given sea area. Besides, generation of the same driving force requires more slow TC translation at high HHP and vice-versa. This inverse relationship allows to assume, for the equilibrium translation, rough constancy of the so-called heat involvement factor equal to the share of HHP removed by TC through passage of a given area (most of the initial HHP goes down through upwelling [10]).

Then, returning to the dominant role of steering wind, the conclusion must be made that establishment of the equilibrium translation is possible only through favoring by large-scale environmental field. Only accurate inscribing of TC in the steering wind, in the sense of compatibility of the internal tendency with external dynamic field, can turn an "intended" equilibrium translation to the real one.

By the way, in accordance with the MET, later it was established that, in the western North Pacific, "very intense TCs and TCs with rapid intensification rate are found only to occur in a narrow range of translational speeds between 3 and 8 m×s^{-1}" [11], that is, in the range of speeds of trade winds.

Within accepted assumptions, integral heat flow (sensitive and latent) removed from sea strip left behind TC (Fig. 2) can be written as follows:

$$A_{34} \cdot q = C_i \cdot Q \cdot \delta S_c , \qquad (1)$$

where A_{34} is an area inside tangent wind velocity 34 knots (TC outer boundary is assumed at the minimum tangent wind specified in regular forecast advisories); q is integral heat flux (sensitive and latent) averaged inside A_{34}; C_i is heat involvement factor; Q is HHP averaged inside A_{34}; δS_c is increment of sea surface cooled by TC (cooled surface remaining behind TC during unit time).

Since the involvement factor, constancy of which determines the equilibrium translation, is much less than unity, for convenience, we use its reciprocal to characterize TC development. Accordingly, the following condition for the establishment of the equilibrium translation can be written:

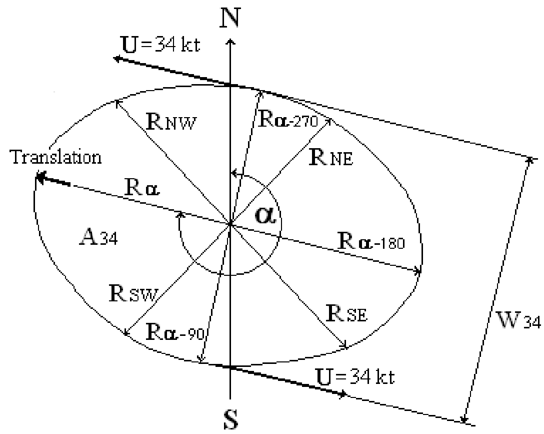

Fig. 2. Scheme of non-circular TC: R_{NE}, R_{SE}, R_{SW} and R_{NW} - TC radii at tangent velocity 34 knots in Northeast, Southeast, Southwest and Northwest quadrants, respectively; a - TC translation azimuth; W_{34} - TC transverse size at tangent velocity 34 knots.

$$Shk_{cr} = \frac{Q \cdot \delta S_c}{A_{34} \cdot q} = Const , \qquad (2)$$

where Shk_{cr} is a critical value of Shekriladze number.

Accurate determination of Shk_{cr}, using equation (2), requires the availability of detailed continuous data on TC outer boundary translation and HHP field. Really we use restricted discrete data specified in forecast advisories and HHP maps which gives quite approximate estimates. At that, the following, equivalent to (2), within certain assumptions, relationship [12] is used:

$$Shk_{cr} = \frac{Q \cdot U_{bb}}{R_{ef} \cdot q} = Const , \qquad (3)$$

where U_{bb} is translational speed of TC back boundary center; $R_{ef} = 2A_{34}/\pi W_{34}$ is effective radius of TC (it is equal to the radius in the case of circular TC).

Specific Mode of Heat Transfer Associated with Alignment Effect

Dynamic impact of TC involves intensive vertical stirring of sea water (upwelling) [10]. It is easy to show that new SST field that emerged below TC after vigorous stirring is much more dependent on the initial heat content of sea upper layer (that is, on the initial HHP) than on the initial SST field. In this regard, further, the initial HHP field (that existed before entering TC) is assumed as the main parameter characterizing, at the stage of forecasting, SST field below TC.

Of course, SST field below TC could most accurately be defined by direct measurements, but such data (leaving aside the technical feasibility) may not be available at the stage of forecasting.

In general, the complex problem of heat and mass transfer from sea surface to TC is far from being fully resolved needing further analytical and experimental studies.

The constancy of Shk_{cr} provides important features of heat transfer from sea surface to TC during equilibrium translation, which significantly simplify the analysis of this particular mode.

Removal by TC of constant share of HHP takes longer at high HHP and vice-versa. In this context, equilibrium translation is characterized by different combinations of translational speed, TC size and integral heat flux resulting in less intense cooling at low HHPs and more intense cooling at high HHPs.

Based on the above negative feedback between HHP and seawater cooling, it may be assumed that SST field below TC is roughly uniform during equilibrium translation, regardless of initial SST and HHP fields. Accordingly, in this mode, the average integral heat flux is approximately independent of the initial fields and becomes a unique function of tangent wind distribution.

At the same time it is clear that the subject matter reduces to near-equilibrium mode of translation, restricting the applicability of the simplified approach outside of this mode. However, such specializing is quite allowable at this stage in respect of our focusing on equilibrium translation.

Further, taking into account the structure of field data in regular forecast advisories, the three-zone model of heat transfer is offered. The first (outer) zone covers the area between tangential winds of 34 knots (17.5 m/s) and 50 knots (25.75 m/s). The second (intermediate) zone covers the area between tangential winds of 50 knots and 64 knots (33 m/s). The third (central) zone covers the area inside tangential wind of 64 knots.

Next, using available field data, the empirical formula is designed for the average integral heat flux from the sea surface during equilibrium translation:

$$q = \left[400\left(R_1^2 - R_2^2\right) + 600\left(R_2^2 - R_3^2\right) + \right.$$

$$\left. + 1,200\left(U_{\max}/130\right) R_3^2 \right] R_1^{-2} \text{ W×m}^{-2}, \qquad (4)$$

where R_1, R_2 and R_3 are average outer radii of the first, second and third zones in meters determined as a quarter of the square root of the sum of squares of the radii of the above four quadrants; U_{max} is maximum tangential wind speed in knots; 130 is maximum tangential wind velocity of reference TC Opal (1995) in knots.

Characteristic zones reference averages 400 W×m^{-2} and 600 W×m^{-2} are determined based on analysis and rounding the data recorded by NDBC buoy 42001 during development of TC Opal in 1995 [10].

Characteristic of the central zone reference average (1,200 W×m^{-2}) is determined taking into account that buoy 42001 was located at around 25 km from Opal's center during its maximum intensity and recorded by the buoy maximum heat flux can be accepted as average for all central zone. At the same time, the possibility of a linear extrapolation of this parameter to other cases is assumed.

TC Geometrics and Translation of Back Boundary Center

Firstly, four radii R_α, $R_{\alpha-90}$, $R_{\alpha-180}$ and $R_{\alpha-270}$ are defined by simple trigonometric interpolation of the forecast advisory data (a is TC translation azimuth):

$$R_\alpha = R_{SW} - \frac{R_{SW} - R_{NW}}{90}\left(\alpha - 315\right) \qquad (5)$$

$$R_{\alpha-90} = R_{SE} - \frac{R_{SE} - R_{SW}}{90}\left(\alpha - 90 - 135\right) \qquad (6)$$

Table 1. Selected strongest TCs.

Q (kJ·cm^{-2})	TC (year), U_{max} (knots)	Q (kJ·cm^{-2})	TC (year), U_{max} (knots)
40	Ma-On (2004), 140	80	Nida (2009), 155
45	Celia (2010), 140	90	Chaba (2004), 155
50	Monica (2006), 155	100	Dianmu (2004), 155
60	Rick (2009), 155	120	Megi (2010), 155

$$R_{\alpha-180} = R_{NE} - \frac{R_{NE} - R_{SE}}{90}\left(\alpha - 180 - 45\right) \quad (7)$$

$$R_{\alpha-270} = R_{NW} - \frac{R_{NW} - R_{NE}}{90}\left(\alpha - 270 + 45\right) \quad (8)$$

Next TC transverse size (W_{34}), the average radii at the tangential winds of 34 knots, 50 knots and 64 knots (R_1, R_2 and R_3, respectively), the area inside tangential wind of 34 knots (A_{34}) and the coordinates of TC back boundary center (latitude – Lt_{bb}, longitude – Ln_{bb}) are defined:

$$W_{34} = R_{90} + R_{270} \quad (9)$$

$$R_1 = 0.25\left(R^2_{NE,34} + R^2_{SE,34} + R^2_{SW,34} + R^2_{NW,34}\right)^{0.5} \quad (10)$$

$$R_2 = 0.25\left(R^2_{NE,50} + R^2_{SE,50} + R^2_{SW,50} + R^2_{NW,50}\right)^{0.5} \quad (11)$$

$$R_3 = 0.25\left(R^2_{NE,64} + R^2_{SE,64} + R^2_{SW,64} + R^2_{NW,64}\right)^{0.5} \quad (12)$$

$$A_{34} = \left(\pi / 4\right)\left(R^2_{NE,34} + R^2_{SE,34} + R^2_{SW,34} + R^2_{NW,34}\right) \quad (13)$$

$$Lt_{bb} = Lt_c \pm \left(R_{\alpha-180} / 1.11\cdot10^5\right) Cos\alpha \quad (14)$$

$$Ln_{bb} = Ln_c \pm \left[R_{\alpha-180} / \left(1.11\cdot10^5 \cdot CosLt_{bb}\right)\right] Sin\alpha \quad (15)$$

Here Lt_c and Ln_c are coordinates of TC center specified in regular advisories; the lengths of degrees of latitude and longitude are accepted as 1.11×10^5 m and $1.11\times10^5\times CosLt_{bb}$ m, respectively.

U_{bb} is defined by geographical coordinates of TC back boundary center as average of uniform straight translation at a track length prior to given position:

$$U_{bb} = \left[1/\left(\tau - \tau_{-1}\right)\right]\left\{\left[\left(Lt_{bb} - Lt_{bb-1}\right)\cdot 1.11\cdot10^5\right]^2 + \right.$$
$$\left. + \left[\left(Ln_{bb} - Ln_{bb-1}\right)\cdot 1.11\cdot10^5 CosLt_{bb}\right]^2\right\}^{0.5}, \quad (16)$$

where τ is time of passing by TC given position; subscript -1 corresponds to the same parameter at TC position prior to given position at one track length.

Correlation of the Field Data

As follows from the logic of the above analysis, one must first confirm the linkage of the alignment effect to constant Shk_{cr} and then interpret the data on MPI. Below such an approach is realized relative to 8 TCs reached greatest intensity at a given initial HHP (Table 1).

Taking into account the above limitations with possibly valuable energy contribution of inflowing air at low HHP, only the cases at HHPs exceeding 40 kJ×cm^{-2} are considered. Specified in the forecast advisory maximum sustained wind based on one-minute average is accepted as TC intensity. The values of initial HHP are determined using HHP Maps.

In order to assess the accuracy of the correlation of the field data two values of Shekriladze number are used. The major value Shk_m is based on U_{bb} (eq. (16)). The supplementary value Shk_s is based on the current translation speed of TC center specified in the forecast advisory.

It is assumed that the close agreement between the two values points to nearly uniform straight translation of TC with a nearly constant outer radius. In this case the accuracy of the calculation based on discrete in time and space data can be considered as satisfactory, and, conversely, a significant difference

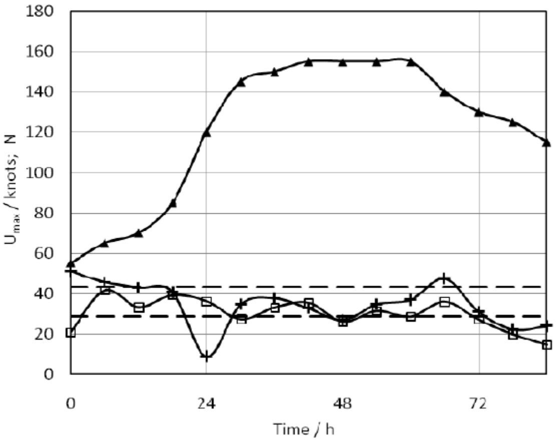

Fig. 3. Correlation of the field data on TC Dianmu: ▲ – maximum tangent wind; + – Shk_m; □ - Shk_s; dotted lines Shk=35±20%; the position 0 - 12:00 hour (UT) 14 JUN 2004.

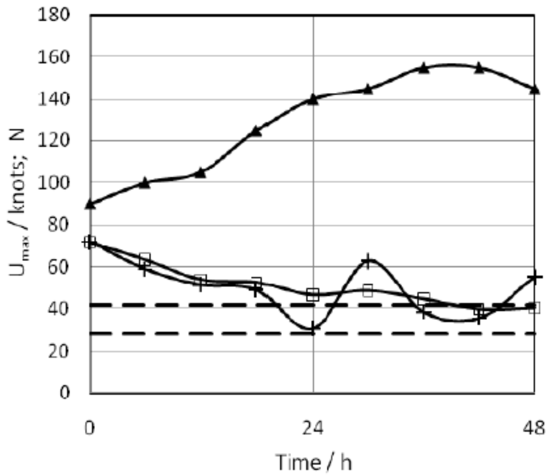

Fig. 4. Correlation of the field data on TC Megi: ▲ – maximum tangent wind; + – Shk_m; □ – Shk_s; dotted lines: Shk=35±20%; the position 0 - 00:00 hour (UT) 16 OKT 2010

between these two values calls into question the accuracy of the calculation procedure.

The calculations produce discrete values of *Shk* presented in the figures below by points. As for the smoothed curves, they are of purely conventional character.

Super typhoon Dianmu (Fig. 3) emerged in the zone with HHP 70-80 kJ/cm^2 in tropical western North Pacific. Further it translated through the zone with rather high HHP (90-110 kJ/cm^{-2}) and rapidly intensified up to 155 knots. The record intensity of Dianmu, supposedly, is linked to the alignment effect at Shk_{cr}≈35. Besides, Shk_m and Shk_s are roughly the same at this stage.

Super typhoon Megi emerged in the zone with HHP 70-80 kJ/cm^2 in tropical western North Pacific. It translated through the zone with rather high HHP (90-130 kJ/cm^{-2}) and rapidly intensified. According to Fig. 4, the record-breaking intensity of Megi also is linked to the alignment effect at Shk_{cr}≈35. The above correlations are common to most selected strongest TCs except Chaba and Celia the development of which was accompanied by tangible variations of translation speeds and outer radii (as reflected by large differences between Shk_m and Shk_s). As noted above, in this situation, the used approximate calculation procedure cannot provide sufficient accuracy of the correlation.

In general, the results of correlation show the validity of the MET at sufficiently high HHPs (50 kJ×cm^{-2} and more). Maximum intensification of TC (alignment effect) is linked to Shk_{cr} that can be refined as:

$$Shk_{cr} = 35 \pm 20\% \qquad (17)$$

By the way, the rapid intensification of TC Charley (2004), left out of sight prediction services, also took place at about the same Shk_{cr} [12].

Due differences in calculation schemes average heat flux, it is difficult to establish the equivalence of (17) with the previous evaluation $Shk_{cr} \approx 25$ [8]. Since the critical value may vary somewhat depending on the assumptions (e.g., on the location of TC outer boundary) and the calculation procedure, the most refined values will be obtained from equation (2) based on continuous detailed field data.

Dependence of maximum intensities of selected strongest TCs on initial HHP is presented in Fig. 5.

The constancy of real maximum intensity in the wide range of HHP supports the MET along with all accepted assumptions and consequences, including the conclusion that alignment effect takes place at roughly constant average SST, irrespective of initial

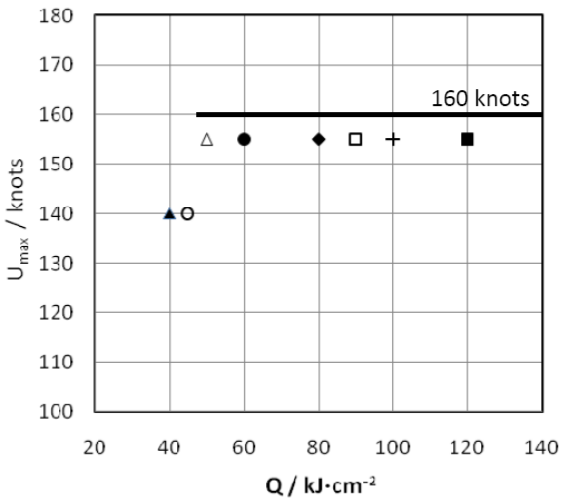

Fig. 5. Relationship between TC maximum intensity and initial HHP; ▲ – Ma-On; ○ – Celia; Δ – Monica; • – Rick; ◆ – Nida; □ - Chaba; + – Dianmu; ■ - Megi.

HHP and SST fields. It also can be concluded that MPI is roughly equal to 160 knots at HHP more than 50 kJ×cm^{-2}.

This removes the above-mentioned qualitative contradiction of the field data with the thermodynamic theory MPI. As for the quantitative agreement, it can be checked only after collection of reliable statistics on the average SST below rapidly developing TCs.

Finally, about TC development at very high HHP (150 kJ×cm^{-2} and more).

According to the MET, at very high HHP, the translational speed related to alignment effect falls significantly lower of characteristic range of dominant regional steering wind. This discrepancy strongly inhibits TC development and makes the development of strong TC unlikely in general, as evidenced by the vast field data, including above strong TCs.

In such a manner, as strange as it may seem, in some cases, increasing HHP and SST, caused, for example, by climate change, may lead even to preventing TC development detuning favorable thermo-hydrodynamic balance in OCAS. And, conversely, in some cases, reduction of HHP could step up TC development.

Concluding Remarks

The MET relates TC development to conformity of thermal and dynamical fields in the SOCA. When favored by large-scale environmental wind, TC tends to rapid intensification at the critical Shekriladze number (alignment effect).

The MET reveals negative feedback between HHP and TC translational speed during the alignment effect. This leads to roughly constant SST below TC and, equally, to rough constancy of MPI at sufficiently high HHP, removing qualitative contradiction of the field data with the thermodynamic theory MPI.

Analysis of the strongest tropical cyclones supports the MET along with accepted assumptions and the main consequences. The same analysis allows to refining the value of critical Shekriladze number to 35±20% and establishing roughly constant MPI (~160 knots) at HHP exceeding 50 kJ×cm^{-2}.

The presented results and conclusions require further refinement based on more detailed and continuous data on parameters of TC and sea upper layer. At the same time monitoring of Shekriladze number of acting TCs can be recommended as potential predictor of forthcoming developments.

გეოფიზიკა

ტროპიკული ციკლონი: თანადობის ეფექტი და მაქსიმალური პოტენციური სიმძლავრე

ი. შეყრილაძე

საქართველოს ტექნიკური უნივერსიტეტი, ჰიდროსაინჟინრო დეპარტამენტი, თბილისი

(წარმოდგენილია აკადემიის წევრის თ. ჭელიძის მიერ)

ტროპიკული ციკლონების საველე მონაცემებსა და მაქსიმალური პოტენციური სიმძლავრის თერმოდინამიკურ თეორიას შორის არსებულ წინააღმდეგობათა გარკვევის მიზნით, წონასწორული ტრანსლაციის მოდელის ჩარჩოებში, ჩატარებულია რამდენიმე მძლავრი ტროპიკული ციკლონის ანალიზი. დადასტურებულია თანადობის ეფექტის წამყვანი როლი ციკლონის განვითარებაში და, გარკვეულ მიახლოებაში, მძლავრი ციკლონების ქვეშ ოკეანის ზედაპირის საშუალო ტემპერატურის მუდმივობა, მიუხედავად განსხვავებებისა საწყის თბურ ველებს შორის. რეალურ მაქსიმალურ სიმძლავრეთა მუდმივობა ფიქსირდება ოკეანის ზედა ფენის საკმარისად მაღალი თბოშემცველობის დროს, რაც, ზედაპირის საშუალო ტემპერატურის ხსენებულ მუდმივობასთან ერთად, ხსნის თვისებრივ წინააღმდეგობას თერმოდინამიკურ თეორიასთან.

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