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Intensification of a Tropical Cyclone During Landfall: A Critical Forecasting Challenge

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ABSTRACT

Not very rare in reality, socially very dangerous rapid intensification (RI) of tropical cyclone (TC) during landfall remains actually an unpredictable phenomenon. Attempts to identify the presence of such a critical forecasting problem have so far been unsuccessful. In the work, the problem is again considered within the framework of the alternative so-called Equilibrium Translation Model (ETM). The basis for the consideration is TC Ian (2022), the unique parameters of which make it possible to refine and strengthen the previously obtained results. The new findings are further supported by analysis of the parameters of TC Charley (2004) who committed landfall in the same region. Potential of so-called Alignment number (An) is once again demonstrated to be an effective hazard identifier.

Key words: *tropical cyclone, rapid intensification, landfall, equilibrium translation, Alignment number.*

Introduction

Judging by the practice of forecasting the TC development, existing theoretical and numerical models do not even allow for the existence in nature of the phenomenon of the TC intensification during landfall: forecasts based on them practically never predict such a development [1].

In general, there is indeed at least one strong factor aimed at reducing the TC intensity during landfall. This is a fairly rapid decrease in the area of the sea surface underlying a TC with a decrease in seawater heat inflow serving as "fuel" for the cyclonic motion. Existing models seem to give to this factor an absolutely dominant role.

At the same time, during landfall, not only simple but even the TC RI is in fact not at all a rare natural phenomenon.

According to [1], among 38 powerful (fourth and fifth intensity categories) TCs that made landfall around the world in 2004–2013, more than a third (16 TCs) rapidly intensified during landfall with the most severe consequences (among them, TCs Charley (2004), Felix (2007), Haiyan (2013)).

However, regular forecasts in no case predicted the TC intensification during landfall.

A similar rigid standard of not predicting the phenomenon was also maintained in subsequent years, including, for example, the landfall of TC Ian in southwest Florida in 2022 [2]. By the way, all this is happening even against a trend towards improving the prognosis of cases of TC RI in areas of the open sea (not related to the landfall stage) [3-4].

The very existence of the TC RI phenomenon during landfall fundamentally calls into question the adequacy of existing theoretical and numerical models. Overcoming resulting deadlock long ago required identification of the problem by separating it from the general class of RI, which was not done. No steps were taken for a general analysis of individual cases of the TC RI during landfall. Despite being based on extensive field data, the first generalization of the critical forecasting problem [1] remained outside the attention of researchers of tropical cyclogenesis (not a single citation).

In important reviews published later [3-5], the problem of forecasting the TC RI during landfall is not even mentioned. In a slightly different aspect, only work concerning the possible multiplication of this phenomenon with global warming [6] addresses the problem (more details below).

At the same time, the above seemingly fundamental contradictions find a logical resolution within the framework of the ETM [7-12], which considers a TC as a giant natural heat engine, the mechanical output power of which depends on two parameters - heat inflow and heat conversion efficiency. By the way, the latter can vary widely regardless of the former.

Below, the problem is again considered within the framework of the ETM, using as a new base TC Ian (2022), rapidly intensified during landfall in southwest Florida [2, 13].

The unique parameters of Ian make it possible to refine and strengthen the previously obtained results. The new findings are further supported by analysis of the parameters of the similar landfall of TC Charley (2004) in the same southwest Florida. A much more reliable determination of the critical value of the An (An_{cr}) corresponding to RI has been achieved. This was also facilitated by new, more accurate TCHP maps [14].

Equilibrium Translation Model: concept and promotion strategy

The long-term inability to correctly predict the TC RI, reflecting the need to overcome the lack of understanding of the thermohydrodynamics of decisive interactions in the system sea-cyclone-atmosphere has attracted the author's attention since the 2000s [3-4].

At the first stage of a purely qualitative analysis, the conclusion was made that, in a TC, an internal thermal drive arises, directed towards an increase in the sea surface temperature (SST). Next, the presence of a negative feedback between the internal thermal drive and TH translation speed was established, which made it possible to introduce the TC equilibrium translation concept.

Next, the key assumption was made that equilibrium translation mode is the basis of the RI phenomenon. In other words, it was assumed that when the main TC drive, large-scale environmental wind and the TC internal thermal drive are in certain conformity, this huge natural heat engine becomes most efficient in converting sea water heat into wind energy, resulting in the RI.

The validity of the ETM can be assessed by the adequacy of its final product - the dimensionless similarity number, named by the author Alignment number – ***An*** (Dr. Gvelesiani suggested calling this parameter the Shekriladz*e* number [15]).

An is equal to the ratio of the total amount of TCHP contained under the sea surface, "processed" by a TC per unit time, to the heat transferred during the same time from the sea surface to the TC - a factor that determines the establishment of equilibrium translation (if we wanted to use a physically more logical reciprocal, we would have to deal with fractional quantities that are inconveniently small for the similarity number).

The basic equation for the An can be written as follows [7-12]:

$$An = \frac{Q \cdot \delta S_{sc}}{A_{34} \cdot q}, \qquad (1)$$

where A_{34} is an area inside tangent wind velocity 34 knots (corresponding to the TC outer boundary, as assumed in regular forecast advisories) (m^2); q is integral heat flux (sensitive and latent) from the sea surface to a TC averaged inside A_{34} (w / m^2); Q is tropical cyclone heat potential (TCHP) averaged inside A_{34} (J / m^2); δS_c is increment of the cooled sea surface (cooled sea surface remaining behind a TC during unit time) (m^2 / s).

Here, the role of the tangential wind speed field is reflected by the parameter q, determined by a three-zone heat transfer model [12] taking in account the wind speed distribution specified in the regular forecast advisory. The combined effect of the environmental wind and internal driving force is reflected by the parameter δS_c. Based on comparison with available field data, the main conclusion was made that the TC equilibrium translation, accompanied by the RI, always must occur at a constant, critical value of the alignment number $An_{cr} = const$.

The prospect arose to overcome the historical impasse in forecasting the TC intensity and, most importantly, the TC RI. In addition, the ETM has shown the potential to provide a basis for analysis of a number of other important aspects of tropical cyclogenesis, including the TC unusual trajectories, the formation of secondary eyewalls, and the impact of global warming.

It became clear that the results obtained could only make sense if, after a thorough re-verification, they became the basis for a virtually complete restructuring of large-scale studies of tropical cyclogenesis. It was also clear that achieving widespread interest in a field of research new to the author of the study was also not an easy task.

To this end, a strategy was adopted to highlight the identification, for the first time in almost a hundred years of research, of the similarity number characterizing the TC development, and to reinforce the significance of the latter as much as possible by demonstrating the correlation of its critical value with RIs in an ever-increasing number of real TCs.

Of course, optimism was built on the general recognition of the TC RI forecasting as the most important unsolved problem in the field.

As for other aspects of tropical cyclogenesis, it was decided not to focus on them at all, since they could only be supported by qualitative considerations.

Simultaneously, there was hope that when reading the publications, colleagues themselves would reveal the multidimensionality of the ETM. Moreover, some of these possibilities were practically lying on the surface.

First of all, this concerned the almost obvious projection of the model onto the phenomenon of so-called unusual trajectories, the second most important unsolved problem of tropical cyclogenesis after the RI forecasting.

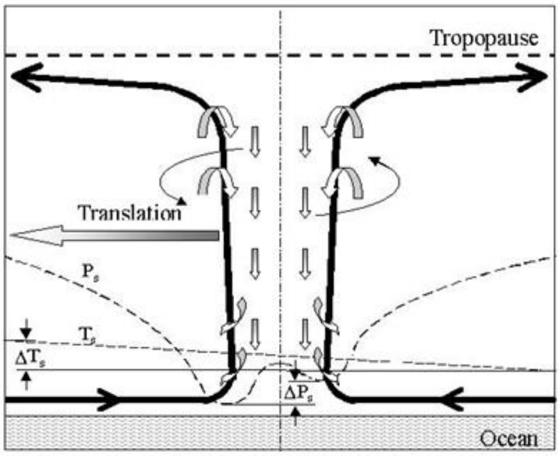

Fig. 1. Scheme of internal thermal drive.

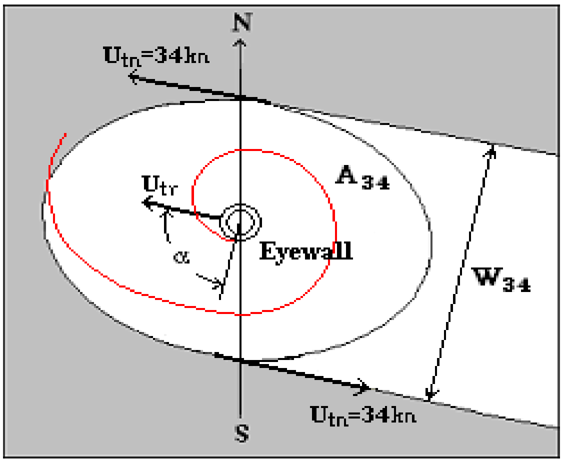

Fig. 2. The occurrence of TH lateral movement.

Internal thermal drive (Fig. 1) is formed by a transverse gradient of static pressure on the eyewall cloud, which, in turn, arises due to the presence of a difference in the temperature of the air sucked into the wall around its circumference. In general, the internal drive direction depends on the point at which the warmest air hits the wall, which may not coincide with the frontal point of the eyeall (Fig. 2).

In our publications, without any explanation, the condition $\alpha = 0$ is automatically accepted as one of the conditions for the implementation of equilibrium translation. Such a situation could have caused serious criticism of the model, but, unfortunately, even this did not happen.

The fact is that an attempt at such criticism, even with the simplest qualitative reasoning, would reveal the rich consequences of the internal thermal drive concept itself.

For example, with reasonable assumption of a strong excess of external drive over internal one in most regimes of the TC translation, in the presence at the initial moment of a non-zero value of angle α one would reveal the TC self-organized evolution to equilibrium translation (movement to $\alpha = 0$).

Indeed, using the example of Fig. 2 it is easy to notice that the additional movement of the eyewall at a relatively low speed to the left, with subsequent deformation of the field of spiral flows, will be constantly directed towards a reduction in angle α.

The situation will change dramatically if there is a temporary, but sufficiently long-term decline in wind speed or complete calm. Internal drive will become the leading force, the direction of which will depend on the distribution of TCHP along the TC perimeter (in our studies the TCHP filed was assumed to be roughly uniform).

In such a situation, any movement of the TC can occur, from zigzag to marking time.

Projection can be continued onto another important phenomenon – the formation of the TC secondary eyewall, if we keep in mind the possible occurrence of internal instability in a TC, when the regional wind speed recovers and internal drive begins to quickly change direction and amplitude.

Further progress, of course, requires detailed analysis. However, the very fact that the occurrence of both of the above phenomena is much more likely with existence, in a TC, of an additional drive of variable direction and amplitude, should not raise much doubt.

Returning to the main line of the strategy, it should be noted that its implementation to a certain extent goes beyond the author's capabilities.

The fact is that accurate and reliable establishment of the An value by Eq. (1) for a given situation is only possible by the relevant research and monitoring centers that are able to determine with high accuracy all of necessary parameters, including the most difficult to determine δSc.

Unfortunately, such work has not yet been done.

As if assuming such a risk, in order to at least approximately verify the ETM, from the very beginning another equation was introduced [3-4], definable using solely publicly available information, such as regular forecast advisories and daily TCHP maps:

$$An = \frac{Q \cdot U_{bb}}{R_{ef} \cdot q} \quad (2)$$

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

In Eq. (2) the role of the $\delta S_c / A_{34}$ ratio is reflected by the ratio U_{max} / R_{ef}, while U_{bb}, A_{34}, W_{34} and R_{ef} are determined by the data from relevant forecast advisories [2] using the methods [12].

Based on Eq. (2), a number of studies [1, 7-12, 16-17] were conducted analyzing the life cycles of numerous real TCs by constructing curves of the correlation of the maximum tangential wind speed (U_{max}) and ***An*** over time. The high repeatability of the correlation between ***Umax*** and An_{cr} over a sufficiently large number of TCs, with a spread of $An_{cr} = 35 \pm 20\%$, allowed us to conclude that the ETM has fundamental potential in terms of understanding and describing the TC development.

Of course, the cases with the TC RI during landfall were also involved, e.g., TC Charley that made devastating landfall in the same southwest Florida in 2004 [16].

However, similar results could not shake the wall of total ignorance of the model and the similarity number, combined with a difficult to explain persistent avoidance of identification of the real critical forecasting challenge - the problem of forecasting the TC RI at landfall.

Regarding the latter, one episode is also remarkable.

In 2017, study [6] was published, which focuses on an assessment of the potential impact of global warming on the incidence of the *RI* before landfall. The conclusion was made about potential significant increase in this important parameter when global warming.

As the review of the article showed, the validity of this conclusion raises serious doubts.

The fact is that the conclusion was based on the results of simulation future events using exactly the above-mentioned numerical models, based on which forecasts have never predicted the real not so rare manifestations of the phenomenon [1].

The article does not say anything about the existing negative experience in using these models in forecasting practice. Conclusions [1] are not only not refuted, but not even mentioned.

The possibility of a very useful public examination of an important problem arose.

To this end, in the same 2017, the author addressed the Bulletin of the American Meteorological Society with a "letter to the editor" with a detailed consideration and criticism of the article, of course, involving the *ETM-An*. The letter ended with a paragraph:

"In general, the above circumstances, together with the unsuccessful experience of using the modern numerical models in real forecasting practice, create serious doubts regarding the validity of the conclusion about significant increase in the incidence of *TH* rapidly intensifying before landfall when global warming."

Ultimately, we were faced with a shocking precedent for the suppression of scientific debate: the letter was rejected by the journal based on reviewer conclusions. Another attempt to bring a critical problem out of the silence zone failed. Serious signs of a strong position in the area of non-scientific corporate interests have emerged.

TCs Ian (2022) and Charley (2004): two landfalls with rapid intensification

The main object of consideration is TC Ian (September 23 – 30, 2022), which made successive landfalls in Cuba, southwest Florida, and South Carolina [1]. It became one of the costliest hurricanes in the history of observations with the lion's share of damage in Florida. Ian's landfall in Florida was accompanied by the RI, once again highlighting the still unresolved problem with predicting the parameters of such development.

TC Ian's RI during landfall is characterized by a unique set of parameters recorded in regular forecast advisories. They made it possible to refine the method for determining the An. Examination of TC Charley (2004) using a refined method allows to reinforce the previous findings.

Ian moved in a straight line at five distances between points corresponding to successive forecast advisories, of which two distances until approaching the shore. For the first four of these distances, including the start of landfall, it moved at a constant speed. The TC constant external dimensions are recorded in three consecutive forecast advisories, the intermediate of which (advisory number 22, 0900 UTC 09/28/2022) we link to the start of landfall (here we assume that landfall begins with the transition to land of 10 ÷ 15% of the A_{34} area).

Since in such an "ideal" case the increment of the cooled sea surface is equal to the product of the TC transverse size (***W***) by the TC center translation speed ($\boldsymbol{U_{tr}}$), then Eq. can be transformed to the following form:

$$An = \frac{Q \cdot W \cdot U_{tr}}{A_{34} \cdot q}, \qquad (3)$$

Although Eq. 1 is strictly applicable only to the above section of the Ian's translation, to a certain approximation, it can also be applied to the life cycles of Ian and Charley as a whole, as was done in this study. $\boldsymbol{U_{tr}}$ is taken directly from the relevant forecast advisory, ***W,*** the transverse size of $\boldsymbol{A_{34}}$**,** is determined based on interpolations between corresponding pairs of radii of the TC recorded in the same advisory. ***Q*** is determined from the TCHP map for the previous day [14].

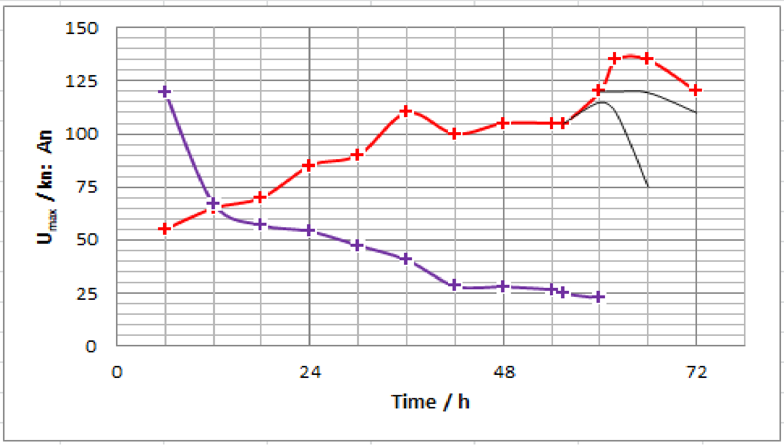

Fig. 3. Time course *of* $\boldsymbol{U_{max}}$ (red crosses) and *An* (purple crosses) before and during landfall of TC Ian (2022) in southwest Florida and regular forecasts (black curves).

The correlation between U_{max} and *An* before and during Ian's landfall can be traced by Fig. 3.

The data covers a segment of Ian's life cycle from the northern coast of Cuba to Southwest Florida. The main interest, of course, is the landfall stage, which began around the 60^{th} hour (here we assume that landfall begins with the transition to land of 10 ÷ 15% of the A_{34} area.). Time 0 in Fig. 3 corresponds to 21:00 UTC 09/25/2022.

The curves are constructed based on discrete points, each of which corresponds to a specific forecast advisory issued at a given point in time. The standard time step for issuing the advisory is 6 hours, however, during the landfall they were issued more often, which is reflected in Fig. 3.

Ultimately, any An value corresponds to a specific advisory, and all parameters used are among the parameters available at that time to the compilers of the corresponding advisory. In other words, when compiling any forecast advisory, there was a theoretical possibility of judging the situation also by the current value of An.

The situation presented in the graph is quite meaningful.

At 04:30 on September 28, 2022, the regular forecast advisory correctly predicted the RI starting on the open sea, which is consistent with the conclusion made in the review [3-4] about the presence of progress in this part.

Further, apparently, in the numerical models the taboo embedded in them on allowing the TC intensification during the Landfall period worked reliably. At the 60^{th} hour, at the conditios of real intensification, its cessation with a further decline in intensity was predicted.

In contrast, the An predicted both the onset of the RI and its continuation. The absolute values of An_{cr} will be discussed in more detail below.

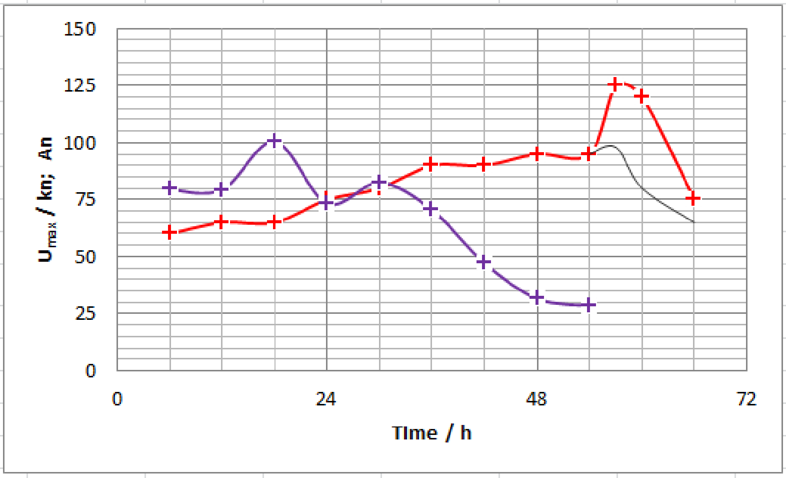

Fig. 4. Time course *of* U_{max} (red crosses) and *An* (purple crosses) before and during landfall of TC Charley (2004) in southwest Florida and regular forecast (black curve).

Ian's famous predecessor, T.S. Charlie, made a devastating landfall accompanied by RI in roughly the same area of Florida in 2004. The correlation between U_{max} and An before and during Charley's landfall (according to Eq. 3) is presented in Fig. 4.

Forecasters, also based on numerical models, also predicted a decrease in TC intensity with the onset of landfall, although at that time there were quite compelling circumstances for this: Charley itself was not at all at the RI stage and there was not so warm water ahead, with TCHP 2 - 3 times less than in Ian's case (striking evidence of the powerfulness of the RI's mechanism).

The difference between the An_{cr} values for the Charley case obtained from Eq. 2 [16] (***An_{cr} = 35***) and in this work by Eq. 3 (***An_{cr} = 29***), cast doubt on the equality of similar values for Ian published in the report [17] and obtained in this work (***An_{cr} = 23*** in both cases). A re-check revealed a calculation error when preparing the report [17]; in fact, for Ian they are 35 and 23, respectively.

Based on the above arguments, preference in terms of accuracy can be given to that obtained in this work (***An_{cr} = 23***), although this is only an intermediate result.

Ultimately, the sought critical value must be identified by the relevant research and monitoring centers which can do this using the basic Eq. (1) with much greater accuracy (by the way, in this case another absolute value of ***An_{cr}*** can be identified, without changing anything in principle, remaining the same for different TCs).

In general, the results of the work this time more accurately confirmed the previous conclusion about the fundamental potential of the ETM in terms of predicting the TC development.

Conclusion

Not very rare in reality, but the most socially dangerous cases of a TC landfall with simultaneous RI have actually never been predicted correctly. However, attempts to convince the relevant scientific community to identify the existence of such a critical forecasting challenge still remain unsuccessful.

In parallel, over the course of two decades, the same community consistently ignored the model and similarity number formed a framework that claimed to comprehensively reflect the features of the TC development, including its rapid intensification.

This work continues to move toward overcoming these barriers.

Still working within the same framework of the ETM, previously made conclusions about the potential of the Alignment number to be an effective hazard identifier are confirmed here with comparatively high accuracy through the analysis of the unique landfall parameters of TCs Ian (2022) and Charley (2024).

Due to the use of approximate equations in all studies, all obtained results require re-checking and refinement by the relevant research and monitoring centers using Eq. (1).

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ტროპიკული ციკლონის გაძლიერება ხმელეთზე გადასვლისას: კრიტიკული გამოწვევა პროგნოზირების სფეროში

ი. შეყრილაძე

რეზიუმე

ტროპიკული ციკლონის არც თუ ისე იშვიათი, სოციალურად ძალზე საშიში სწრაფი გაძლიერება ხმელეთზე გადასვლისას პრაქტიკულად არაპროგნოზირებად მოვლენად რჩება. სიტუაციის პრობლემური ხასიათის იდენტიფიცირების მცდელობები ამ დრომდე წარუმატებელი იყო. ნაშრომში პრობლემა კვლავ განიხილება ალტერნატიული, ე.წ. წონასწორული ტრანსლაციის მოდელის ფარგლებში. განხილვის საფუძველია ტროპიკული ციკლონი იანი (2022), რომლის უნიკალური პარამეტრები ადრე მიღებული შედეგების დაზუსტებისა და დახვეწის საშუალებას იძლევა. ახალი დასკვნები მხარდაჭერილია ტროპიკული ციკლონის ჩარლის (2004) ხმელეთზე მსგავსად გადასვლის პარამეტრების ანალიზით. კიდევ ერთხელ არის დემონსტრირებული ე.წ. თანადობის რიცხვის პოტენციალი, როგორც საფრთხის ეფექტური იდენტიფიკატორისა.

საკვანძო სიტყვები: ტროპიკული ციკლონი, სწრაფი გაძლიერება, ხმელეთზე გადასვლა, წონასწორული ტრანსლაცია, თანადობის რიცხვი.

Усиление тропического циклона во времяв ыхода на сушу: критический вызов прогнозирования

И. Шекриладзе

Резюме

Не столь редкое, социально весьма опасное быстрое усиление тропического циклона во время выхода на сушу остается практически непредсказуемым явлением. Попытки идентифицировать проблемный характер ситуации пока не увенчались успехом. В работе проблема вновь рассматривается в рамках альтернативной, так называемой модели равновесной трансляции (МРТ). Основным объектом рассмотрения является тропичекий циклон Иан (2022), уникальные параметры которого позволяют уточнить и усилить полученные ранее результаты. Новые результаты подтверждаются анализом параметров аналогичного выхода на берег тропического циклонф Чарли (2004). Еще раз продемонстрирован потенциал так называемого числа выравнивания как эффективного идентификатора опасности.

Ключевые слова: тропический циклон, быстрая интенсификация, выход на сушу, равновесное перемещение, число вырвнивания.