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Original article

Dataset on Wind and Waves to Study Tropical Cyclones

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Abstract
Purpose. The aim of the paper is to systematize information on the characteristics of the wind field and the wave heights along the altimeter tracks in the region of tropical cyclones, as well as to visualize this information in detail for assessing the data availability and applicability to a particular cyclone in order to use the obtained information for various scientific studies.
Method and Results. To form the database, the open source data were used including the tropical cyclone parameters (Best Track Data) in 2020–2022, and the along-track altimeter measurements performed from seven satellites. For each cyclone, in which the maximum wind speed exceeded 30 m/s, the files in the NetCDF and MAT formats were created; they contained altimetry data on the significant wave heights and wind speed in a cyclone area, information on the trajectory of each cyclone and its main characteristics renewed every 3 hours. To describe the radial distribution of wind speed, the standard data on the distances from a cyclone centre to the points where the wind speeds achieved 34, 50, and 64 knots, were proposed to be approximated using the Holland analytical function. Each cyclone is provided with the graphical files illustrating the evolution of its main parameters (radius, maximum wind speed, and translation velocity), the quality of approximation of the wind speed radial distribution, the location of altimeter tracks, and the along-track values of wave heights and wind speed. The developed MATLAB computer programs allow automatic updating of the created data array. By the time of paper publication, the dataset had been supplemented with the information on tropical cyclones and the available altimetry measurements for 1985–2018.
Conclusions. The structured dataset has been created to provide the information on waves and wind speed of all the intense tropical cyclones for the period from 2020 to 2022. The data and the corresponding illustrations can be used for planning and implementing the case studies, and for validating the models of tropical cyclones formation and wave development under their action.

Keywords: tropical cyclones, dataset, satellite altimetry, wave height, wind speed, wind field, extreme conditions

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Introduction

Tropical cyclones (TCs) appearing around the equator (between 10 and 30 degrees of latitude in both hemispheres) often cause severe economic damage and death in dozens of countries, not only in tropical regions, but also at higher latitudes. Up to a hundred TCs are formed annually in the Atlantic, Pacific and Indian oceans. Most of them are generated in the Northern Hemisphere and spread over hundreds and thousands of kilometers within a few weeks. The influence of typhoons originating in the northwestern Pacific Ocean is also felt in Russian territories, in the Far East coasts [1–3]. In addition to the damage caused by strong winds and flooding associated with precipitation, abnormally high waves, posing a threat to maritime navigation and coastal infrastructure, can be generated in TC areas.

Detailed information about TC frequency and intensity, characteristics of wind and waves is necessary to be predicted to prevent social and economic risks created by cyclones. In addition, these characteristics are of fundamental and practical interest for studying the mechanisms of extreme weather system formation and the atmospheric and wave model development [4, 5]. Observations of the interannual variability of TC activity make it possible to establish patterns associated with global climate change [6].

Until the end of the previous century, there were no automated systems for TC registering and forecasting. The first such system, the Automated Tropical Cyclone Forecasting System (ATCF) [7], was created in 1988 and is still used by the Joint Typhoon Warning Center (JTWC). During the following decades, similar forecasting systems were developed by other TC warning agencies, such as the Australian Bureau of Meteorology, the India Meteorological Department, the Japan Meteorological Agency, the China Meteorological Administration and others.

Despite a large number of parameters necessary to obtain a detailed understanding of TCs, the data on cyclones worldwide mainly contain just estimates of their coordinates and intensity, and only in some databases they include estimates of the radial and azimuthal distribution of wind speed. The information on the TC position and intensity, as a rule, is updated after the end of each season as a result of a reanalysis of all available shipborne, surface and satellite observation data. With the progress in technologies of observing systems and the development of methods for interpreting satellite measurements, it becomes possible to include additional information about wind, waves and precipitation in existing datasets [8, 9]. The joint use of data from different sources allows to effectively compose statistical models for predicting the intensity of TC and solve a number of scientific problems, such as modeling and forecasting wind waves and swell [10], assessing global changes in the extreme precipitation amount [11], etc. Such studies depend on the completeness of the global TC dataset.

The present paper is aimed at systematizing altimetry data in application to the study of TCs. For this purpose, joint analysis of open data archives on the TCs movement and intensity, spatial distribution of wind in them and altimetry measurements of wave heights and wind speeds, starting from 2020 was carried out. Particular attention is paid to the generated dataset clarity: for each case, illustrations that allow to estimate the evolution of the TC characteristics and the wave field, the number of altimeter tracks in the area of interest and other parameters are provided. The structured data set and figures associated can be useful to search cases for various studies, to obtain auxiliary visual information about the wind and waves in the already studied TCs and to validate wave development and cyclone evolution models.

Principal TC characteristics

Wind field. Cyclone track and intensity data were taken from the International Best Track Archive for Climate Stewardship (IBTrACS) [1] provided by the National Oceanic and Atmospheric Administration (NOAA). This archive is the product of a global coordinated collaboration of various climate agencies, the first publicly available centralized repository that combines and unifies disparate data on TCs in the Pacific, Atlantic and Indian Oceans, taking into account internal specifics and differences between international agencies [12]. The data cover the period from 1842 to the present, interpolated at three-hour intervals. The main parameters provided are the TC position and intensity (maximum sustained wind speed or minimum central pressure). The archive also includes additional data documented by some agencies, such as maximum wind radius, pressure, hurricane-force wind radius, etc.

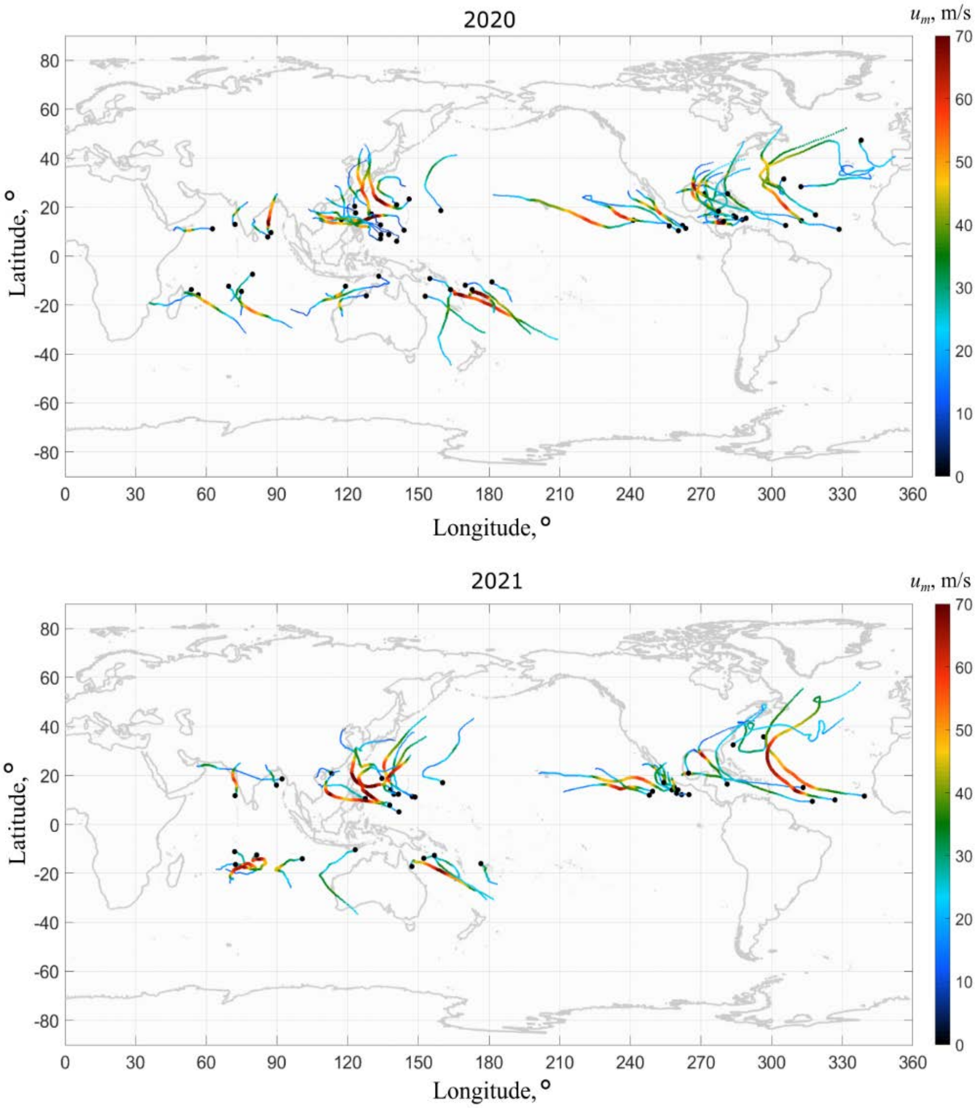
In this paper, information on the most intense cyclones was collected. Also, in addition to data on the TC characteristics, an archive of altimetry measurements from the considered satellites (SARAL/AltiKa, CryoSat-2, CFOSAT, HY-2B, Jason-3, Sentinel-3A and Sentinel-3B) is provided. The dataset includes all TCs, starting from 2020, where the maximum wind speed exceeded 30 m/s. Up to 50 such TCs are formed annually, their trajectories for 2020–2021 are shown in Fig. 1, where the color indicates the maximum wind speed in the TC on a given section of the trajectory. Hereinafter, longitude is given in the range of 0–360°, where values greater than 180° correspond to the Western Hemisphere.

Besides the maximum wind speed, the radius of the maximum winds, the coordinates and the TC speed and direction calculated from them, the generated archive includes standard characteristics of the radial distribution of wind speed – the distance from the TC center to points with wind speeds of 34, 50 and 64 knots (in some cases radii for wind speeds of 30 knots are also available). Since practical problems often require information about the complete profile of the wind speed, for each moment of time it is proposed to approximate its known values by the axisymmetric Holland function [13]:

$$u(r) = \sqrt{(u_m^2 + u_m R_m f)\left(\frac{R_m}{r}\right)^B \exp\left(1 - \frac{R_m{}^B}{r^B}\right) + \frac{r^2 f^2}{4}} - \frac{rf}{2}, \quad (1)$$

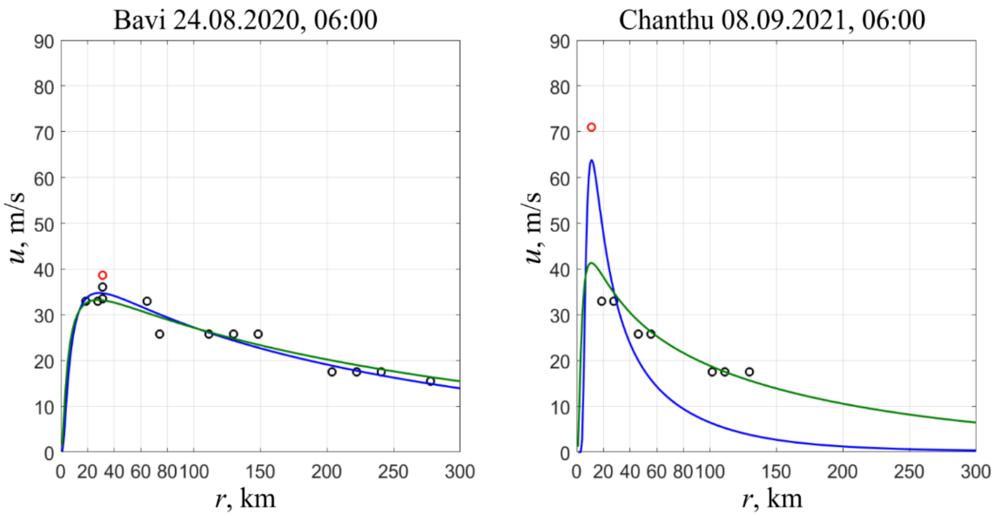
where u is the wind speed at the r distance from the cyclone center; u_m is the maximum wind speed; R_m is the maximum wind; f is the Coriolis parameter; B is the wind shape parameter.

[1] Knapp, K.R., 2018. *International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4*. NOAA National Centers for Environmental Information. doi:10.25921/82ty-9e16



F i g. 1. Trajectories of the most intense tropical cyclones in 2020 (top) and 2021 (bottom) (black circles denote the TC start points)

Approximation (1) does not always permit to describe the wind field simultaneously in the near and far TC zones. To simulate the profile in all areas correctly, it is proposed to consider the TC center and periphery separately, using a curve with the $1/r$ weight for the near zone and a curve with the r weight for the periphery. At the same time, for the near zone, the search for the optimal value in expression (1) is restricted by the limits (0.9–1) of the maximum wind speed value in the Best Track Data (BTD), and in the far zone, by the limits (0.3–1). In both cases, it is fixed at the BTD maximum wind speed radius value. Examples of the modelled wind speed distributions are shown in Fig. 2. The envelope of the obtained lines can serve as a wind profile model.

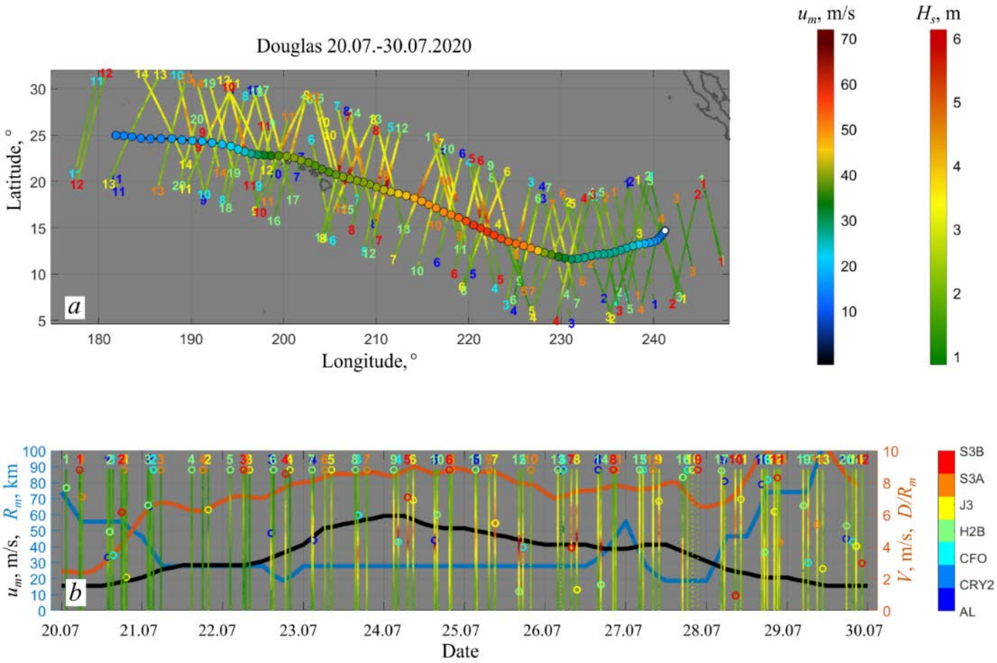


F i g. 2. Examples of approximating the data on wind speed (black circles) in the TC *Bavi* and *Chanthu* by the Holland function (1) (blue line denotes the TC near zone, green one – the TC periphery; red circles are the radius and the maximum wind speed based on the Best Track Data)

Note that when approximating by function (1), data on wind speed in different quadrants of the cyclone are taken into account with equal weights. The scatter of points makes it possible to estimate the asymmetry degree of the two-dimensional distribution of wind speed. The proposed functions are one of the ways to describe this distribution under the assumption that it is uniform in azimuth. Since the archive contains the initial data indicating the quadrant, the user can make his own estimates of the two-dimensional wind field distribution. In this case, the illustrations shown, similar to Fig. 2 can serve as a guide.

Wave height and wind speed according to altimetry data. Data on significant wave height and wind speed along the altimeter tracks installed on the seven aforementioned satellites were taken from the open archives of the Copernicus Marine Environment Monitoring Service (CMEMS) (https://resources.marine.copernicus.eu/products), which provides free, regular and systematic reference information on the ocean state and variability. In the product used (Level 3), the altimetry measurements data is brought to a uniform format after careful editing, combining various criteria (parameter thresholds, quality flags, ice presence flags, etc.) and applying filters to reduce measurement noise.

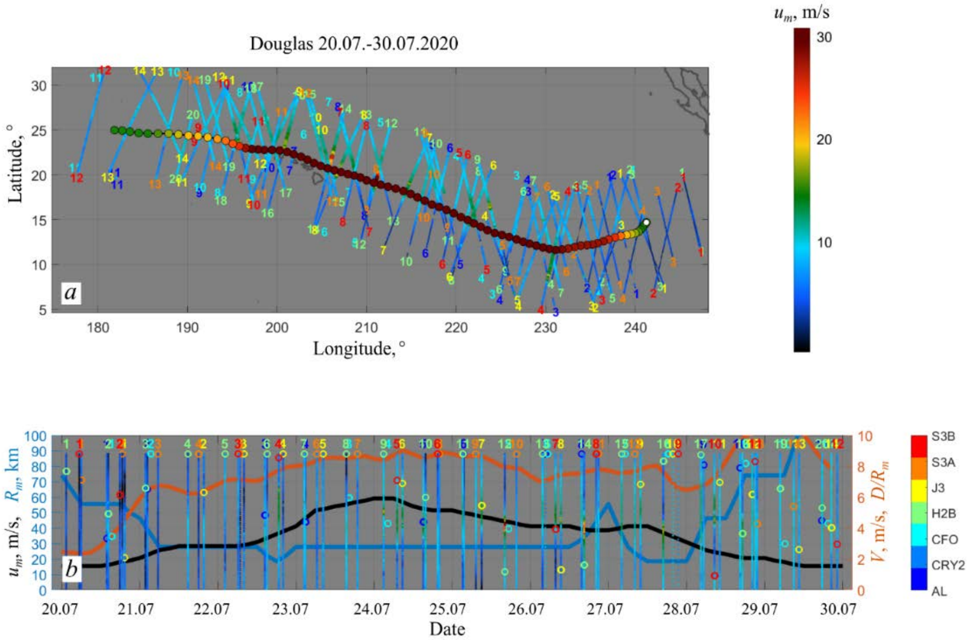
When selecting sections of altimetry tracks for the base of cyclones, the criterion $\sqrt{(lat-lat_0)^2+(lon-lon_0)^2}<7°$ was used, where (lat, lon) are altimetry measurement coordinates; (lat_0, lon_0) is the TC position at the time of the satellite passage.



F i g. 3. Characteristics of TC Douglas: *a* – the TC trajectory and the crossing it altimeter tracks (white circle is the TC start point); *b* – time evolution of the TC parameters

To illustrate the time evolution of TC parameters (coordinates, heading speed and direction, maximum wind speed and radius of maximum wind speed), the number of available altimeter measurements, spatial and temporal variability of wave heights in the TC area, for each case, figures that visually combine all of the characteristics above are presented. In Fig. 3, color shows the maximum wind speed in the TC and the height of the waves according to altimetry data; the digits indicate the serial number of the altimeter track corresponding to the MAT/NetCDF file numbering for the given TC, the color of the digit is the satellite name; circles in the lower figure indicate the minimum distances D to the TC center for each track, expressed in radii of maximum winds, while (due to the limited ordinate axis) $D/R_m = 9$ corresponds to $D/R_m \geq 9$.

Similar figures were constructed for the wind speed measured by altimeters (Fig. 4). Note that around the TC center, in the region of the strongest winds, the wind speed can be underestimated, since the standard algorithms used in altimetry are considered reliable only at wind speeds up to 20–30 m/s [14, 15]. In addition, the radar signal is affected by intense precipitation typical for TCs, and as a result, part of the wind speed and wave height data in the TC center area are filtered out.



F i g. 4. The same as in Fig. 3, but for the wind speed measured along the altimeter tracks

Data array structure

Data array on cyclones, including data files and illustrations, can be generated automatically if the current version of the file with information on the trajectories and intensity of cyclones from the IBTrACS archive and access to the Copernicus FTP server are provided. For this purpose, two blocks of MATLAB programs are sequentially launched:

1. Analysis of the IBTrACS*.nc file: selection of the most intense TCs that meet the $u_m > 30$ m/s criterion, creation of MAT-files with data on the TC coordinates, time, heading speed and direction, maximum wind speed, radius of maximum winds, wind speed at other radii; approximation of the radial wind profile by function (1) and saving the figures illustrating the approximation quality (see Fig. 2);

2. Altimetry data analysis via the CMEMS FTP-server: determination of track sections located at a distance of up to 7° from each TC center; construction of figures (see Fig. 3, 4); creation of files that combine information about the TC characteristics and altimetry data.

For the user convenience, the files indicated in block 2 are provided in two formats: MAT (for the MATLAB environment) and in the NetCDF machine-independent binary format; MAT-files include the BTD structure with fields containing data on TC characteristics, and similar structures AL, CFO, CRY2, H2B, J3, S3A and S3B with information on SARAL/AltiKa, CFOSAT, CryoSat-2, HY-2B, Jason-3, Sentinel-3A and Sentinel-3B data, respectively. More information about the variables contained in MAT and NetCDF-files is provided below.

TC parameters (BTD structure)

ax............................ Distribution area boundaries, °
t...............................Time, days starting from 01.01.01. 00:00:00
lon........................... Longitude, °
lat............................ Latitude, °
VMAX.......................Maximum wind speed, m/s
RMW........................Radius of maximum winds, km
V..............................Translation velocity, m/s
DIR..........................Direction of movement, ° (counterclockwise from the axis pointing east)
U..............................Wind speed at distances *R* from the TC center, m/s
R...............................Distances from the TC center to points with wind speed *U*, km
Q.............................. Quadrant number for radial wind profile points *U*(*R*) (*1* – NE, *2* – SE, *3* – SW, *4* – NW)
Holland_Rm............. R_m in approximation (1) in near zone, km
Holland_um............. u_m in approximation (1) in near zone, m/s
Holland_B............... B in approximation (1) in near zone,
Holland_far_Rm....... R_m in approximation (1) in periphery, km
Holland_far_um........ u_m in approximation (1) in periphery, m/s
Holland_far_B.......... B in approximation (1) in periphery,

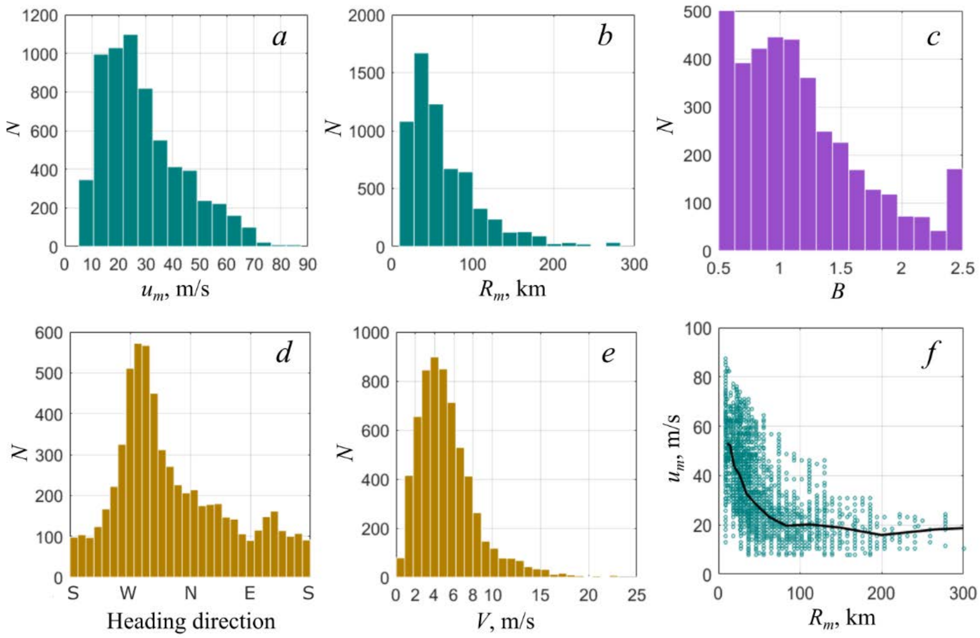
Altimetry data (AL, CFO, CRY2, H2B, J3, S3A and S3B structure)

numb..........................Number of altimeter tracks crossing the TC zone
time_i........................*The i*$^{\text{th}}$ observation time, days from 01.01.01. 00:00:00
hs_i...........................Considerable wave height, m
wind_i........................Wind speed, m/s
lon_i..........................Longitude, °
lat_i...........................Latitude, °
TC_lon_i....................Cyclone longitude, °
TC_lat_i.....................Cyclone latitude, °

Dataset application examples

The created dataset can be used for a wide range of tasks. Thus, the data on the TC *Goni* characteristics and altimetry measurements in it were jointly analyzed in [10], where the possibilities of using satellite data of various types and numerical modeling to predict waves formed in the TC were demonstrated. In [16], the created archive was used to validate self-similar functions that predict wave fields in a TC using its radius, maximum wind speed, translation speed and the Holland parameter *B*.

Characteristics of wind, waves and kinematic properties of TC can be studied independently and/or their relationship can be determined. Statistical distributions (histograms over the entire dataset) of the maximum wind speed in the TC area are shown in Fig. 5, *a*, maximum wind radius – in Fig. 5, *b*, the parameter *B* in wind profile approximation (1) – in Fig. 5, *c*, the direction and speed of the TC heading – in Fig. 5, *d*, *e*. In Fig. 5, *f*, the maximum wind speed in the TC is given versus its radius. From the above graphs, in particular, it can be concluded that most of the observed TCs move westward (Fig. 5, *d*) with speeds of ~ 5 m/s; cyclones with more intense winds, as a rule, have a smaller radius (Fig. 5, *f*), and the typical shape of the wind profile corresponds to *B* values around 1. Note that the frequency peaks corresponding to the left and right columns of the histogram for the parameter *B* are related with a limitation of *B* values when approximating the wind profile by formula (1) within 0.5–2.5: all cases where the wind profile is wider/narrower, values of *B* fall into the boundary columns of the distribution.

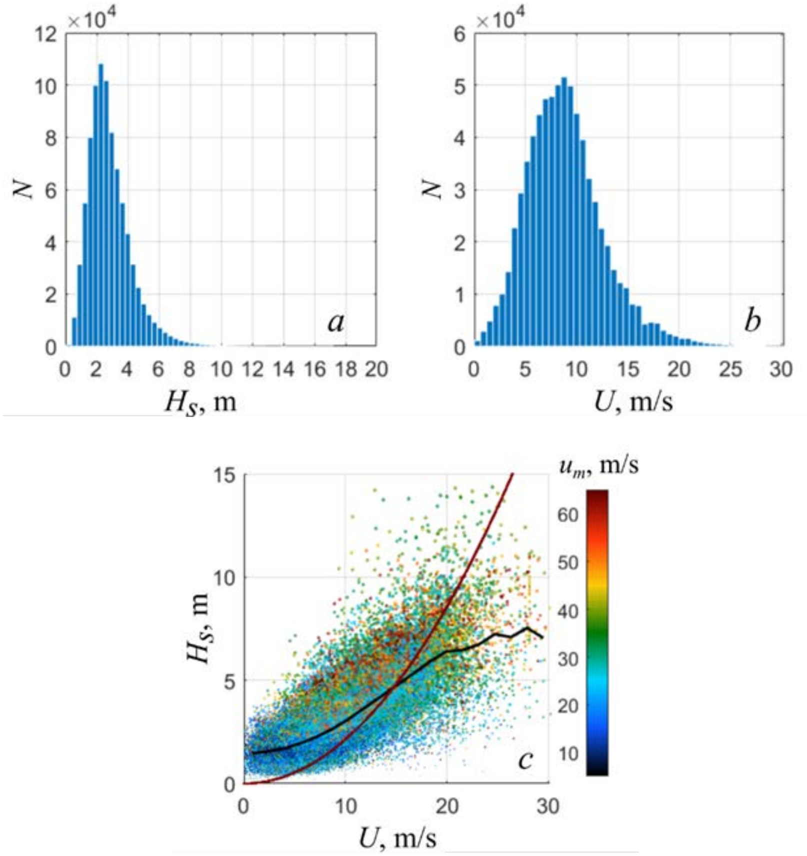


F i g. 5. Histograms of the TC characteristics' distribution (*a* – *e*) and relationship between the maximum wind speed and the TC radius (*f*) (black line is the bin average)

Of greatest interest may be the joint analysis of wind and wave data. The distribution histograms of significant wave heights and wind speeds measured by altimeters are shown in Fig. 6, *a*, *b*. Remind that altimetry observations of wind speed are limited to values up to 20–30 m/s, so the use of this data is possible only on the TC periphery. A direct comparison of the measured wind speed and wave height gives a significant scatter of data (Fig. 6, *c*), indicating the presence of other factors, in addition to the local wind speed, affecting the wave height in the region of cyclones. Thus, even at weak winds far from the TC center, where altimetry data on wind speed is reliable, the wave height significantly exceeds the upper estimate corresponding to fully developed waves [17]:

$$H = 0.21U^2/g, \tag{2}$$

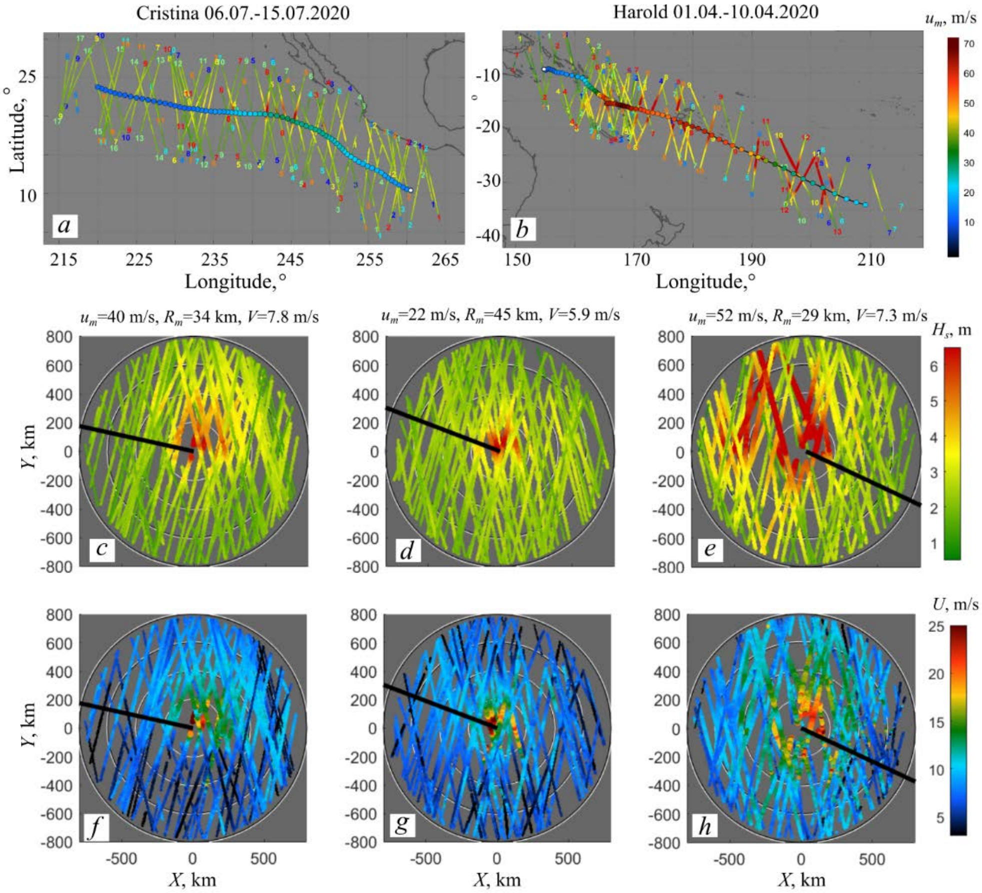
(g is gravity), which, apparently, is associated with the presence of swell formed in the region of maximum winds. The expected trend is observed: the greater the maximum wind speed in the TC, the greater the measured wave height at the same local wind speed.



F i g. 6. Histograms of distribution of the significant wave heights (*a*) and the wind speed (*b*) based on the altimetry data; relation between the wave heights and the wind speed (*c*) (black line is the bin average, red one – the heights of the completely developed waves estimated by expression (2))

A set of altimetry measurements over the TC lifetime permits to estimate the spatial distributions of the wave height and wind speed in it along the trajectory sections where the TC parameters remained stable. Examples of such distributions are shown in Fig. 7 for cyclones *Douglas* (the trajectory is shown in Fig. 3), *Cristina* (Fig. 7, *a*) and *Harold* (Fig. 7, *b*). Fig. 7, *c* – *e* show the trajectory-averaged values (with a weight of ~u_m) of the maximum wind speed in the TC, its radius and translation speed. The obtained distributions confirm the well-known effect of energy intensification in the right (left in the Southern Hemisphere, Fig. 7, *f*) part of the TC relative to its heading direction. This effect is associated not only with the wind field asymmetry (Fig. 7, *f* – *h*), but to a greater extent with the so-called wave trapping effect (the resonance of wave and the TC heading velocities)

[18–20], when waves developing in the TC heading direction remain in the region of maximum winds longer than in the left (right in the Southern Hemisphere) part of the TC, reaching a greater degree of development.



F i g. 7. Trajectories of TC *Cristina* (*a*) and *Harold* (*b*). The wave significant heights (*c* – *e*) and the wind speed (*f* – *h*) in the area of TC *Douglas, Cristina* and *Harold,* respectively (black lines denote mean direction of each TC movement)

Conclusion

Based on open data on the TC characteristics and altimetry observations of significant wave heights and wind speeds, a systematized data array that summarizes information on wind and waves in TC areas in 2020–2022 has been created. For each TC, figures illustrating the evolution of the cyclone parameters, the distribution of wave heights and wind speeds, were constructed. By the time of the paper publication, the archive has been expanded: data on wind and waves in the TC for 1985–2018 were included. More information about these data can be found in the description of the archive on the zenodo.org.

The archive can be used to carry out case studies, interpret satellite ocean observations and validate various wave, atmospheric and climate models. All materials are freely available at: https://doi.org/10.5281/zenodo.7746159

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The author has read and approved the final manuscript.
The author declares that she has no conflict of interest.