WIND WAVES MODELING UNDER HURRICANE WIND CONDITIONS
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Abstract. The CFSv2 reanalysis wind field for the real-case condition of the Irma hurricane that took place in the 31/08/2017 - 13/09/2017 was used as the wind forcing for WAVEWATCH III model. Wave parameters under Irma hurricane were calculated and compared with NDBC buoys data. The spectra of surface waves created by the hurricane allowed the evaluating the air-sea exchange processes parameters at hurricane wind.

1. Introduction
Tropical cyclones, or hurricane phenomena directly affect the lives of people in coastal regions and can cause destruction [1]. Nowadays the average storm intensity is increasing due to climate change [2]. Hurricanes are followed by strong winds that create large waves that can flood coastal areas and cause shoreline erosion. At the same time, high quality weather and sea state forecasts will make it possible to secure the population and minimize losses from such natural phenomena. Performing numerical simulations, validating it and improving physical parameterizations in forecast models are essential for correct hurricane prediction. Forecasting hurricane requires accurate prediction of hurricane-induced ocean surface waves.

The wave modelling may be implemented in the framework of modern third generation wave model WAVEWATCH III [3]. It has various packages of physical processes parameterizations, among them there are parameterizations that are able to reproduce correctly waves in storm conditions [4, 5]. The resulting values of mean wave and wind parameters allowed the evaluating of the air-sea exchange processes parameters at hurricane wind.

2. Simulation
In this paper, we focus on numerical simulation of a hurricane Irma that took place in 30/08/2017 - 12/09/2017 in the North Atlantic Ocean. Hurricane Irma was an extremely powerful and catastrophic Cape Verde hurricane. Irma developed from a tropical wave near Cape Verde on August 30, then it rapidly intensified into a Category 3 hurricane on the Saffir–Simpson wind scale on August 31. The intensity fluctuated on the next days, but on September 4, Irma resumed intensifying, becoming a Category 5 hurricane on the next day. The best track of the hurricane is made by USA National Hurricane Center and is shown on the Fig.1 taken from the tropical cyclone report [6].
Figure 1. Best track positions for Hurricane Irma, 30 August–12 September 2017 taken from [6].

The numerical simulations of waves under hurricane Irma conditions are performed within WAVEWATCH III v.5.16 model (WW3). The modelling is performed for the period of 01/09/2017 – 04/09/2017. The area with longitudes varying from 14 up to 24 degrees and latitudes varying from 280 up to 330 degrees is considered. The ETOPO1 data is used to create bathymetry and mask files. The JONSWAP initial conditions are used to start the model. The subsequent development of the waves is forced by the wind field from the CFSv2 reanalysis with 0.205° resolution. The simulations are carried out at the IAP RAS cluster using pure MPI option of the model code.

Two parameterizations of wind input (ST4 - Ardhuin et al [7] and ST6 - Zieger et al [8]) are tested. The resulting significant wave height distribution is obtained for two types of wind input parameterizations: ST4 and ST6. The model reproduces the rotating and motion of the hurricane. On the Fig.2 the typical phases of a hurricane development and the increase of its intensification are shown. The asymmetry of distribution of the surface wave field is obtained. ST6 parametrization gives values higher than ST4 on approximately 25%.
Figure 2. The evolution of significant wave height distribution under hurricane Irma conditions simulated in WW3 with ST4 wind input (left) and ST6 wind input (right) from 02/09/2017 to 04/09/2017 at the fixed time.

The calculated significant wave height of surface waves induced by the hurricane is compared with the NDBC buoys data. We examine significant wave height ($H_s$) at three NDBC buoys. The buoy 41044 is located at (301.26, 21.71); the buoy 41040 is located at (307.28, 14.45); the buoy 41060 is located at (308.983, 14.83). The NDBC buoys have a frequency range from 0.02 to 0.485 Hz. The wave instrumentation and data acquisition of the NDBC buoys are described in [9].
3. Estimation of the air-sea exchange processes parameters

In this last concluding part of the paper we demonstrate the skill of the coupled model to estimate the parameters of the air-sea exchange processes for hurricane wind. These novel results are very preliminary and will be extended and possibly revised in future.

Using the above calculations of the wind and wave field, we estimated one of the major parameter of exchange between the atmosphere and ocean, the surface drag coefficient, and estimated the effects associated with the sea spray production. In the estimates, we used the effect which was recently identified as the dominant spray production mechanism at high winds, the "bag-breakup" fragmentation (see [10-12]). This is inflating and consequent blowing of short-lived, sail-like pieces of the water-surface film, "bags". The process is similar to "bag-breakup" mode of fragmentation of liquid droplets and jets in gaseous flows.

Basing on these data we constructed the spray generation function (SGF) for the bag-breakup mechanism. And then we suggested the fetch dependent SGF valid both for laboratory and field conditions using the scaling by the dimensionless wind-sea Reynolds number (Re) (this term was suggested later in [13]):

\[
\text{Re}_B = \frac{u^*}{\omega_p v}. \tag{1}
\]

Where \( u^* \) is the friction velocity, \( \omega_p \) is the peak frequency in the spectrum of surface wind waves, and \( v \) is the kinematic viscosity of the air. The best fit of the experimental data has shown that the specific number of "bags" can be fitted by the following equation (see Fig.4(a))

\[
\langle N \rangle = M_0 R e_B^{7/3} \exp \left( -\frac{M_1}{R e_B^{3/3}} \right), \tag{2}
\]

where \( M_0 = 2.08, M_1 = 972. \)
Figure 4. (a) The specific number of "bags" versus the wind-sea Reynolds number. (b) The sea-surface drag coefficient versus the surface wind speed. Red line - estimations within the model from [14, 15] for the wave age parameter $\Omega=3$, symbols are available experimental data [16, 17, 18, 19].

With the use of the statistics of the spray-generation events, the contribution of the spray to the air-sea exchange processes can be estimated (see details in [14, 15]). In particular, it enables one to explain the unusual peaking dependence of the sea-surface drag coefficient on the surface wind speed (see Fig.4b).

The curve in Fig. 4 (b) was obtained for the assumption of a certain wave-age parameter, defined as the ratio of the surface wind speed $U_{10}$ to the phase velocity of the waves corresponding to the peak in the frequency spectrum of the wind surface waves $c_p = \frac{U_{10}}{\Omega}$. Here we estimated the surface drag coefficient for the parameters of the waves calculated within the WW3 model for the major hurricane Irma. Fig. 5 shows the examples of the maps of the parameters controlling the spray production and associated exchange parameters. Fig.5a shows the surface wind velocity field and the wind direction in the hurricane Irma according to the reanalysis CFSv2. Fig 5b demonstrates the spectral peak frequency map calculated with the use of the WW3 model. Fig. 5c shows the map of the surface drag coefficient estimated for the parameters of Figs 5 a, b taking into account the contribution of sea spray. One can see the reduction of the surface drag coefficient in the area of the strong winds. The pronounced asymmetry of the surface drag distribution with respect to the direction of motion of the storm center reflects the asymmetry of distribution of the surface wind and wave field.

Figure 5. The maps of wind field (a), the spectral peak frequency (b) and the surface drag coefficient (c). In the panel (a) the black arrows show the wind direction, the grin large arrow shows the direction of the storm motion, the color scales are in m/s. In the panel (b) the color scale is in Hz. In the panel (c) the color scale is dimensionless. the horizontal axis is the relative longitude, the vertical axes is the relative latitude, both are in degrees.
4. Conclusion
In this paper, we use WW3 to simulate wave parameters under hurricane Irma wind field. The model reproduces the rotating and motion of the hurricane. The asymmetry of distribution of the surface wave field is obtained. The calculated significant wave height of surface waves induced by the hurricane is compared with the NDBC buoys data. The generally good correlation is found between the observational $H_s$ values and WW3 wave model results under tropical cyclone conditions both for ST4 and ST6 parametrizations. With the use of the statistics of the spray-generation events, the contribution of the spray to the air-sea exchange processes is estimated. The reduction of the surface drag coefficient in the area of the strong winds is obtained. The asymmetry of the surface drag distribution with respect to the direction of motion of the storm center reflects the asymmetry of distribution of the surface wind and wave field.

References
[1] Sivakumar M.V. (2005) Impacts of Natural Disasters in Agriculture, Rangeland and Forestry: an Overview. // Springer, Berlin, Heidelberg
[2] Emmanuel K // Nature, 436 (7051) (2005), pp. 686-688
[3] Tolman H and WAVEWATCH III Development Group. User manual and system documentation of WAVEWATCH III version 4.18. //Environmental Modeling Center, Marine Modeling and Analysis Branch. 282 pp. + Appendices. 2014
[4] Port J, Hara T, Reichl B G, Ginis I, // American Geophysical Union, Ocean Sciences Meeting 2016, abstract #A54C-2735
[5] Liu Q, Babanin A, Fan Y, Zieger S, Guan C, Moon I-J, // Ocean Modeling, Vol 118, pp 73-93.
[6] https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf
[7] Ardhuin F, Chapron B and Collard F, // Geophys. Res. Lett., 2009a, 36.
[8] Babanin A V // Cambridge University Press, 2011, 480 pp
[9] Steele K E, Chi-Kin Lau, Hsu Y-H L // IEEE J of Oc. Eng., Vol OE-10, NO4, 1985.
[10] Troitskaya Y, Kandaurov A, Ermakova O, Kozlov D, Sergeev D, and Zilitinkevich S // Sci. Rep., 2017, 7, 1614.
[11] Troitskaya Y I, Ermakova O S, Kandaurov A A, Kozlov D S, Sergeev D A, and Zilitinkevich S S // Dokl. Earth Sc., 2017, 477, 1330
[12] Troitskaya Y, Druzhinin O, Kozlov D, and Zilitinkevich S // J. Phys. Oceanogr., 2018, https://doi.org/10.1175/JPO-D-17-0104.1
[13] Zhao D, Toba Y, Sugio K, and Komori S // J. Geophys. Res., 2006, C02007, doi:10.1029/2005JC002960.
[14] Troitskaya Y I, Ermakova O S, Kandaurov A A, Kozlov D S, Sergeev D A, and Zilitinkevich S S // Dokl. Earth Sc., 2017, 477, 1373
[15] Troitskaya Y, Druzhinin O, Kozlov D, and Zilitinkevich S // J. Phys. Oceanogr., 2018, https://doi.org/10.1175/JPO-D-17-0105.1
[16] Powell M D, Vickery P J, and Reinhold T A // Nature, 2003, 422, 279–283.
[17] Holthuijsen L H, Powell M D, and Pietrzak J D // J. Geophys. Res. Ocean., 2012, 117, C09003, https://doi.org/10.1029/2012JC007983.
[18] Jarosz E, Mitchell D A, Wang D W, and Teague W J // Science, 2007, 315, 1707–1709, https://doi.org/10.1126/science.1136466.
[19] Richter D H, Bohac R, and Stern D P // J. Atmos. Sci., 2016, 73, 2665–2682, https://doi.org/10.1175/JAS-D-15-0331.1.

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