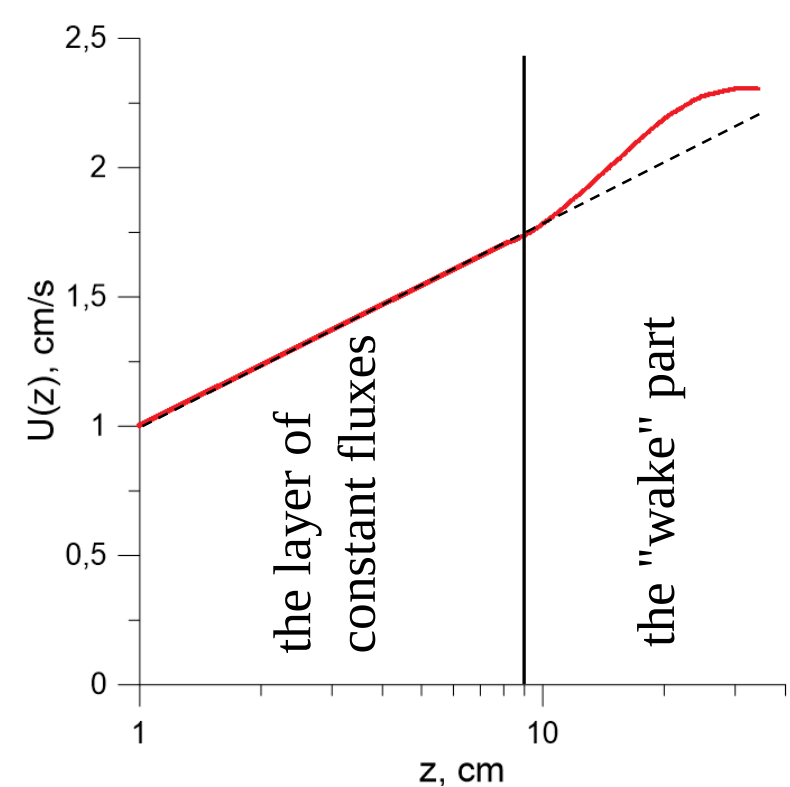


Summary. Remote sensing methods for determining the parameters of the marine atmospheric boundary layer have advantages associated with simplicity of use, wide coverage of the studied water areas, and all-weather conditions. The work is concerned with the development of a method for the retrieval of atmospheric boundary layer parameters in tropical cyclones (wind friction velocity, wind speed at meteorological height, aerodynamic drag coefficient) based on wind speed profiling by GPS dropwindsondes and collocated data of the Stepped Frequency Microwave Radiometer (SFMR). A dataset included the Category 5 hurricanes from 2000 to 2017 in the Atlantic Basin. The parameters were obtained from the data of GPS dropwindsondes with the use of the self-similarity of the velocity profile in the atmospheric boundary layer, previously proposed and successfully tested in laboratory conditions.

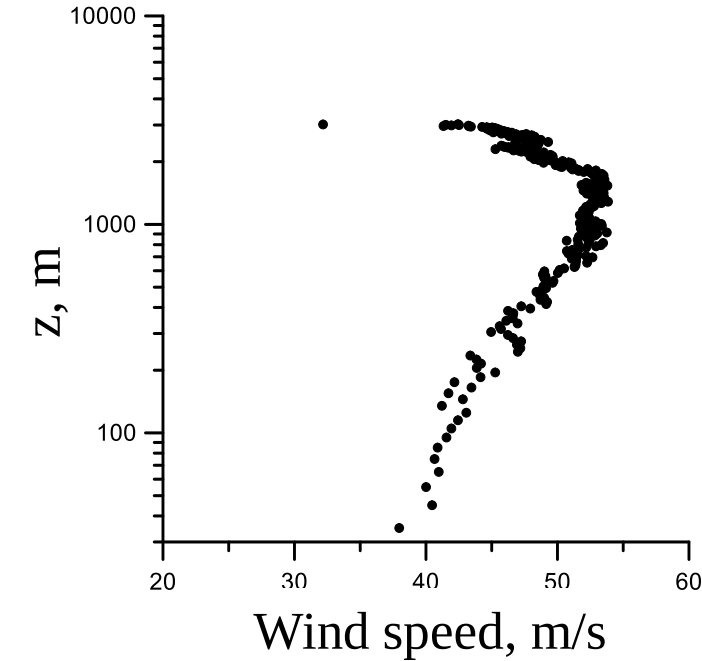
The wind friction velocity can be retrieved from the airflow velocity profiles averaged over turbulent fluctuations (see for example, (Hinze, 1959)). This approach is based on the use of the self-similarity of the velocity profile in the boundary layer, which consists of the layer of constant fluxes with a logarithmic profile and the "wake" part, in which the flow adapts to the undisturbed flow. The advantage of this method is concerned with the opportunity to use measurements of the airflow velocity profile at a considerable distance from the surface, where the data loss is significantly less than near the surface. Here this approach is applied to the wind velocity profiles obtained by GPS dropwindsondes NOAA.



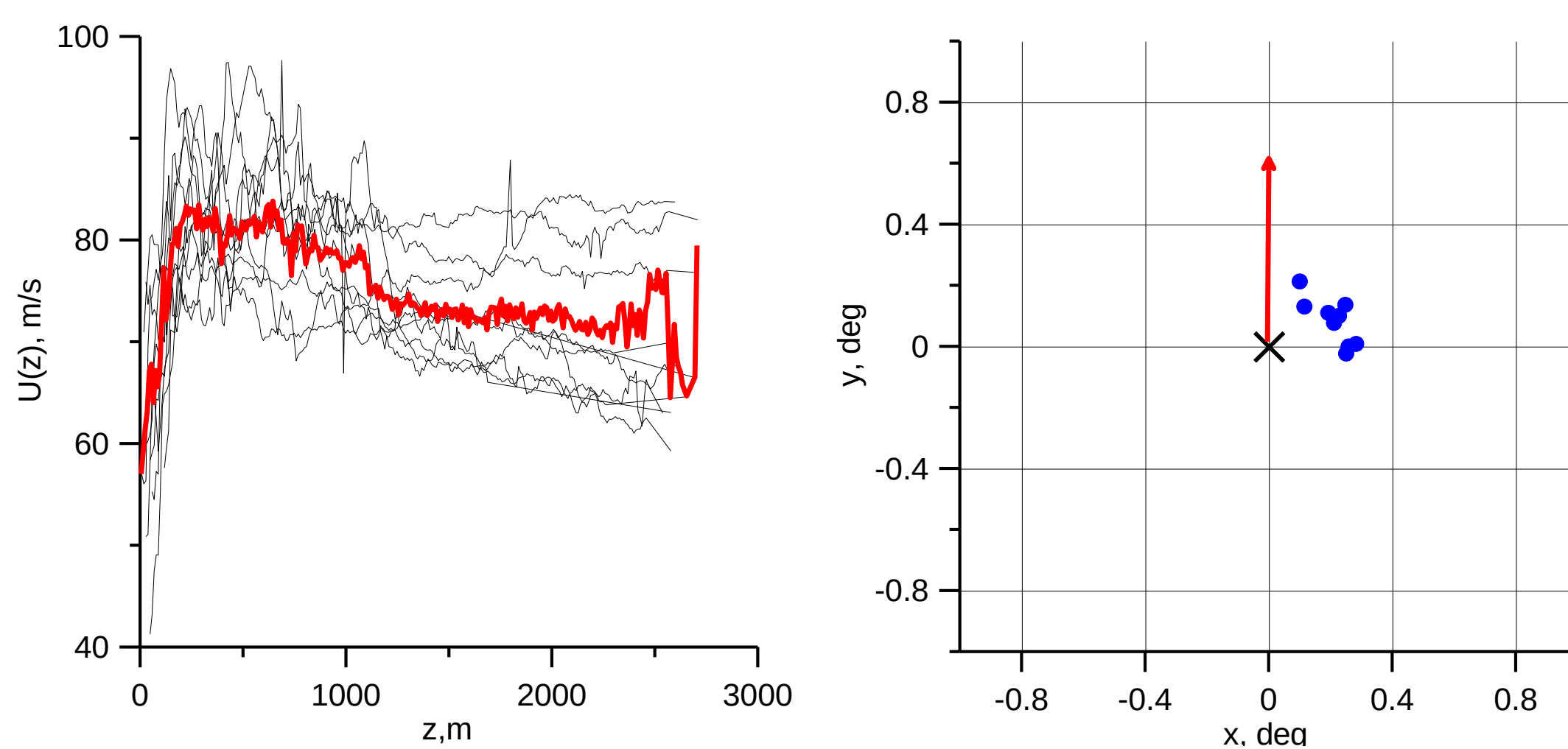
Structure of the developing turbulent boundary layer (Hinze, 1959)



GPS dropwindsondes measures vertical profiles of wind speed, pressure, temperature and humidity during a fall with a frequency of 2 Hz. www.aoml.noaa.gov/hrd/

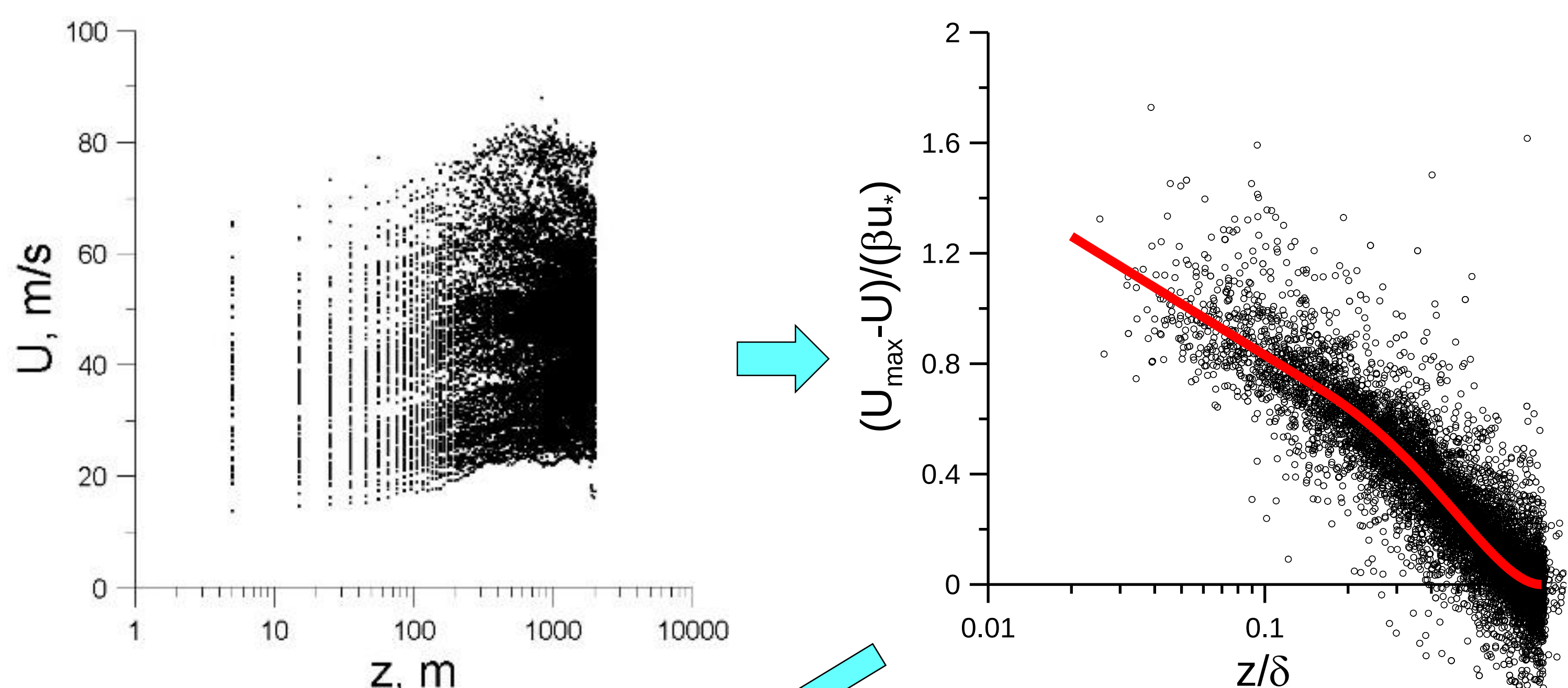


However, it should be noted that the self-similar laws are applicable only to the statistically averaged velocity profiles in the turbulent boundary layer. At the same time, the individual airflow velocity profiles measured by the GPS dropwindsondes are the individual elements of the statistical ensemble, which represent stochastic functions of the coordinate. The result of velocity profiles averaging is sensitive to the choice of the statistical ensemble. In the present study we use as statistical ensembles the sets of wind velocity profiles, measured under the same conditions, namely, at approximately the same distance from the center of a hurricane in a certain sector and on the same day. An example of such a statistical ensemble is shown in the figures below for hurricane Irma 09.09.2017.



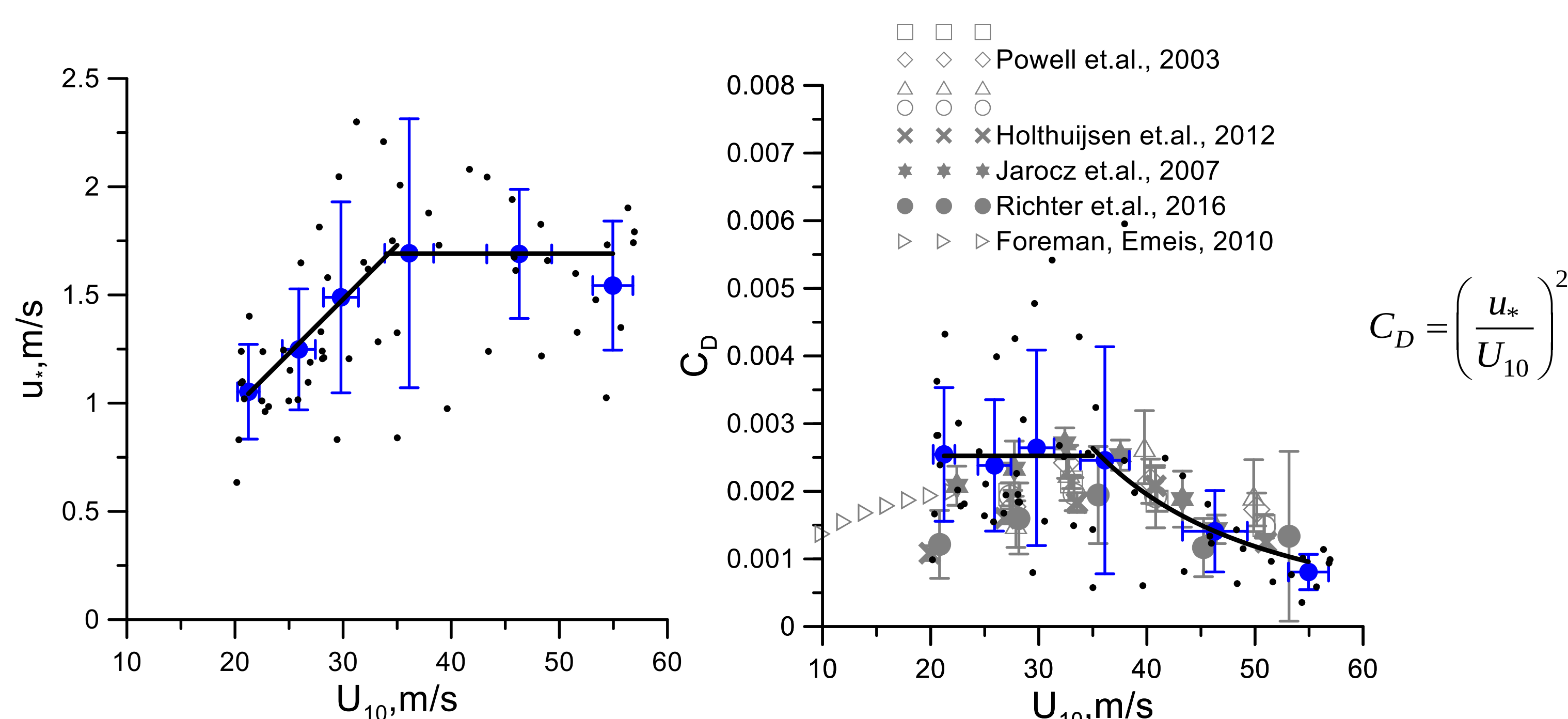
Left panel - air flow velocity profiles: thin lines are individual measured velocity profiles, bold line - velocity profile averaged over the ensemble. Right panel - coordinates of the GPS dropwindsondes reset (circles) relative to the center of the hurricane (cross). The arrow indicates the direction of the hurricane.

Obtaining atmospheric boundary layer parameters



$$\frac{U_{\max} - U(z)}{\beta u_*} = \begin{cases} -\frac{1}{k\beta} \ln(z/\delta) + \frac{\gamma}{\beta}; & z/\delta < 0.3 \\ \frac{\gamma}{\beta(1 - z/\delta)^2}; & z/\delta > 0.3 \end{cases} \Rightarrow \beta, \gamma \Rightarrow u_*, U_{10}, C_D$$

Dependence of the wind friction velocity and the drag coefficient of the ocean surface on the surface wind speed.



Small symbols are the results of calculations for individual statistical ensembles constructed of velocity profiles measured under approximately the same conditions, large symbols are averaged values, lines are power-law approximations. The gray symbols on the left panel are field measurements.

Comparison of the atmospheric boundary layer parameters with the emissivity of the sea surface

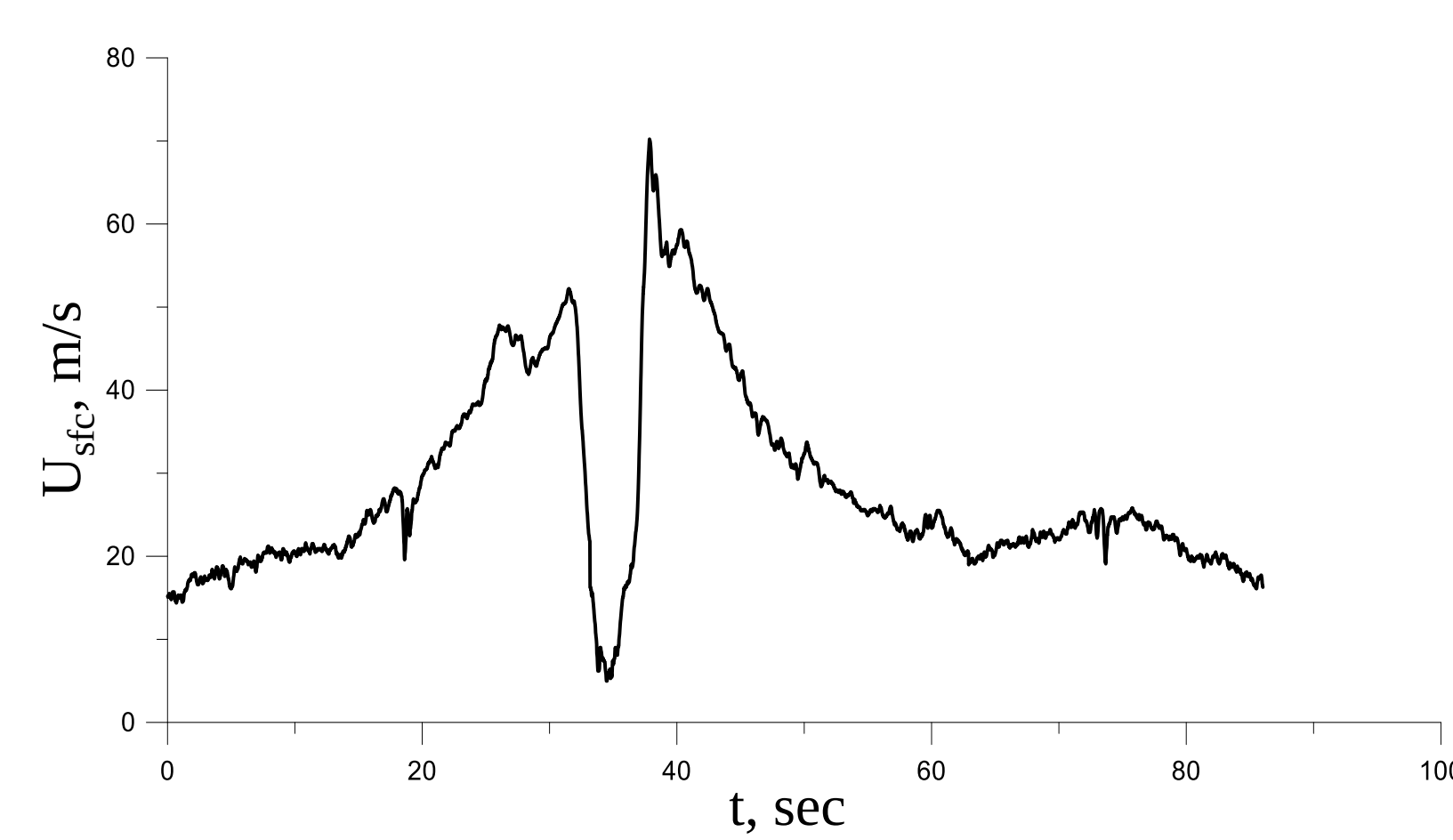


a) Radiometer under the wing of the aircraft NOAA

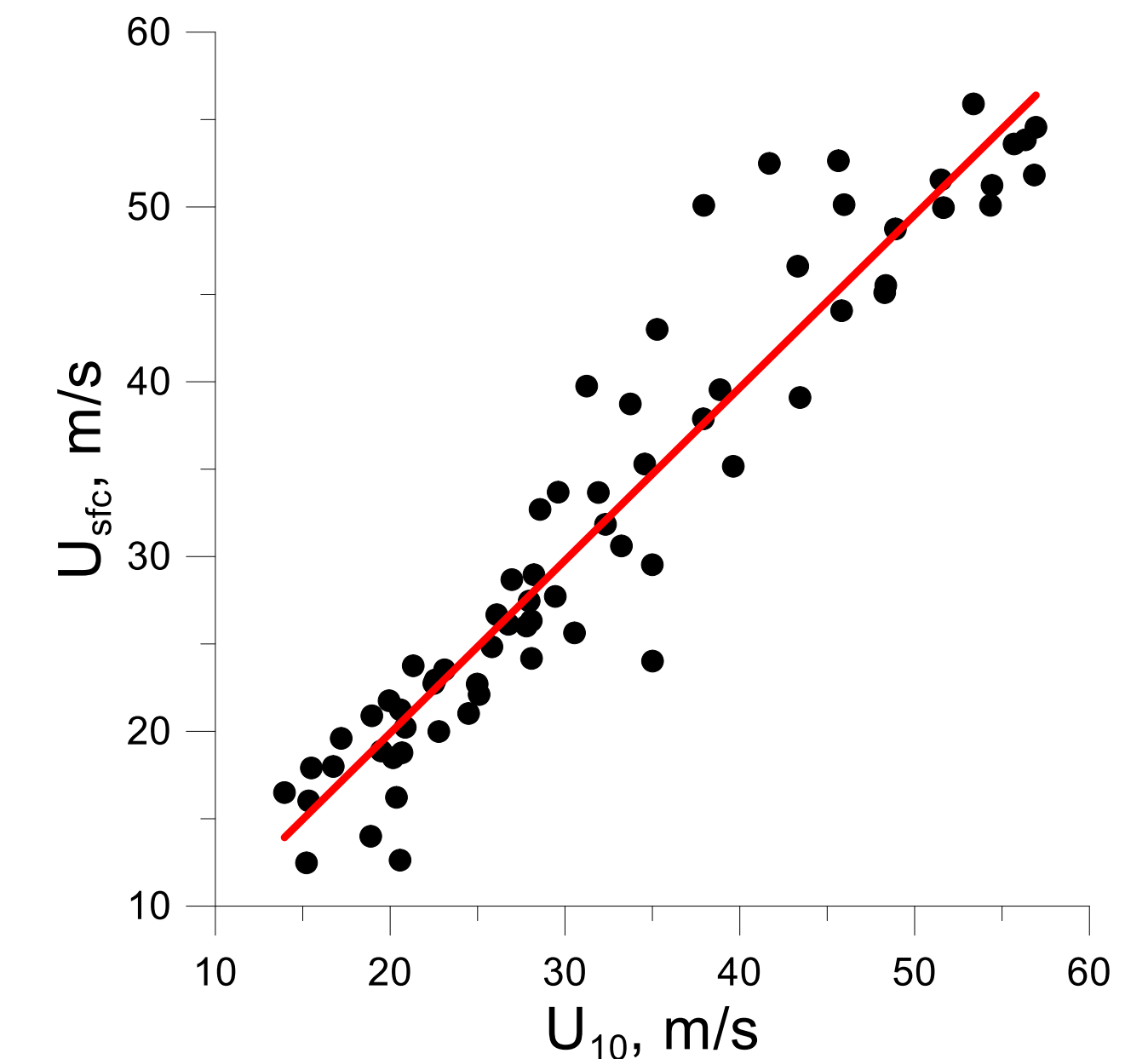


b) GPS dropwindsonde

The atmospheric boundary layer parameters retrieved from the data of the GPS dropwindsondes were compared with the remote sensing data of the Stepped Frequency Microwave Radiometer (SFMR) installed on board the same research aircraft from which the GPS dropwindsondes were launched. The algorithm for retrieving wind speed in a hurricane is based on the use of a geophysical model function (GMF) associating the emissivity of the ocean surface, E_w , and the surface wind speed U_{sfc} developed in (Uhlhorn et al., 2007) (Eq. 1). The values of E_w at the points corresponding to the coordinates of the GPS dropwindsondes were averaged over the ensemble of GPS dropwindsondes and compared to the U_{10} , u_* and C_D calculated according to the procedure described above.



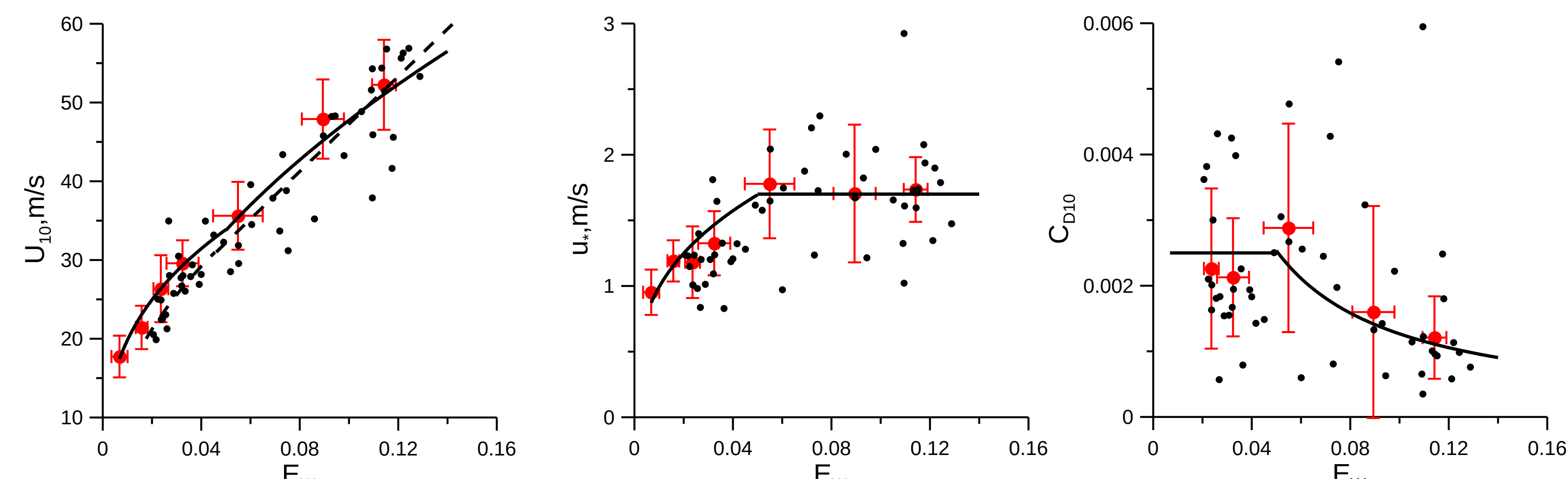
Example of U_{sfc} measured with SFMR as a function of time (hurricane Irma (2017/09/07))



Comparison of the near-surface wind speed: U_{sfc} , determined by the method (Uhlhorn et al., 2007) (Eq. 1) and U_{10} calculated by the profiling method described above, the solid line corresponds to the approximation $U_{sfc} = 0.99 U_{10} + 0.14$.

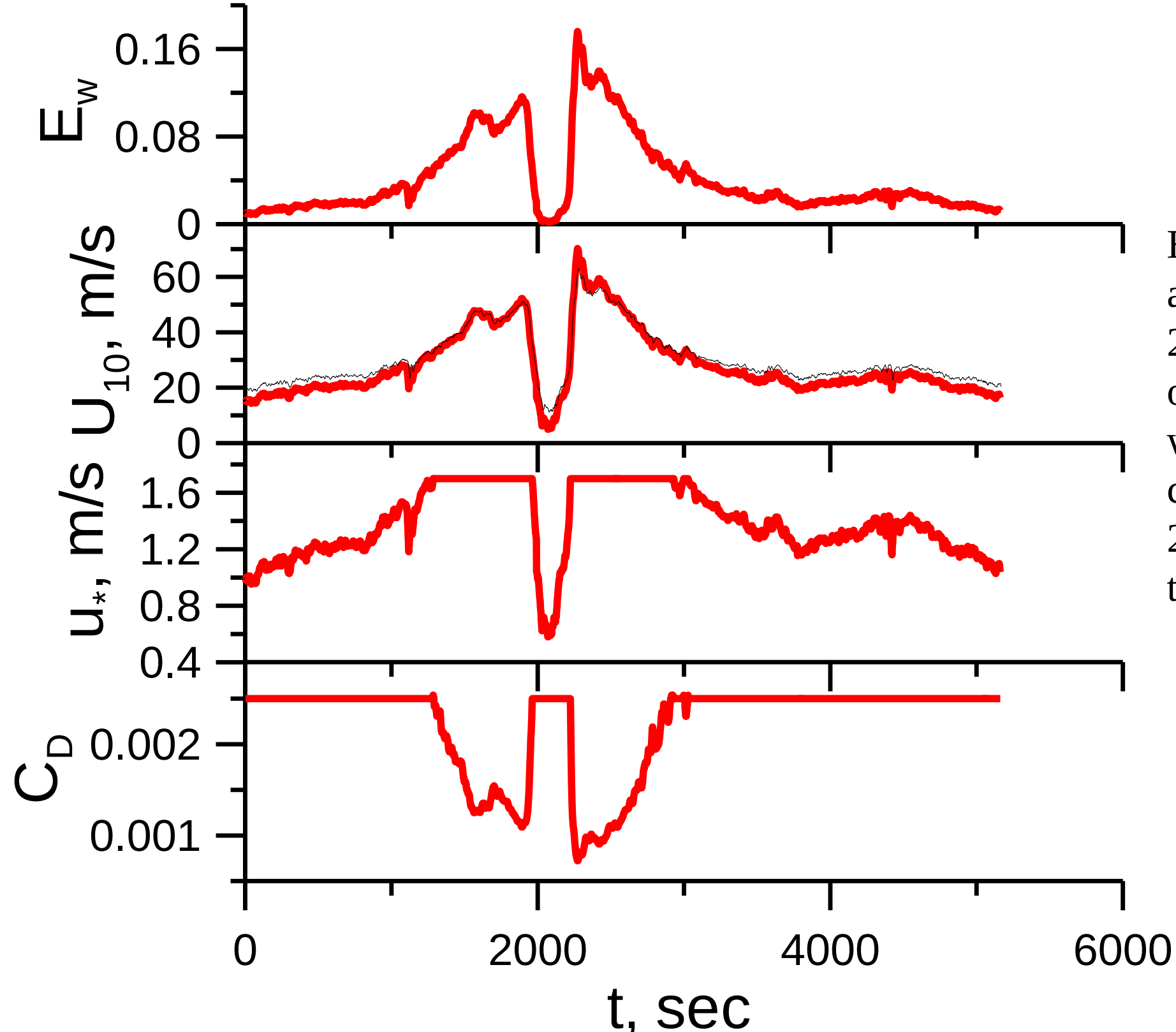
U_{sfc} is determined by GMF (Uhlhorn et al., 2007):

$$E_w = \begin{cases} a_1 U_{sfc}, & U_{sfc} \leq 7 \text{ m/s}, \\ a_2 + a_3 U_{sfc} + a_4 U_{sfc}^2, & 7 \text{ m/s} < U_{sfc} \leq 31.9 \text{ m/s}, \\ a_5 + a_6 U_{sfc}, & U_{sfc} > 31.9 \text{ m/s} \end{cases} \quad (1)$$



$$U_{10} = \begin{cases} 91.9 E_w^{1/3}, & E_w \leq 0.05, \\ 151 E_w^{1/2}, & E_w > 0.05 \end{cases} \quad (2) \quad u_* = \begin{cases} 4.6 E_w^{1/3}, & E_w \leq 0.05, \\ 1.7, & E_w > 0.05 \end{cases} \quad (3) \quad C_D = \begin{cases} 0.0025, & E_w \leq 0.05, \\ 1.27 \cdot 10^{-4} E_w^{-1}, & E_w > 0.05 \end{cases} \quad (4)$$

Comparison of the surface wind speed (left panel), the wind friction velocity (middle panel), and drag coefficient of the ocean surface (right panel), retrieved from the data of falling GPS dropwindsondes. Small symbols are the results of calculations for individual statistical ensembles composed of velocity profiles measured under approximately the same conditions, large symbols are averaged values, lines - approximations by the corresponding formulas. The dotted line on the left panel is the GMF from work (Uhlhorn et al., 2007) (Eq. 1).



Emissivity of the ocean surface, E_w , measured along the track of an aircraft over Hurricane Irma 2017/09/07 (1st graph). Red lines - retrieved values of the surface wind speed (Eq. (2), graph 2), the wind friction velocity (Eq. (3), graph 3), drag coefficient (Eq. (4), graph 4). The black line on the 2nd graph is the surface wind speed retrieved by the method (Uhlhorn et al., 2007).

Conclusions

The results of data processing showed that at surface wind speeds exceeding 35 m/s, the friction velocity saturates and the surface drag coefficient decreases accordingly. Based on the comparison of the measured dynamic parameters and the surface emissivity, empirical equations are proposed, which take into account the discovered properties of the dynamic parameters of the atmospheric boundary layer and potentially can be used for remote diagnostics of the boundary layer parameters. However, it should be noted that in this work the empirical functions are preliminary, since they were obtained on the base of the limited experimental data. It is assumed that they will be refined in the future.