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Sea spray at high winds: mechanisms of production and role in heat transfer and surface drag

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Sea sprays is a typical element of the marine atmospheric boundary layer (MABL) of large importance for marine meteorology, atmospheric chemistry and climate studies. They are considered as a crucial factor in the development of hurricanes and severe extratropical storms, since they can significantly enhance exchange of mass, heat and momentum between the ocean and the atmosphere. This exchange is directly provided by spume droplets with the sizes from 10 microns to a few millimeters mechanically torn off the crests of a breaking waves and fall down to the ocean due to gravity. The fluxes associated with the spray are determined by the rate of droplet production at the surface quantified by the sea spray generation function (SSGF), defined as the number of spray particles of radius r produced from the unit area of water surface in unit time. However, the mechanism of spume droplets' formation is unknown and empirical estimates of SSGF varied over six orders of magnitude; therefore, the production rate of large sea spray droplets is not adequately described and there are significant uncertainties in estimations of exchange processes in hurricanes.

Experimental core of our work comprise laboratory experiments employing high-speed video-filming, which have made it possible to disclose how water surface looks like at extremely strong winds and how exactly droplets are torn off wave crests. We classified events responsible for spume droplet, including bursting of submerged bubbles, generation and breakup of "projections" or liquid filaments and "bag breakup", namely, 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 statistical analysis of results of these experiments we show that the main mechanism of spray-generation is attributed to "bag-breakup mechanism

On the base of general principles of statistical physics (model of a canonical ensemble) we developed statistics of the "bag-breakup" events and constructed sea spray generation function (SSGF) for the mechanism of "bag-breakup". The "bag breakup" SSGF is shown to be in reasonable agreement in magnitude with SSFGs considered as the most reliable source function for spume droplets. The new SSGF is employed for estimate of the new"bag-breakup" mechanism to momentum and energy exchange in marine atmospheric boundary layer at hurricane conditions.

Basing on the developed statistics, we estimated the surface stress caused by "bag-breakup" as the average sum of stresses caused by individual "bags" depending on their geometrical parameters. The resulting stress is subjected to counteracting impacts of the increasing wind speed: the increasing number of bags, and their decreasing sizes and life times and the balance yields a peaking dependence of the bag resistance on the wind speed: the share of bag-stress peaks at U10 about 35 m/s and then reduces. Peaking of surface stress associated with the "bag-breakup" explains seemingly paradoxical non-monotonous wind-dependence of surface drag coefficient peaking at winds about 35 m/s.