Effect of polydisperse spray on hurricane and severe storm dynamics

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I. MOTIVATION AND OBJECTIVES

Motivation:

Wide observational and theoretical evidence exists that ocean spray strongly affects hurricane dynamics thermodynamically and mechanically by modifying the vertical enthalpy and momentum fluxes, respectively. It has been shown that both these influences of ocean spray essentially depend on the size of spray droplets. Hence, accounting for the droplet size distribution is important for accurate description and modeling of the spray effect on hurricane dynamics.

Objectives:

- Develop a rigorous and consistent Eulerian multi-fluid model of a Marine Atmospheric Boundary Layer (MABL) laden with polydisperse spray.
- Carry out an in-depth study of the ocean spray effect on hurricane dynamics using numerical and theoretical analyses of the MABL model.

II. EFFECTS OF OCEAN SPRAY ON TROPICAL CYCLONE

The effect of the ocean spray on the hurricane dynamics is two-fold:

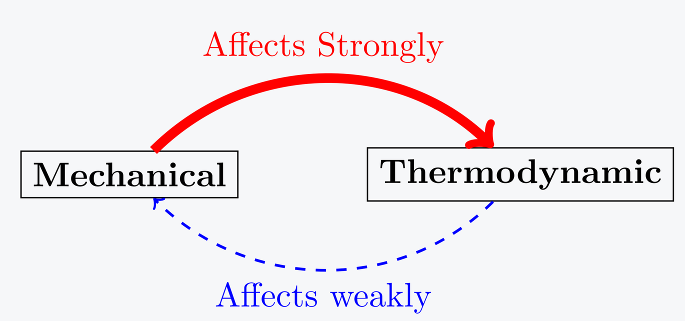
I. Thermodynamic (*Rastigejev & Suslov 2016, 2019*). Evaporating sea spray modifies latent and sensible heat fluxes in a MABL.

II. Mechanical (*Rastigejev & Suslov 2022*). Sea spray affects the vertical momentum transport.

Accelerating effect due to turbulence attenuation by the spray --- Droplet Slip (DS) and "Gravity Lubrication" (GL)

Decelerating effect due to spray inertia.

The thermodynamic and mechanical effects are coupled but coupling is not symmetric (*Rastigejev & Suslov, JPO 2019*)



Hence, the mechanical effect can be considered separately.

III. MECHANICAL EFFECT OF SPRAY

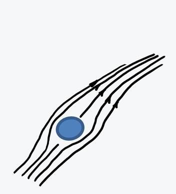
The decelerating effects of spray inertia

Horizontal velocities of injected droplets are much smaller than that of the airflow,

$$u_i^1 \ll u_a$$

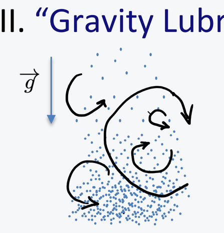
The accelerating effects of spray due to turbulence suppression, two mechanisms

I. Droplet slip (DS) causes air-droplet "friction" that leads to turbulence attenuation



Turbulent flow loses its energy due to air-droplet friction ⇨ turbulent transport becomes less intensive ⇨ reduction in air-ocean drag ⇨ wind acceleration

II. "Gravity Lubrication" (GL) due to upward transport of spray by the turbulent flow



Turbulent flow lifts spray ⇨ it works against gravity ⇨ loses its energy ⇨ turbulent transport becomes less intensive ⇨ reduction in air-ocean drag ⇨ wind acceleration

DS>GL

IV. MATHEMATICAL MODEL OF SPRAY-LADEN MABL

Multi-fluid Eulerian model of MABL laden with polydisperse sea spray

Spray continuity

$$\frac{d}{dz}\left(d_i\frac{ds_i}{dz}+s_ia_i\right)=\frac{1}{\Delta r}(f_{i+1}-f_i)-\dot{q}_is_i-a_{0i}s_{0i}\delta_{z-z_w} \qquad i=1\dots N$$

(N=10 for present calculations)

Moisture conservation

$$\frac{d}{dz}\left(k_a\rho_a\frac{dq}{dz}\right)=\rho_w\sum_{i=1}^{N}\dot{q}_is_i$$ ⟵ specific humidity

Momentum conservation

$$\frac{d}{dz}\left(k_a\rho_a\frac{du_a}{dz}\right)=\rho_w\sum_{i=1}^{N}\frac{s_i(u_a-u_i)}{\tau_{di}}$$ ⟵ horizontal wind speed

$$\frac{d}{dz}\left(k_is_i\frac{du_i}{dz}\right)-s_iw_i\frac{du_i}{dz}+\frac{s_i}{\tau_{di}}(u_a-u_i)+(u_i^1-u_i)a_{0i}s_{0i}\delta_{z-z_w}=0$$ ⟵ horizontal spray motion

$$\frac{d}{dz}\left(\frac{4}{3}k_is_i\frac{dw_i}{dz}-\frac{2}{3}s_ie_i\right)-s_iw_i\frac{dw_i}{dz}-s_ig+\frac{s_i}{\tau_{di}}(w_i^d-w_i)+(w_i^1-w_i)a_{0i}s_{0i}\delta_{z-z_w}=0$$

vertical spray motion

$$\frac{dP}{dz}=-\rho g$$

Thermal energy conservation

$$\frac{d}{dz}\left(k_a\rho_d\frac{d\theta}{dz}\right)=\sum_{i=1}^{N}\gamma_i\left(T_a-T_i\right)$$ ⟵ potential air temperature

$$\frac{d}{dz}\left(s_id_i\frac{dT_i}{dz}+H_{z-z_w}s_ia_iT_i\right)=\left[\gamma_i(T_i-T_a)-l\dot{q}_i\right]s_i-a_{0i}s_{0i}T_s\delta_{z-z_w}$$ ⟵ spray temperature

E-epsilon (k-epsilon) 1.5 order model

$$\alpha_e\frac{d}{dz}\left(\rho_ak_a\frac{de_a}{dz}\right) = \rho_a(\epsilon_a-p_a)-q_{ae}$$

$$\alpha_\epsilon\frac{d}{dz}\left(\rho_ak_a\frac{d\epsilon_a}{dz}\right) = \rho_a(d_{a\epsilon}-p_{a\epsilon})-q_{a\epsilon}$$

+ various constitutive relationships

V. VOLUMETRIC SPRAY GENERATION FUNCTION (VSGF)

VSGF

$$f_v(u_c,r)=s_0(u_c)p(r)$$

u_c – characteristic speed of the airflow, $u_c=u_*$ or $u_c=u_{a10}$
r – droplet radius

VSGF — Volumetric density of spray in quiescent air — shape function

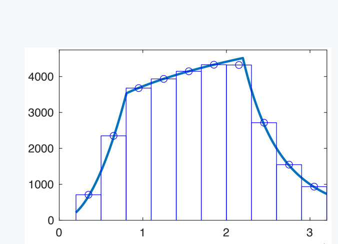
Large uncertainty over spray production rates:

- Six orders of magnitude in field experiments (the wind speeds ≲ 20 m/s)
- Two-three orders of magnitude in laboratory experiments (the wind speeds ≲ 60 m/s)

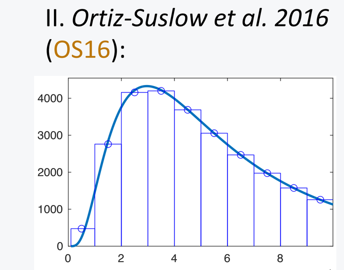
How to relate: Laboratory ⇨ Field ???: 2-3 orders of magnitude difference

Shape of VSGF, p(r)

I. *Andreas 1998* (A98):



II. *Ortiz-Suslow et al. 2016* (OS16):



Spray production intensity $s_0(u_c)$

$$s_0(u_\star)=A_nu_\star^n$$ (*Fairall et al. 2009* and others)

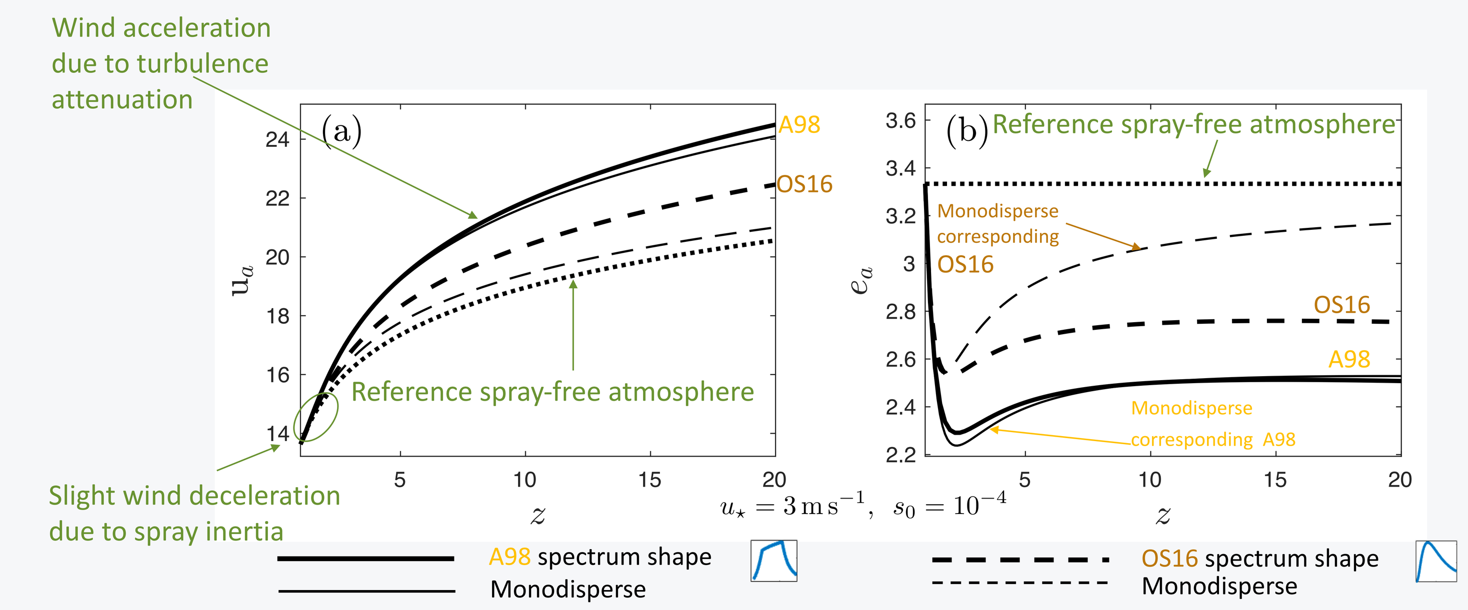
$$n\sim2-16$$

$$s_0(u_{a10})=A\exp[\delta(u_{a10}-u_r)]$$

$$\delta\sim0.2-0.875$$ (*Monahan 1986, Wu 1993*)

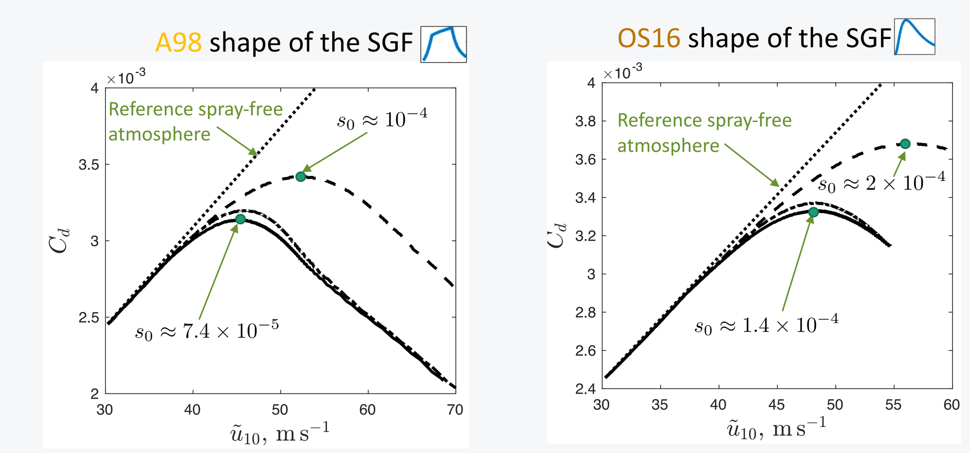
VI. NUMERICAL SIMULATION: MECHANICAL EFFECT OF SPRAY

Horizontal velocity (u_a) and TKE (e_a) of air vs altitude (z)



I. Due to the larger fraction of small droplets, sea spray with the A98 spectrum shape suppresses air turbulence more efficiently than that with the OS16 counterpart for the same value of the volumetric spray production intensity s_0 causing greater acceleration of the wind above the wave crest level.
II. Monodisperse spray assumption leads to a quantitative underprediction of the wind speed.

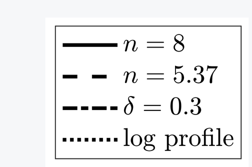
C_d vs u_{10} for different correlation laws between s_0 and u_* (u_{a10})



We consider the exponential and power law relations for the dependence of the volumetric density s_0 on the wind speed

$$s_0(u_{a10})=A\exp[\delta(u_{a10}-u_r)]$$

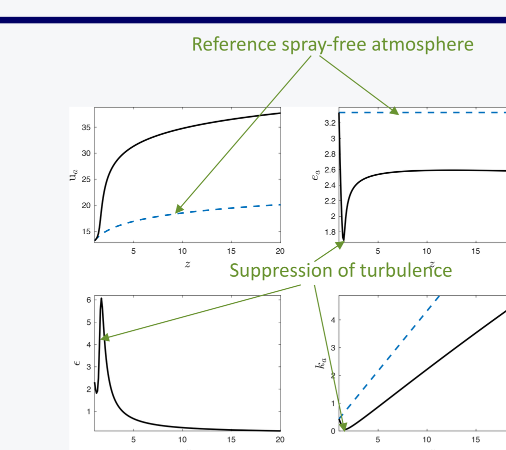
$$s_0(u_\star)=A_nu_\star^n$$



The spray-induced reduction of drag causes the wind to accelerate above the wave crest level. The reduction of the drag coefficient (C_d) occurs even at relatively low spray concentrations. C_d reaches its maximum at the volumetric spray concentration ~10^{-4}, which corresponds to the spray mass fraction of ~10%.

Collapse of turbulence in a thin layer ("slip sheets")

Numerical simulations show that thin layers (~1-2 m), where turbulence is strongly suppressed, develop a few meters above the wave crest level for large values of spray volumetric density s_0 and the friction velocity u_* and the A98 spectrum. The presence of these structures causes a rapid decrease in the air-sea drag coefficient followed by a strong increase in the wind speed.



VII. CONCLUSIONS

- The Eulerian multi-fluid model has been developed to describe a marine atmospheric boundary layer laden with polydisperse ocean spray. The model considers droplets of various sizes and air as separate interacting turbulent continua.
- This approach enables us to account for the turbulence attenuation due to air-droplet slip (DS) and due to the "gravity lubrication" (GL), and the effect of spray inertia.
- The acceleration due to DS is much stronger than due to GL and occurs even for low volumetric spray concentrations s_0~10^{-4} (~10% spray mass mixing ratio). This can explain a substantial air-ocean drag reduction detected in field observations.
- Two "shapes" of the volumetric spray generation function, A98 and OS16, have been studied. The fraction of large droplets in OS16 is much higher than that in A98. The shapes yield substantially different values of the air-sea drag coefficient C_d for volumetric spray concentrations $s_0\gtrsim10^{-4}$.
- Polydisperse spray results are generally not quantitatively comparable to those obtained using a simpler monodisperse-spray approach. In particular, the monodisperse spray model may underestimate the spray-induced wind acceleration.
- Numerical simulations show that thin layers, where the turbulence is strongly suppressed (turbulent viscosity is small), may develop a few meters above the wave crest level for sufficiently large values of volumetric spray density s_0 and friction velocity u_*. Such layers effectively act as slip sheets between the air and the ocean. The presence of these structures causes a rapid decrease in the air-sea drag coefficient and an increase in wind speed.

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