A Fresh Look at Wind Stress Parametrizations

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1. Motivation

- Accounting for ocean surface velocities in wind stress parametrizations leads to a 30% reduction of wind power input by removing energy from mesoscale eddies **[1]**. This is known as "eddy killing".
- However, recent studies **[2]** show that forcing ocean-only models with reanalysis winds can yield too much eddy killing. This is due to an ocean signature in the reanalysis 10-m winds, referred to as the "Current FeedBack Effect" (CFB).
- Here, a new formulation (NEW) for the stress is suggested by revisiting turbulent Ekman layer theory **[3]**, compared with an earlier formation (DS) from **[4]** and an empirically derived version (RE) from **[5]**.

2. Methods

- Using 10-m winds $\boldsymbol{u}_{10}$ or geostrophic winds $\boldsymbol{u}_g$ with or without the ocean $\boldsymbol{u}_o$, the wind stress can be written as

$$\boldsymbol{\tau}_0 = \rho_a c_{10} |\boldsymbol{u}_{10}| \boldsymbol{u}_{10}$$
$$\boldsymbol{\tau}_1 = \rho_a c_{10} |\boldsymbol{u}_{10} - \boldsymbol{u}_o| (\boldsymbol{u}_{10} - \boldsymbol{u}_o)$$

$$\boldsymbol{\tau}_A = \rho_a c_d |\boldsymbol{u}_g| \boldsymbol{u}_g^{\phi}$$
$$\boldsymbol{\tau}_B = \rho_a c_d |\boldsymbol{u}_g - \boldsymbol{u}_o| (\boldsymbol{u}_g - \boldsymbol{u}_o)^{\phi}$$

- We compare their difference because it projects well onto mesoscale eddies. Define $\boldsymbol{v}_o := \boldsymbol{u}_o + \frac{\boldsymbol{u}_o \cdot \boldsymbol{u}_{10}}{|\boldsymbol{u}_{10}|} \hat{\boldsymbol{u}_{10}}$.
- Compare With

$$\boldsymbol{\tau}_B - \boldsymbol{\tau}_A \approx -\rho_a c_d |\boldsymbol{u}_g| \boldsymbol{v}_o^{\phi}$$
$$\boldsymbol{\tau}_1 - \boldsymbol{\tau}_0 \approx -\rho_a c_{10} |\boldsymbol{u}_{10}| \boldsymbol{v}_o$$

  → Need to relate $\boldsymbol{u}_g$ to $\boldsymbol{u}_{10}$?
- May assume that $\boldsymbol{\tau}_A = \boldsymbol{\tau}_1$ if the ocean is at rest, which leads to $c_d |\boldsymbol{u}_g| = \delta c_{10} |\boldsymbol{u}_{10}|$, with $\delta = (c_d/c_{10})^{1/2} < 1$.
- The BT theory **[3]** allows us to calculate δ as a function of the roughness length z_0 (or c_{10}) and the latitude. A and B are universal constants.

$$\ln\left(\frac{u^*}{f z_0}\right) = A - \ln\left(\frac{u^*}{G}\right) + \left(\frac{k^2 G^2}{u^{*2}} - B^2\right)^{1/2},$$
$$\sin\phi = \frac{B u^*}{kG}.$$

$$c_{10} \equiv [k/\log(10/z_0)]^2$$

→ $$c_d \triangleq (u^*/G)^2$$

- Thus, $\boldsymbol{\tau}_{\text{diff, DS}} = -\rho_a c_{10} |\boldsymbol{u}_{10}| \boldsymbol{v}_o, \quad \boldsymbol{\tau}_{\text{diff, NEW}} = -\delta \rho_a c_{10} |\boldsymbol{u}_{10}| \boldsymbol{v}_o^{\phi}.$
- Renault et al. **[5]** assume $\boldsymbol{\tau}_{\text{diff, RE}} = -s_\tau \boldsymbol{u}_o$, where s_τ is related to $|\boldsymbol{u}_{10}|$ and is found empirically using 9 years of wind stress curl (QuickSCAT) and vorticity (AVISO) data.
- By regression, they find that $s_\tau = -2.5 \times 10^{-3} |\boldsymbol{u}_{10}| + 0.013$, which yields a positive coefficient when $|\boldsymbol{u}_{10}|$ falls below a threshold value u_{offset}.
- Overall, their fit provides a fairly accurate global representation of the energy transfer budget compared to the data; however, it lacks a solid physical foundation.

3. Results

Below, we rewrite the three parametrizations for comparison:

$$\boldsymbol{\tau}_{\text{diff, DS}} = -\rho_a c_{10} |\boldsymbol{u}_{10}| \boldsymbol{v}_o$$
$$\boldsymbol{\tau}_{\text{diff, RE}} = -\gamma_1 (|\boldsymbol{u}_{10}| - u_{\text{offset}}) \boldsymbol{u}_o, \quad \gamma_1 = \rho_a \tilde{c}_{10}$$
$$\boldsymbol{\tau}_{\text{diff, NEW}} = -\gamma_2 |\boldsymbol{u}_{10}| \boldsymbol{v}_o^{\phi}, \quad \gamma_2 = \delta \rho_a c_{10}$$

❖ Figure 1: δ as a function of c_{10} and f

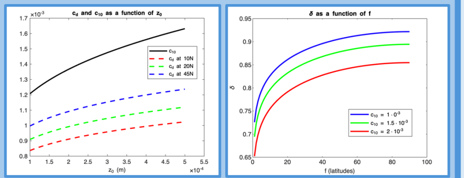
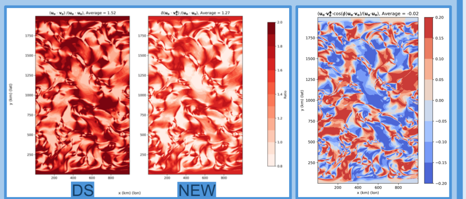
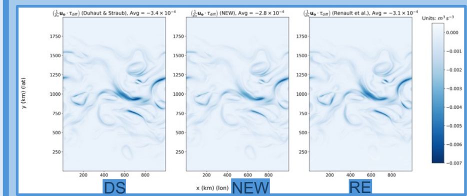


Figure 2 and Figure 3 below use the surface current and the 10-m wind speed profile from L-P Nadeau and J.K. Rieck. Note that c_{10} is taken to be 0.001 for all, and $\delta = 0.9$ is assumed to be a reasonable estimate.

❖ Figure 2: Comparison between DS and NEW evaluating the effect of δ and ϕ (no wind involved)



❖ Figure 3: Mean eddy wind work plotted for the three formulations. A negative value indicates a transfer of energy from the oceanic eddies to the atmosphere. Comparison of the absolute values: DS > RE > NEW



4. Key Observations

- Figure 1 shows that δ ranges from 0.7 to 0.9.
- The NEW formulation reduces the eddy killing due to δ and a rotation of v_o through an angle ϕ compared to DS. The reduction from the rotation can be approximated as $\cos(\phi)$, which is about 93%.
- The differences in P_{diff} aren't huge. Nonetheless, NEW reduces eddy killing by about 18% and 10%, compared to DS and RE, respectively.

5. Conclusions

<u>The NEW Parametrization</u>

- ❑ Reduces eddy killing by about 20%
- ❑ Damps eddies differently depending on how they align with atmospheric winds
- ❑ Provides a link to theory, so that other effects, such as SST dependence & thermal wind shear, can be added

6. Future Work

So far, the theory has primarily been developed in the context of mesoscale eddies and currents. However, this may fail in the submesoscale. To test this, a single column model **[6]** may be considered.

Define $\boldsymbol{u} = \boldsymbol{u}_h - \boldsymbol{u}_g$

$$\partial_t \boldsymbol{u} = -\boldsymbol{f} \times \boldsymbol{u} + \partial_z (K_m \boldsymbol{u}_z)$$
$$\partial_t \theta = \partial_z (K_s \theta_z) + \lambda(\theta_g - \theta)$$
$$\partial_t q = \partial_z (K_s q_z) + \lambda(q_g - q)$$
$$\partial_t e = \partial_z (K_e e_z) + K_m |\boldsymbol{u}_z|^2 - K_s N^2 - \frac{\alpha e}{N}$$

Run this over small-scale currents, change ocean surface conditions, and see how long it takes for the stress to adjust to the equilibrium state.

7. Selected References

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