CESM-ocean-atmosphere flux exchange-some background on flux computations

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Acknowledging

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Main points

- Ocean-atmosphere fluxes based on Monin-Obukhov similarity theory (MOST) and analytical forms of exchange coefficients from Large and Yeager (2004, 2009).
- It has been extensively used for model lowest-level variables centered at ~ 55m (coupled) and 10m (forced-ocean simulations).
  - Now being applied at 10m or 20m in CESM3 development cases.
- Surface waves are not explicitly included in the surface flux calculations.
- High wind speed regime is an area of uncertainty – how to modify the drag coefficient at extreme winds?
- Libraries of various different flux schemes exist
  - E.g. Brodeau software package Aerobulk
- Flux parameterization not developed for short time-scale (e.g.minutes) or short length-scale (kms)
  - Field measurements of turbulence averaged e.g. over 10s of minutes
  - This is an issue for ultra high-resolution models

Air-sea exchange fluxes of momentum , heat, moisture

	Momentum Flux	Sensible Heat flux	Latent heat flux
• Turbulent quantities Measured by direct covariance or inertial dissipation methods – not common but needed as baseline for bulk flux	$|\underline{\tau}| = \sqrt{(\rho\overline{u'w'}^2 + \rho\overline{v'w'}^2)}$	$Q_h = \rho c_p \overline{\theta' w'}$ *Note the overbars – time averages*	$Q_L = \rho L_v \overline{q' w'}$
• Friction velocity etc form	$\tau = \rho u^{*2}$	$Q_h = \rho c_p u^* \theta^*$	$Q_L = \rho L_v u^* q^*$
• Bulk flux form Based on variables easily measured	$\tau = \rho C_D U^2$	$Q_h = \rho c_p C_H U(\theta - SST)$	$Q_L = \rho L_v C_E U(q - SSQ)$ SSQ= $q_s(SST)$

Main iteration loop of Large and Yeager 2004, 2009

Neutral drag coefficients at 10m empirically defined (Large and Pond, Large and Yeager)

$$1000\ C_D = \frac{2.70(m/s)}{U_N(10m)} + .142 + \frac{U_N(10m)}{13.09(m/s)} \qquad (6a)$$

$$1000\ C_E = 34.6\ \sqrt{C_D} \qquad (6b)$$

$$1000\ C_H = 18.0\ \sqrt{C_D}\,, \qquad stable\ \ \zeta > 0 \qquad (6c)$$

$$= 32.7\ \sqrt{C_D}\,, \qquad unstable\ \ \zeta \leq 0 \qquad (6d)$$

Step 1. Define turbulent scales u* etc using neutral coefficients and bulk variables

$$u^* = \sqrt{\rho_a^{-1}\ |\vec{\tau}|} = \sqrt{C_D}\ |\Delta\vec{U}| \qquad (7a)$$

$$t^* = \frac{Q_H}{\rho_a\ c_p\ u^*} = \frac{C_H}{\sqrt{C_D}}\ [\theta(z_\theta) - SST] \qquad (7b)$$

$$q^* = \frac{E}{\rho_a u^*} = \frac{C_E}{\sqrt{C_D}}\ [q(z_q)\ -\ q_{sat}(q_1, q_2, SST)] \qquad (7c)$$

Step 2a. Get initial guess of zeta=z/L

$$\zeta(z) = \frac{\kappa\ g\ z}{u^{*2}}\left[\frac{t^*}{\theta_v} + \frac{q^*}{(q(z_q) + 0.608^{-1})}\right] \qquad (8a)$$

Step 2b. Get empirical functions PSIM(zeta), PSIH(zeta) etc

$$U(z) = Uo + \frac{u*}{\kappa}\left\{ln\frac{z}{z_0} - \psi_m\right\} \qquad \theta(z) = SST + \frac{\theta*}{\kappa}\left\{ln\frac{z}{z_\theta} - \psi_h\right\} \qquad q(z) = SSQ + \frac{q*}{\kappa}\left\{ln\frac{z}{z_q} - \psi_h\right\}$$

Step 3. Shift wind to 10m and neutral stability, temp and humidity to wind height

$$U_N(10m) = |\Delta\vec{U}|\ \left(1 + \frac{\sqrt{C_D}}{\kappa}[ln(z_u/10m) - \psi_m(\zeta_u)]\ \right)^{-1} \qquad (9a)$$

$$\theta(z_u) = \theta(z_\theta) - \frac{\theta^*}{\kappa}\ [ln(\frac{z_\theta}{z_u}) + \psi_h(\zeta_u) - \psi_h(\zeta_\theta)] \qquad (9b)$$

$$q(z_u) = q(z_q) - \frac{q^*}{\kappa}\ [ln(\frac{z_q}{z_u}) + \psi_h(\zeta_u) - \psi_h(\zeta_q)]\ . \qquad (9c)$$

Step 4. Get new neutral coefficients from (6) then shift to measurement height and stability

$$C_D(z_u, \zeta) = C_D\left(1 + \frac{\sqrt{C_D}}{\kappa}\ [ln(z_u/10m) - \psi_m(\zeta_u)]\right)^{-2} \qquad (10a)$$

$$C_H(z_u, \zeta) = C_H\sqrt{\frac{C_D(z_u, \zeta)}{C_D}}\left(1 + \frac{C_H}{\kappa\sqrt{C_D}}\ [ln(z_u/10m) - \psi_h(\zeta_u)]\right)^{-1} \qquad (10b)$$

$$C_E(z_u, \zeta) = C_E\sqrt{\frac{C_D(z_u, \zeta)}{C_D}}\left(1 + \frac{C_E}{\kappa\sqrt{C_D}}\ [ln(z_u/10m) - \psi_h(\zeta_u)]\right)^{-1} \qquad (10c)$$

Step 5. Use the new coefficients in (10) to compute new turbulent scales in (7). Then go back to step 2

Alternative Flux schemes

- COARE (Fairall et al. 1996, 2003, Edson et al. 2013)
- ECMWF (Beljaars 1995, 1997)
- WRF (Zhang and Anthes 1982,
- All Iterate on roughness length
- They include “cool skin” and diurnal warm layer
- All use standard stability profiles (PSIM,PSIH etc.) based on field measurements (e.g. Businger-Dyer) but differ in other aspects

Relationship of roughness length and drag coefficient

$$z_0 = 10exp\left(\frac{-\kappa}{\sqrt{C_{Dn}}}\right)$$

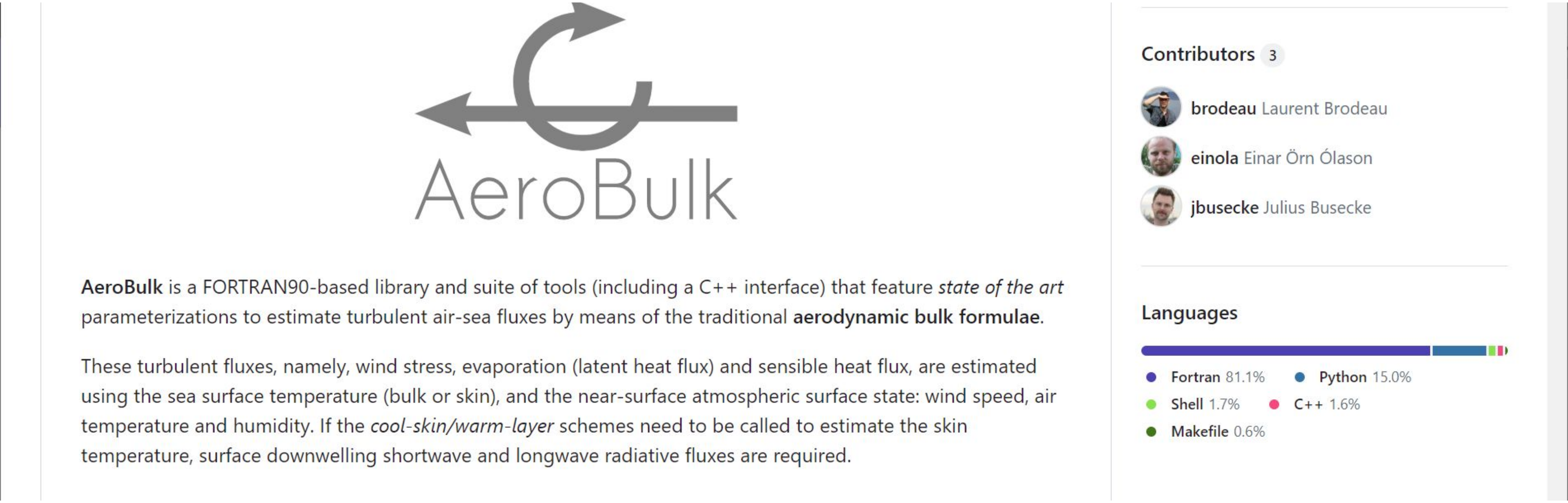
Roughness length a function of wind speed or wave state via Charnock coefficient

$$z_0^{\mathrm{rough}} = \alpha \frac{u_*^2}{g}, \qquad (8)$$

where α is Charnock coefficient, and g is the gravita-

Skin temperature question/diurnal cycle

Github library of flux routines by L. Brodeau and collaborators



AeroBulk

AeroBulk is a FORTRAN90-based library and suite of tools (including a C++ interface) that feature *state of the art* parameterizations to estimate turbulent air-sea fluxes by means of the traditional **aerodynamic bulk formulae**.

These turbulent fluxes, namely, wind stress, evaporation (latent heat flux) and sensible heat flux, are estimated using the sea surface temperature (bulk or skin), and the near-surface atmospheric surface state: wind speed, air temperature and humidity. If the *cool-skin/warm-layer* schemes need to be called to estimate the skin temperature, surface downwelling shortwave and longwave radiative fluxes are required.

Contributors 3

- **brodeau** Laurent Brodeau
- **einola** Einar Örn Ólason
- **jbusecke** Julius Busecke

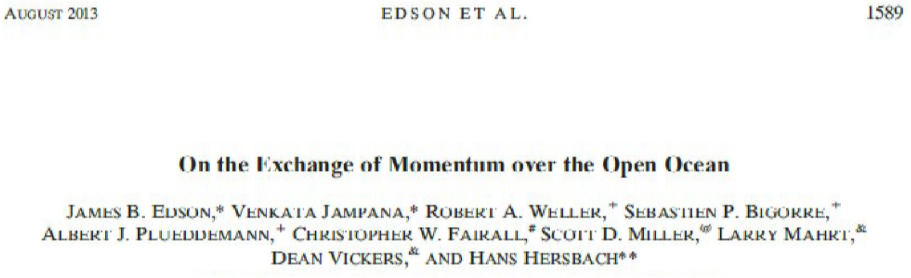
Languages

- ● **Fortran** 81.1%
- ● **Python** 15.0%
- ● **Shell** 1.7%
- ● **C++** 1.6%
- ● **Makefile** 0.6%

Currently, in AeroBulk, 5 bulk parameterizations are available to compute C_D, C_E, and C_H used in the bulk formula:

- COARE v3.0 (Fairall *et al.*, 2003)
- COARE v3.6 (Edson *et al.*, 2013 + Chris Fairall, *private communication*, 2016)
- ECMWF (IFS (Cy40) documentation)
- ANDREAS (Andreas *et al.*, 2015)
- NCAR (Large & Yeager 2004, 2009)

Role of surface waves



AUGUST 2013 EDSON ET AL. 1589

On the Exchange of Momentum over the Open Ocean

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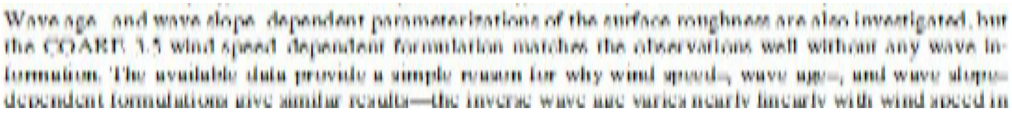
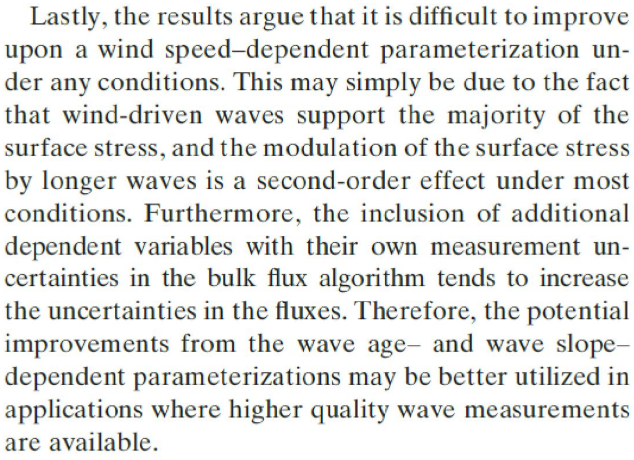
DEAN VICKERS,& AND HANS HERSBACH**



Wave age– and wave slope–dependent parameterizations of the surface roughness are also investigated, but the COARE 3.5 wind speed dependent formulation matches the observations well without any wave information. The available data provide a simple reason for why wind speed–, wave age–, and wave slope–dependent formulations give similar results—the inverse wave age varies nearly linearly with wind speed in



Lastly, the results argue that it is difficult to improve upon a wind speed–dependent parameterization under any conditions. This may simply be due to the fact that wind-driven waves support the majority of the surface stress, and the modulation of the surface stress by longer waves is a second-order effect under most conditions. Furthermore, the inclusion of additional dependent variables with their own measurement uncertainties in the bulk flux algorithm tends to increase the uncertainties in the fluxes. Therefore, the potential improvements from the wave age– and wave slope–dependent parameterizations may be better utilized in applications where higher quality wave measurements are available.

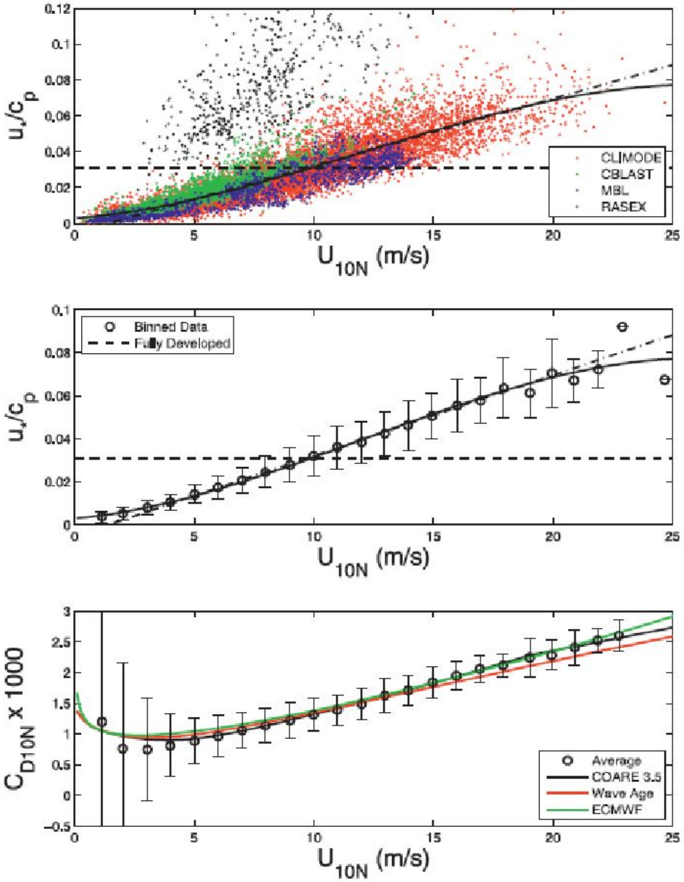
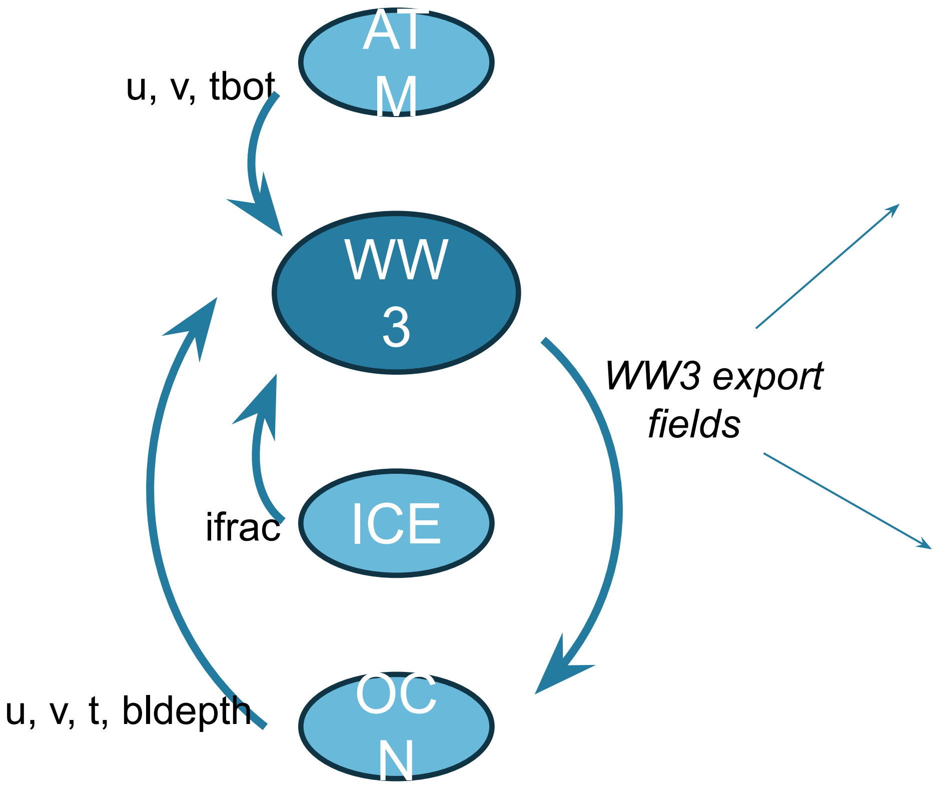


FIG. 9. Inverse wave age plotted vs relative wind speed. (top) The individual data from each experiment, and (middle) the data averaged over wind speed bins. The RASEX data are not included in this average. The dashed black line represents the inverse wave age commonly associated with fully developed seas. The dashed–dotted line is a linear fit to the averaged data, while the solid line is a third-order fit. (bottom) As in Fig. 6, but with the addition of the green line representing the function derived by ECMWF as given by (20), and the red line that combines the third-order fit with (15).

WW3 Coupling in CESM



Legacy Coupling:

- Langmuir multiplier (lamult) passed to OCN and used within CVMix to enhance KPP mixing.

New Coupling:

- A number of stokes drift bands passed to OCN for WAB eqn computations that modifies MOM6 momentum eqn. A newer KPP mixing enhancement parameterization is also being developed.

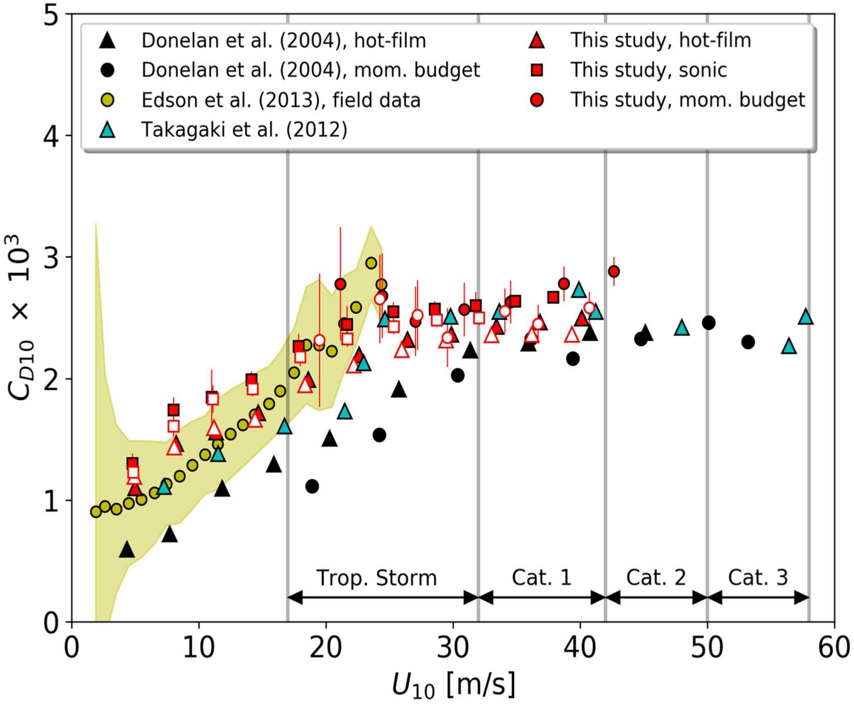
Extreme wind speed regime

- Important especially for high-resolution models
  - Is drag coefficient capped or reduced at high wind speeds?
- Surface waves are very important here
  - Misalignment of stress and wind vectors, wind and wave

- Temporal averaging for turbulent statistics ?

Uncertainty in drag coefficient at high winds

Laboratory experiments



From dropsonde data

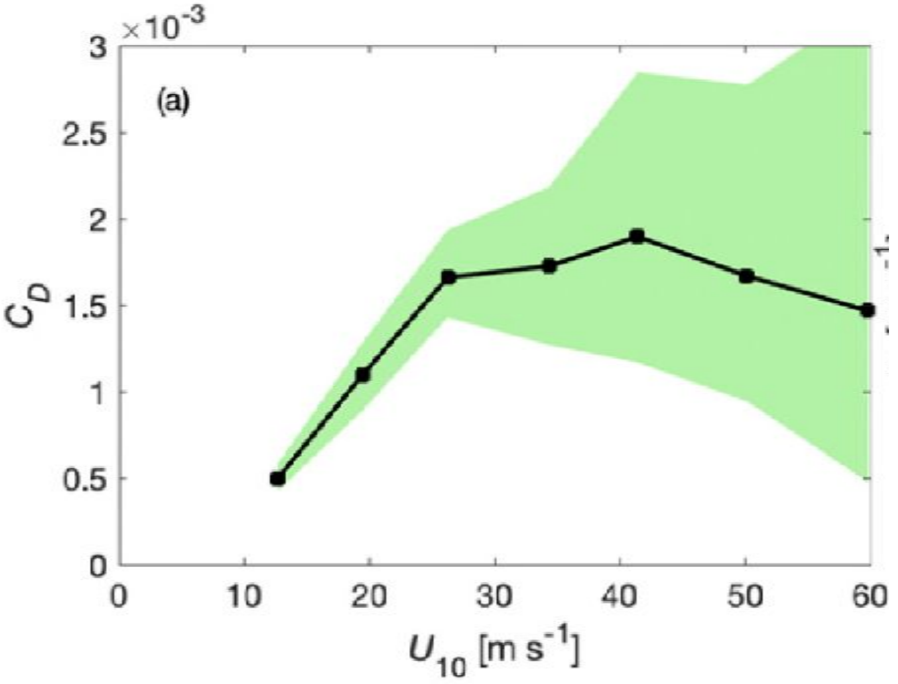


FIG. 6. (a) The black squares show C_D calculated as in Fig. 2a, and the shading represents the variability in C_D when performing 20 repeated tests of randomly subdividing the sonde database into thirds. (b) As in (a), but for u_*.

Curcic and Haus, 2020, Revised Estimates of Ocean Surface Drag in Strong Winds. GRL https://doi.org/10.1029/2020GL087647

Richter et al. 2021. Potential Low Bias in High-Wind Drag Coefficient Inferred from Dropsonde Data in Hurricanes. JAS, https://doi.org/10.1175/JAS-D-20-0390.1