Stokes drift and wind drift in a rotating equilibrium sea*

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* Samelson and Zippel, 2026. JPO, doi: 10.1175/JPO-D-25-0198.1.

Context: Wind and wave drift

- Wind and wave drift currents in upper few meters of water column, with surface (upper meter) velocities up to 0.1-0.3 m s^{-1} (10-30 km day^{-1}), ubiquitous across global ocean.
- Speeds (upper meter) comparable to mid-ocean mesoscale geostrophic surface currents.
- Various rules of thumb (1%-3% of wind speed, 15^o right of wind in NH; linear regressions on wind for specific datasets; etc.) for surface or near-surface wind drift but no broadly accepted quantitative description or physical understanding.
- No standard model of neutral near-surface (upper few meters) ocean boundary layer [e.g., analogous to the standard model of neutral near-surface neutral atmospheric boundary layer that has existed for decades and is the foundation of bulk aerodynamic flux schemes such as COARE 3.5].
- Risk reduction for satellite Doppler scatterometer mission planning.
- Quantitative characterization and physical understanding of near-surface ocean response to vector wind forcing.

Background: Equilibrium-sea wind drift*

Starting point: In a statistically homogeneous, stationary equilibrium sea under neutral stability conditions, the profile of mean water motion in the upper few meters of the water column should be a unique function of wind speed (and latitude).

This function would be the near-surface, ocean equivalent of the standard model of the near-surface neutral atmospheric boundary layer.

Samelson (2022)* proposed a candidate standard model for the near-surface, neutral ocean boundary layer and this mean near-surface drift.

The proposed model uses a novel wave-averaged mean drift velocity [mass-weighted, surface-conforming Eulerian mean] that includes the equilibrium wind-sea wave (Stokes) drift.

*Samelson, 2022. JPO, doi: 10.1175/JPO-D-22-0017.1.

Recent results – motivation and approach

Samelson (2022) candidate standard model:

- What part of the wind drift is carried as wave (Stokes) drift?
- Equilibrium-sea model (Samelson 2022): Diffusive vertical momentum transport. (Law-of-the-wall mixing-length eddy viscosity with empirical ocean roughness length and wave-effect parameters dependent on neutral 10-m wind speed; wave-breaking turbulence interpretation for large roughness lengths at high wind speeds.)
- In the presence of waves, would it be more physically consistent to include a body force?
- What is the wave-drift momentum balance?
- Can an evolution equation be formulated for Stokes drift forcing in simulations of Langmuir circulation?

To address these questions, Samelson and Zippel (2026)* revisited the Samelson (2022) model, developing an explicit mean momentum balance for equilibrium-sea wind-waves.

*Samelson and Zippel, 2026. JPO, doi: 10.1175/JPO-D-25-0198.1.

Recent results*

- Equilibrium-sea wave-drift:

  Dynamic wave drift driven by mean wave-correlated pressure forcing

- Total equilibrium-sea wind and wind-wave drift:

  Dynamic wave drift driven by mean wave-correlated pressure forcing

  +

  Wind drift driven by viscous fraction of wind stress and wave-breaking force.

- New proposed wave-averaged turbulence equations for modeling upper ocean dynamics and Langmuir circulations.

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Rotating equilibrium sea: wind-wave drift

$$\boxed{-fV_{Sd} = \overline{-\frac{1}{\rho_0}\frac{\partial p'_p}{\partial x}} - \Gamma_{eq}U_{Sd}, \quad fU_{Sd} = -\Gamma_{eq}V_{Sd}}$$

Equilibrium-sea (Phillips 1985) condition: mean rates of wave growth and wave-breaking momentum loss are equal.

Similar to Hasselmann (1970) picture but…:

The equilibrium-sea wave momentum balance is forced-damped (and stationary) rather than inviscid-unforced (and time-dependent); i.e., there is an explicit, non-trivial momentum balance for the waves.

The mean wave momentum balance is consistently calculated using a mass-weighted, surface-conforming Eulerian mean rather than a reconstituted mixture of Eulerian and Lagrangian representations.

Two different Stokes (wave) drifts are defined:

Kinematic Stokes drift (Stokes 1847), $U_S(z) = \sigma k a^2 e^{2kz}$,
which here appears in wave-correlated pressure forcing and breaking, not wave drift, but remains directed downwind.

Dynamic Stokes drift, $\mathbf{U}_{Sd} = U_S \cos\gamma_{eq}(\cos\gamma_{eq}, -\sin\gamma_{eq}), \quad \gamma_{eq} = \arctan\left(\frac{f}{\Gamma_{eq}}\right) = \arctan(fT_{eq})$,

which is the rectified wave drift driven by the mean wave-correlated pressure and rotates away from downwind.

Monochromatic and spectral (Phillips 1985) representations of the equilibrium wind-sea are both considered.

Rotating equilibrium-sea: wind + wave drift

Formulation: Mean rate of wave-breaking loss of momentum enters mean drift balance as component of forcing.

"Wave-forced wind drift": Mean drift $\mathbf{W}=(U,V)$ forced by

{viscous wind-stress fraction} $(1-b_0)\,\tau_0$ + {wave-breaking body force} $\mathbf{F}_{br}(z)$.

The total wind + wave drift: Sum $\mathbf{W} + \mathbf{U}_{Sd}$ of wave-forced wind drift $\mathbf{W}=(U,V)$ and dynamic Stokes drift $\mathbf{U}_{Sd}$.

W:

$$\boxed{\begin{aligned} -fV &= \frac{d}{dz}\left[\phi_w \kappa u_*(z_0 - z)\frac{dU}{dz}\right] + F^x_{br}(z) \\ fU &= \frac{d}{dz}\left[\phi_w \kappa u_*(z_0 - z)\frac{dV}{dz}\right] + F^y_{br}(z) \end{aligned}}$$

$\mathbf{U}_{sd}$:

$$\boxed{-fV_{Sd} = \overline{-\frac{1}{\rho_0}\frac{\partial p'_p}{\partial x}} - \Gamma_{eq}U_{Sd}, \quad fU_{Sd} = -\Gamma_{eq}V_{Sd}}$$

$\mathbf{F}_{br}$:

$$\boxed{\mathbf{F}_{br}(z) = -\tau_{br}(z) = \Gamma_{eq}\mathbf{U}_{Sd}}$$

New wave-averaged turbulence equations

$$\mathbf{u}: \quad \boxed{\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} + f\hat{\mathbf{z}}\times\mathbf{u} = -\frac{1}{\rho_0}\nabla p - g\frac{\rho'}{\rho_0}\hat{\mathbf{z}} + D(\mathbf{u}) + \underline{\mathbf{U}_S}\times(\nabla\times\mathbf{u}) + \underline{\mathbf{F}_{br}}}$$

$$\mathbf{F}_{br}: \quad \boxed{\mathbf{F}_{br}(z) = -\tau_{br}(z) = \Gamma_{eq}\mathbf{U}_{Sd}}$$

These equations are forced at the surface by the viscous wind-stress fraction $(1\text{-}b_0)\ \tau_0$ and in the interior by the wave-breaking body force $\mathbf{F}_{br}$, and are supplemented by the mean dynamic drift momentum balance:

$$\mathbf{U}_{sd}: \quad \boxed{-fV_{Sd} = \overline{-\frac{1}{\rho_0}\frac{\partial p'_p}{\partial x}} - \Gamma_{eq}U_{Sd}, \quad fU_{Sd} = -\Gamma_{eq}V_{Sd}}$$

which gives:

$$\mathbf{U}_{sd}: \qquad \mathbf{U}_{Sd} = U_S\cos\gamma_{eq}(\cos\gamma_{eq}, -\sin\gamma_{eq}), \quad \gamma_{eq} = \arctan\left(\frac{f}{\Gamma_{eq}}\right) = \arctan(fT_{eq})$$

New wave-averaged turbulence equations

Monochromatic and spectral representations of the equilibrium wind-sea

Monochromatic:

$$\underline{U_S(z)} = \sigma k a^2 e^{2kz} \qquad T_{eq} = \frac{1}{\Gamma_{eq}} = \frac{\rho_0 g \overline{\zeta^2}}{b_0 c \tau_0}$$

$$\underline{\mathbf{F}_{br}(z)} = -\tau_{br}(z) = \underline{\Gamma_{eq}\mathbf{U}_{Sd}}$$

$$\mathbf{U}_{Sd} = U_S \cos\gamma_{eq}(\cos\gamma_{eq}, -\sin\gamma_{eq}), \qquad \gamma_{eq} = \arctan\left(\frac{f}{\Gamma_{eq}}\right) = \arctan(fT_{eq})$$

Spectral (Phillips 1985):

$$\underline{\hat{U}_S(z;k)} = 2\,\sigma\,k\,\Psi(k)e^{2kz} = 2\,\beta\,I(p)\,v_*\,k^{-2}e^{2kz}, \qquad \Gamma_{eq} \to \Gamma_k = 1/T_k$$

$$\underline{\mathbf{F}_{br}(z)} = -\tau_{br}(z) = \int_{k_0}^{k_1} \underline{\Gamma_k \hat{\mathbf{U}}_{Sd}}(z;k)\,k\,dk = \int_{k_0}^{k_1} \frac{1}{T_k}\hat{\mathbf{U}}_{Sd}(z;k)\,k\,dk$$

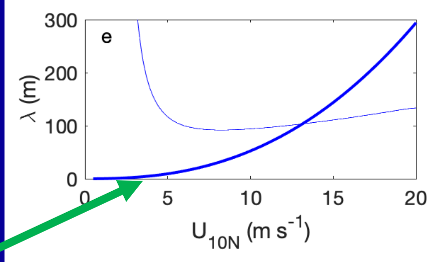
$$\bar{\mathbf{U}}_{Sd}(z) = \int_{k_0}^{k_1} \hat{\mathbf{U}}_{Sd}(z;k)\,k\,dk = 2\ \beta\,I(p)\,v_* \int_{k_0}^{k_1} k^{-1}\cos\gamma_k\,e^{2kz}\,(\cos\gamma_k, -\sin\gamma_k)\,dk$$

$$\gamma_k = \arctan(fT_k) = \arctan(25 f\,v_*^{-2} g^{1/2} k^{-3/2})$$

$\Gamma_k = \beta_k$ for wave growth rate β_k from Plant (1982)

Results: Monochromatic dynamic wave (Stokes) drift

$$\mathbf{U}_{Sd} = U_S \cos\gamma_{eq}(\cos\gamma_{eq}, -\sin\gamma_{eq}), \quad \gamma_{eq} = \arctan\left(\frac{f}{\Gamma_{eq}}\right) = \arctan(fT_{eq})$$

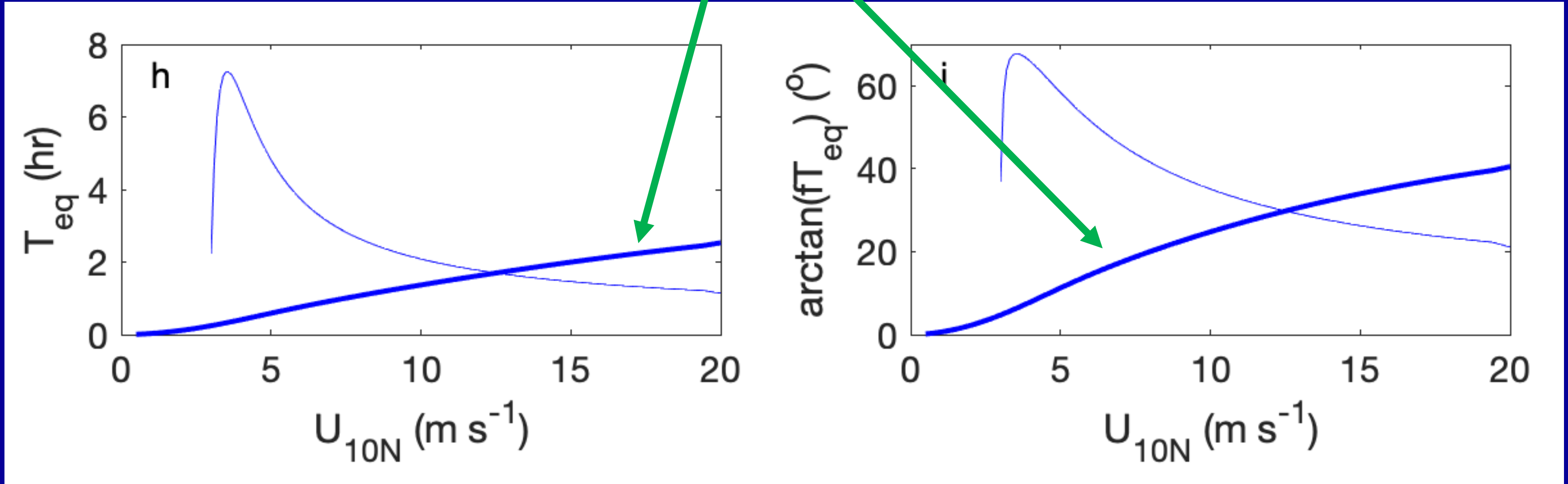


Monochromatic waves at Resio et al. (1999) peak wavelength

$$\boxed{T_{eq} = \frac{1}{\Gamma_{eq}} = \frac{\rho_0 g\overline{\zeta^2}}{b_0 c \tau_0}}$$

Equilibrium-sea timescale (hr)

Angle clockwise from downwind (40 °N)

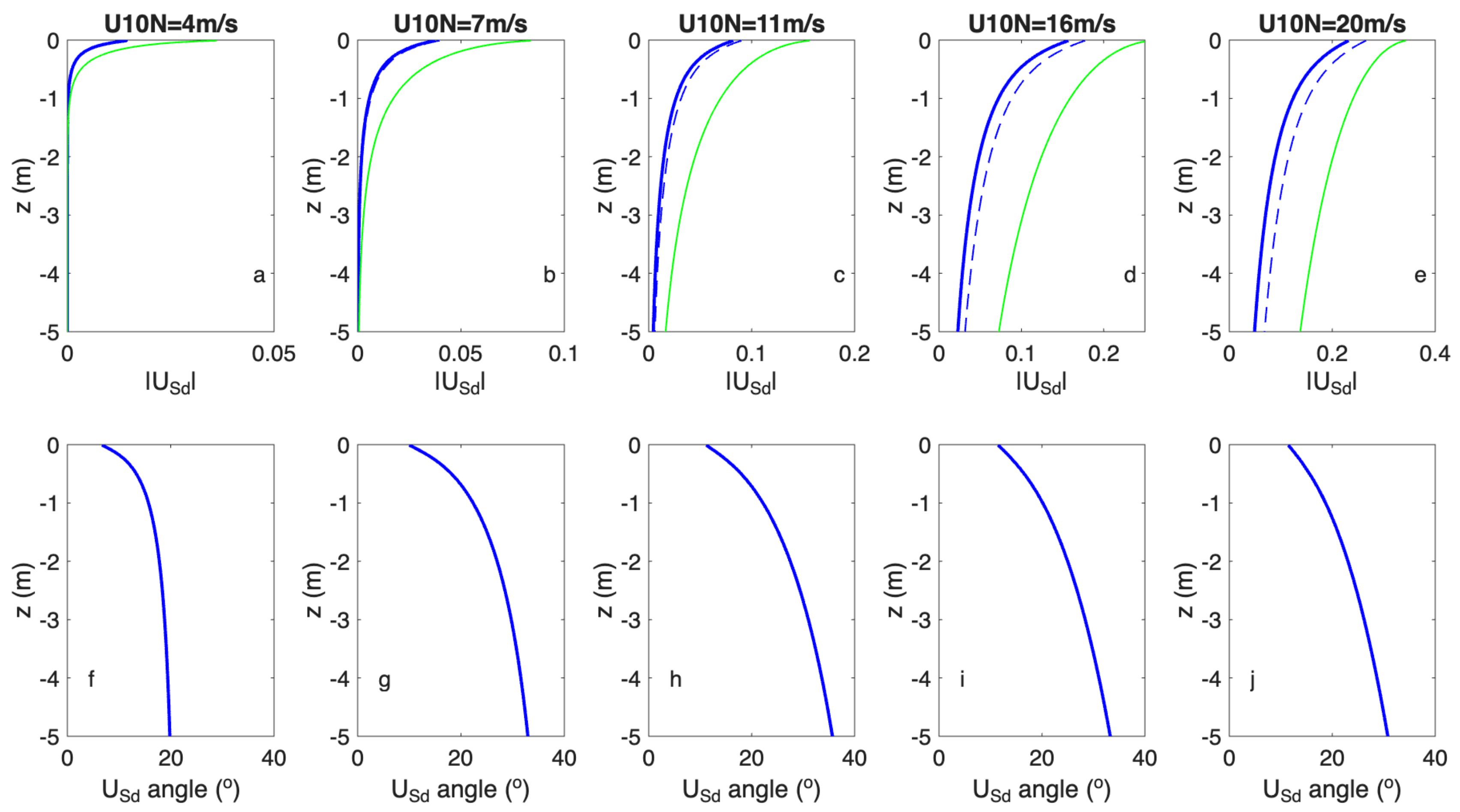


Results: Spectral dynamic wave (Stokes) drift

Phillips (1985) σ^{-4} equilibrium spectrum with Resio et al. (1999) peak wavelength

Drift magnitude (m s^{-1})

Angle clockwise from downwind (40° N)



Green: Breivik et al. (2016), using Phillips (1958) σ^{-5} spectrum

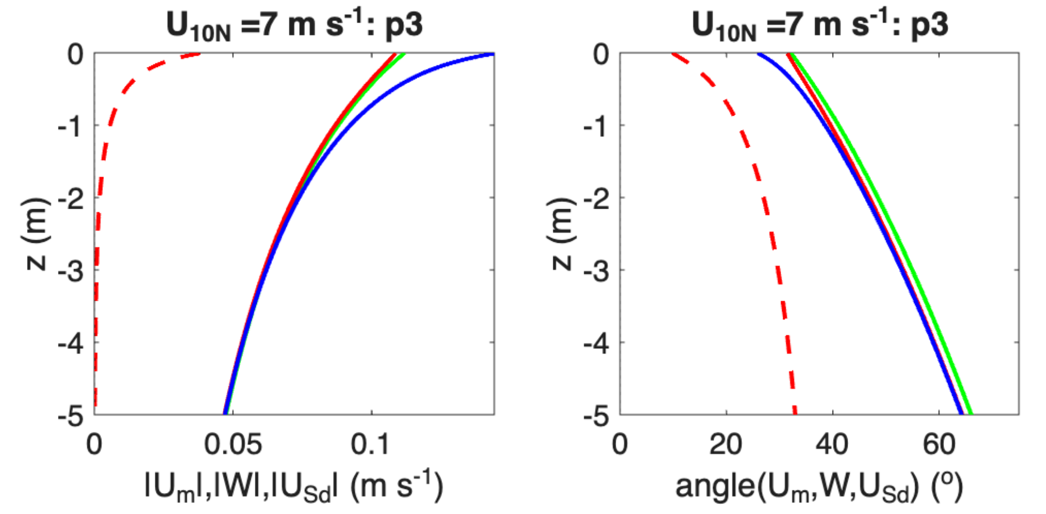
Dynamic drift (40° N) : solid blue line
Kinematic drift (no rotation): dashed blue line (upper panels only)

Results: wind + spectral dynamic wave drift

P3 wind-drift model
(P5 wind + wave drift)

Total wind + wave drift: blue
Dynamic wave drift: red dashed
Wave-forced wind drift: red
Wind drift only ($b_0=0$): green

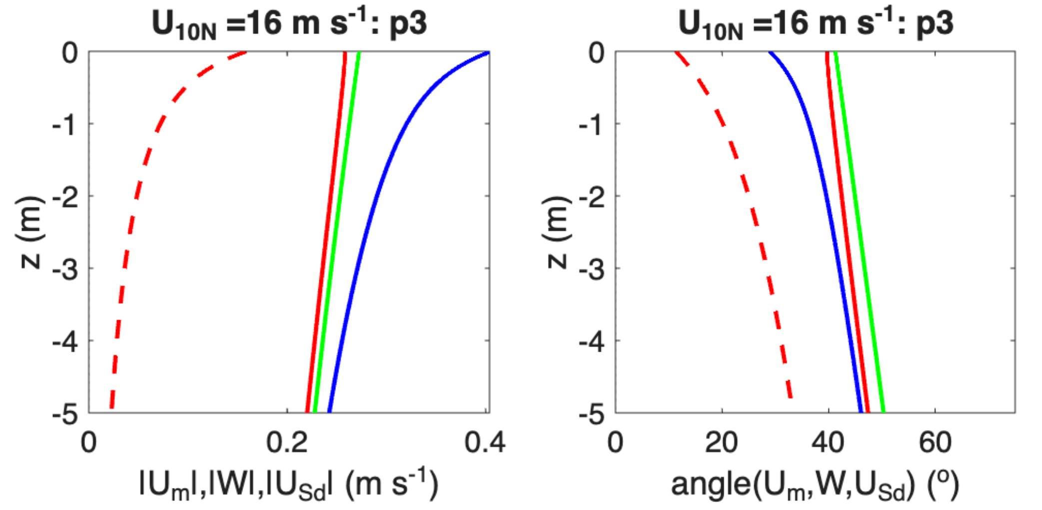
7 m s^{-1}



Drift magnitude (m s^{-1})

Angle clockwise from downwind (40 °N)

16 m s^{-1}

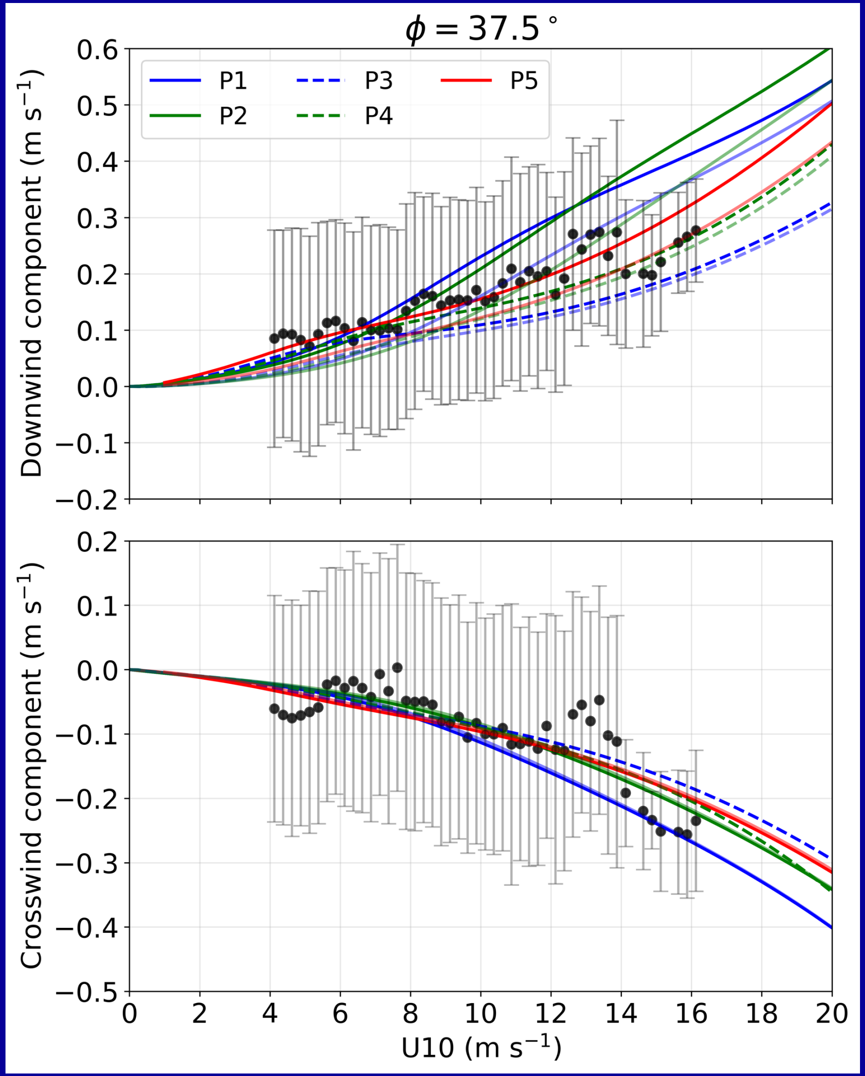


Drift magnitude (m s^{-1})

Angle clockwise from downwind (40 °N)

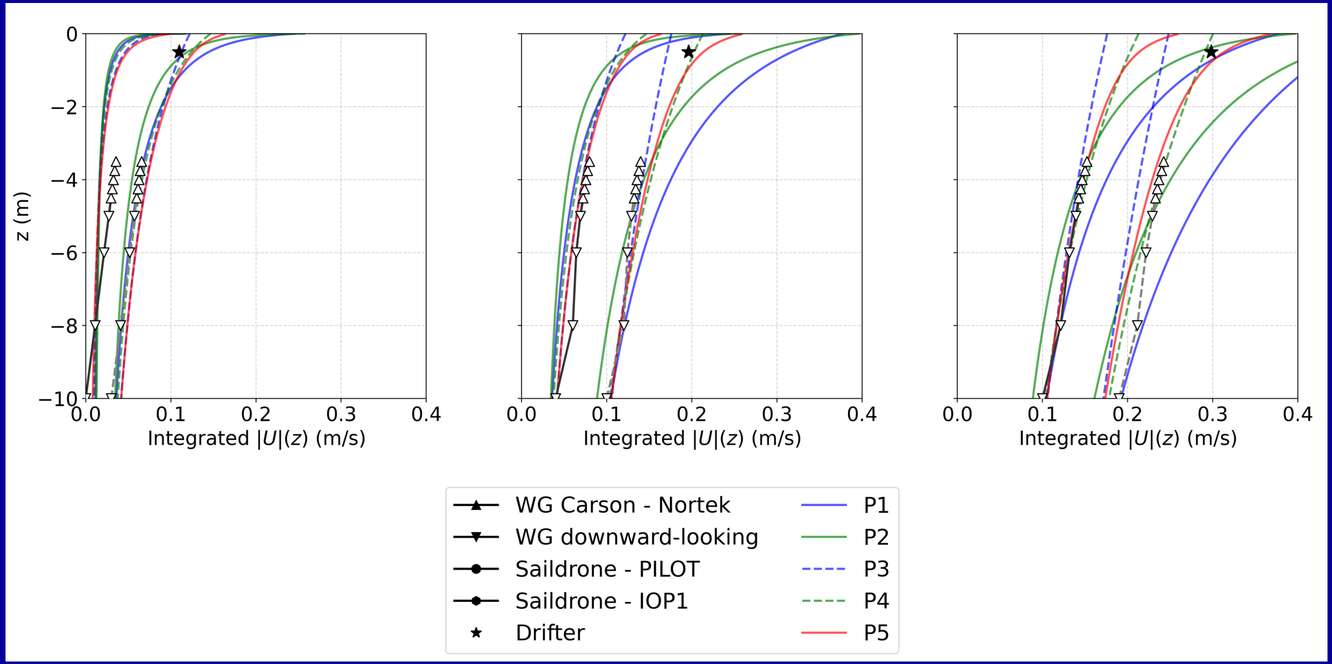
Comparison with S-MODE observations*

Surface drifters



Surface drifters and integrated WG ADCP vertical shear

4-8 m s^{-1} 8-12 m s^{-1} 12-15 m s^{-1}



Total wind + wave drift: red
Wind drift only (b_0=0): blue, green

*Leyba, Samelson, Farrar, Rocha, and Rodríguez. JAOT, submitted.

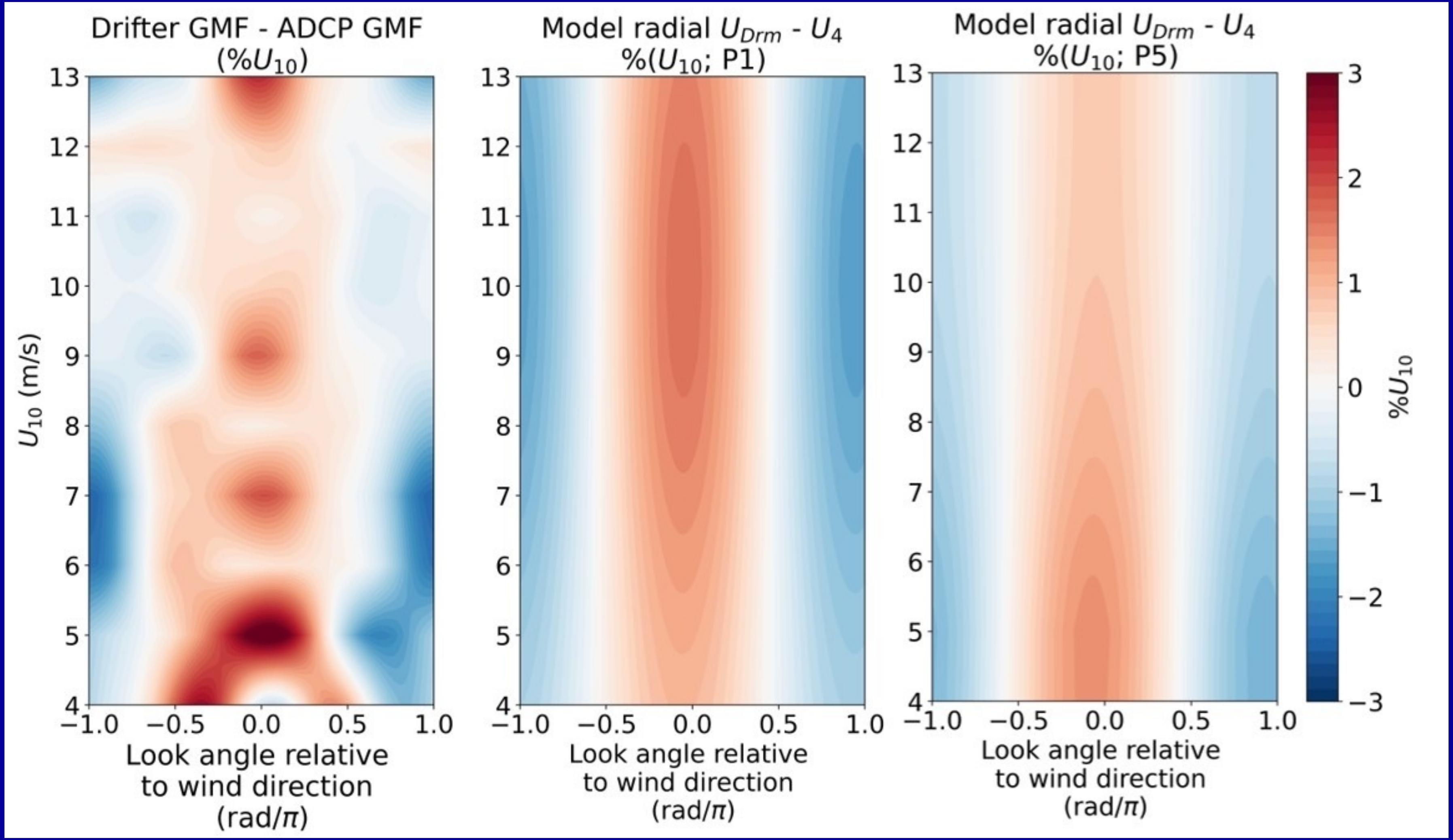
Comparison with S-MODE observations*

DopplerScatt "wind-drift" (GMF shear) estimate

Wind-drift model prediction

P1

P5



*Leyba, Samelson, Farrar, Rocha, and Rodríguez. JAOT, submitted.

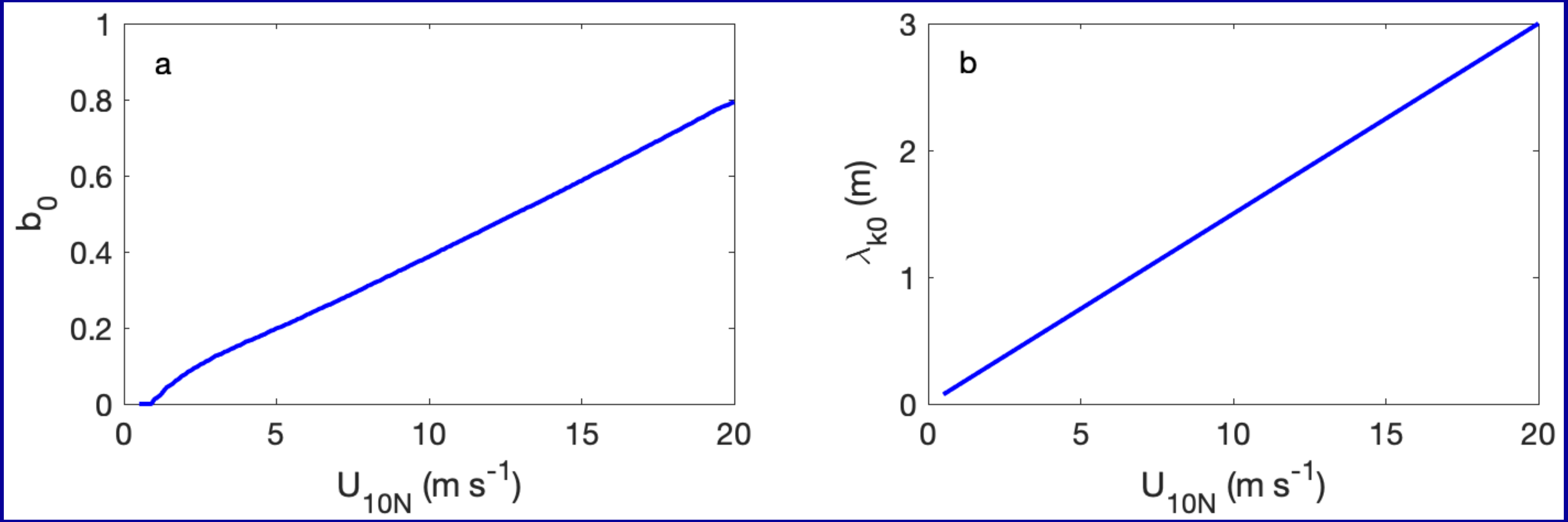
Results: pressure fraction of wind stress

Spectral (Phillips 1985) representation of equilibrium wind-sea

Wave-correlated pressure-forcing fraction of wind stress: $\tau_p = b_0\,\tau$

$$b_0 = \frac{\tau_p}{\tau}$$

Short-wave cut-off $\lambda_{k0} = 2\pi/k_0$

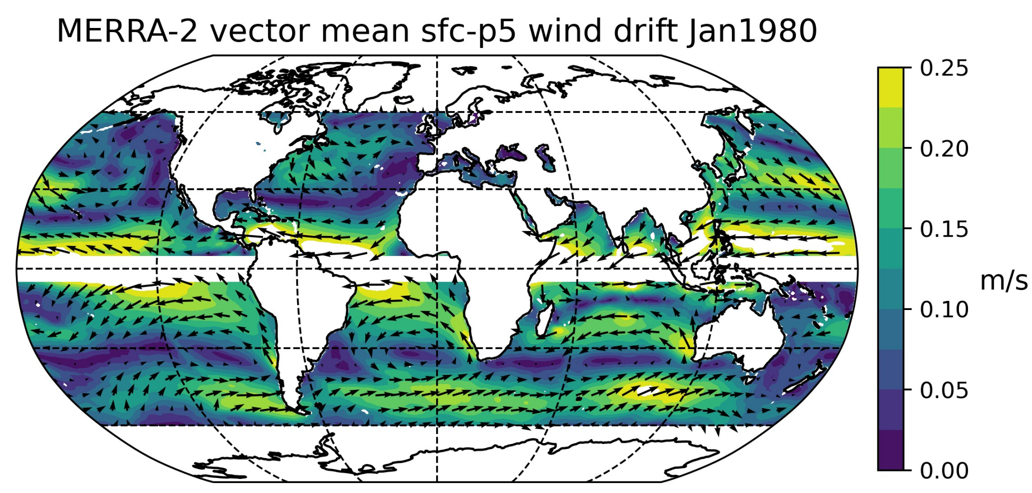


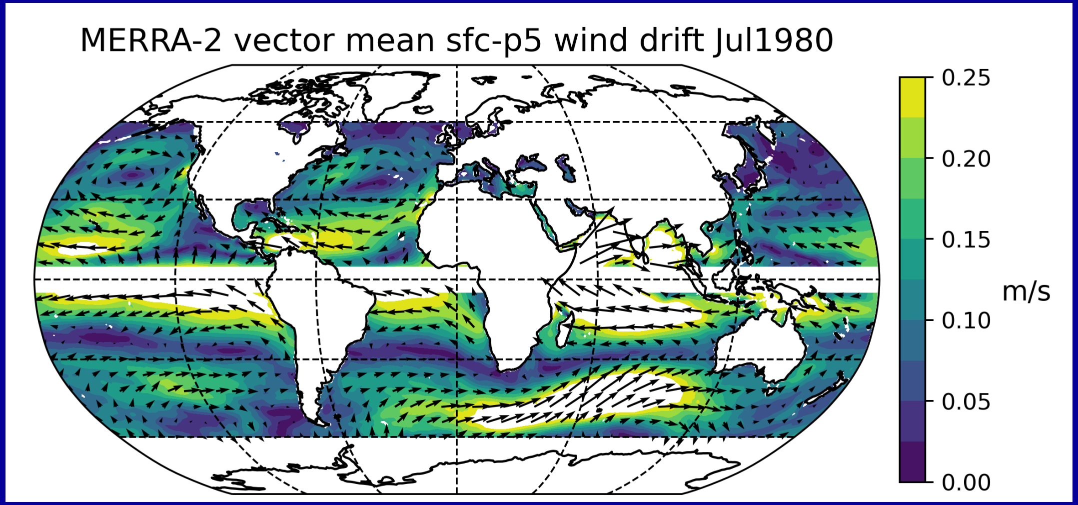
MERRA-2 reanalysis winds: model-predicted drift

January 1980

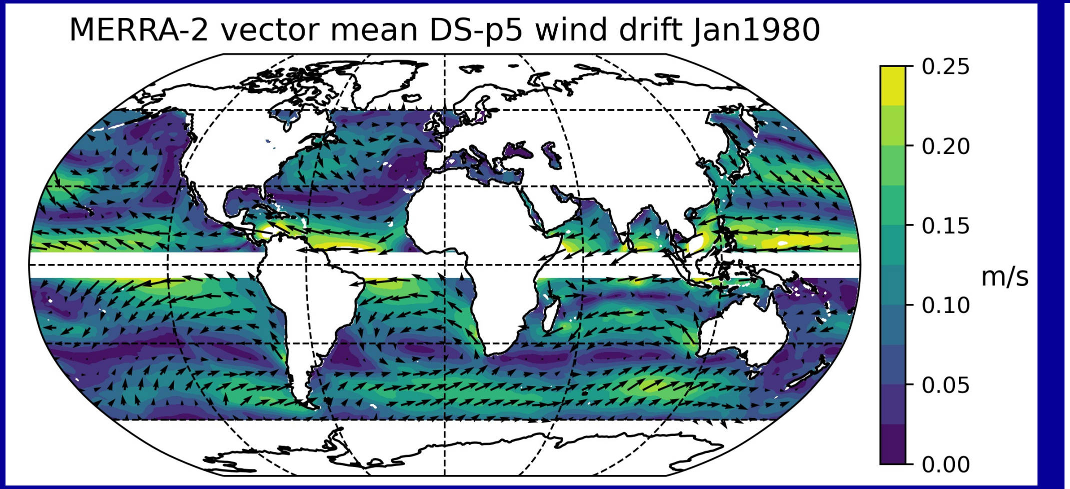
July 1980

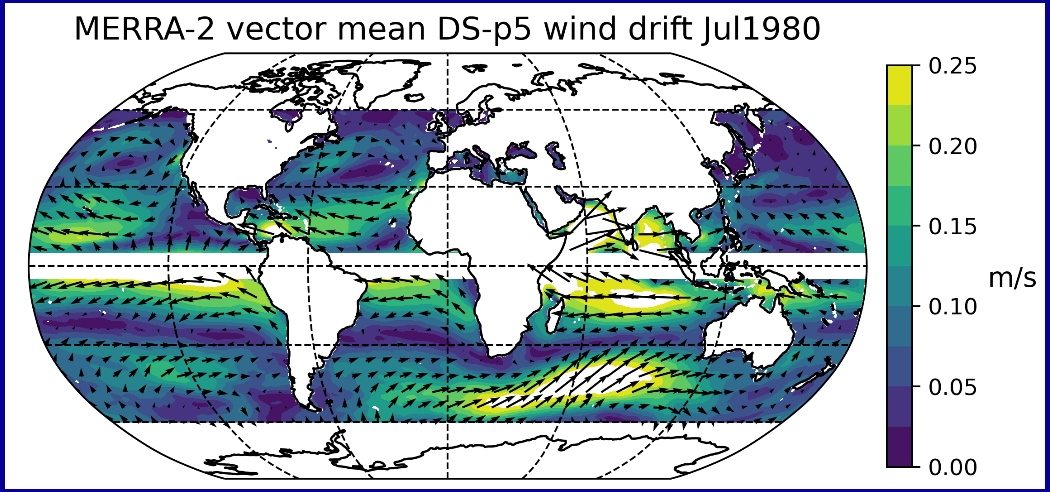
Surface


MERRA-2 vector mean sfc-p5 wind drift Jan1980


MERRA-2 vector mean sfc-p5 wind drift Jul1980

0-1.6 m depth mean


MERRA-2 vector mean DS-p5 wind drift Jan1980


MERRA-2 vector mean DS-p5 wind drift Jul1980

Summary*

- Equilibrium-sea wave-drift:
    - Dynamic wave drift driven by mean wave-correlated pressure forcing.
    - Dynamic wave-drift rotates, giving a “Stokes-Ekman” layer.
- Candidate standard model for neutral wind-forced near-surface ocean boundary layer:
  - Equilibrium-sea wind and wind-wave drift consisting of sum of…
    - Dynamic wave drift driven by mean wave-correlated pressure forcing

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      Wind drift driven by viscous fraction of wind stress and wave-breaking force.
- New proposed wave-averaged turbulence equations.
- Comparison with observations (calibration) in progress.

*Samelson and Zippel, 2026. JPO, doi: 10.1175/JPO-D-25-0198.1.

Open questions & future opportunities

- Exploration of new wave-averaged equations.
- Dynamic wave-drift: linear breaking force; swell; time-dependent forcing.
- Surface-referenced “true” drag coefficient [COARE3.5: 10-m ref. level].
- Candidate standard model as neutral near-surface limit of 1-d mixing models.
- Extended observational testing and calibration of candidate standard model for neutral wind-forced near-surface (upper few meters) ocean boundary layer and dynamic wave-drift theory.*

*Leyba, Samelson, Farrar, Rocha, and Rodríguez. JAOT, submitted.