Scale-Dependent, Episodic Pathways of Turbulent Air-Sea Kinetic Energy Transfer

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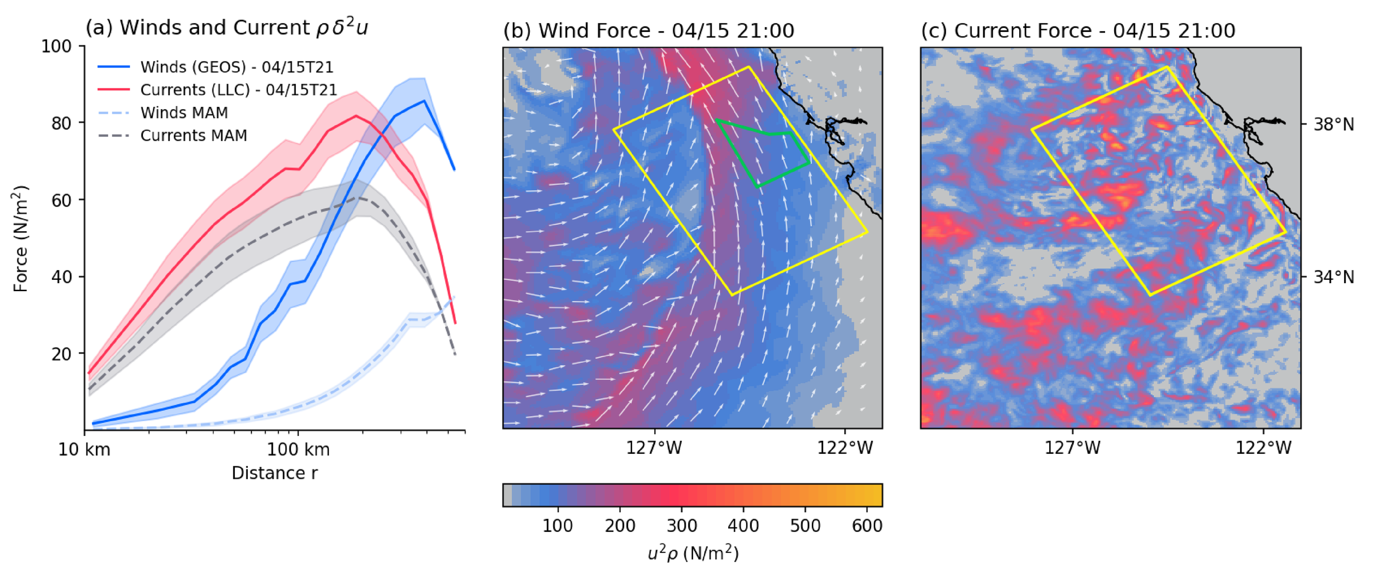
Objective

This workshop asks where km-scale resolution adds value — and how to measure success. Here: a scale-selective, bootstrapped kinetic-energy budget that turns coupled submesoscale variability into a testable metric — applied alike to NASA's COAS km-scale coupled simulation and to S-MODE airborne remote sensing.

Why air-sea coupling must be scale-dependent

The two boundary layers host opposite turbulent cascades: forward (downscale) in the atmosphere; inverse + forward around the ocean submesoscale. Weighted by density, submesoscale currents rival or exceed the overlying winds in kinetic energy — the sign of cross-interface work flips with scale (here near $r \approx 300$ km). Bulk-flux closures assume scale-independent exchange; km-scale models let us test what that hides.

Cascades differ in energization scale and slope — scale-dependent energy contrasts between atmosphere and ocean are inevitable, and the exchange can reverse direction with scale.



Density-weighted 2nd-order structure functions of BL wind (blue) and current (red); dashed: MAM climatology; shading: 95% CI. Maps: wind and current speed² (N m⁻²), 2020-04-15. Yellow box: budget region; green: S-MODE DopplerScatt region.

An exact, scale-selective KE budget from structure functions

Mass-weighted momentum balance of each Ekman layer (atm. & ocean):

$$\partial_t \hat{u}_\alpha + \hat{\mathcal{A}}_\alpha + \epsilon_{\alpha k l} f_k \hat{u}_l = -\nabla_\alpha \hat{\Phi}_k - \bar{m}_k^{-1}\tau_{k\alpha} + \dot{R}_\alpha$$

Increment operator at separation s:

$$\delta u_\alpha(x_j; s_j) = u_\alpha(x_j + s_j) - u_\alpha(x_j), \qquad \overline{(\cdot)} \;=\; \text{instantaneous field average}$$

Dot with δû, average — exact: no filtering, no commutation

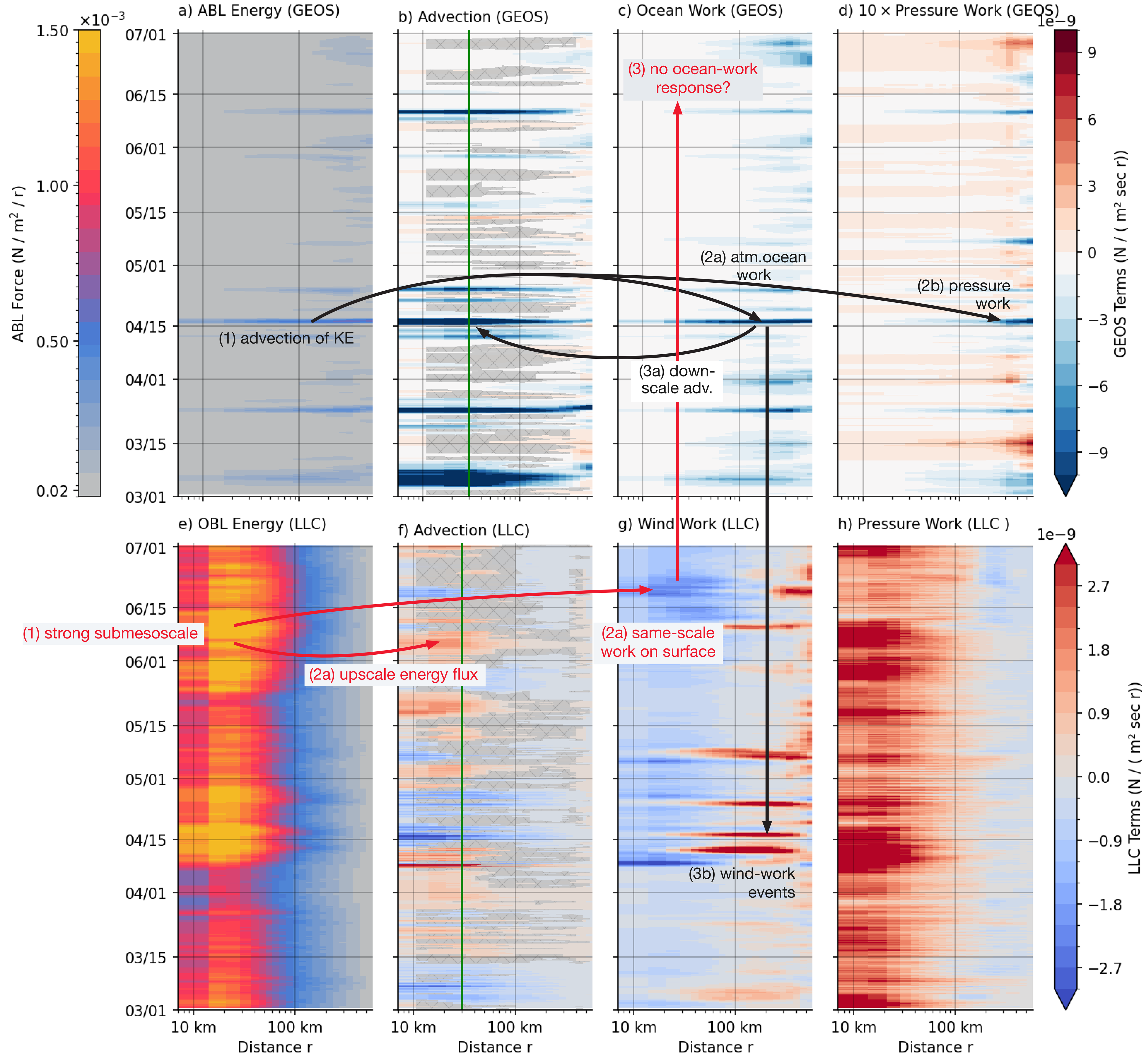
$$\underbrace{\overline{\delta\hat{u}_\alpha\,\delta\partial_t\hat{u}_\alpha}}_{\partial_t \mathrm{KE}} + \underbrace{\overline{\delta\hat{u}_\alpha\,\delta\hat{\mathcal{A}}_\alpha}}_{\text{cross-scale advection}} = \underbrace{-\overline{\delta\hat{u}_\alpha\,\delta\nabla_\alpha\hat{\Phi}_k}}_{\text{pressure work}} - \underbrace{\bar{m}_k^{-1}\,\overline{\delta\hat{u}_\alpha\,\delta\hat{\tau}_\alpha}}_{\text{wind / ocean work}} + \underbrace{\overline{\delta\hat{u}_\alpha\,\delta\dot{R}_\alpha}}_{\text{residual}}$$

Every term is bootstrapped to 5–95% confidence from hourly instantaneous fields with PyTurbo_SF — works on gappy, sparse, or asynchronous data.

Applied to NASA COAS (GEOS ~6-km atmosphere MITgcm LLC2160 ~4-km ocean; 14 months; California Current System) and to S-MODE IOP-2 DopplerScatt winds & currents (April 2023).

Two competing, episodic pathways of energy transfer

Coupled Boundary Layer Budget in the California Current Region



Scale-selective Ekman-layer budgets, Spring: atmosphere (GEOS, a–d) and ocean (LLC2160, e–h). (a,e) kinetic energy; (b,f) cross-scale advection (positive = upscale); (c) ocean work; (g) wind work; (d,h) pressure work (d ×10). Hatching: not significant (5–95%). Green line: 30-km scale used in the DopplerScatt comparison below right.

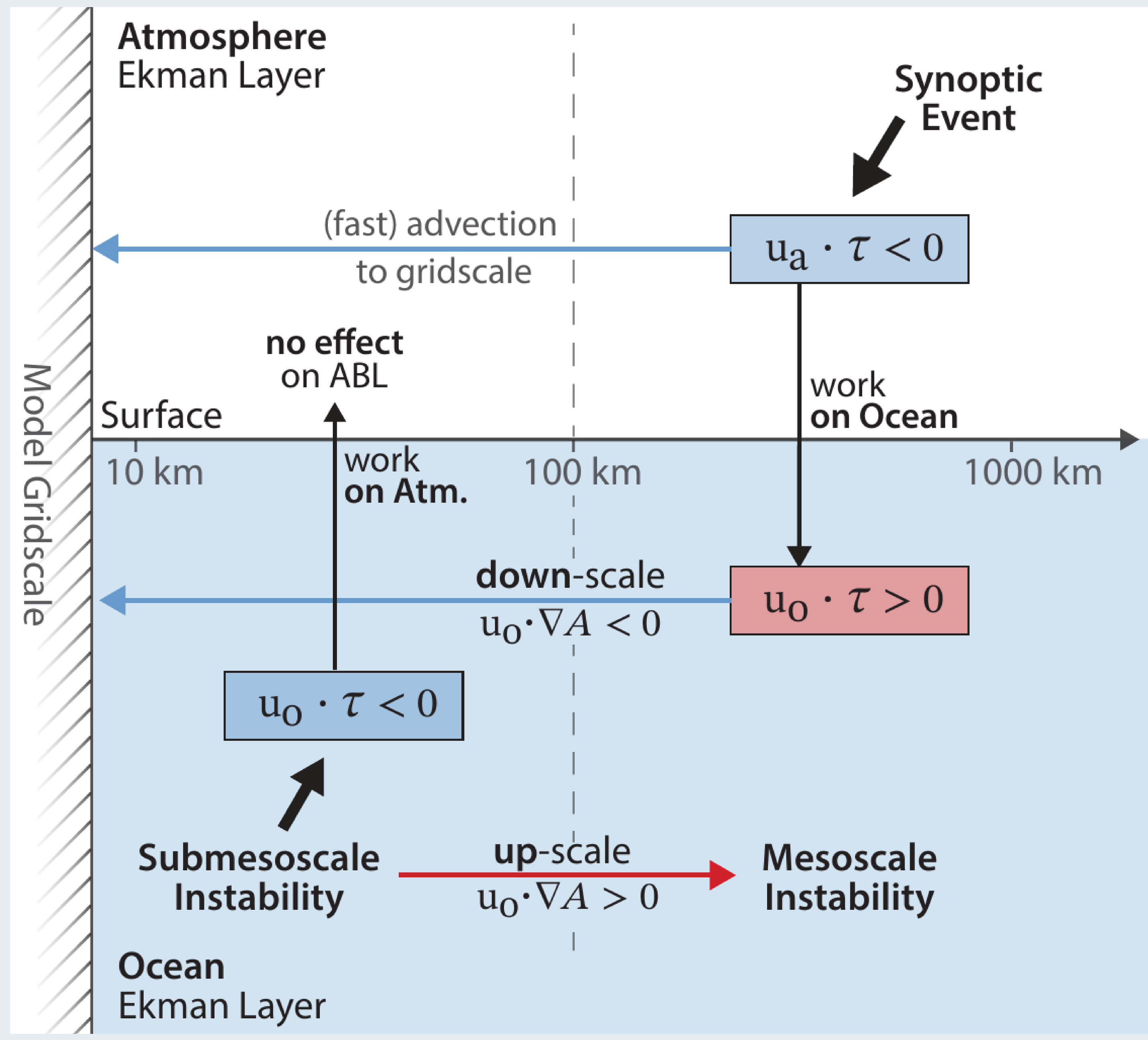
Synoptic events force the ocean from above Atmospheric fronts drive mesoscale ocean work and wind work (1–2-day events, 100–200 km). In energy cascades forward in both fluids — from ~200 km to the grid scale within a day. At $r > 50$ km wind work dominates the upper-ocean KE budget ("eddy-killing" regime).

Submesoscale instability pushes back from below Growing toward summer, submesoscale instability drives an inverse cascade to the mesoscale plus its own wind- and pressure-work signatures (10–100 km). Episodes of negative wind work return ocean KE to the surface — but excite no detectable response in the 6-km atmosphere (eddy viscosity limits its effective resolution).

In the 10–100 km band the two routes compete: cross-scale advection is episodic and bi-directional — its sign and strength are set event-by-event, beyond any single-pathway description.

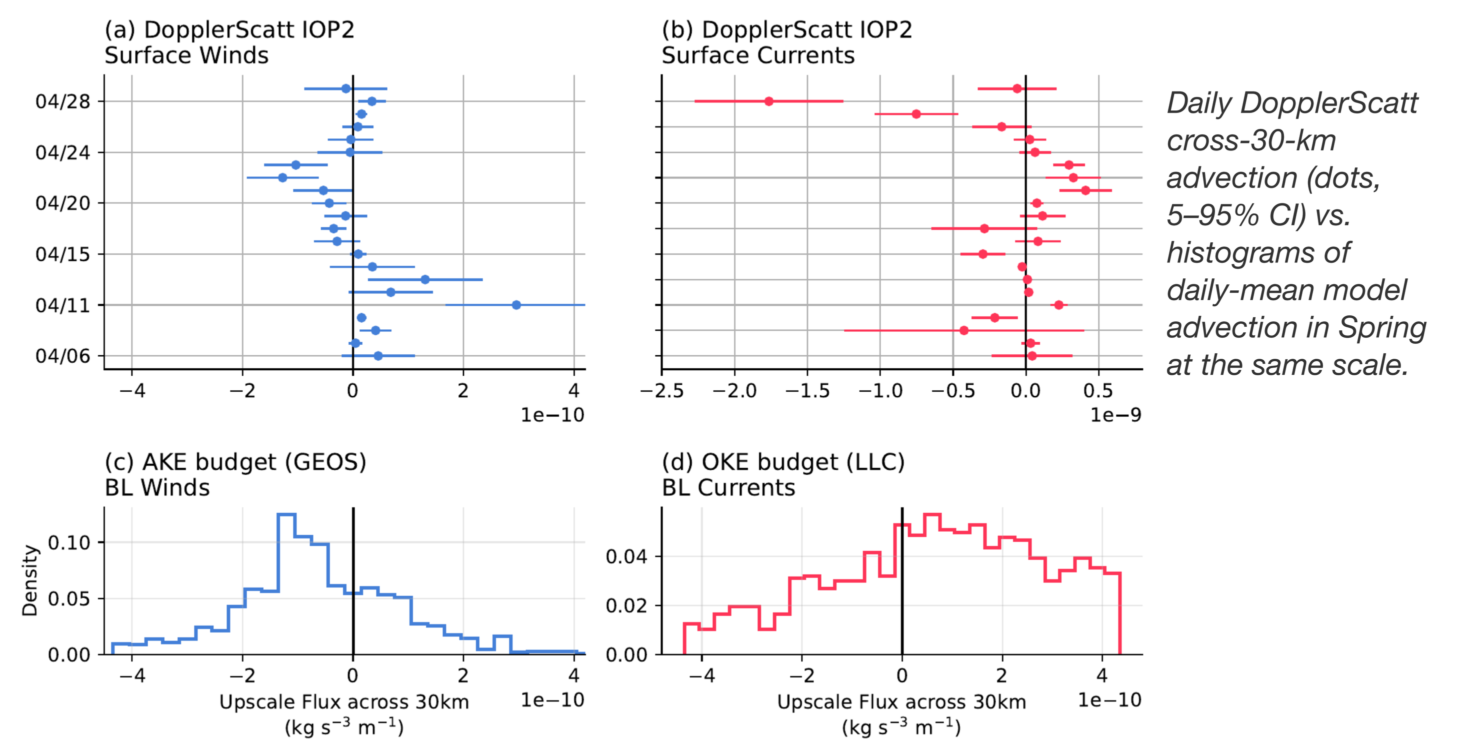
The coupled pathways at a glance

Blue/red arrows: down-/upscale transfer; vertical: cross-interface work.



Consistent with S-MODE airborne DopplerScatt

Cross-30-km advection from 22 days of DopplerScatt winds and currents (IOP-2, 2023) matches the model's Spring distributions in sign and amplitude. Distributionlevel comparison of budget terms — not phase-matched snapshots — is the right validation target for submesoscale-permitting models.



Daily DopplerScatt cross-30-km advection (dots, 5–95% CI) vs. histograms of daily-mean model advection in Spring at the same scale.

Takeaways for km-scale modeling

- Cascade-rate differences between the two boundary layers trace the sign, strength & scale of cross-interface energy transfer.
- Coupled scale-selective budgets expose episodic, competing up- and downscale transfers that bulk-flux assumptions cannot represent.
- Bootstrapped SF budgets are a practical success metric for km-scale coupled models — from model output or gappy observations alike.

Next: seasonal & regional regimes · surface-wave effects (absent in COAS) · scale-aware flux parameterizations informed by the coupled BL state.

Data & code:
COAS output: portal.nccs.nasa.gov/datashare/G5NR/DYAMONDv2 · S-MODE DopplerScatt L2 v2: PO.DAAC · PyTurbo_SF: Ayouche et al. (2026), JOSS.

Key references
Fox-Kemper et al. 2022 · Renault et al. 2016 · Callies et al. 2016 · Pearson et al. 2021 · Farrar et al. 2025 (S-MODE overview) · Ayouche et al. 2026.

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