Submesoscale Horizontal Advection Drives High-Frequency Upper-Ocean Temperature Variability

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01 Motivation: The Energy Gap

Climate models overall capture **low-frequency** upper-ocean temperature variability across resolutions, but systematically underestimate it at **sub-seasonal periods** (< $O(100)$ days).

Q1. What drives higher-frequency upper-ocean temperature variability?

Q2. What processes may be underrepresented in coarse models?

02 Budget & Cross Spectral Density

$$\frac{\partial \langle T \rangle}{\partial t} = A_h + A_v + Q + R$$

- $\langle T \rangle$ — layer averaged temperature
- A_h — horizontal advection
- A_v — vertical advection across the layer base
- Q — surface flux retained within the layer
- R — sub-grid mixing, parametrized processes

Terms are reconstructed offline from **hourly GEOS/ECCO C1440-LLC2160 (1/24°) output.**

We compute 3-D **(t, x, y) cross-spectral-densities (CSDs)** between T and each budget term over 1100 km sliding tiles and four independent 108-day windows.

$$\mathrm{Var}(\langle T \rangle) = CSD(A_h, \langle T \rangle) + CSD(A_v, \langle T \rangle) + CSD(Q, \langle T \rangle) + R$$

SIGN CONVENTION
CSD($\langle T \rangle$, term) > 0 → the term is a **source** of temperature variance at that scale.
CSD($\langle T \rangle$, term) <0 → the term is a **sink** of temperature variance at that scale.

03 Region of Interest: Kuroshio Extension & Northeastern Pacific

Region	domain	layer used for full budget	deepest MLD in the simulation
Kuroshio Extension	31–42°N, 147–163°E	0-400m	379 m
Northeastern Pacific	23–36°N, 152–138°W	0-200m	156 m

04 Horizontal advection: The Dominant Source at *(0.2-50) day* and *O(10-100) km*

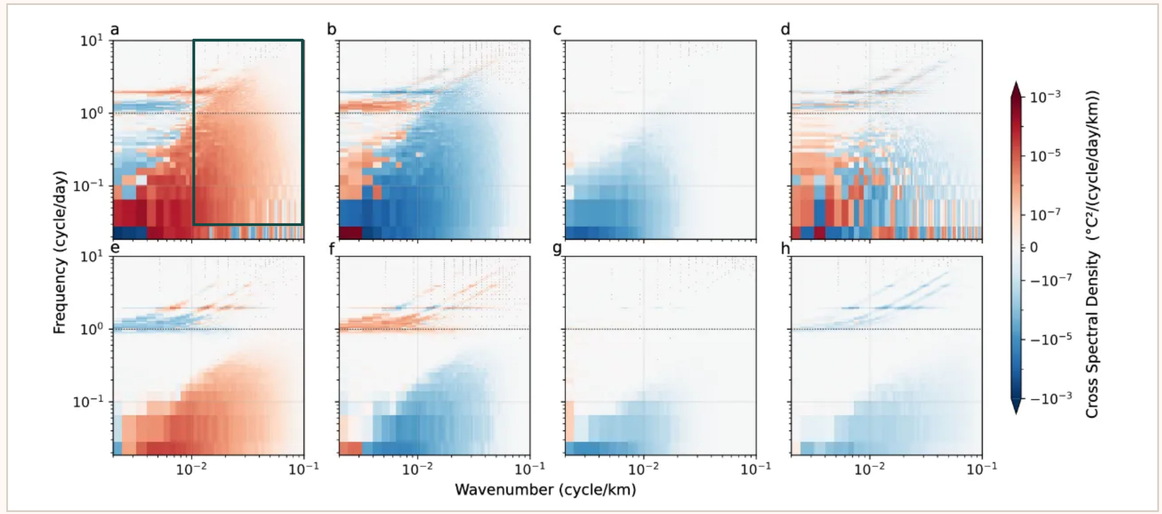

Fig. 1. Spectral contribution of each budget term to upper-ocean temperature variability across 8-500 km spatial scale and 0.2-54 day spatial scales, quantified by the CSD between each term and temperature.(a-d) CSD for horizontal advection (A_h), **(b)** vertical advection (A_v), **(c)** surface heat flux (Q) , and **(d)** residual (R) in the Kuroshio Extension (KE). **(e-h)** Same as **(a-d),** but for the Northeastern Pacific (NEP). Positive CSD (red) indicates a source of temperature variance; negative CSD (blue) indicates a sink.

05 Horizontal advection: Important Source in Small Scales

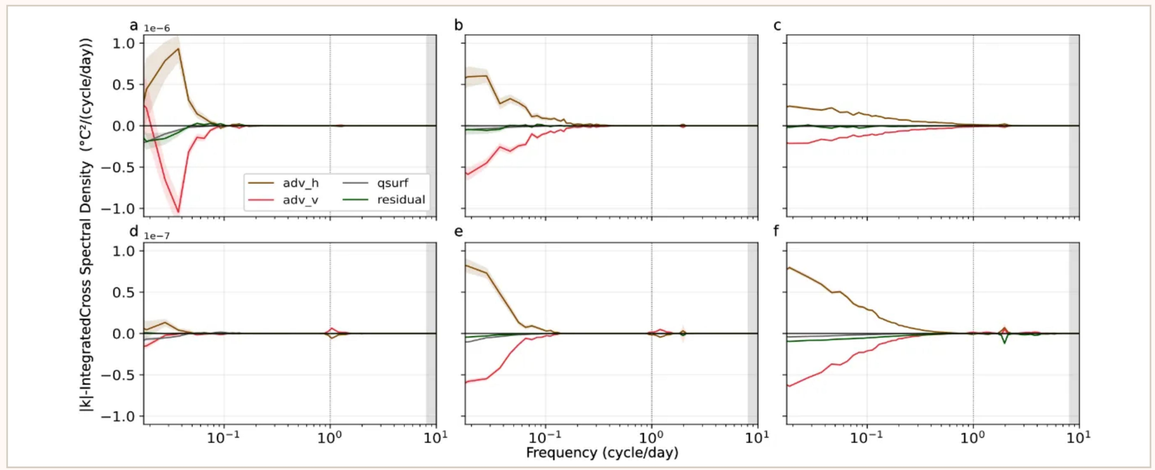

Fig. 2. Contribution of each budget term to upper-ocean temperature variability as a function of frequency for three spatial-scale bands. CSD is integrated over wavelengths of **(a)** >200 km, **(b)** 100–200 km, and **(c)** 10–100 km in the KE. **(d–f)** Same as **(a–c)**, but for the NEP. Positive CSD indicates a source of temperature variance; negative indicates a sink.

06 Horizontal Advection at *O(10-100) km* : Dominant Driver of High-Frequency Upper-ocean Temperature Variability

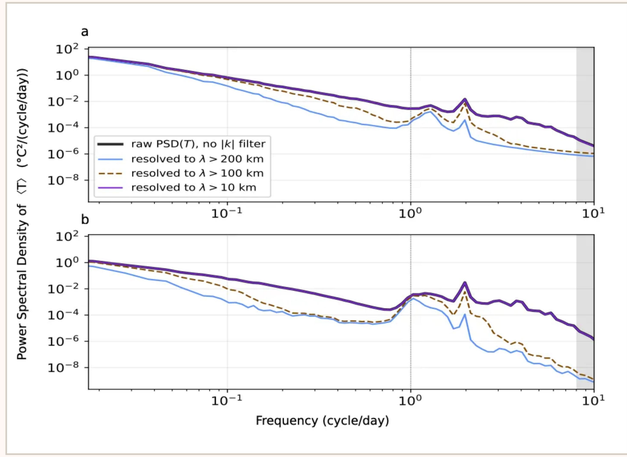

Fig. 3. Upper-ocean temperature variability as a function of frequency for progressively finer minimum resolved spatial scales. Temperature variability is calculated using budget terms resolved at wavelengths of (blue) >200 km, (dashed brown) >100 km, (purple) >10 km, and (black) > 8 km, illustrating the increase in variability as smaller spatial scales are resolved **(a)** in the KE. **(b)** Same as **(a)**, but for the NEP.

07 Key Findings & Implications

1. We first quantify how upper-ocean temperature budget terms contribute to temperature variance across spatial and temporal scales in a fully coupled, 1/24° simulation.
2. Horizontal advection is the only budget term that acts as a source of temperature variance across 10-100 km and 0.2-54 days—scales not resolved by a ~1° ocean model.
3. Unresolved 10-100 km horizontal advection provides a potential mechanism for the sub-seasonal temperature variance deficit in coarse-resolution models.

REFERENCES
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[3] Menemenlis, D. et al (2026). The GEOS/ECCO C1440-LLC2160 Coupled Atmosphere-Ocean Simulation Dataset. *Scientific Data*.

Acknowledgements
C.L and D. G. are supported by NSF Award #2524936.