Characterization of Global Internal Tides at High Horizontal Resolution

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Abstract

The Coupled-Mode Shallow Water Model (CSW) is used to generate an ensemble of global 1/25° internal-tide simulations with linear drag coefficients, *r*, corresponding to 0.25-32 day decay time scales. In the deep ocean (H>1000 m), mode-1 generation is 180 GW regardless of *r*, but mode-1 energy and scattering, C_n, increase as the drag time scale increases. Therefore, *r* and C_n can be inferred from satellite observations of mode-1 SSH. Inferred drag is large near the equator, implicating meanflow effects. Meanflow effects are diagnosed in the Tasman Sea. Internal-tide advection by the meanflow produces non-stationary tides and provides drag on the stationary mode-1 tide. A global drag parameterization based on eddy kinetic energy largely replicates the inferred dissipation.

The CSW Model

This linearized model projects vertical variability onto free-surface, flat-bottom modes, φ_n, which individually obey the shallow water equations with eigenspeed c_n. The modes are coupled where sloping topography produces horizontal variability in the mode shapes (Kelly et al., 2016).

$$\mathbf{U}_{nt} + f\hat{\mathbf{k}} \times \mathbf{U}_n = -H\nabla p_n - \sum_{m=0}^{\infty} H\mathbf{T}_{mn}p_m$$

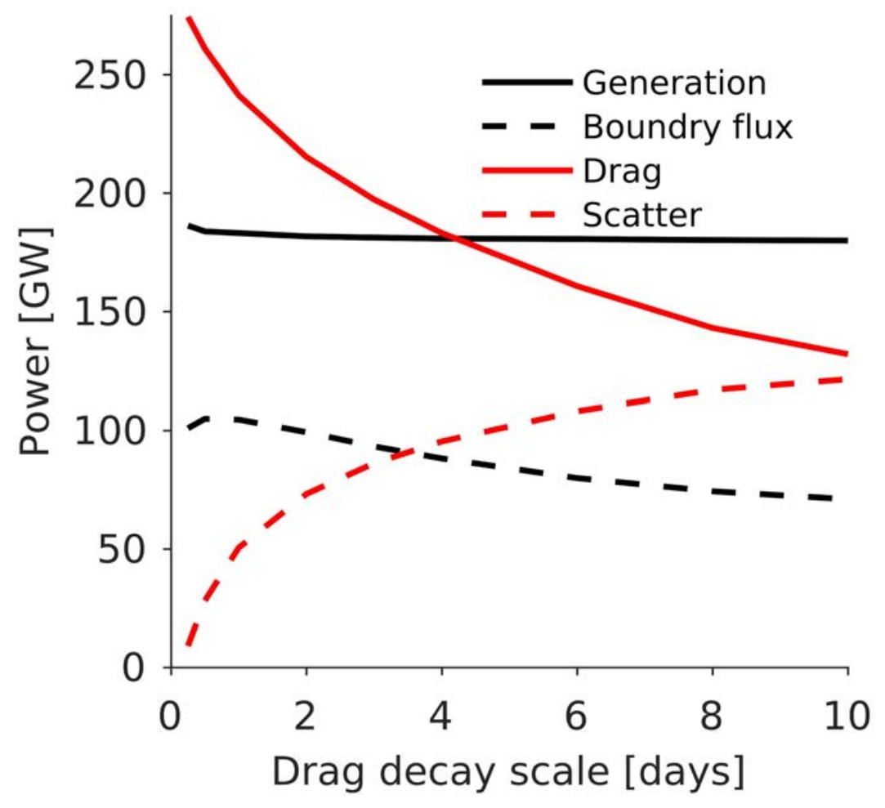
$$\frac{Hp_{nt}}{c_n^2} = -\nabla \cdot \mathbf{U}_n + \sum_{m=0}^{\infty} \mathbf{T}_{nm} \cdot \mathbf{U}_m$$

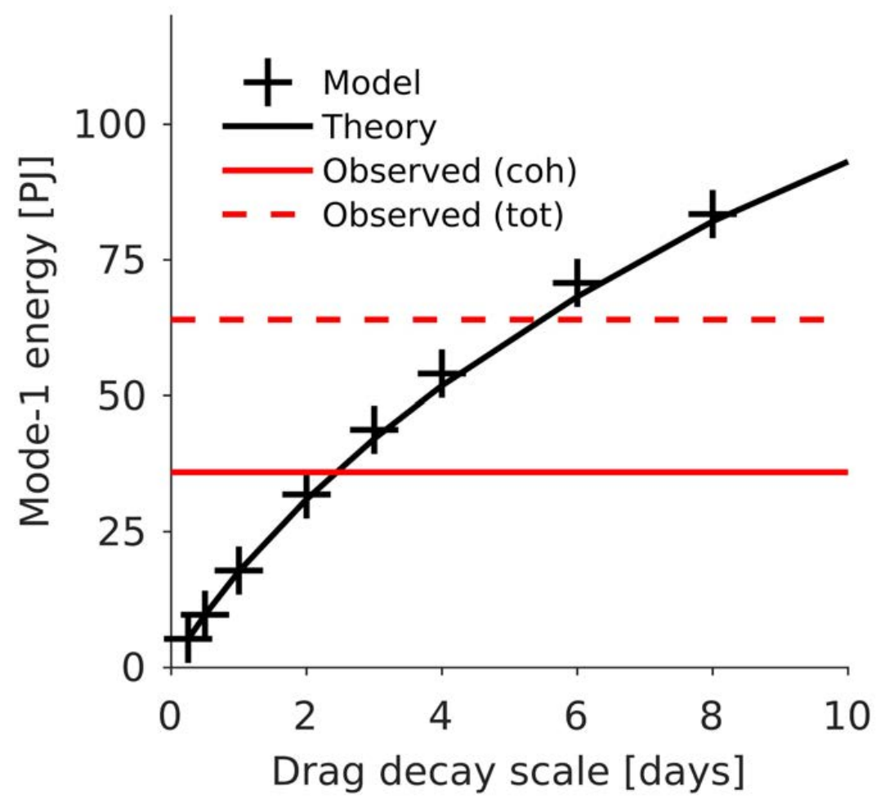
$$\mathbf{T}_{mn}(\mathbf{x}) = \frac{1}{H}\int_{-H}^{0} \phi_n \nabla \phi_m \mathrm{d}z$$

In practice, the equations also include linear drag, corresponding to a decay time scale. The equations are solved, using spherical coordinates, a finite-volume formulation and an Adams-Bashforth time stepping algorithm. The modes are determined *a priori* using global bathymetry and HYCOM stratification. TPXO.8 surface tides (Egbert et al.,1994) are prescribed to generate the internal tide. The approximate energy balance in the deep ocean (H>1000 m) is:

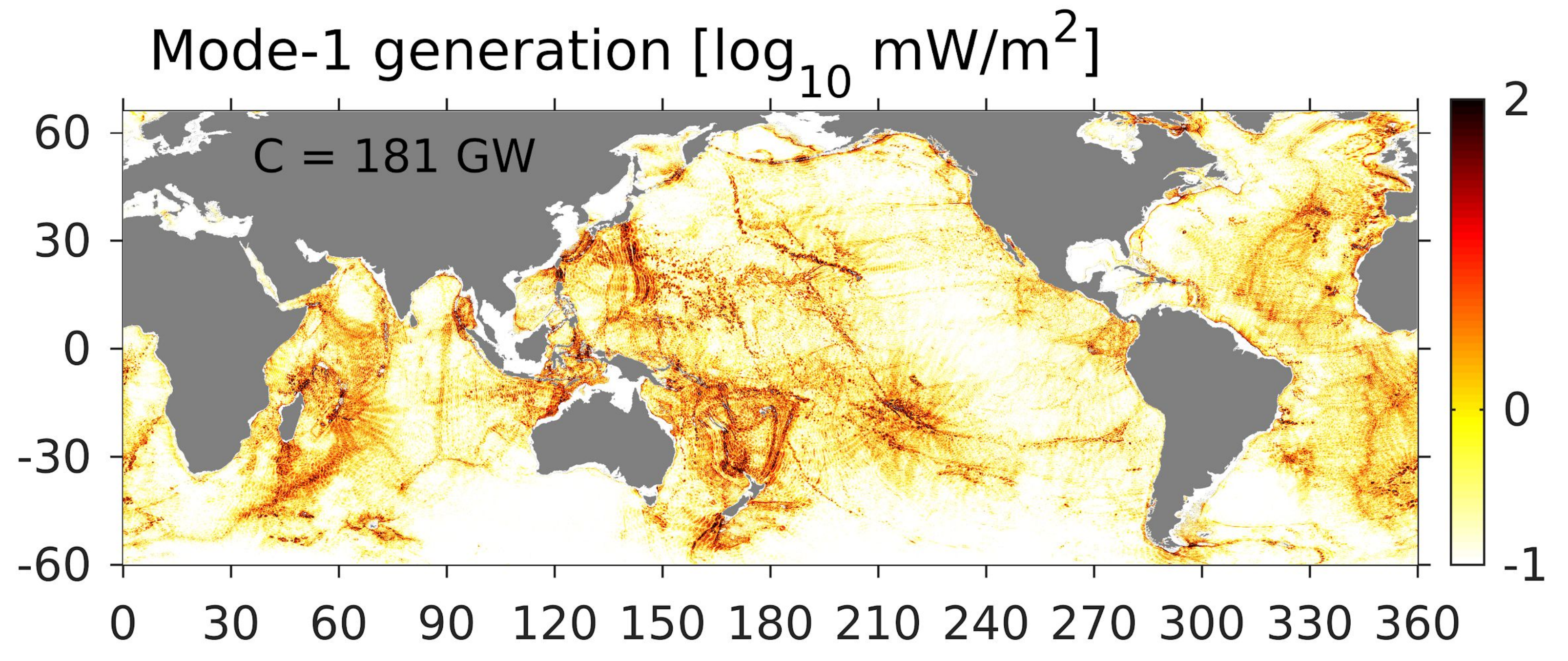
$$\nabla \cdot \mathbf{F}_1 = C_1 - C_n + 2r\mathrm{KE}_1$$

where C_1 is generation, C_n is low-mode scattering, *r* is the drag coefficient, and KE is kinetic energy. Deep ocean flux divergence is negative because the coasts are a source of internal tides.





Mode-1 generation [$\log_{10}$ mW/m^2]



Above: Mode-1 generation (r^{-1} = 3 days, 1/25°, 4 vertical modes).

Upper left: Mode-1 generation is independent of drag. Loss to scattering increases as drag decreases. Dissipation by drag and net boundary (coastal) flux decrease as drag decreases. Budget errors are 5 GW.

Lower left: Mode-1 energy increases as drag decreases. Energy is predictable from the power input and drag coefficient. Satellite estimates of coherent (Zhao et al., 2016) and total energy (Zaron, 2017) imply a 2-6 day decay scale.

Simulations with Meanflows

Leading-order meanflow effects in CSW arise from a two-timescale asymptotic method (Wagner et al. 2017) and assuming a (locally) flat bottom. After the geometric approximation, the equations are:

$$\mathbf{U}_{nt} + \underbrace{\sum_{m=0}^{\infty} (\overline{\mathbf{u}}_{mn} \cdot \nabla)\,\mathbf{U}_m}_{\text{Advection}} + \underbrace{\sum_{m=0}^{\infty} (\mathbf{U}_m \cdot \nabla)\,\overline{\mathbf{u}}_{mn}}_{\text{Shear}} + f\hat{\mathbf{k}} \times \mathbf{U}_n = -H\nabla p_n - \sum_{m=0}^{\infty} H\mathbf{T}_{mn}p_m$$

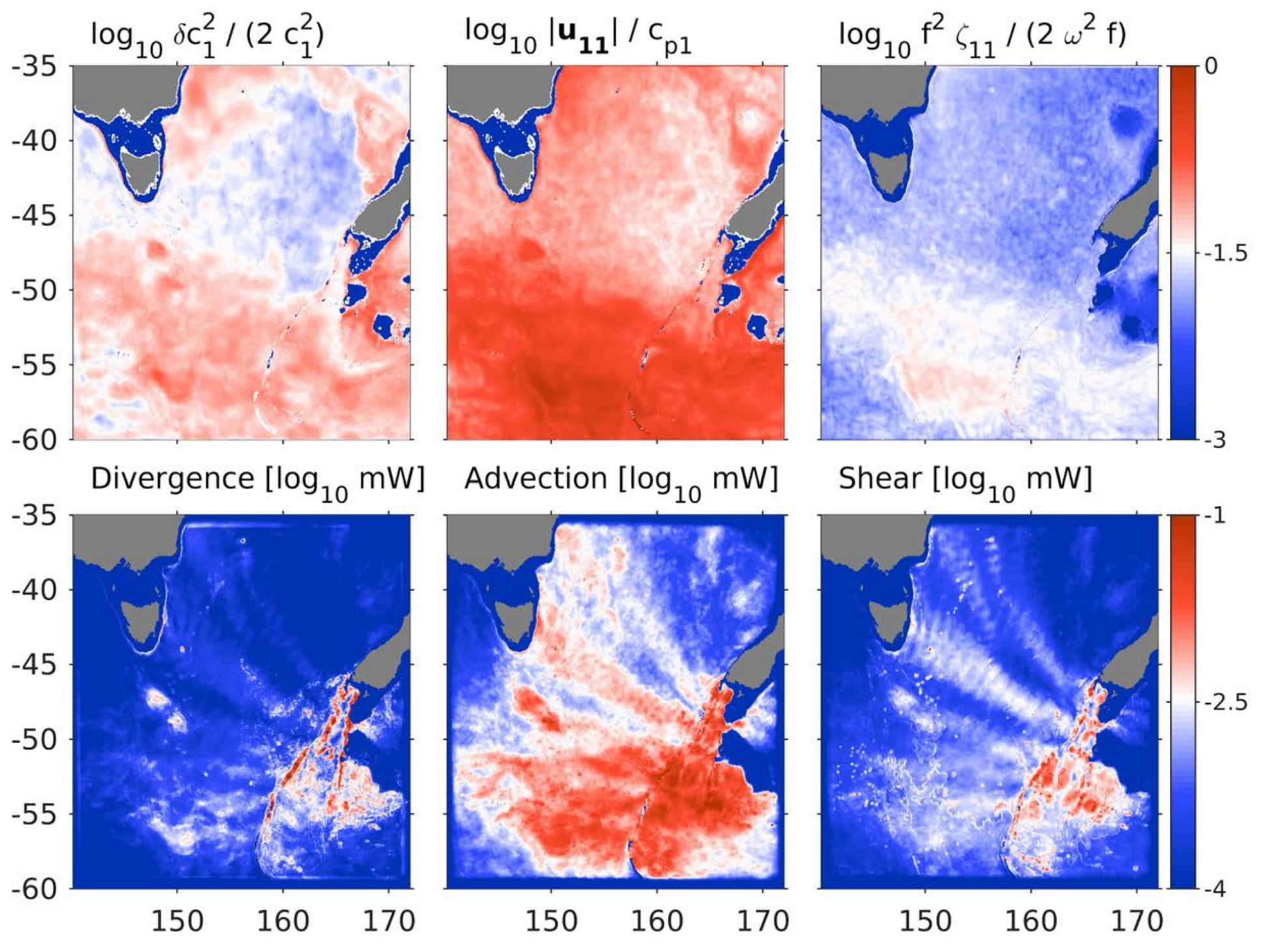
$$\frac{Hp_{nt}}{c_n^2} + \underbrace{\sum_{m=0}^{\infty} \frac{\overline{\mathbf{u}}_{p,mn}}{c_m c_n} \cdot H\nabla p_m}_{\text{Advection}} + \underbrace{\frac{\delta c_n^2}{c_n^2}\nabla \cdot \mathbf{U}_n}_{\text{Divergence}} = -\nabla \cdot \mathbf{U}_n + \sum_{m=0}^{\infty} \mathbf{T}_{nm} \cdot \mathbf{U}_m$$

$$\overline{\mathbf{u}}_{mn}(\mathbf{x},t) = \frac{1}{H}\int_{-H}^{0} \overline{\mathbf{u}}(\mathbf{x},z,t)\phi_m\phi_n \mathrm{d}z$$

$$\overline{\mathbf{u}}_{p,mn}(\mathbf{x},t) = \frac{1}{H}\int_{-H}^{0} \overline{\mathbf{u}}(\mathbf{x},z,t)\frac{N_0^2}{c_m c_n}\Phi_m\Phi_n \mathrm{d}z$$

$$\delta c_n^2(\mathbf{x},t) = \frac{1}{H}\int_{-H}^{0} \delta N^2(\mathbf{x},z,t)\Phi_n\Phi_n \mathrm{d}z$$

where the advection terms can produce inter-modal scattering. Meanflow effects are diagnosed using a 13-month, 1/20°, simulation of the Tasman Sea with an imposed HYCOM meanflow. Macquarie Ridge (south of New Zealand) generates an energetic M2 internal tide that propagates northwest, toward Tasmania. The T-Beam experiment (Waterhouse et al., 2018) collected observations in 2015.



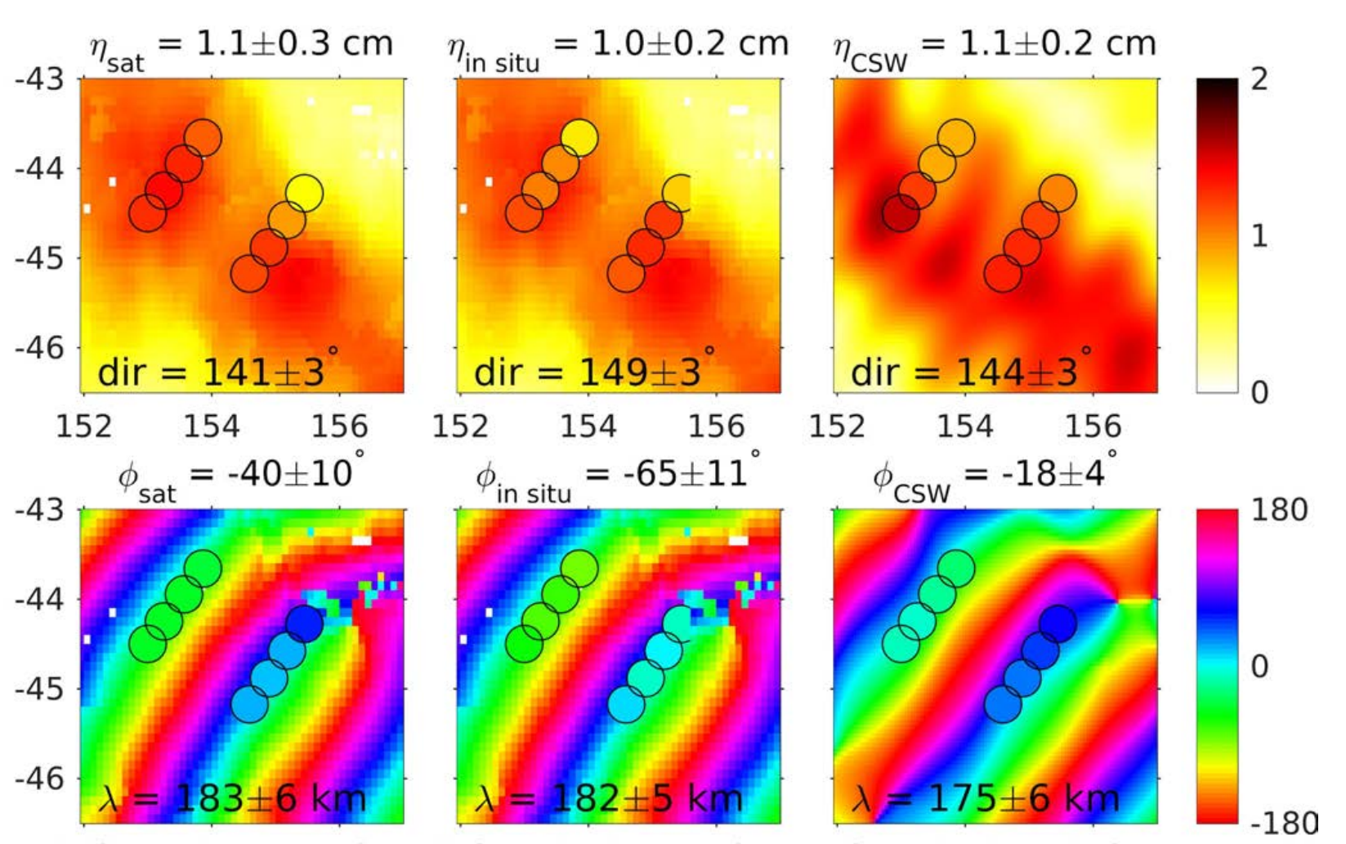
Top left: The relative impacts of the divergence, advection, and shear meanflow terms are predicted by the internal-tide dispersion relation (Zaron and Egbert, 2014)

Bottom left: The magnitude of the energy balance terms associated with divergence, advection, and shear meanflow terms.

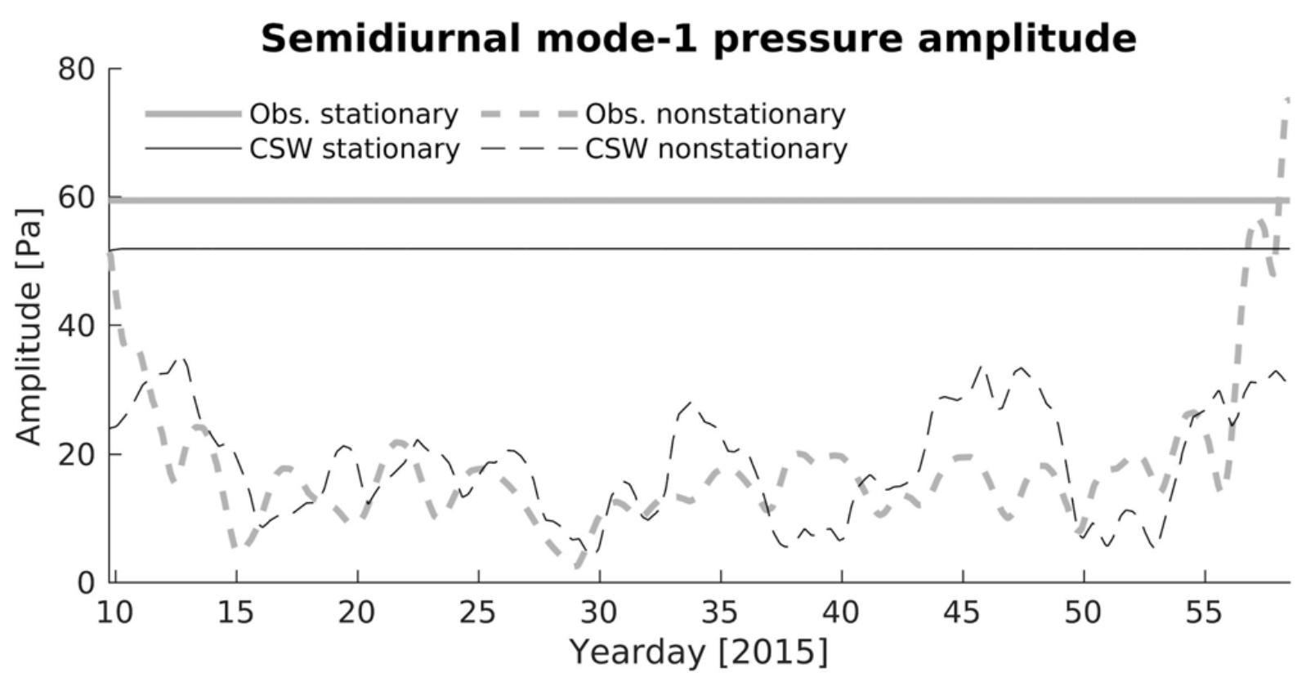
Note: meanflow shear terms in CSW permit exponential (unstable) solutions, so they were evaluated *a posteriori*.

Comparison of CSW with T-Beam Observations

Below: Satellite, in situ, and simulated M_2 SSH agree (Waterhouse et al., 2018). Circles indicate values sampled at the sites of 30-h CTD stations.



Below: The simulation largely replicates the mode-1 pressure observed during a 40-day mooring deployment at 153° E, 44.5° S (Waterhouse et al., 2018). The comparable non-stationary pressures suggest similar meanflow effects.



Acknowledgments

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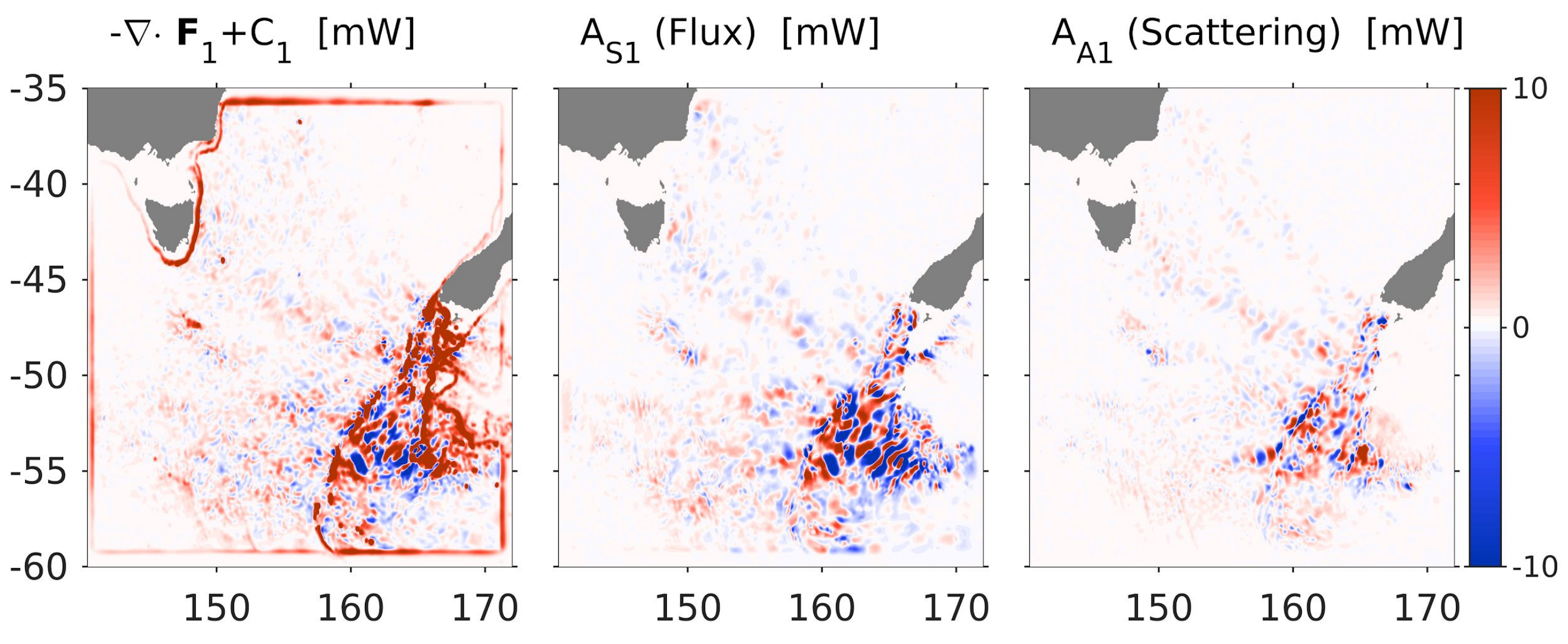
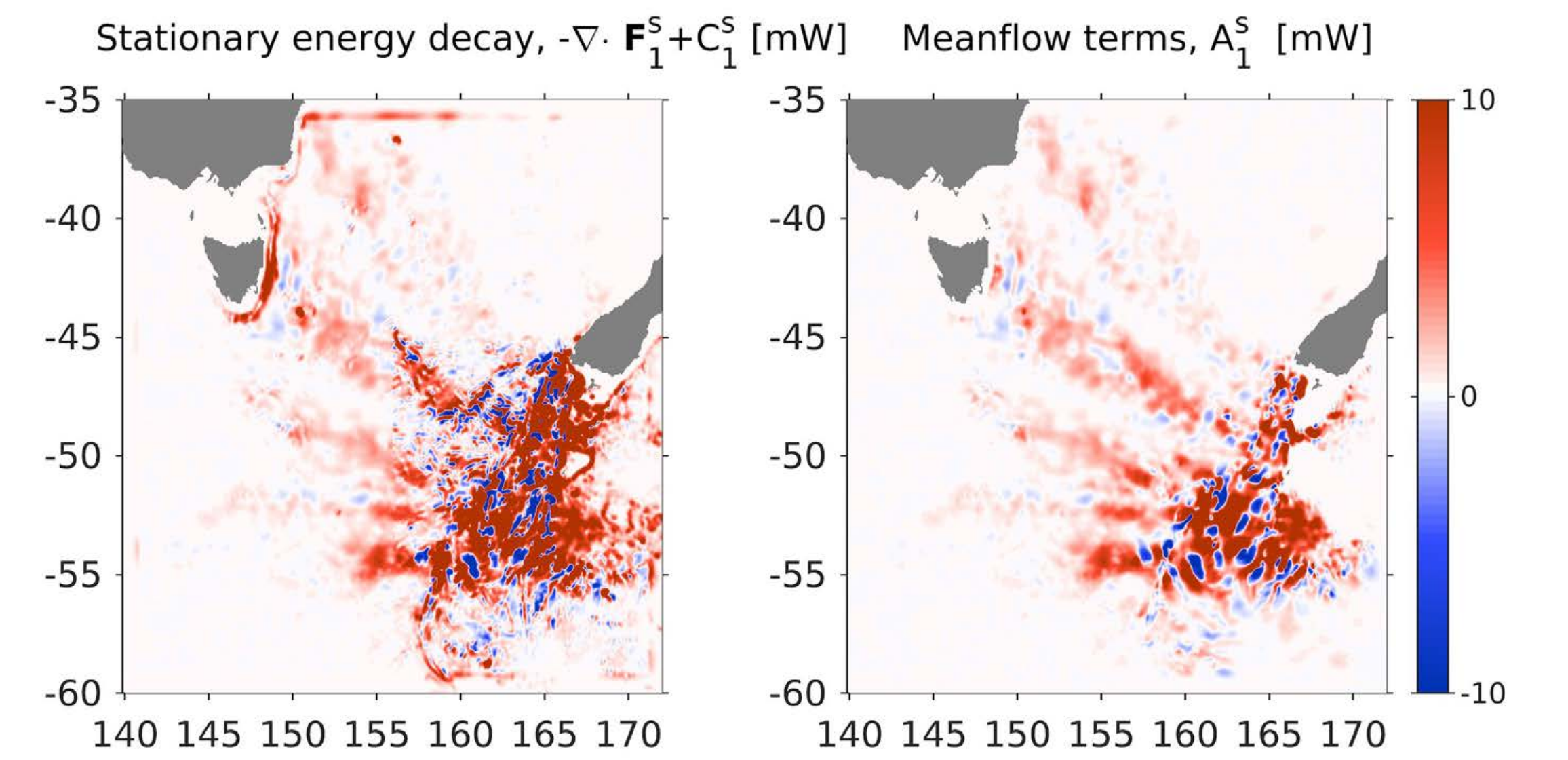
Decay of the Mode-1 Tide



Above: Total energy-flux convergence in the center of the Tasman Sea is relatively weak and mostly explained by the advection term. The advection matrix is separated into symmetric and antisymmetric components representing flux-divergence and inter-modal scattering terms, respectively. Scattering is weak.

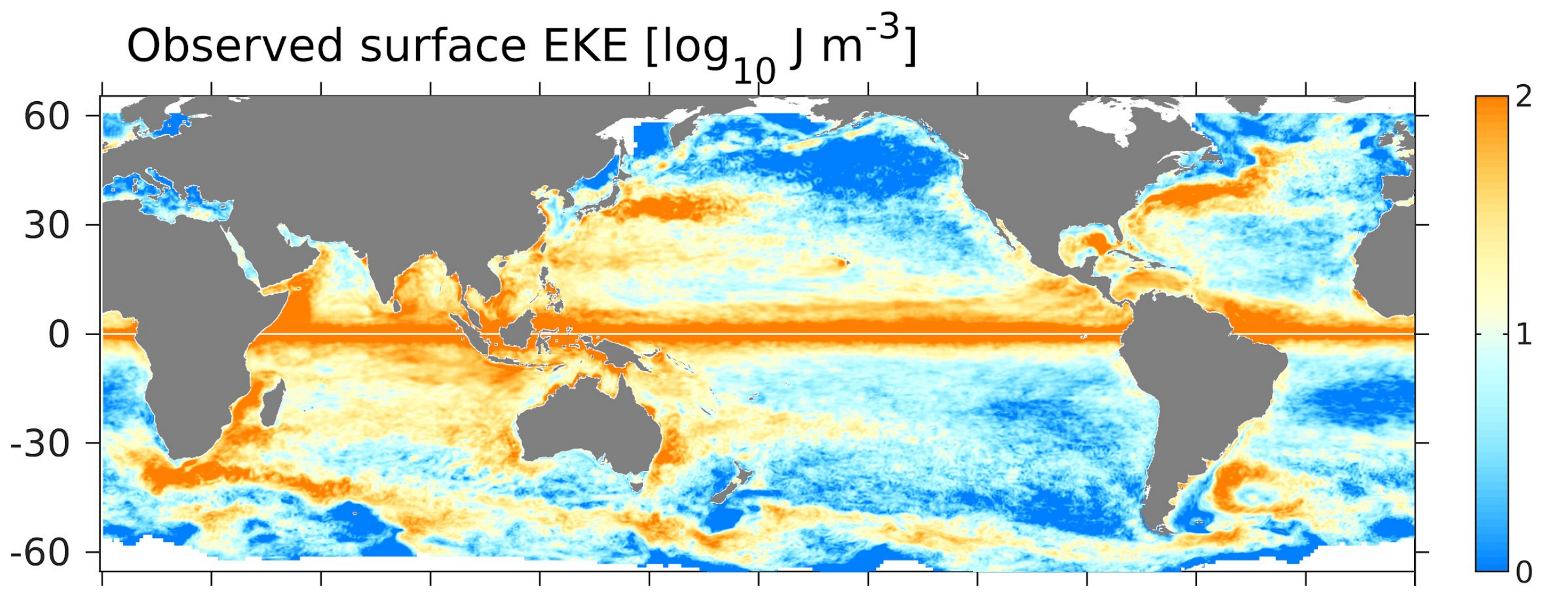
Below: AVISO surface EKE (Qiu et al. 2018).



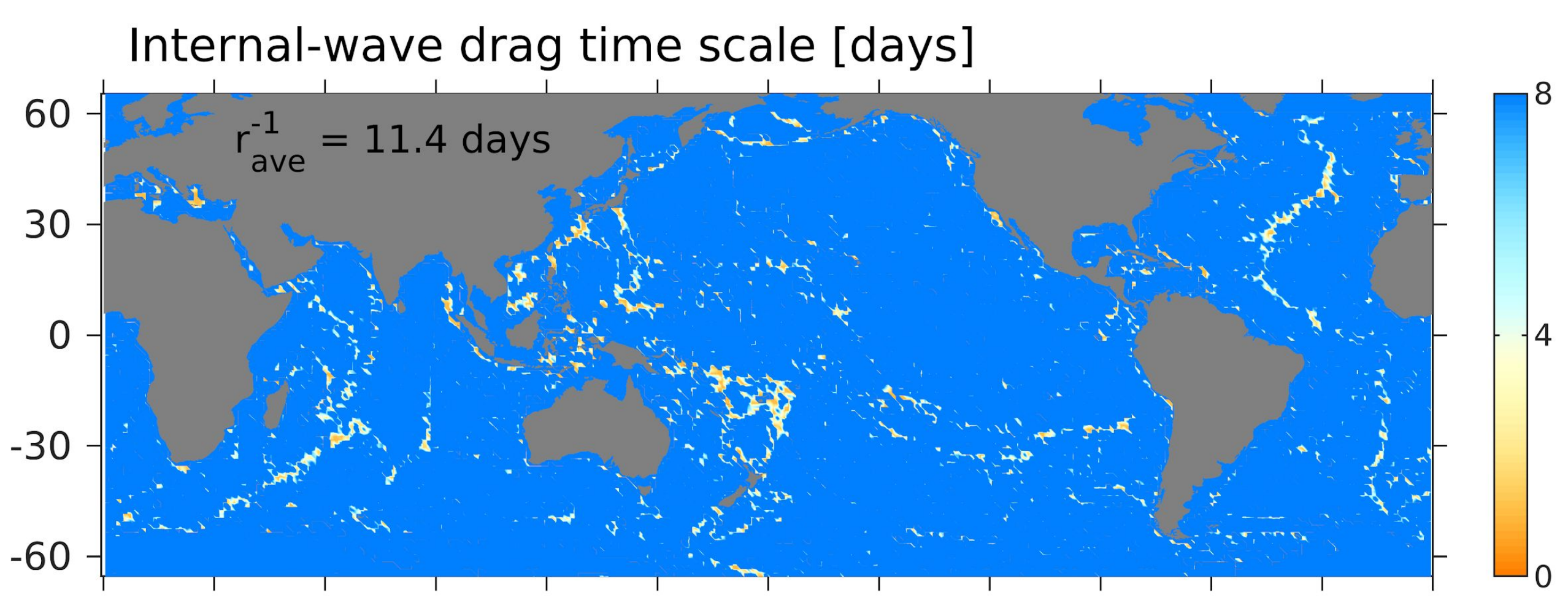
Above: Stationary energy-flux convergence is large in the center of the Tasman Sea, consistent with a large drag. Advection by the meanflow provides this drag.

Below: Topographic internal-wave drag based on Jayne and St Laurent (2001) is too weak to account for observed satellite SSH.

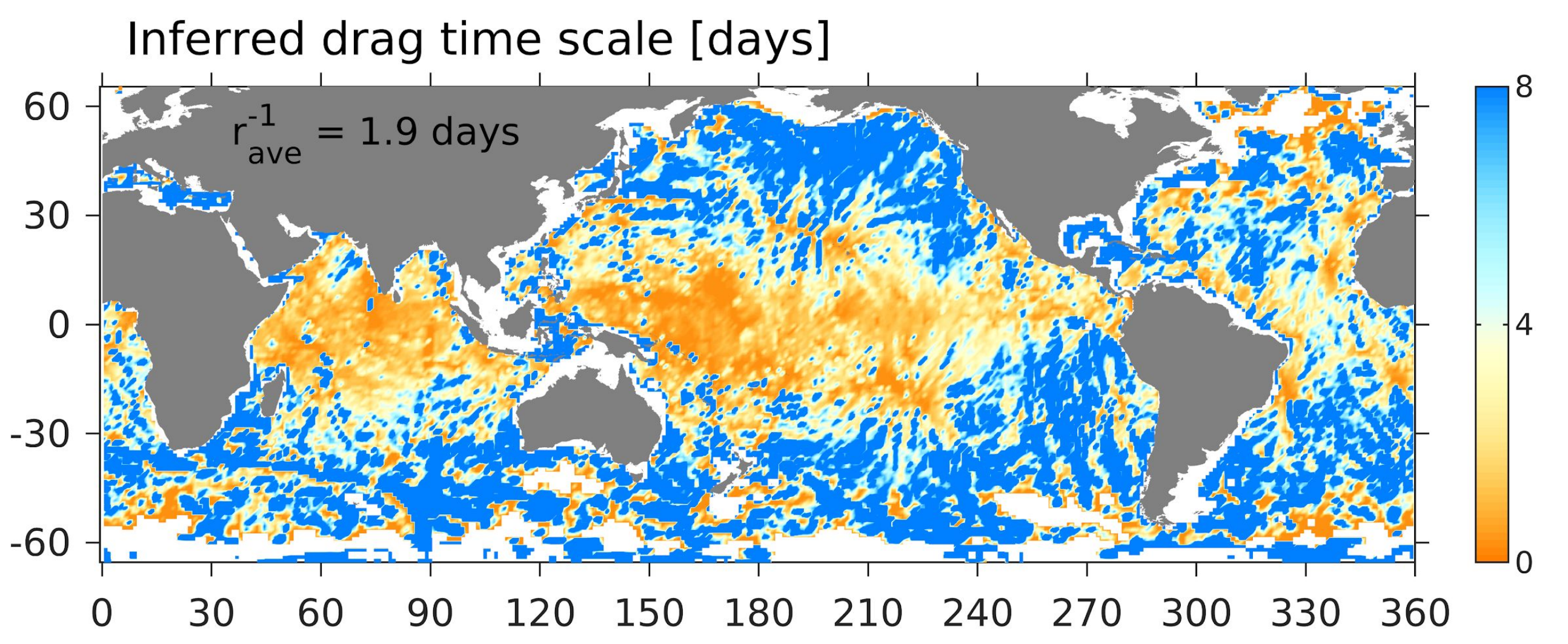
Observed surface EKE [$\log_{10}$ J m^{-3}]



Internal-wave drag time scale [days]

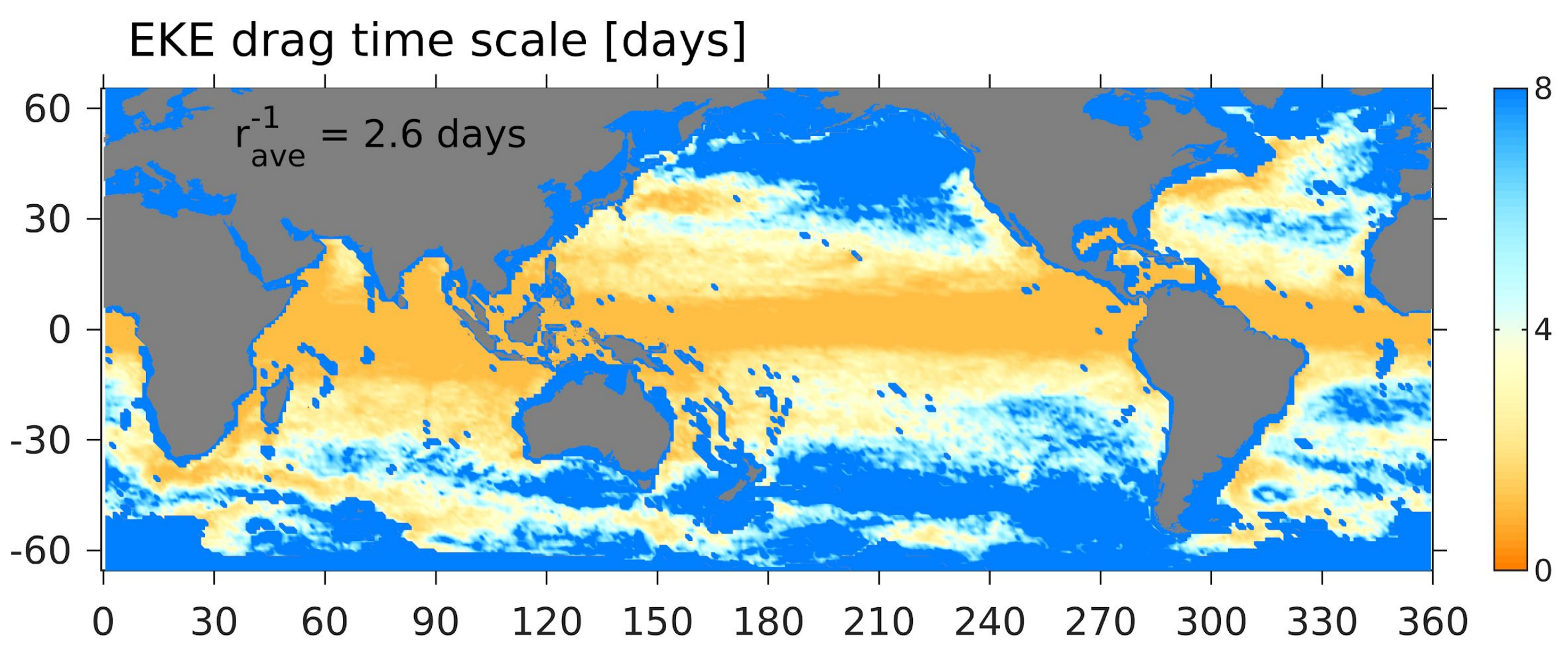


Inferred drag time scale [days]



Above: A suite of global CSW simulations were conducted with different linear drags, resulting in different SSH amplitudes. The drag that resulted in the observed (stationary) SSH amplitude is the inferred drag.

EKE drag time scale [days]



Above: An eddy diffusivity is defined using surface eddy kinetic energy (EKE) following Klocker and Abernathy (2014). Diffusivity is converted to a linear drag by multiplying by the mode-1 wavelength squared.

Conclusions

1. In CSW, drag controls mode-1 energy, but generation is insensitive to model parameterizations.
2. Internal-tide advection by the meanflow is the most important meanflow effect in CSW. This term produces realistic non-stationary mode-1 tides and produces drag on the stationary mode-1 tide.
3. The drag time scales inferred from satellite SSH are <1 day near the equator and abrupt topography, and >7 days in less energetic regions. These time scales are largely replicated by a drag parameterization based on surface EKE, but not topographic scattering.