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Wind Damping of Internal Tides in the Global Ocean

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3 **Internal tides (ITs) play a crucial role in transferring tidal energy to small-scale turbulence,**
4 **thereby driving ocean mixing that sustains ocean circulation and regulates biogeochemical**
5 **cycles and Earth's climate. While the wind is normally an energy source for oceanic flows,**
6 **it tends to damp ITs because of the difference in spatial scale between the wind field and**
7 **ITs. Yet, the overall contribution and geographic distribution of wind's impact on ITs**
8 **energetics remain to be elucidated. Here, we diagnose wind work on ITs in a realistic ITs-**
9 **resolving simulation and use the results to formulate and validate a physically based scaling**
10 **for application to observations. The observation-based estimate reveals that wind forcing**
11 **exerts systematic damping on ITs, with a globally integrated wind work of -15 GW and a**
12 **median local contribution of ~4% relative to the energy sinks of ITs. This finding extends**
13 **the prevailing view of topographically-dominated ITs energy sinks by suggesting that wind**
14 **work needs to be included in the ITs energy budget.**

Introduction

Understanding the global ocean energy budget, particularly the pathways of energy into and out of the internal wave reservoir, is of fundamental importance. This knowledge is key to quantifying how internal wave-driven mixing shapes global ocean circulations¹⁻⁴ and, in turn, modulates biogeochemical cycles and Earth's climate⁵. A major component of this reservoir is internal tides (ITs)⁶, which are generated as barotropic tides interact with complex topography, transferring about one terawatt (TW) of energy into the internal wave field globally^{7,8}. Due to nonlinear interactions during propagation^{9,10}, ITs transfer their energy to smaller scales, ultimately leading to dissipation via generating small-scale turbulence^{2,11}. Evaluations of ITs energy sinks commonly account for mechanisms such as dissipation at critical slopes, breaking due to shoaling, attenuation by wave-wave interactions, and scattering by abyssal hills¹²⁻¹⁴. However, recent studies suggest that wind-current feedback may contribute to the energy budget of ITs, representing an additional sink alongside the aforementioned topographic processes¹⁵.

Wind is the primary driver of oceanic flows¹⁶⁻¹⁹, yet its role as an energy source is not uniform across spatiotemporal scales²⁰. In an analysis of scale-dependent wind work on surface geostrophic currents, Rai et al.²¹ find that on scales smaller than 260 km, wind dampens ocean currents at a global average rate of 0.14 mW/m². This wind damping, commonly termed as 'eddy killing', arises from the dependence of wind stress on the relative velocity between the wind and ocean currents. The underlying mechanism can be understood by noting that the interaction between a large-scale wind field and a smaller-scale symmetric oceanic eddy induces asymmetric wind work, with negative work exceeding positive work in magnitude, leading to a net loss of kinetic energy upon spatial integration. Furthermore, Rai et al. demonstrate that this

wind damping acts not only on vortical motions but also, with comparable efficiency, on straining motions²².

Indeed, a similar mechanism operates between wind and internal waves. Spectral analysis of internal wave resolving global ocean simulations reveals ubiquitous wind damping across the entire internal wave band^{23–25}. Near the U.S. West Coast, Delpech et al.¹⁵ find that wind damping of ITs reaches 0.2 mW/m², corresponding to 8% of local generation. Analogous to the ‘eddy killing’ concept, the wind damping of ITs is termed as ‘ITs killing’¹⁵. Despite increasing recognition that wind forcing can act as an important sink of oceanic energy, its role in the energetics of ITs remains to be fully understood on a global scale. Moreover, the underlying mechanism of ‘ITs killing’ differs from that of ‘eddy killing’. Eddies are roughly axisymmetric, whereas ITs are generally linearly polarised. A detailed mechanistic explanation for this difference, however, remains to be elucidated.

Here, we investigate the interaction between the wind and ITs using a state-of-the-art global ocean simulation (LLC4320, a Latitude-Longitude-Cap global ocean model at 1/48° resolution). This simulation has been extensively validated against observations, showing good agreement with large-scale currents²⁶, mesoscale variability²⁷, and super-inertial flows^{28,29}. Using a robust dynamical decomposition approach³⁰, we quantify the magnitude and spatial distribution of wind damping of ITs in the simulation. To extend this analysis to observations, we further devise a simple scaling that requires only the amplitudes of the wind and tidal velocities, together with their geometric alignment. This scaling not only provides a framework for understanding how the properties of the wind field and ITs combine to produce wind damping of ITs, but also offers a simple approach to estimate wind damping from observations such as QuikSCAT winds and the Global Drifter Program (GDP) data. This estimate demonstrates that wind damping,

previously documented only at the regional scale, is a widespread sink of ITs energy across the global ocean, helping close a critical gap in the global ocean energy budget.

Results

Wind damping of ITs

The wind work W on ITs is calculated as the inner product of the relative wind stress $\boldsymbol{\tau}_t$ and the surface internal tidal velocity $\mathbf{u}_t$. Given the periodicity of $\mathbf{u}_t$, it is standard practice to average W over multiple tidal cycles:

$$\bar{W} = \overline{\boldsymbol{\tau}_t \cdot \mathbf{u}_t} , \quad (1)$$

$$\boldsymbol{\tau}_t = [\rho_a C_d |\mathbf{U} - \mathbf{u}| (\mathbf{U} - \mathbf{u})]_t , \quad (2)$$

where $\mathbf{U}$ is wind velocity at 10-m height, ρ_a is air density, and C_d is the drag coefficient. The subscript t denotes the internal tidal component, while the overbar indicates a time average.

By applying a dynamical decomposition approach³⁰ to the surface ocean velocity and wind stress (see [Methods](#)), we isolate the tidal component and calculate the annually averaged wind work using Eq. 1 (Fig. 1a). Globally, the wind work on ITs is predominantly negative, indicating that the wind acts almost universally as an energy sink rather than a source for ITs. Positive wind work is rare and contributes negligibly. The strongest damping occurs in regions characterised by both intense wind forcing and energetic ITs, such as the Luzon Strait, the Aleutian Ridge, and downstream of the Gulf Stream. Damping rates span several orders of magnitude, from 10^{-6} to 10^{-2} W/m², with a median of $\sim 10^{-4}$ W/m². Overall, this process removes approximately 29.8 GW of ITs energy from the global ocean.

Although numerical simulation allows direct quantification of global wind work on ITs, the resulting estimates depend on how realistically both the wind and ITs fields are represented. For

example, the semidiurnal ITs kinetic energy in LLC4320 is 1.2-3.0 times that inferred from observation-based estimates^{31–33}, indicating that a direct simulation-based diagnosis may not accurately capture the magnitude of wind damping in the global ocean. An independent estimate grounded in observations is therefore needed. However, existing observational datasets such as those from drifters or satellites are not readily applicable to this calculation because isolating the ITs-related component of wind work inherently requires an effective decomposition of the total wind work. This decomposition requires temporally and spatially continuous datasets in which the wind and current fields are precisely time-matched, a condition rarely met by sparse observations. To overcome this limitation, we devise a scaling framework to estimate the tidally averaged wind damping of ITs.

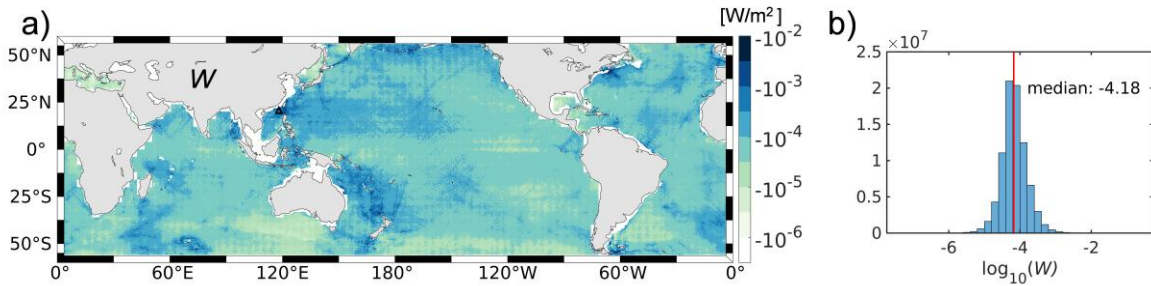


Fig. 1 | Global wind damping of ITs from the LLC4320 global ocean simulation. (a) The annual mean wind damping of ITs, calculated by Eq. 1. The black triangle in the South China Sea marks the location corresponding to the data shown in Fig. 2. (b) The histogram shows the number of samples in each logarithmic wind damping interval, and the red line indicates the median value.

A simple scaling for the tidally averaged wind work

By representing ITs as a coherent tidal ellipse, we propose a simple scaling for the wind work on ITs and validate it against the simulation results. As shown in Eqs. 1 and 2, the wind work can be expanded into four terms via polynomial multiplication. Because wind forcing has a much larger amplitude than ITs and varies on spatial scales much larger than those of the ITs, the odd-order terms involving the surface tidal velocity vanish after tidal averaging. The remaining two terms can be evaluated geometrically using the properties of the tidal ellipses (see the Methods section for derivations). Under these prevalent natural conditions, this approach yields a simplified expression for the wind work from its exact formulation:

$$W_s = - (1 + \beta) \rho_a C_d \cdot \overline{|\mathbf{U}|} \cdot \overline{\mathbf{u}_t^2} . \quad (3)$$

Here, β is a geometric coefficient describing the alignment of the tidal ellipse with the wind; it reaches its maximum when the ellipse's major axis aligns with the wind. This expression shows that the magnitude of wind damping scales with the time-averaged amplitudes of the wind and tidal velocities, as well as with a coefficient representing their misalignment. During the half-cycle when the current flows against the wind, the enhanced relative wind stress generates negative work that exceeds the positive work in the opposing phase, so that the net effect is a damping of ITs over a complete tidal cycle (Fig. 2e).

The performance of our scaling can be demonstrated using the LLC4320 simulation of wind damping of ITs near the Luzon Strait, which faithfully captures the amplitude and spatial pattern of the wind work on the K_1 ITs (Fig. 2). Given the significant seasonality of wind field, we used seasonally averaged variables in the formula. The amplitude of damping is enhanced where both the tidal ellipse and the alignment ratio β are larger. Furthermore, the close agreement between the scaling and the exact wind work is confirmed by the scatter plot (Fig. 2d).

To illustrate the magnitude of wind damping of ITs and the utility of the scaling, we evaluate Eq. 3 using representative values observed under realistic conditions: $1+\beta \sim 1$, air density $\rho_a \sim 1 \text{ kg/m}^3$, drag coefficient $C_d \sim 10^{-3}$, wind speed $U \sim 10 \text{ m/s}$, and ITs kinetic energy $u_t^2 \sim 0.01 \text{ m}^2/\text{s}^2$. This yields $W_s \sim 10^{-4} \text{ W/m}^2$, in good agreement with the global distribution derived from the numerical simulation (Fig. 1). The scaling thus not only captures the correct magnitude but also provides a transparent framework for understanding how wind, tidal energy, and their misalignment combine to produce wind damping of ITs. With only time-averaged wind velocity and tidal harmonic constants required, this approach greatly improves the feasibility of estimating wind damping of ITs on a global scale.

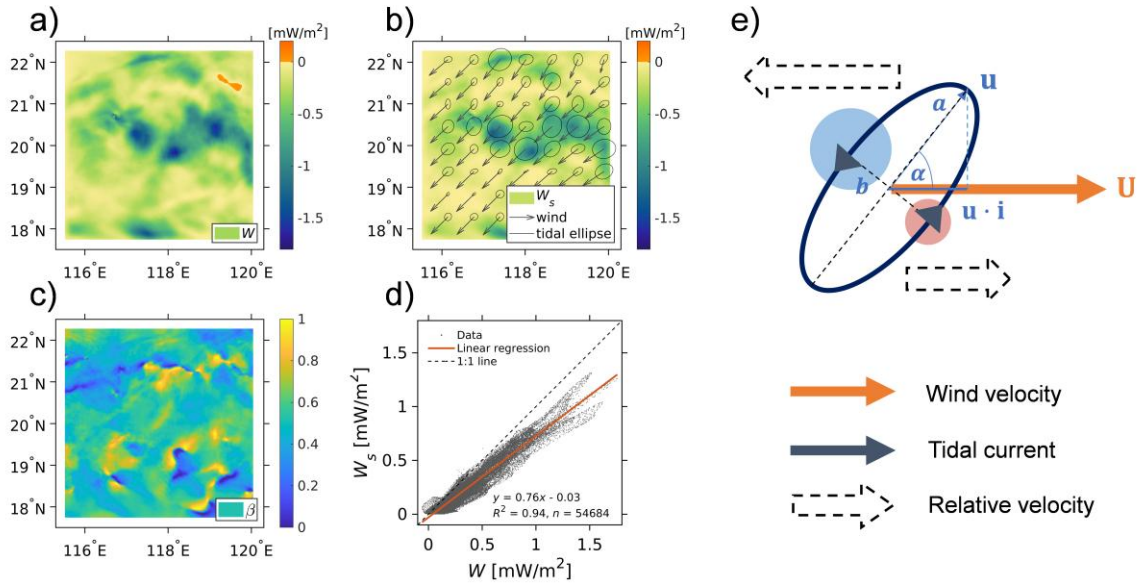


Fig. 2 | Illustration of the tidally averaged wind damping of ITs. (a) Wind work (Eq. 1) of the K_1 ITs obtained through dynamical decomposition and bandpass filtering from numerical simulations near Luzon Strait during winter (black triangle in Fig. 1a). (b) Tidally averaged wind damping of ITs calculated using the scaling (Eq. 3). Arrows represent wind vectors, and circles

represent tidal ellipses. (c) The coefficient β , describing the alignment of the tidal ellipse with the wind. (d) Scatter plots of the exact wind damping of ITs versus the results from the scaling. The high correlation indicates that the scaling provides a reasonable approximation of the exact wind work on ITs. (e) Schematic diagram illustrating the mechanism of tidally averaged wind damping of ITs. a and b represent the semi-axes of the tidal ellipse. α is the angle between the major axis of the tidal ellipse and the wind. $\mathbf{i}$ is the unit vector in the direction of the wind velocity. Enhanced relative wind stress occurs when the tidal current opposes the wind, producing negative work that exceeds the positive work when the current flows with the wind, resulting in net damping over a complete tidal cycle. The schematic is illustrative and not drawn to scale, with non-quantitative ellipse size and wind velocity.

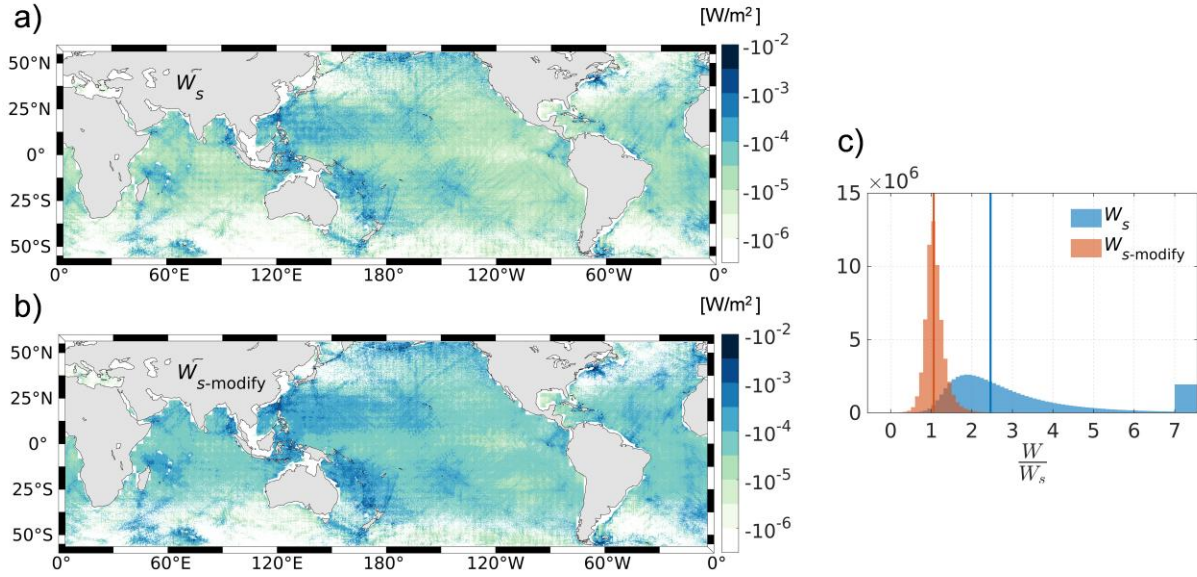
Global evaluation and refinement of the scaling

We now apply the scaling devised in the previous section to the LLC4320 wind field and the surface internal tidal ellipses to assess the global estimate of the tidally averaged wind damping of ITs (Fig. 3a). Because each tidal constituent is characterised by a distinct tidal ellipse, we compute the wind work for each tidal constituent (K_1 , O_1 , M_2 and S_2) separately and then sum their contributions to obtain the total W_s . To account for the strong seasonality of the wind field, the scaling is evaluated using seasonal means, and then averaged to produce the annual estimate. The spatial pattern of the W_s closely resembles the wind work diagnosed directly from the LLC4320 simulation (Fig. 1a), indicating that the scaling captures the dominant geographical structure of wind-ITs interactions. However, the global integral of the scaled estimate $W_s = -13.7$ GW, is approximately half the value of the simulation-based direct estimate (W). This systematic

underestimation is further evident from the histogram of their ratio (Fig. 3c), which peaks near two.

Such bias is expected because the harmonic analysis retains only the coherent component of each tidal constituent, thereby omitting incoherent components and the superposition of multiple constituents. To test this interpretation, we compare the ratio W_s/W (Fig. S1a) with the ratio of the summed kinetic energies of each tidal constituent, computed individually from the harmonic constants, to the total ITs kinetic energy calculated from the full ITs velocity (Fig. S1b). The two ratios closely match, with nearly identical spatial distributions and tight correspondence. These results identify the absence of incoherent ITs energy as the primary source of bias, emphasising the need to match the tidal input to the wind work component being estimated. While harmonic ellipses are appropriate for coherent ITs damping, estimating total ITs damping requires an equivalent statistical representation of the full ITs velocity field.

Motivated by this interpretation and the energetic consistency described above, we introduce a statistically derived modification to W_s by multiplying it by the ITs kinetic energy ratio (total over sum of each harmonic constituent). The modified estimate yields a global damping of 25.5 GW, in close agreement with the directly diagnosed value of W from the LLC4320 simulation (Fig. 3b). The distribution of their ratio is tightly centred around unity (Fig. 3c), indicating that the scaling provides an accurate estimate of wind damping when ITs kinetic energy is properly derived from full ITs velocities.



180

181 **Fig. 3 | Global application of the scaling for the tidally averaged wind damping of ITs.**

182 (a) The annually averaged wind damping of ITs estimated by the scaling (Eq. 3), using the wind
 183 field and surface harmonic internal tidal ellipses in LLC4320, calculated separately for each tidal
 184 constituent (K_1 , O_1 , M_2 and S_2) and then summed. (b) The modified tidally averaged wind
 185 damping of ITs, obtained by multiplying W_s by the ratio (Fig. S1b) of total ITs kinetic energy
 186 (calculated from the full ITs velocity) to the sum of kinetic energies of individual tidal
 187 constituents (computed from their harmonic constants). (c) Histogram of the ratio of the wind
 188 work W to the estimates in (a) and (b). The vertical lines indicate the median values. The
 189 estimate based on harmonic tidal ellipses systematically underestimates the directly diagnosed
 190 wind damping because harmonic analysis captures only the coherent ITs energy. Accounting for
 191 the additional ITs energy represented in the full velocity field shifts the ratio toward unity,
 192 indicating that the scaling closely reproduces the directly diagnosed wind damping when the full
 193 ITs kinetic energy is represented.

Observational estimate of the global wind damping of ITs

Having established and validated the scaling using the LLC4320 simulation, we apply it to QuikSCAT winds and GDP-derived surface internal tidal velocities to obtain an observation-based estimate of global wind damping of ITs (see [Methods](#)). The conservative estimate shown in [Fig. 4](#), which includes all semidiurnal ITs but only coherent diurnal constituents, yields a global damping rate of 15.4 GW. Including the full diurnal-band kinetic energy increases the estimate to 21.7 GW ([Fig. S2](#)), although this band may also contain non-tidal motions (see [Discussion](#)).

To place the conservative estimate in the context of the global ITs energy budget, we compare it with the total diagnosed ITs energy sinks. Globally integrated, wind damping accounts for 2% of the diagnosed ITs energy sinks, with a median pointwise contribution of approximately 4% ([Fig. 4f](#)), indicating a modest contribution to the global ITs energy budget. However, its global integral does not fully reflect its regional importance because wind damping and ITs dissipation have markedly different spatial distributions. Whereas ITs dissipation is concentrated in narrow bands associated with steep topography ([Fig. 4c](#)), wind damping extends across much broader regions of the ocean ([Fig. 4a](#)). Its local contribution is therefore highly heterogeneous, reaching approximately 10% in several mid-latitude regions characterised by strong wind forcing and intermediate levels of ITs energy ([Fig. 4e](#)). These results identify wind damping as a globally modest but spatially extensive ITs energy sink.

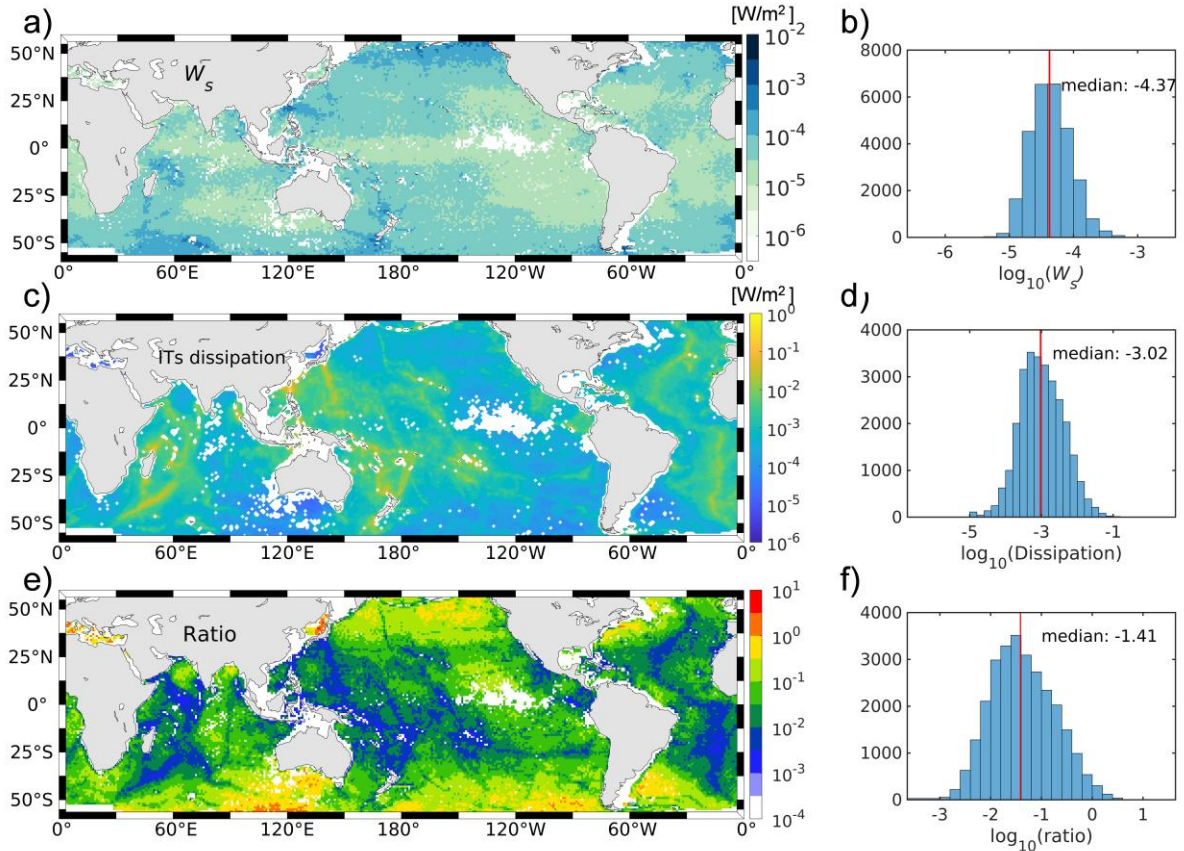


Fig. 4 | Global observation-based estimate of wind damping of ITs. The observation-based estimate is compared with previously estimated ITs dissipation to assess the relative contribution of wind damping to ITs energy sinks. (a) Global distribution of wind damping derived from the scaling framework applied to the QuikSCAT wind product and GDP-derived surface internal tidal velocities. (c) Global map of ITs energy sinks estimated by de Lavergne et al.¹³ (e) Ratio of wind damping to ITs dissipation. (b, d, f) Corresponding histograms, with the red vertical lines indicating the median values.

Discussion

The wind damping of ITs, albeit conceptually realised, has received little quantitative attention in assessing the ITs energy budget. By applying a physically based scaling to observational

products, we identify wind forcing as a systematic and non-negligible sink of ITs energy, a conclusion independently supported by direct diagnosis in a realistic global ocean simulation. Our conservative observation-based estimate yields a globally integrated damping rate of 15.4 GW, equivalent to approximately 2% of the globally integrated ITs dissipation. Locally, however, wind damping is more appreciable: its median ratio to ITs dissipation is approximately 4%, reaching about 10% in several mid-latitude regions. Moreover, unlike ITs dissipation, which is concentrated around steep topography, wind damping has a much broader spatial footprint. Its globally integrated magnitude is also of the same order as the wind damping of mesoscale eddies ($\sim 50 \text{ GW}^{21}$), highlighting wind damping as an appreciable pathway of mechanical energy exchange across the air-sea interface.

The differences between the LLC4320 diagnosis and the observation-based estimate largely reflect uncertainty in how the kinetic energy of surface ITs is represented and sampled, rather than primarily from limitations of the scaling itself. When applied to the full ITs kinetic energy in LLC4320, the scaling closely reproduces the directly diagnosed wind damping, indicating that it captures the leading dynamics of the interaction within this one-way air-sea forcing framework. Estimates based solely on tidal harmonic constants (W_s) are substantially lower because they omit incoherent variability^{34–36} associated with phase offsets between ITs and barotropic forcing³⁵, modulated by topography³⁷, stratification³⁸, and subtidal flows³⁹. The direct diagnosis from LLC4320 yields a globally integrated net wind work of -29.8 GW. However, comparisons of the kinetic energy of semidiurnal ITs are not uniform across observational datasets. The semidiurnal ITs kinetic energy in the LLC4320 simulation exceeds estimates from moored observations by approximately 20%³², but exceeds the GDP-derived estimate by about a factor of two³¹. Thus, the difference between the simulation and GDP cannot be attributed solely

to excessive ITs energy in LLC4320, but also reflects differences between the Eulerian and Lagrangian samplings. In particular, GDP velocities are affected by spectral smearing relative to the Eulerian framework, whereby tidal peaks are broadened and reduced due to convolution of spatial and temporal variability^{31,40,41}. Previous comparisons show that Lagrangian sampling recovers, on average, approximately 75% of the corresponding Eulerian energy³³. Despite this attenuation, GDP is currently the only globally distributed in situ velocity dataset from which semidiurnal tidal-band kinetic energy, including both coherent and incoherent variability, can be estimated. Accordingly, we regard -15.4 GW, obtained using the full semidiurnal band but only coherent diurnal constituents, as a conservative observation-based estimate rather than a definitive global value.

Neither the observation-based scaling nor the LLC4320 diagnosis explicitly accounts for atmospheric adjustment to internal tidal currents. Both therefore estimate the wind-ITs energy transfer under effectively one-way atmospheric forcing. To assess the sensitivity of this energy transfer to fully coupled ocean-atmosphere dynamics, we further examined ITs wind work in a fully coupled ocean-atmosphere simulation (COAS) as a sensitivity test (see [Supplementary Methods](#)). The fully coupled simulation yields a globally integrated ITs net wind work of -6.4 GW ([Fig. S3](#)), with negative and positive contributions of approximately -9.1 and +2.7 GW, respectively. In the fully coupled simulation, the globally integrated wind work is smaller in magnitude but remains negative, both annually and in all four seasons. In regions with high ITs energy, the wind work also remains predominantly negative ([Fig. S4](#)). Some localised positive values may reflect overlap with near-inertial variability or transient atmospheric forcing ([Fig. S5](#)). Positive high-frequency wind work has been widely associated with near-inertial motions²⁴, whereas coupled simulations of baroclinic tides generally indicate damping¹⁵. Because the

coupled experiment does not isolate current-mediated momentum feedbacks from thermodynamic coupling or associated changes in atmospheric variability, the origin of these localised positive values cannot be determined from the present simulation and may be model-dependent. Consistent with this model dependence, Delpech et al.¹⁵ obtained a more negative integrated wind work (-0.13 GW) than the COAS simulation (-0.07 GW) over the same region (Fig. S6). These coupling-related uncertainties affect the precise global magnitude of the wind-ITs energy transfer, but do not alter the robust tendency toward negative wind work in energetic ITs regions and in the global integral.

Taken together, our results identify wind damping as a previously under-quantified and spatially widespread sink in the global ITs energy budget. Although its precise magnitude remains sensitive to the representation of ITs energy and to ocean-atmosphere coupling, the consistent tendency across observation-based estimates and high-resolution simulations indicates that the net influence of surface winds on energetic ITs is predominantly damping. This air-sea pathway therefore extends the classic ITs energy budget beyond purely oceanic dissipation processes and provides a mechanism through which atmospheric variability can influence the fate of tidal energy and, ultimately, its contribution to ocean mixing.

Methods

Description of datasets

Our analysis of wind work on ITs combines a high-resolution numerical simulation with observationally derived products. For the directly diagnosed simulation-based wind work on ITs (W), we used wind stress and sea surface velocity fields from the high-resolution numerical simulation LLC4320. The simulation is based on the Massachusetts Institute of Technology

General Circulation Model (MITgcm)⁴². It has a time step of 25 seconds, with hourly snapshot outputs. Its spatial resolution is $1/48^\circ$, allowing the resolution of high-mode ITs and submesoscale processes. Surface forcing is derived from 0.14° European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data with a 6-hour temporal resolution, linearly interpolated to hourly results. The wind work is calculated using the bulk formulation of Large and Yeager⁴³. Further details can be found in Arbic et al.⁴⁴. The LLC4320 simulation has been validated in numerous studies^{29,31,33}.

To calculate the tidally averaged wind work using the scaling (W_s), we combined wind field data from 0.14° ECMWF with the surface internal tidal currents obtained from the LLC4320 simulation. We first evaluated the scaling using the harmonic constants of the LLC4320 surface currents, which represent only the coherent component of the ITs. We then repeated the calculation using the complete ITs velocity field isolated from the hourly LLC4320 output, thereby including both coherent and incoherent tidal-band variability.

For the observation-based estimate of wind damping, we combined wind statistics from QuikSCAT with GDP-based estimates of surface internal-tidal currents. We used the QuikSCAT Version 4 ocean surface vector wind product (0.25° gridded global fields) from Remote Sensing Systems (RSS). For each grid cell, the 10-m wind vectors were averaged component-wise over all valid retrievals during 1999-2009. The surface ITs kinetic energy was taken from Arbic et al.³¹, while the orientation of the ITs ellipses was obtained from the E32 drifter-only solution of Zaron and Elipot⁴⁵, which is fitted to GDP velocity observations and cross-validated against geodetic-mission altimetry. Our conservative estimate uses bandpass-filtered GDP velocities in the semidiurnal band to retain both coherent and incoherent ITs energy, while using harmonic constants in the diurnal band to minimise contamination from diurnal jets, Ekman/submesoscale

variability, and near-inertial flows³¹. Specifically, the semidiurnal contribution was calculated using kinetic energy integrated over the 1.7-2.3 cycles per day frequency band. The diurnal contribution was calculated using the K_1 and O_1 harmonic ITs currents from the drifter-only solution. To provide an upper-bound estimate, an alternative estimate using GDP kinetic energy within the full diurnal tidal-frequency band was also calculated.

To compare wind damping of ITs with their energy sinks, we used the results of de Lavergne et al.¹³, who developed a framework for mapping global ITs energy dissipation. This framework is based on Lagrangian tracking of low-mode ITs energy fluxes through observed stratification. Their approach builds on the energy compartment model proposed by Eden and Olbers⁴⁶, which parameterises the propagation and dissipation of internal gravity waves, and extends it to include explicit treatments of interactions with topography and multiple dissipative processes. de Lavergne et al. estimated the contributions to the column-integrated internal tidal dissipation rate from processes such as dissipation at critical slopes, breaking due to shoaling, attenuation by wave-wave interactions, and scattering by abyssal hills. The climatological dissipation rates derived from this parameterisation show excellent agreement with estimates based on fine-structure observations. Therefore, we use their data to compare the ITs energy sinks with wind damping of ITs.

We additionally diagnosed ITs wind work in a two-way coupled ocean-atmosphere simulation²⁴ to assess the sensitivity of the results to atmospheric adjustment. The wind work was calculated using the same procedure as in the LLC4320 simulation. Details of the configuration are provided in the Supplementary Methods.

Wind work decomposition

The dynamical decomposition approach³⁰ effectively decomposes multiscale oceanic motions, offering a significant improvement over previous approaches that relied solely on fixed-frequency and -wavenumber cutoffs. In this study, we apply the dynamical decomposition approach to the wind work by dividing the global domain into $5^\circ \times 5^\circ$ boxes and extracting the ITs components from both the ocean surface velocity $\mathbf{u}$ and the wind stress $\boldsymbol{\tau}$ separately within each box.

Specifically, the decomposition of wind work involves three steps. The first step is to separate the large-scale motions (barotropic tides and large-scale flows) in physical space by removing the mean and linear trends from the data. In the second step, the remaining part is multiplied by a 3D Tukey window to reduce spectral leakage and then Fourier transformed to obtain the matrices $\widehat{u_{mFull}}$ and $\widehat{\tau_{mFull}}$. Internal waves are extracted by comparing the relative amplitudes of horizontal divergence and relative vorticity at each location in Fourier space. We further apply temporal band-pass filtering at 0.9-1.15 cpd and 1.7-2.2 cpd to isolate the tidal components. Finally, the separated physical quantities in 3D Fourier space are inverse Fourier transformed to obtain the results in physical space. Values near the edges, attenuated by the Tukey window, are considered artificial and removed from the analysis. The wind stress is then decomposed using the same method as for the ocean surface velocity. The wind work $\boldsymbol{\tau}_t \cdot \mathbf{u}_t$ is calculated in physical space and then averaged annually.

Tidally averaged wind damping of ITs

Given that the wind speed is usually much larger than the speed of oceanic flows, $|\mathbf{U}| \gg |\mathbf{u}|$, it can be easily shown that $|\mathbf{U} - \mathbf{u}| \approx |\mathbf{U}| - \mathbf{u} \cdot \mathbf{i}$, where $\mathbf{i}$ is the unit vector in the direction of the wind velocity⁴⁷. Therefore, the wind work

$$\begin{aligned} \bar{W} &= \overline{\boldsymbol{\tau}_t \cdot \mathbf{u}_t} \approx \overline{[\rho_a C_d (|\mathbf{U}| - \mathbf{u} \cdot \mathbf{i}) (\mathbf{U} - \mathbf{u})]_t \cdot \mathbf{u}_t} \\ &\approx \overline{[\rho_a C_d (|\mathbf{U}|\mathbf{U} - \mathbf{u} \cdot \mathbf{i} \cdot \mathbf{U} - |\mathbf{U}|\mathbf{u} + \mathbf{u} \cdot \mathbf{i} \cdot \mathbf{u})]_t \cdot \mathbf{u}_t} \end{aligned} \quad (4)$$

Here, t denotes the temporal and spatial filtering at ITs scales. Considering that the spatial scale of the wind is much larger than that of ITs,

$$[|\mathbf{U}|\mathbf{U}]_t \approx 0,$$

$$[\mathbf{u} \cdot \mathbf{i} \cdot \mathbf{U}]_t \approx \mathbf{u}_t \cdot \mathbf{i} \cdot \mathbf{U},$$

$$[|\mathbf{U}|\mathbf{u}]_t \approx |\mathbf{U}| \cdot \mathbf{u}_t. \quad (5)$$

Then,

$$\bar{W} \approx \rho_a C_d \cdot \overline{-|\mathbf{U}|(\mathbf{u}_t \cdot \mathbf{i})^2 - |\mathbf{U}||\mathbf{u}_t|^2 + \mathbf{u}_t \cdot \mathbf{i} \cdot |\mathbf{u}_t|^2}. \quad (6)$$

Again, since $\mathbf{u}_t$ is small compared with $|\mathbf{U}|$, and the third-order tidal velocities average to zero over a cycle, the $\mathbf{u}_t \cdot \mathbf{i} \cdot |\mathbf{u}_t|^2$ term can be neglected. The wind work can be simplified as:

$$\bar{W} \approx \rho_a C_d \cdot \overline{-|\mathbf{U}|(\mathbf{u}_t \cdot \mathbf{i})^2 - |\mathbf{U}||\mathbf{u}_t|^2}. \quad (7)$$

The residual terms can be obtained through the geometric conversion of the tidal ellipse that

$$\overline{\mathbf{u}_t^2} = \frac{1}{2\pi} \int_0^{2\pi} \mathbf{u}_t^2 d\theta = \frac{a^2 + b^2}{2}, \quad (8)$$

$$\overline{(\mathbf{u}_t \cdot \mathbf{i})^2} = \frac{1}{2\pi} \int_0^{2\pi} (\mathbf{u}_t \cdot \mathbf{i})^2 d\theta = \frac{a^2 \cos^2 \alpha + b^2 \sin^2 \alpha}{2}. \quad (9)$$

Here, α is the angle between the direction of the major axis of tidal ellipse and the wind direction. a and b represent the semi-axes of the tidal ellipse (Fig. 2e). Finally, we can obtain the scaling as follows:

$$W_s = -(1 + \beta) \rho_a C_d \cdot \overline{|\mathbf{U}|} \cdot \overline{\mathbf{u}_t^2}, \quad (10)$$

$$\beta = \frac{(\mathbf{u}_t \cdot \mathbf{i})^2}{\mathbf{u}_t^2} = \frac{a^2 \cos^2 \alpha + b^2 \sin^2 \alpha}{a^2 + b^2} = 1 - \frac{(a^2 - b^2) \sin^2 \alpha}{a^2 + b^2} < 1. \quad (11)$$

Here, β is a coefficient describing the alignment of the tidal ellipse with the wind direction.

Data availability

The LLC4320 data are available at https://data.nas.nasa.gov/ecco/eccodata/llc_4320/. The 0.14° wind field data from ECMWF used in the LLC4320 are downloaded from <https://rda.ucar.edu/datasets/d113000/>. The QuikSCAT Version 4 wind product (0.25° × 0.25° global gridded product) was obtained from Remote Sensing Systems (RSS; <https://www.remss.com/>). Near-surface oceanic kinetic energy data from GDP observations are available at <https://doi.org/10.7302/PTG7-YW20>. The GDP-based harmonics data are accessible at https://podaac.jpl.nasa.gov/dataset/BAROCLINIC_HRET14. The data of ITs energy sinks are downloaded from <https://doi.org/10.17882/58105>.

Code availability

The MATLAB code used to decompose ocean surface velocity and wind stress into internal-tide-associated components is publicly available on Zenodo at <https://doi.org/10.5281/zenodo.22069515>.

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505 **Author contributions**

506 Z.L. and Y.L. designed the study. Y.L. performed the analysis and drafted the paper with
507 assistance from D.W. and Z.L. C.W. contributed to the refinement of the manuscript.

508

509 **Competing interests**

510 The authors declare no competing interests.

511

512 **Additional information**

513 **Supplementary information**

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