1. Why the Penman equation should not be directly used to estimate PET and PETa under dry (unsaturated) conditions

For a saturated surface, the Penman equation is derived based on two key conditions:

1) **The evaporative surface is saturated**, allowing the introduction of the slope of the saturation vapor pressure curve (Δ) into the Penman equation. This eliminates the dependence on surface temperature (Ts), and combination of the energy-based ET (ETe) and the aerodynamics-based ET (ETa) yields:

$$\Delta\lambda ET_e + \gamma\lambda ET_a = \Delta R_n + \frac{\rho c_p(e_a^* - e_a)}{r_a} \quad (R1)$$

2) **Under wet conditions, ET is equal to both ETe and ETa**, leading to the classic Penman equation:

$$\lambda ET = \frac{\Delta R_n + \frac{\rho c_p(e_a^* - e_a)}{r_a}}{\Delta + \gamma} \quad (R2)$$

However, for a dry (unsaturated) surface, these conditions no longer hold. Assuming the surface is saturated, we can estimate an energy-based PET (PETe) and an aerodynamics-based PET (PETa), but under dry conditions, PETe is lower than PETa:

$$\frac{PET_e}{PET_a} = \frac{1 + \frac{1}{\beta}}{1 + \frac{1}{\beta_w}} \quad (R3)$$

where β is the Bowen ratio and β_w is the wet Bowen ratio. Under wet conditions, $\beta = \beta_w$ and $PET_e = PET_a$. However, under dry conditions, $\beta > \beta_w$ leading to $PET_e < PET_a$.

To account for this discrepancy, we introduce an adjustment parameter

$$k' = \frac{1 + \frac{1}{\beta}}{1 + \frac{1}{\beta_w}} \quad (R4)$$

This allows us to modify the Penman equation as follows:

$$\lambda PET_e = \frac{\Delta R_n + k'\frac{\rho c_p(e_a^* - e_a)}{r_a}}{\Delta + \gamma} \quad (R5)$$

$$\lambda PET_a = \frac{\Delta R_n/k' + \frac{\rho c_p(e_a^* - e_a)}{r_a}}{\Delta + \gamma} \quad (R6)$$

Under dry conditions, direct application of the Penman equation (R2) with observed meteorological variables overestimates the PET (or PETe) as vapor pressure deficit ($e_a^* - e_a$) is overestimated (higher than that under wet conditions, i.e., $k'(e_a^* - e_a)$). Conversely, equation (R2) would underestimate the apparent PET (or PETa) because it neglects additional energy input from the surrounding environment. By considering this additional energy input (A_e), PETa over a small wet area (e.g., an evaporation pan) can be expressed as

$$\lambda PET_a = \frac{\Delta(R_n + A_e) + \frac{\rho c_p (e_a^* - e_a)}{r_a}}{\Delta + \gamma}, \qquad 0 < A_e < \left(\frac{1}{k'} - 1\right) R_n \ (R7)$$

Since A_e is uncertain—evaporation from a small pan differs from that of a larger pan due to variations in A_e (and thus Ts)—PETa becomes indeterminate. However, an upper limit for PETa can be established when the surface temperature of the small wet area approaches its maximum value, i.e., the surface temperature (Ts) of the surrounding environment, with total energy supply to the small wet area of R_n/k'.

For a detailed derivation of equations (R1-R6), please refer to Sections 2 and 3 and Fig. 1 of Zhou and Yu (2024).

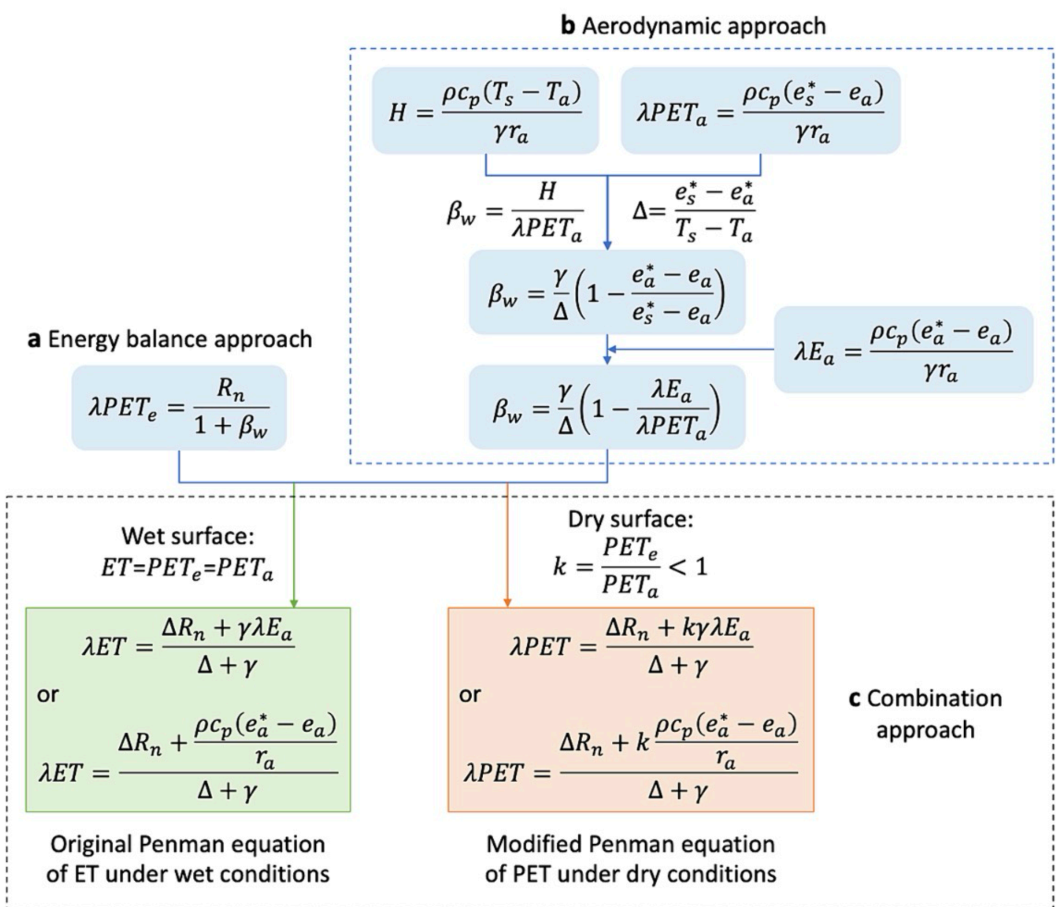

Fig. 1. Derivation of the Penman equation under wet conditions and the modified Penman equation under dry conditions.

2. Why the Priestley-Taylor equation should not be used to estimate PET

Both the Priestley-Taylor equation (PETpt) and the energy-based PETe rely on energy balance principles. However, they differ in the estimation of wet Bowen ratio (β_w and β_{pt}):

$$\lambda PET_e = \frac{R_n}{1+\beta_w} \ (R8)$$

$$\beta_w = \frac{\gamma(T_s - T_a)}{(e_s^* - e_a)} \ (R9)$$

$$\lambda PET_{pt} = \alpha \frac{\Delta R_n}{\Delta + \gamma} \ (R10)$$

$$\beta_{pt} = \frac{1}{\alpha}\frac{\gamma}{\Delta} + \frac{1}{\alpha} - 1 \ (R11)$$

Under wet conditions, such as over the ocean, β_w and PET_e can accurately estimate the wet Bowen ratio and ET with minimal bias. However, the Priestley-Taylor equation requires an empirical parameter α, which varies spatially, as noted by the reviewer. Using a fixed $\alpha = 1.26$ leads to systematic biases, and the bias also varies spatially:

1) Over the tropical ocean (where Ts is higher), the wet Bowen ratio is underestimated, leading to ET overestimation.

2) Over mid- and high-latitude ocean (where Ts is lower), the wet Bowen ratio is overestimated, leading to ET underestimation.

These biases are illustrated in Fig. 5 of Yang and Roderick (2019), Fig. S3 of Zhou and Yu (2025), and Fig. 3d,e of Zhou and Yu (2024).

To correct these biases, the reviewer suggested calibrating α so that PETpt matches ET under wet conditions. However, β_{pt} is highly sensitive to $\frac{\gamma}{\Delta}$ (which depends on Ts) with a sensitivity coefficient of $\frac{1}{\alpha}$. Lowering α over mid- and high-latitude oceans may further exaggerate this sensitivity. Increasing α can reduce this sensitivity and align $\frac{1}{\alpha}$ with ocean observations (~0.24), but this would simultaneously lower β_{pt} to be much lower than the wet Bowen ratio (see the $\frac{1}{\alpha} - 1$ term in equation (R10)).

Since β_{pt} is overly sensitive to temperature changes, the Priestley-Taylor equation is unsuitable for estimating PET under dry conditions, where temperatures are significantly higher than in wet conditions. Fig. 2 and Fig. 3f,g of Zhou and Yu (2024) show that PETpt and β_{pt} exhibit excessive sensitivity to temperature variations driven by surface moisture changes.

This issue highlights a fundamental limitation of the Priestley-Taylor equation in estimating ET under wet conditions and the PET under dry conditions. In particular, the Priestley-Taylor equation fails to accurately capture the sensitivity of the wet

Bowen ratio and hence PET to temperature variations, making it unsuitable for applications in a warming climate.

To overcome this issue, we use β_w and PETe, because

1) β_w can accurately estimate the Bowen ratio for wet surfaces, allowing PETe, estimated with β_w and R_n, to closely match observed/projected ET over the ocean. Please see Figs. 2 and 3 of Zhou and Yu (2024) and Fig. S3 of Zhou and Yu (2025).

2) For dry surfaces, β_w remains a reliable estimator of the Bowen ratio when the surface becomes saturated. While β_w is estimated using observed/projected meteorological variables under dry conditions, it remains fairly constant due to coupled changes in temperature and humidity of the air and at the land surface from dry to wet conditions. Please see Figs. 2 and 3 of Zhou and Yu (2024).

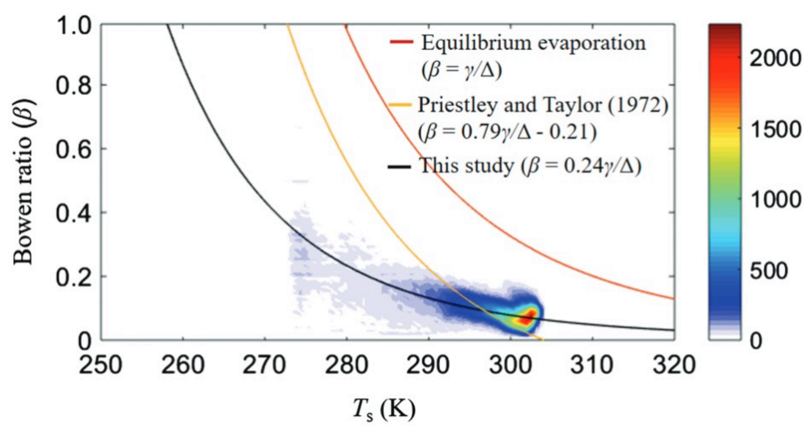

FIGURE 5 Relationship between Bowen ratio (β) and surface temperature (T_s). Colours represent data density. The three solid curves represent equilibrium evaporation (brown), the Priestley–Taylor relationship (yellow) and the best linear fit to the WHOI OAFlux dataset (black), respectively

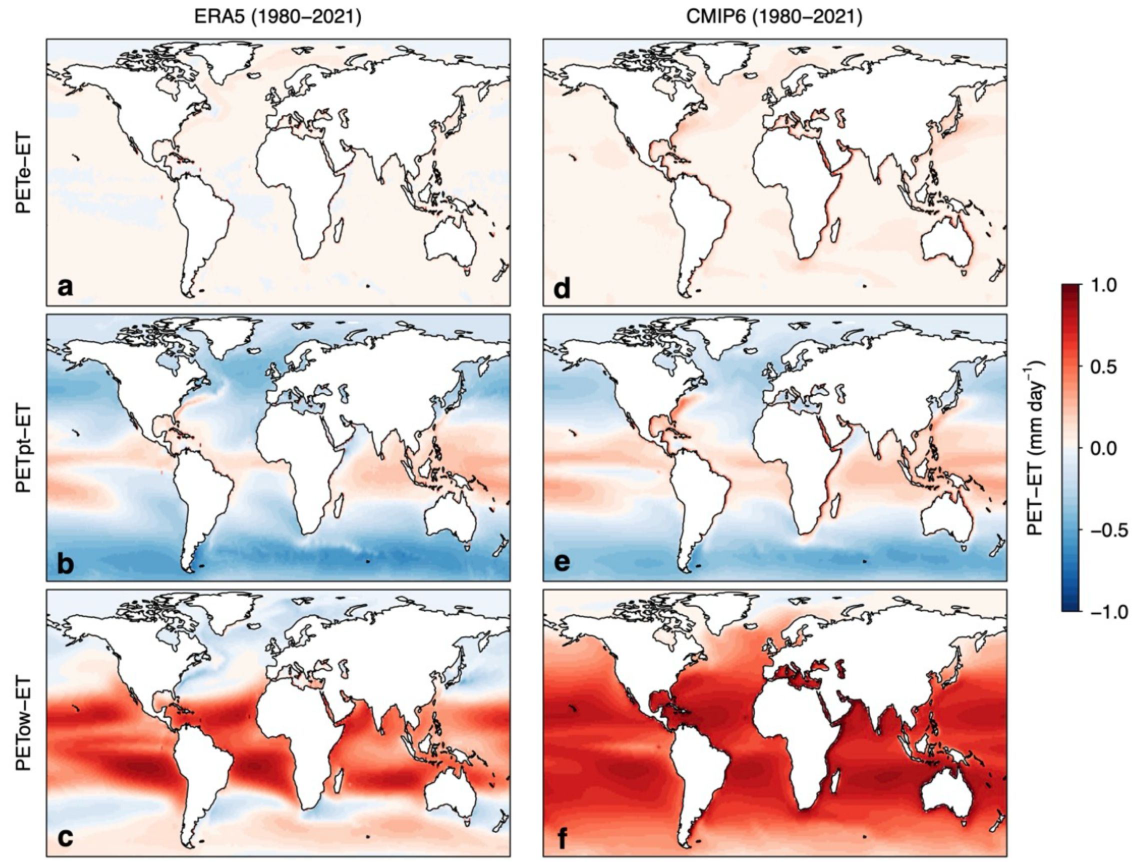

Fig. S3 Differences between the potential and actual evaporation over ocean based on ERA5 and CMIP6. (a-c) Difference between evaporation (ET) and potential evaporation (PET) using the energy-based PETe, the Priestley-Taylor equation (PETpt), and the open-water Penman equation (PETow) for the historical period (1980-2021) based on ERA5. (d-f) The same as a-c, but for the multi-model mean difference based on CMIP6.

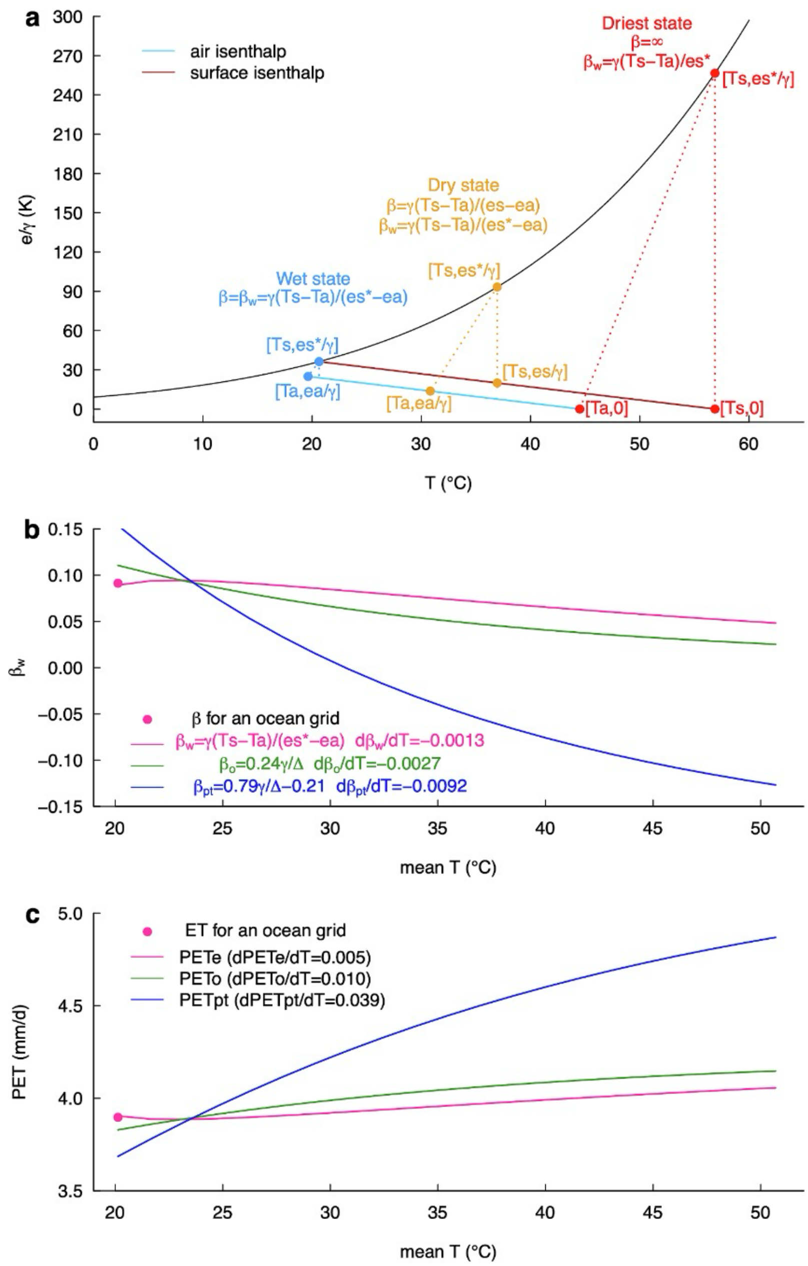

Fig. 2. Illustration of the variation in the wet Bowen ratio (β_w) for an ocean grid cell from the wet to hypothetical driest states (a). The saturation vapor pressure (e^*/γ) is expressed as a function of temperature (T) as shown in the black line. The blue and brown lines represent isenthalpic processes, i.e., constant $T + e/\gamma$, for the air and land surface, respectively. β_w and the Bowen ratio (β) can be calculated under the wet (blue), dry (orange), and driest (red) states. (b and c) Changes in three Bowen ratios (β_w, β_o, and β_{pt}) and related PETs (PET_e, PET_o, and PET_{pt}) with the mean of surface and air temperatures. The pink lines show one possible pathway of changes in β_w and PET_e when surface and air temperatures change in proportion from the wet to the driest states, the green lines show changes in β_o and PET_o based on equation (25), and the blue lines show changes in β_{pt} and PET_{pt} based on the Priestley-Taylor equation (26). The sensitivities of three Bowen ratios and PETs to the mean temperature, for example $d\beta_w/dT$ and $dPET_e/dT$, are calculated as the ratio of their differences over the difference in the mean temperature between the wet and driest conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

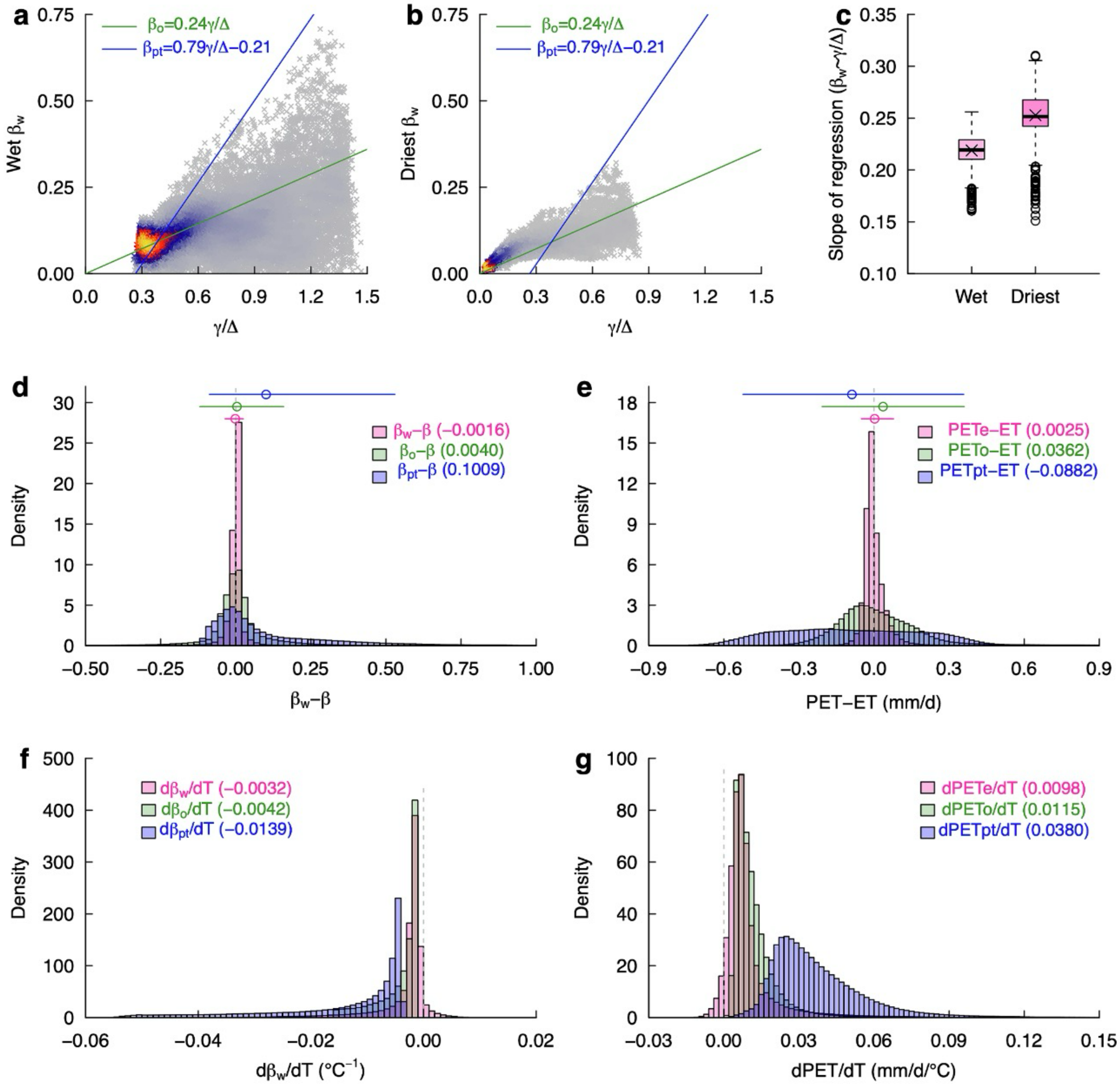

Fig. 3. Variations in the wet Bowen ratio (β_w) under wet and dry conditions. (a, b) Relationship between β_w and γ/Δ under the wet (a) and driest (b) conditions. The color of the scatter points indicates the sample density, with the highest density shown in orange, followed by red and blue, and the lowest density in grey. Monthly data from ocean grid cells for the period 1940–2022 (996 months) in ERA5 are used. (c) Distribution of the linear regression slope between β_w and γ/Δ, i.e., α in equation (27), under the wet and driest conditions. (d) Distribution of the differences between the three Bowen ratios (β_w, β_o, and β_{pt}) and the actual Bowen ratio (β), i.e., sensible over latent heat, for ocean grid cells/months. (e) The same as (d), but for the differences between the three PETs (PET_e, PET_o, and PET_{pt}) and the ET over the ocean. The mean and uncertainty range of the difference (5th to 95th percentile) are shown for each Bowen ratio and PET as circles and horizontal lines. (f, g) Distribution of the sensitivities of the three Bowen ratios (f) and PETs (g) to the mean temperature, for example $d\beta_w/dT$ and $dPET_e/dT$, which are calculated as the ratio of their differences over the difference in the mean temperature between the wet and driest conditions. The values in parentheses show the mean sensitivities of the three Bowen ratios and PETs for ocean grid cells/months. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)