Topographic form stress in the Southern Ocean State Estimate

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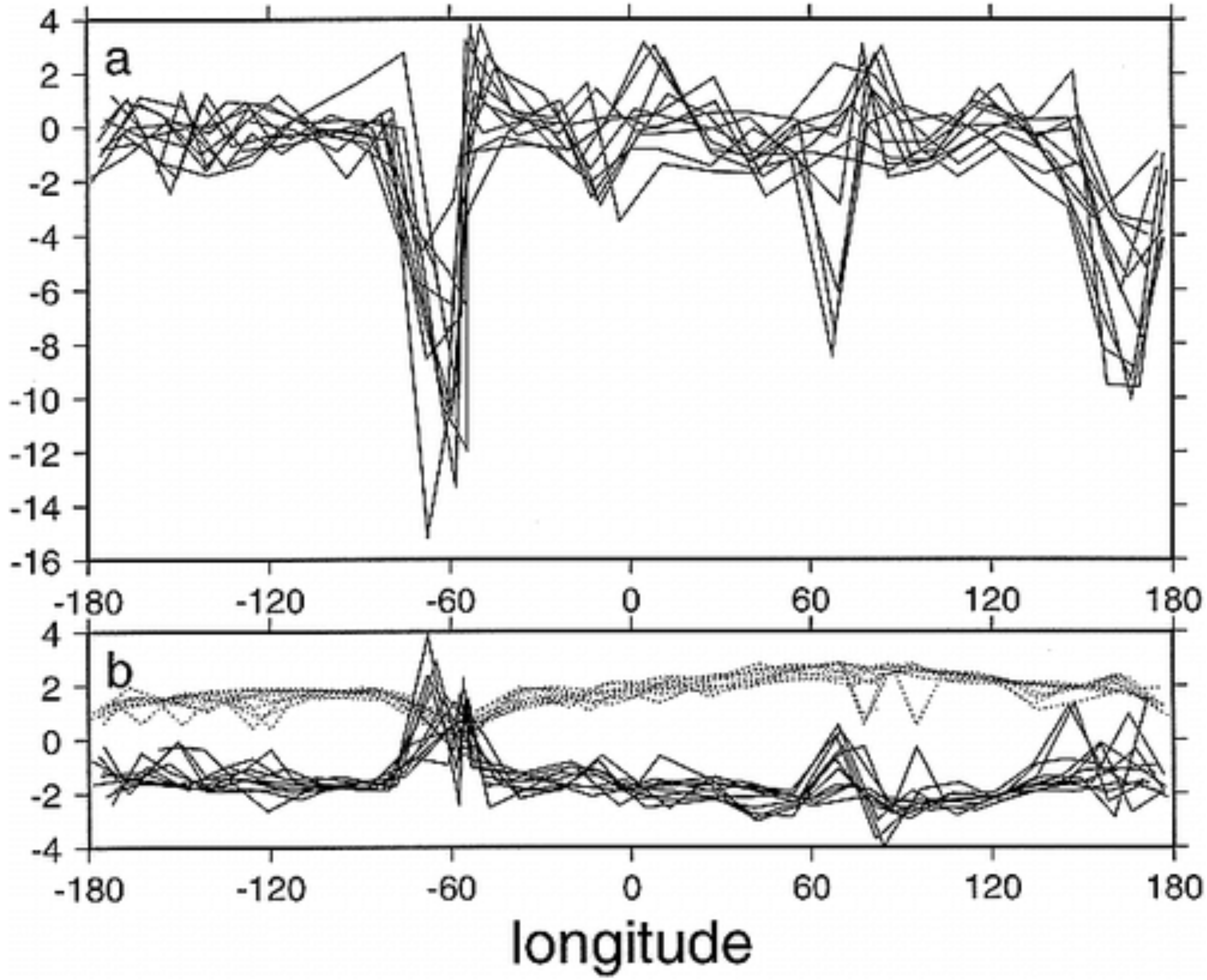
Context

- Theories of the ACC suggest that without boundaries in Drake Passage latitudes, zonal momentum input by wind stress to the ACC is balanced by topographic form stress (The papers we have discussed in this seminar: Munk and Palmen, Johnson and Bryden, Hughes, Olbers)

- Idealized models and high resolution GCM's have demonstrated that wind stress balances form stress in the zonal integral (McWilliams et al. (1978), Treguier and McWilliams (1990), Wolff et al. (1991), and Marshall et al. (1993), Killworth and Nanneh (1994) and Stevens and Ivchenko (1997))

- Gille et al. (1997), looked at the spatial distribution of form stress in 10 degree longitude sections and found that form stress balanced wind stress at all latitudes



Total vertically integrated form stress integrated along streamlines in 10 degree wide swaths

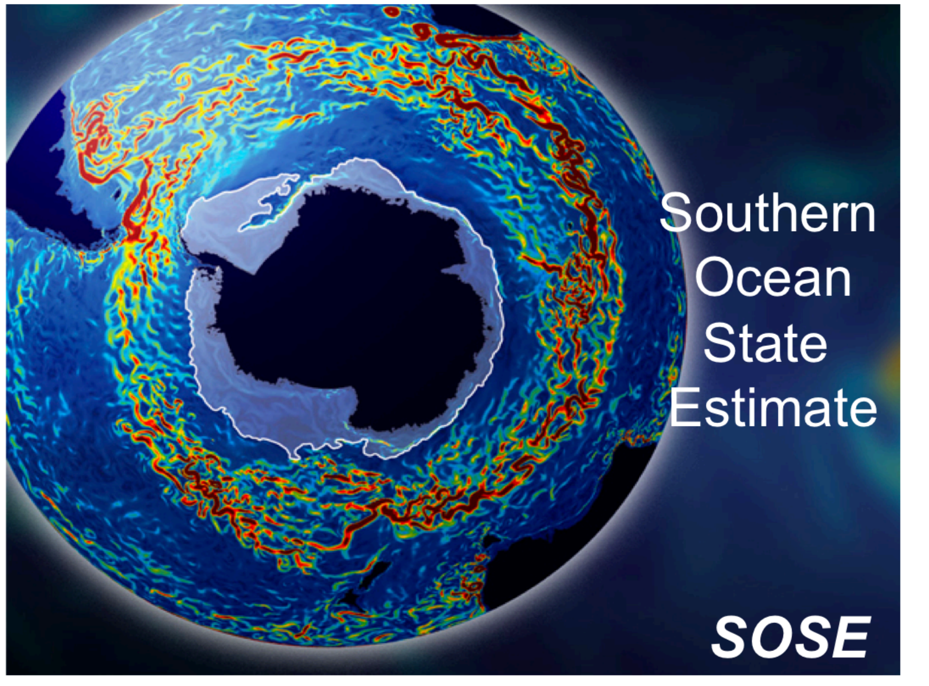
Gille et al. 1997 Fig. 6

This work

- Analyse output from an eddy-permitting data-assimilating state estimate of the Southern Ocean
- Use a direct approach to calculate the pressure gradient across every piece of topography in the domain to obtain full 2-D map of topographic form stress

The Southern Ocean State Estimate

- MITgcm least squares fit to observations using adjoint method
- eddy-permitting, 1/6° resolution, 42 vertical levels, 900 s time step
- data include Argo, CTD, MEOP, satellite SSH, SST, ice cover and geoid
- ERA-interim buoyancy and wind forcing, atmospheric state is adjusted to be consistent with assimilated ocean observations



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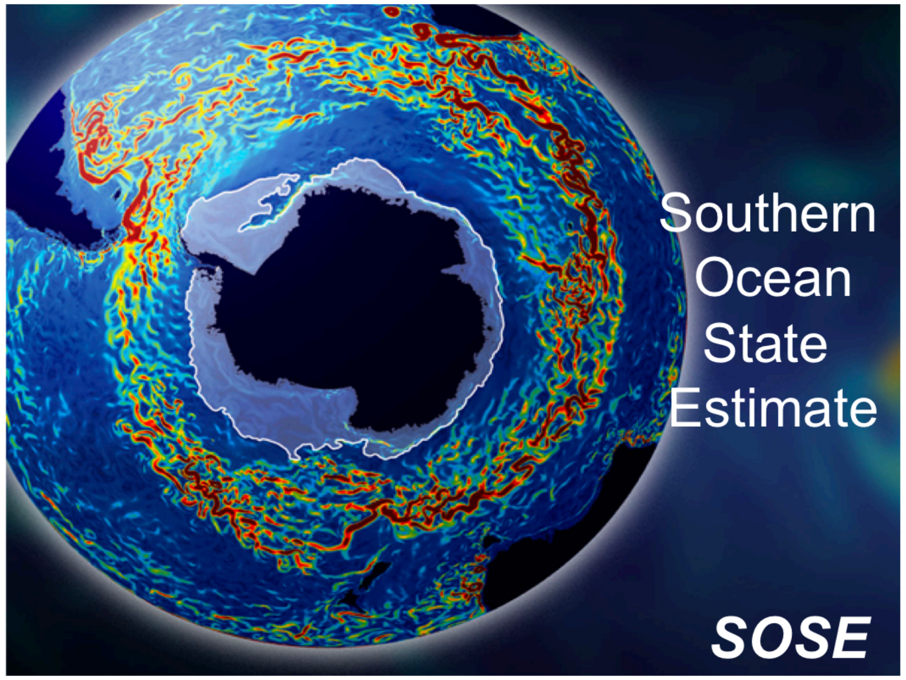
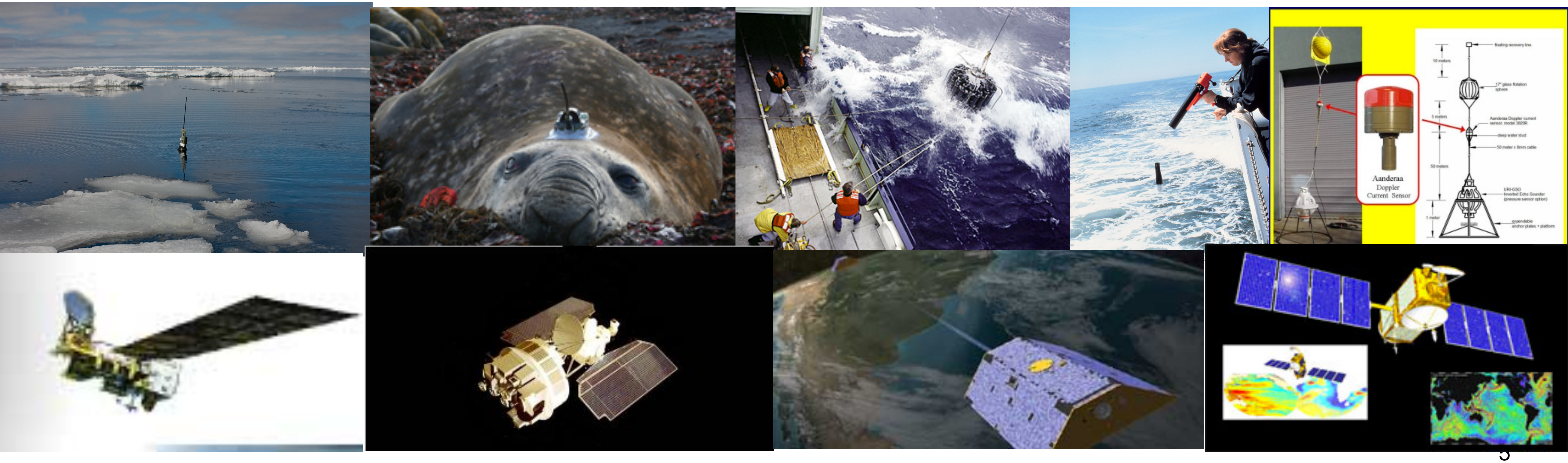




Zonal momentum equation (steady state, continuity):

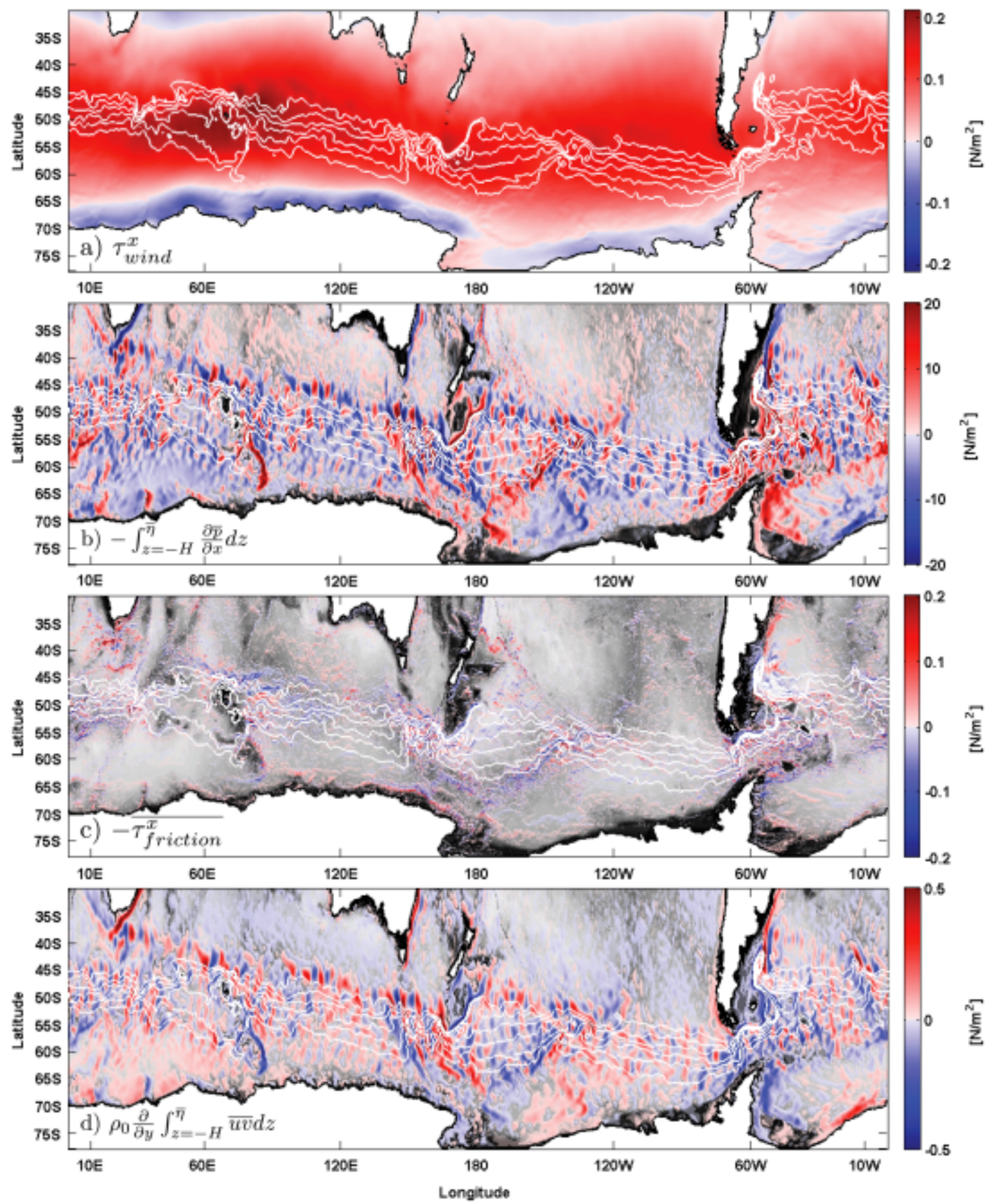
$$\rho_0 \frac{\partial}{\partial x}(\overline{uu}) + \rho_0 \frac{\partial}{\partial y}(\overline{uv}) + \rho_0 \frac{\partial}{\partial z}(\overline{uw}) - \rho_0 f \bar{v} = -\frac{\partial \bar{p}}{\partial x} + \frac{\partial \overline{\tau^x}}{\partial z} + \rho_0 \eta \nabla^2 \bar{u} \quad \text{(A1)}$$

Circumpolar and vertical integral:

$$\rho_0 \oint_x \frac{\partial}{\partial y} \int_{z=-H}^{\bar{\eta}} \overline{uv}\, dz dx = -\oint_x \int_{z=-H}^{\bar{\eta}} \frac{\partial \bar{p}}{\partial x} dz dx + \oint_x \overline{\tau^x_{wind}}\, dx - \oint_x \overline{\tau^x_{friction}}\, dx. \quad (1)$$

meridional momentum flux divergence	topographic form stress in pressure gradient term	wind	friction

Vertically integrated momentum balance terms



wind stress

vertically integrated
zonal pressure gradient

friction

meridional
momentum flux
divergence

$$\rho_0 \oint_x \frac{\partial}{\partial y}\int_{z=-H}^{\overline{\eta}} \overline{uv}\,dzdx = -\oint_x \int_{z=-H}^{\overline{\eta}} \frac{\partial \bar{p}}{\partial x}\,dzdx + \oint_x \overline{\tau^x_{wind}}\,dx - \oint_x \overline{\tau^x_{friction}}\,dx. \quad (1)$$

Fig. 1

Can divide pressure gradient term:

$$-\oint_x \int_{z=-H}^{\overline{\eta}} \frac{\partial \bar{p}}{\partial x} \mathrm{dzdx} = \underbrace{-\oint_x \frac{\partial}{\partial x} \int_{z=-H}^{\overline{\eta}} \bar{p}\,\mathrm{dzdx}}_{i} + \underbrace{\oint_x \overline{p_{atm}} \frac{\partial \bar{\eta}}{\partial x} \mathrm{dx}}_{ii} + \underbrace{\oint_x \overline{p_b} \frac{\partial H}{\partial x} \mathrm{dx}}_{iii}, \quad (2)$$

i: net pressure gradient across zonally bounded basin

ii: transfer of zonal momentum from atmosphere to fluid (negligibly small)

iii: transfer of zonal momentum from fluid to solid earth (topographic form stress?)

Can divide pressure gradient term:

$$-\oint_x \int_{z=-H}^{\overline{\eta}} \frac{\partial \bar{p}}{\partial x} dzdx = \underbrace{-\oint_x \frac{\partial}{\partial x} \int_{z=-H}^{\overline{\eta}} \bar{p}\, dzdx}_{i} + \underbrace{\oint_x \overline{p_{atm} \frac{\partial \bar{\eta}}{\partial x}} dx}_{ii} + \underbrace{\oint_x \overline{p_b \frac{\partial H}{\partial x}} dx,}_{iii} \quad (2)$$

"Total form stress"

i: net pressure gradient across zonally bounded basin

ii: transfer of zonal momentum from atmosphere to fluid (negligibly small)

iii: transfer of zonal momentum from fluid to solid earth (topographic form stress?)

Discretize zonal pressure gradient term to represent distribution of total form stress:

$$-\oint_x \int_{z=-H}^{\overline{\eta}} \frac{\partial \overline{p}}{\partial x} \mathrm{dzdx} = -\sum_x \sum_z \frac{\Delta \overline{p}}{\Delta x} \Delta z \Delta x = -\sum_x \sum_z \Delta \overline{p} \Delta z.$$

Discretize zonal pressure gradient term to represent distribution of total form stress:

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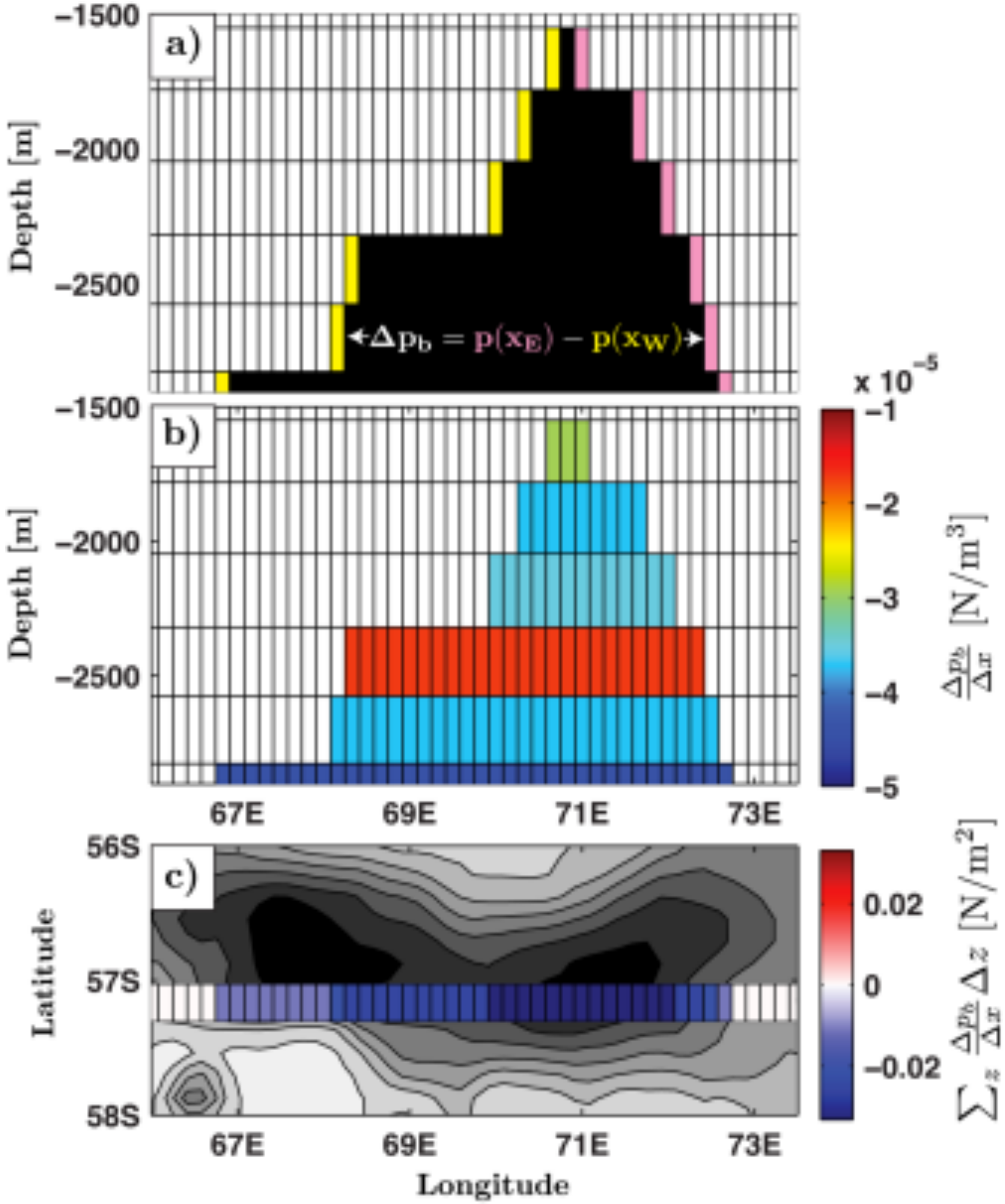
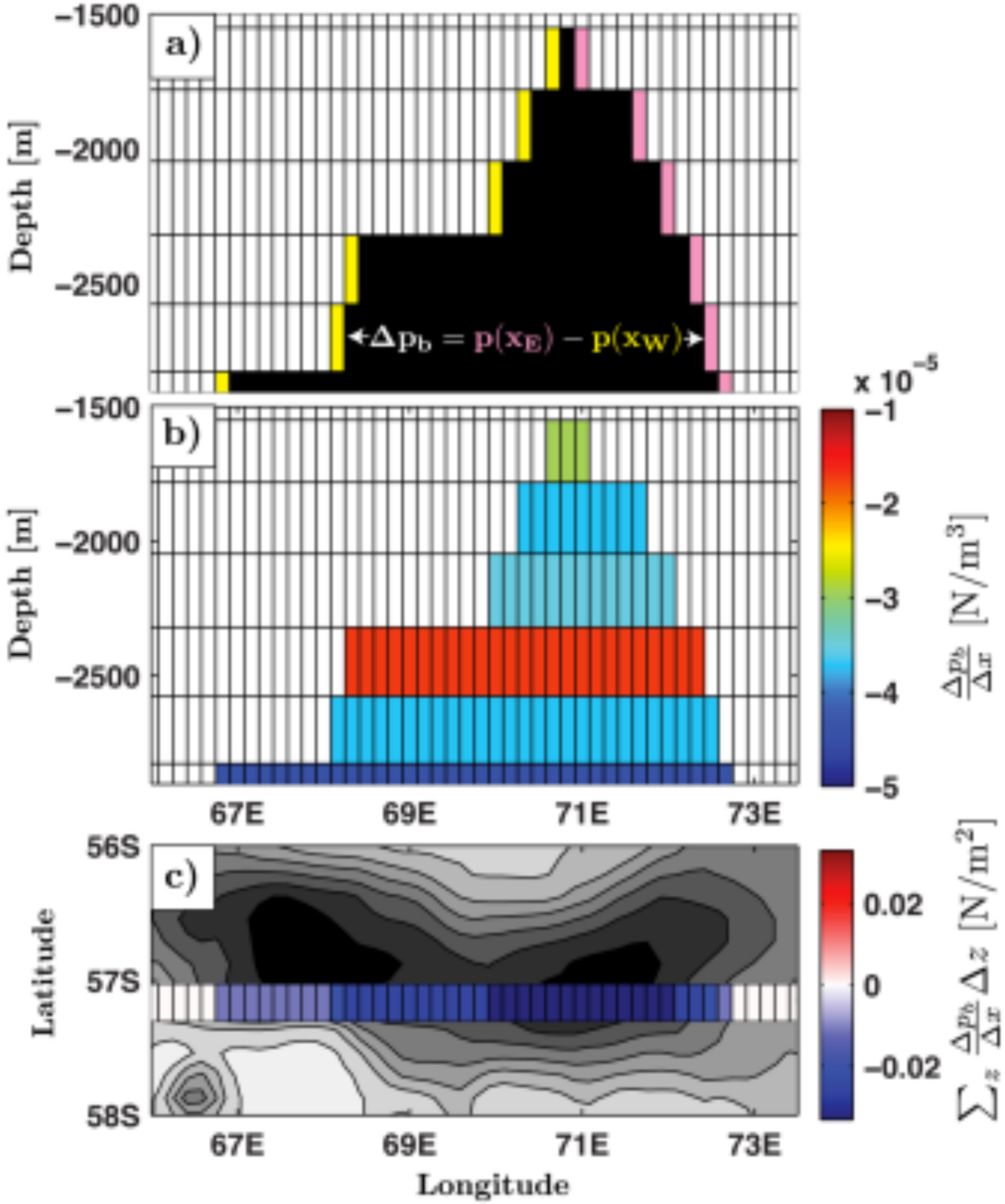
In other words: contribution of each topographic feature to the zonally integrated pressure gradient



$$\Delta\overline{p_b} = \overline{p_b}(x = x_E) - \overline{p_b}(x = x_W)$$

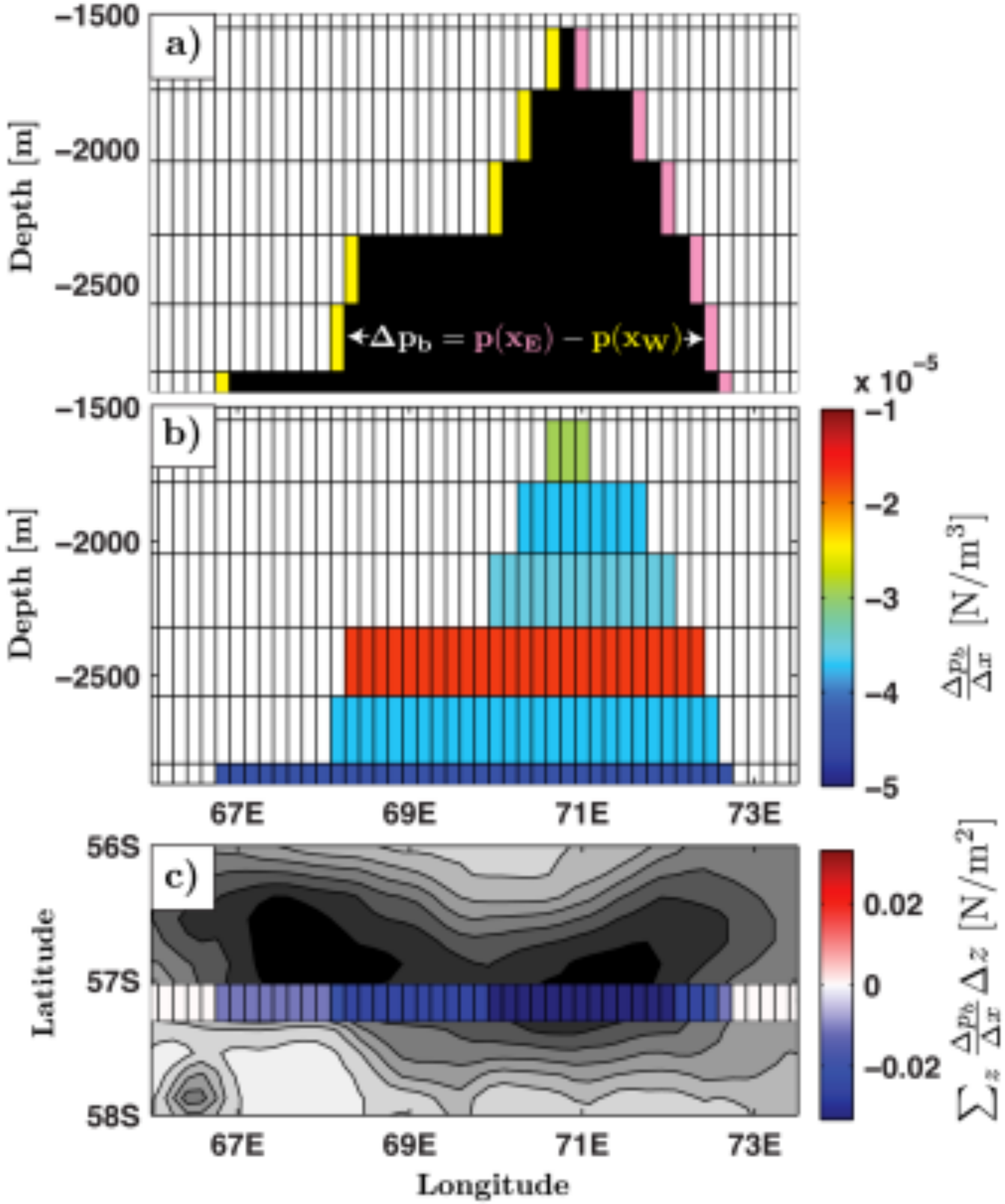
Fig. 2



$$\Delta\overline{p_b} = \overline{p_b}(x = x_E) - \overline{p_b}(x = x_W)$$

$$\frac{\Delta\overline{p_b}}{\Delta x} = \frac{\overline{p_b}(x = x_E) - \overline{p_b}(x = x_W)}{x_E - x_W}$$

Fig. 2



$$\Delta\overline{p_b} = \overline{p_b}(x=x_E) - \overline{p_b}(x=x_W)$$

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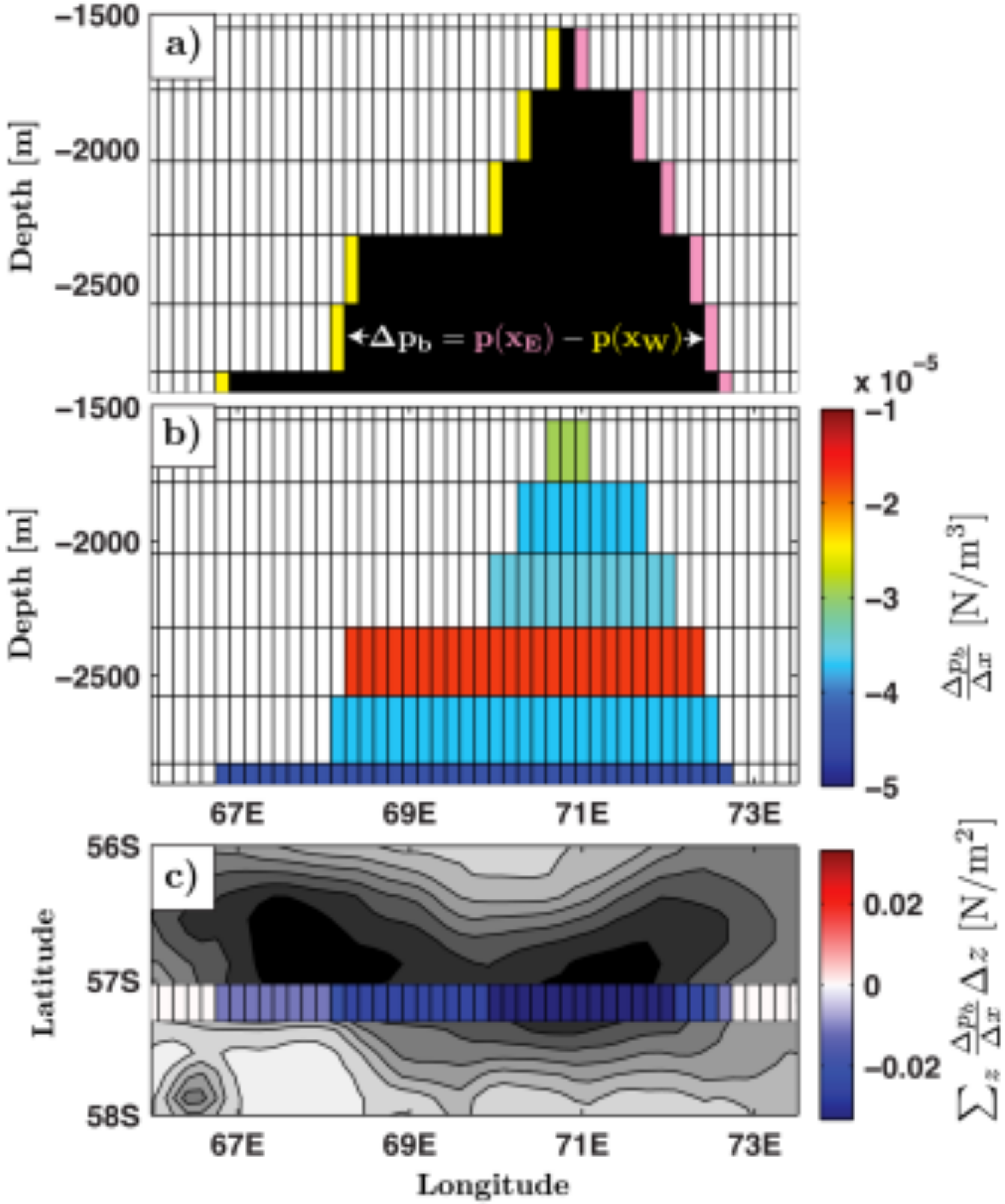
$$\sum_{z=-H}^{\overline{\eta}} \frac{\Delta\overline{p_b}}{\Delta x}\Delta z,$$

Fig. 2



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$$\sum_{z=-H}^{\overline{\eta}}\frac{\Delta\overline{p_b}}{\Delta x}\Delta z,$$

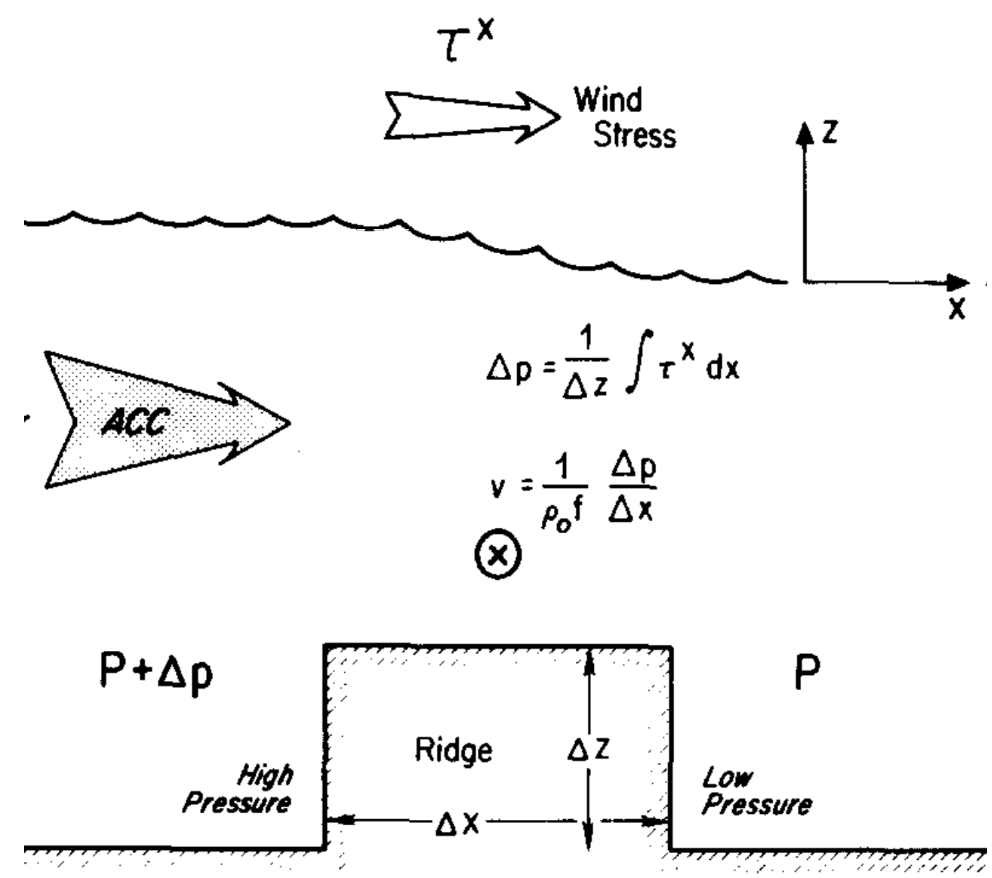


Fig. 2

zonally integrate to find total form stress signal

$$-\oint_x \int_{z=-H}^{\overline{\eta}} \frac{\partial \bar{p}}{\partial x} \mathrm{dzdx} = \sum_{ridges} \sum_{z=-H}^{\overline{\eta}} \frac{\Delta \overline{p_b}}{\Delta x} \Delta z \Delta x = \sum_{ridges} \sum_{z=-H}^{\overline{\eta}} \Delta \overline{p_b} \Delta z$$

Zonal and depth-integrated momentum budget, integrated over meridional domain

Table 1. *xyz*-Integrated Momentum Terms[a]

y Domain	Wind Stress	Topographic Form Stress	Frictional Stress	Flux Divergence
ACC latitudes 42°S to 65°S	6.67×10^{12} N (+100%)	-6.36×10^{12} N (−95%)	-0.19×10^{12} N (−3%)	-0.16×10^{12} N (−2%)
Full domain 30°S to 77°S	8.03×10^{12} N (+100%)	-7.30×10^{12} N (−91%)	-0.11×10^{12} N (−1%)	-0.61×10^{12} N (−8%)

[a]Positive sign indicates eastward direction; negative sign indicates westward direction.

latitudinal distribution of zonal and depth-integrated terms

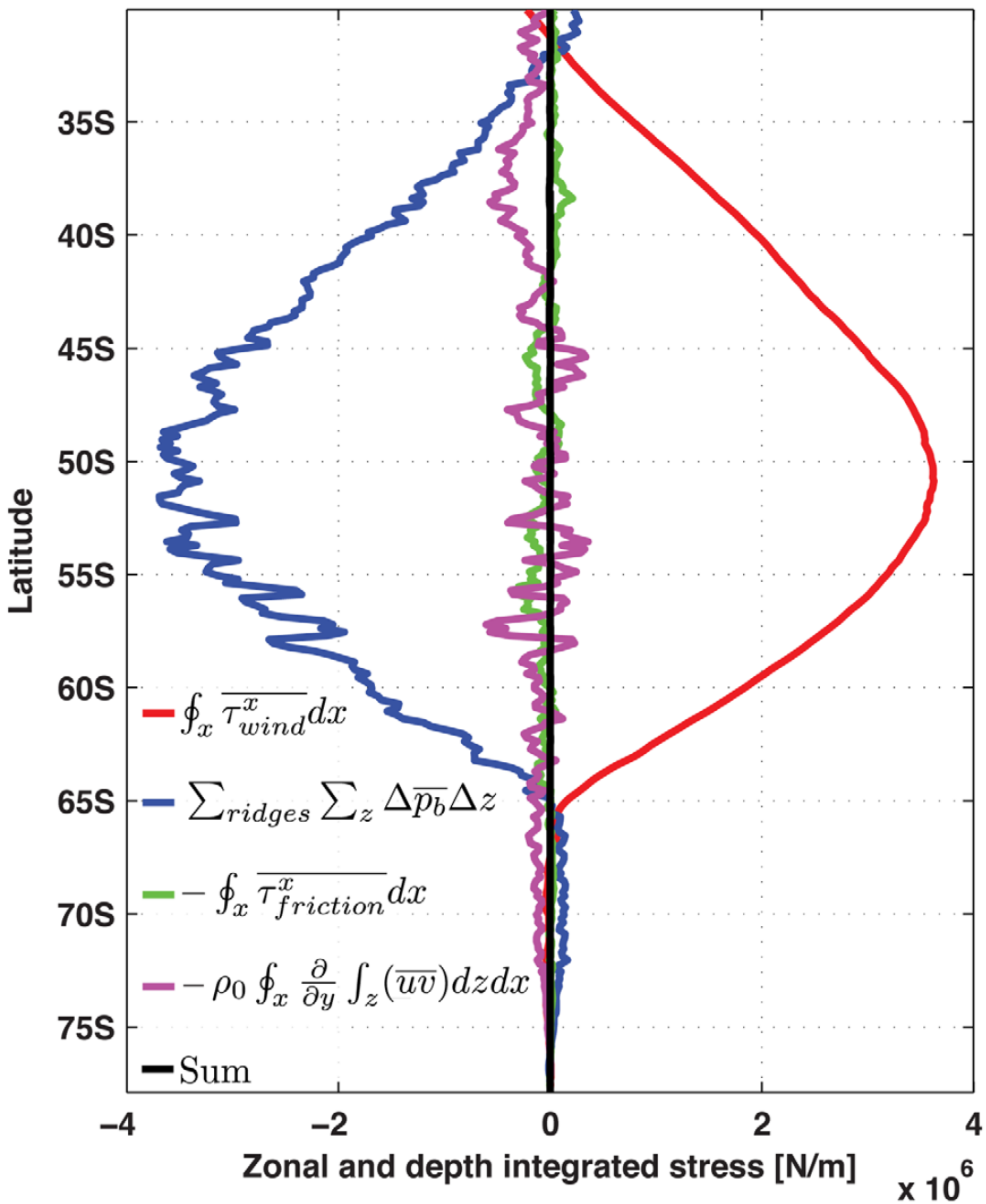
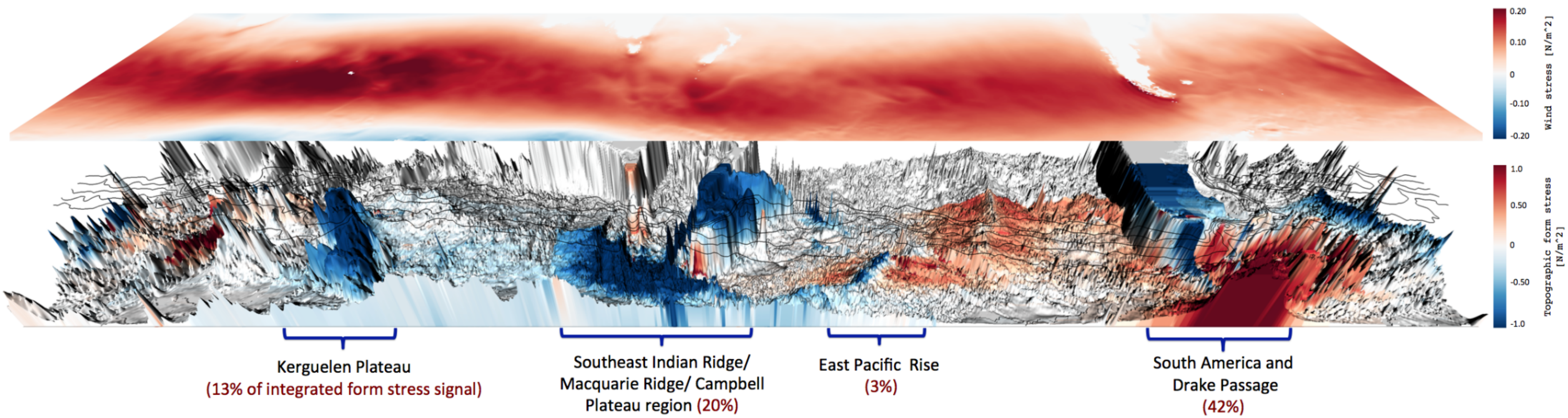


Fig. 3

spatial distribution of wind stress and TFS



spatial distribution of TFS

full depth

0-3700 m

3700 m - bottom

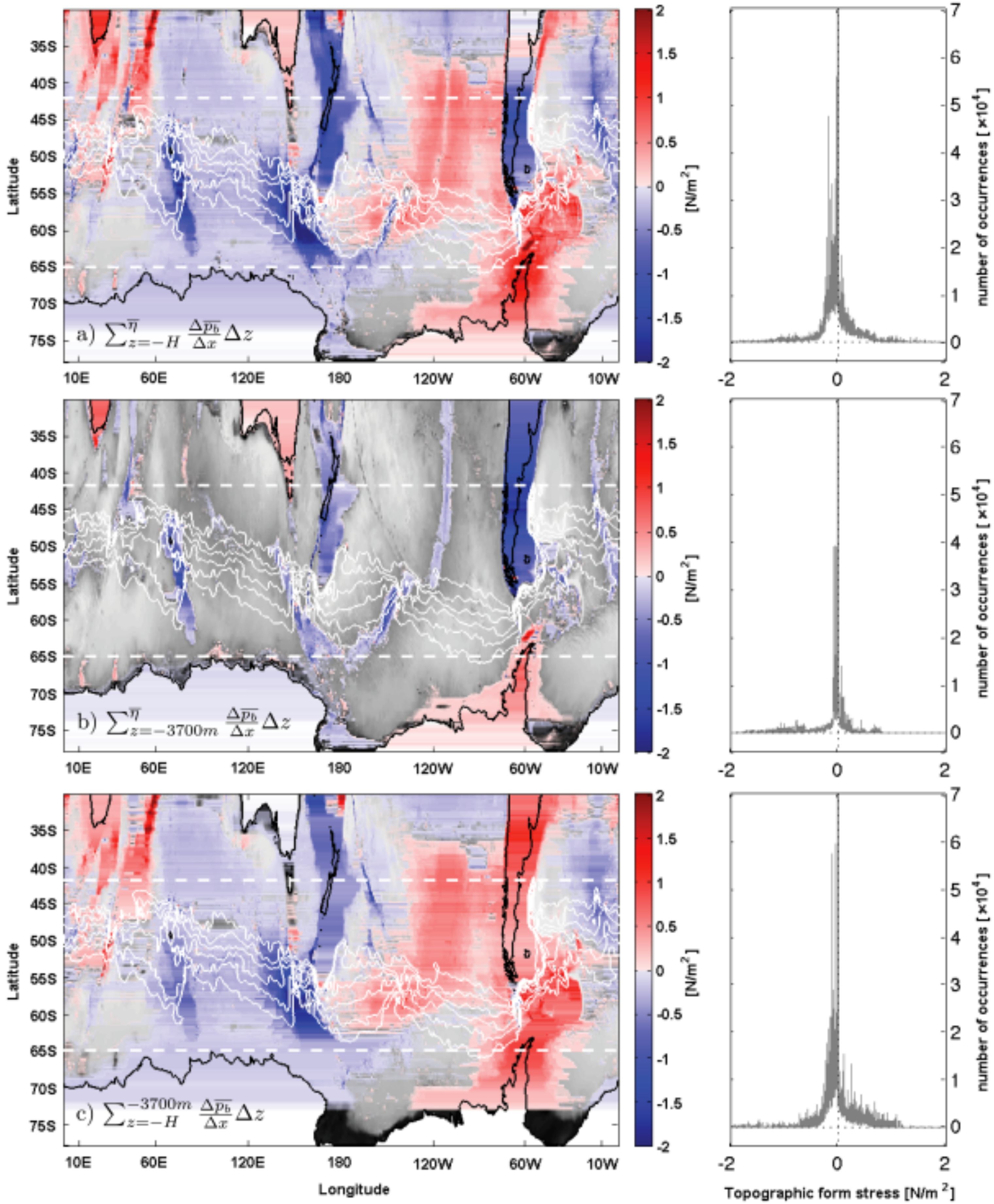


Fig. 4

depth distribution of TFS for different latitude ranges

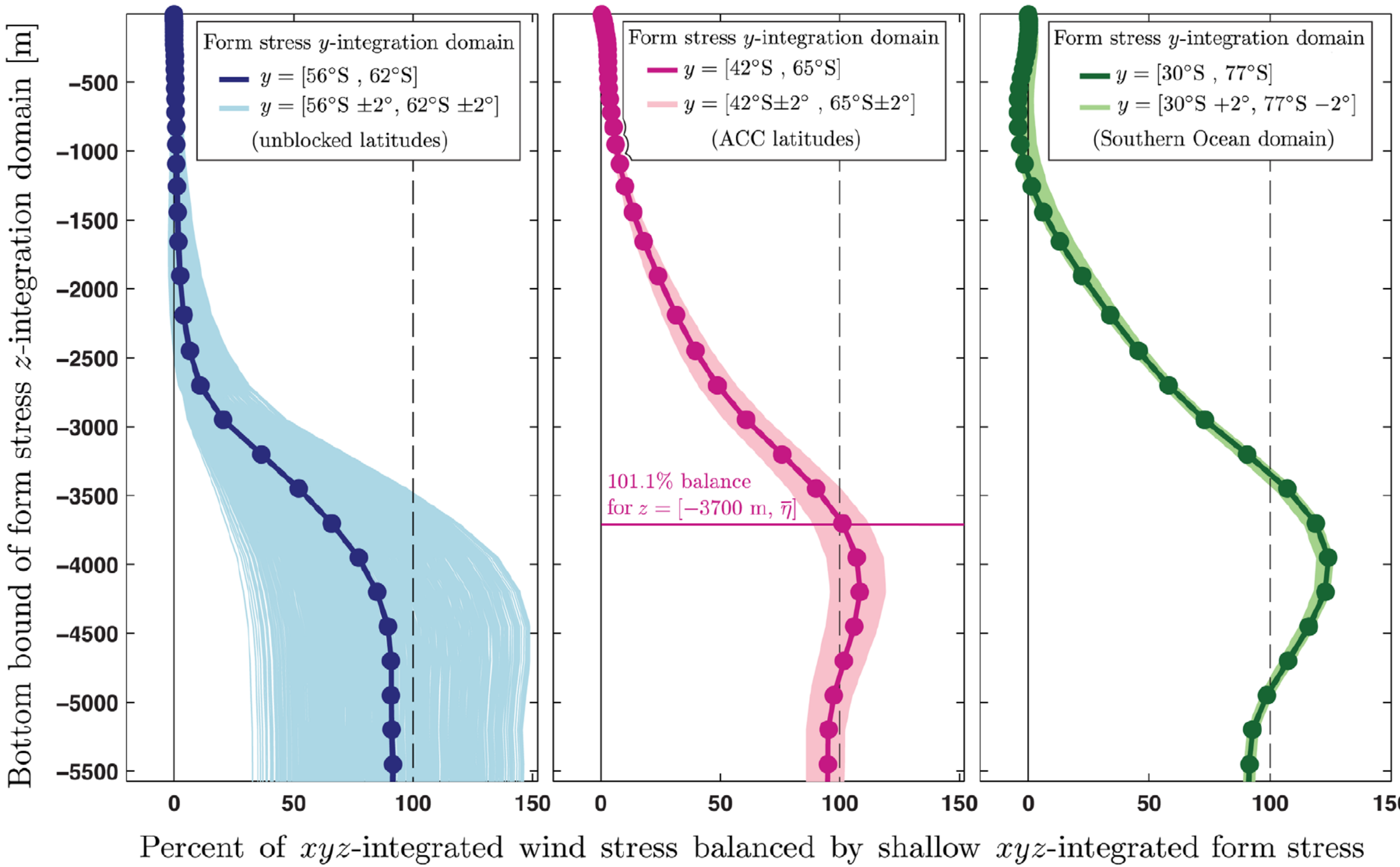


Fig. 5

zonal cumulative sum

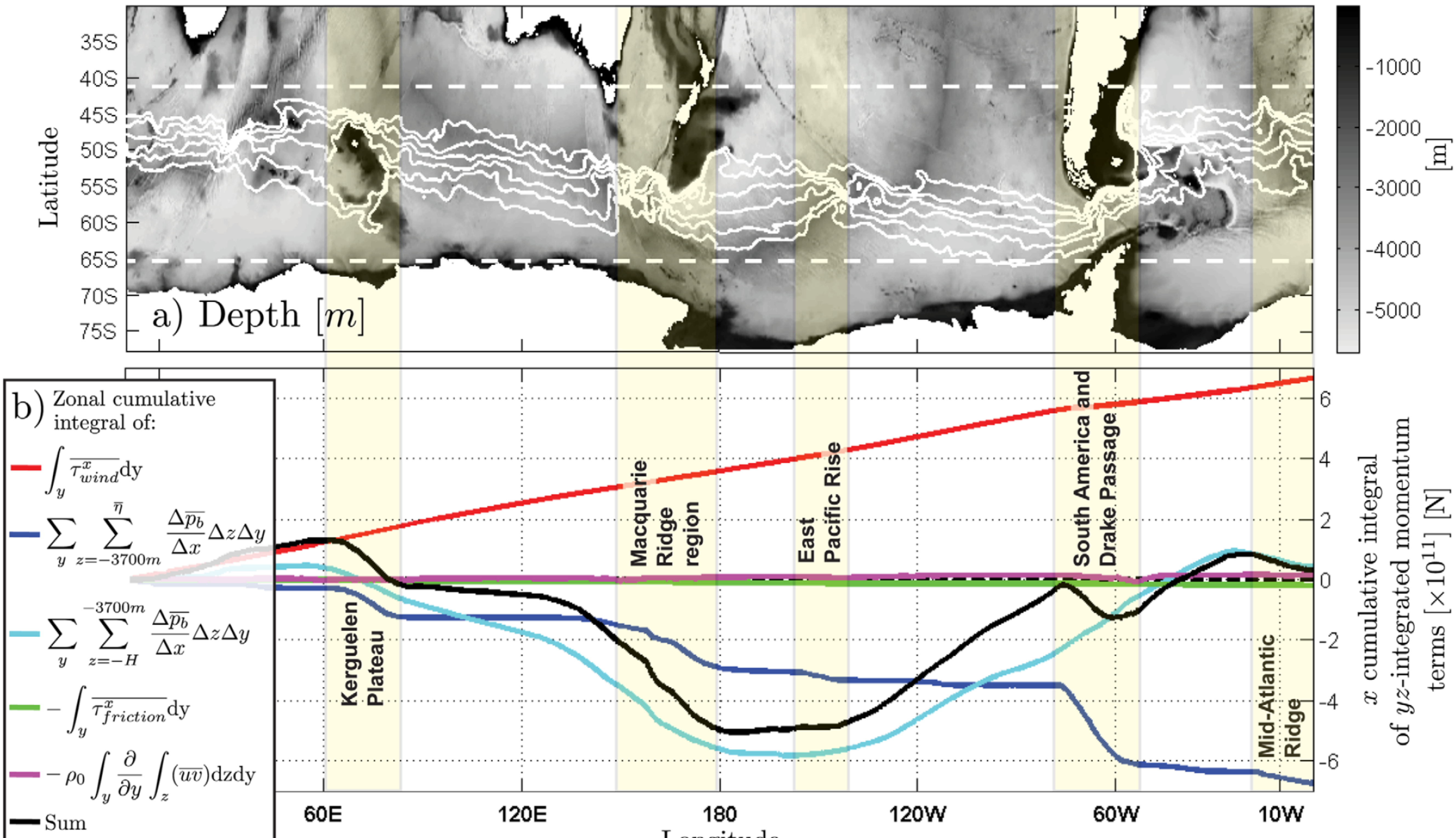


Fig. 6

Abyssal TFS

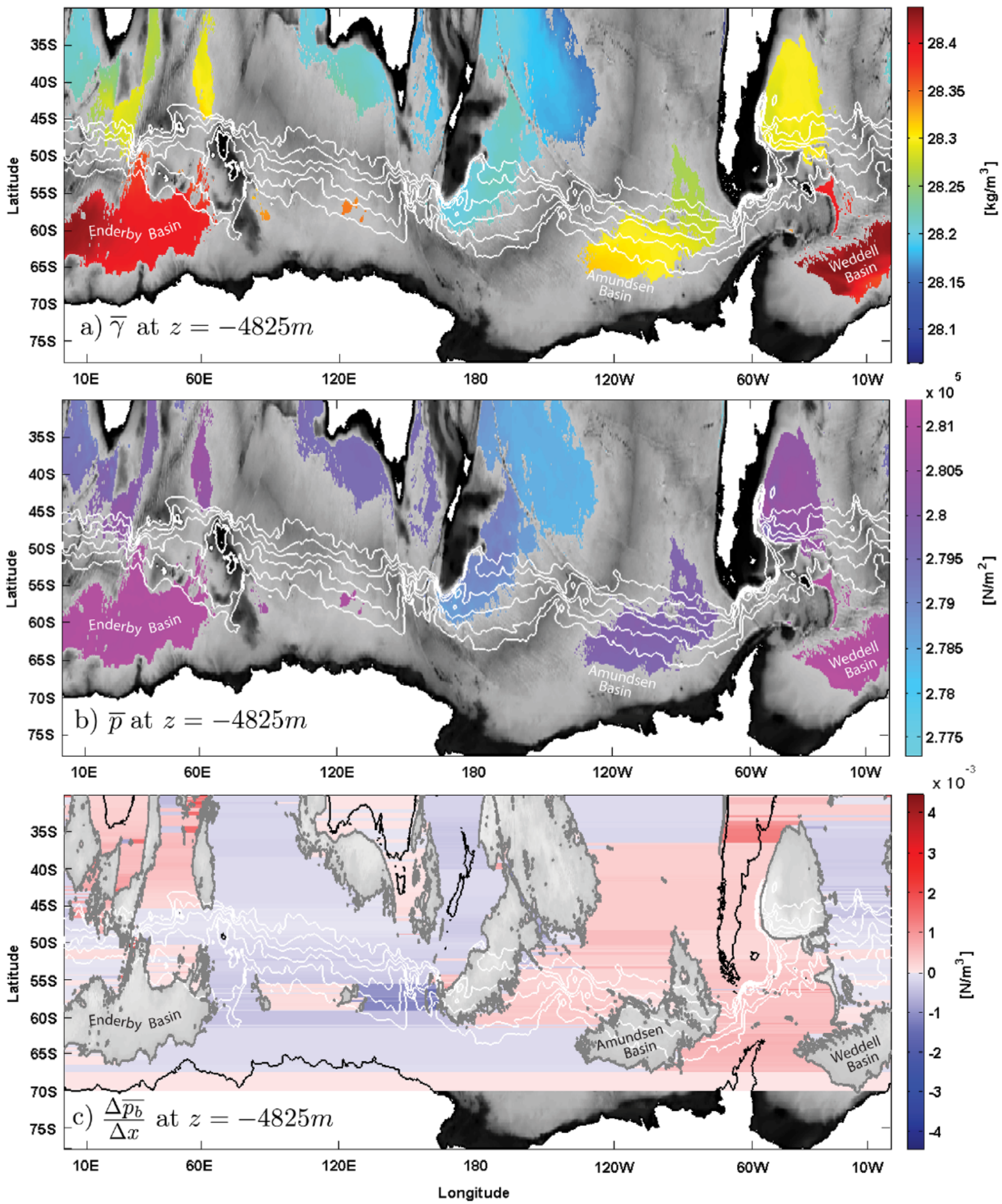


Fig. 8

Temporal variability

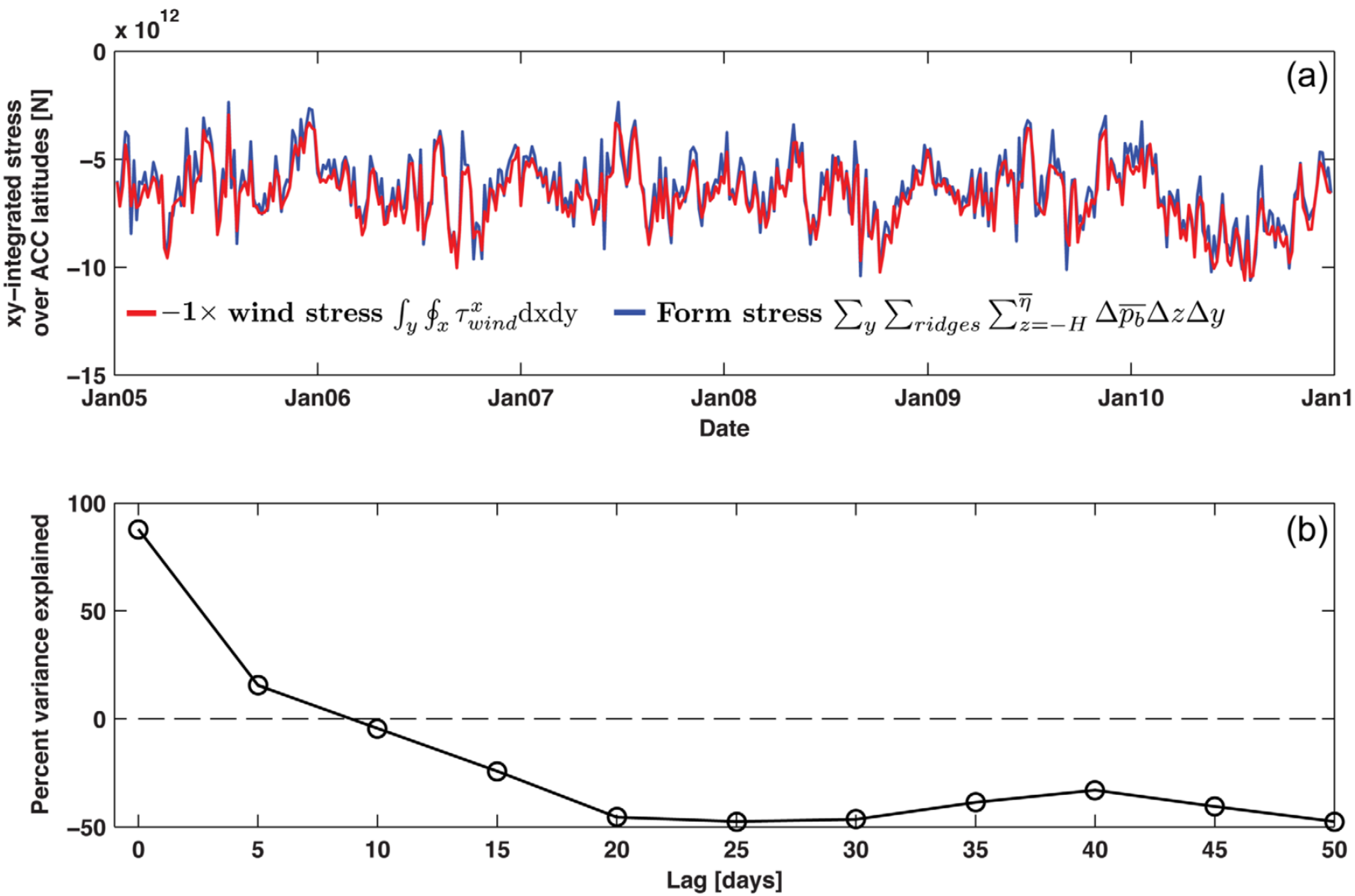


Fig. 9

Temporal variability

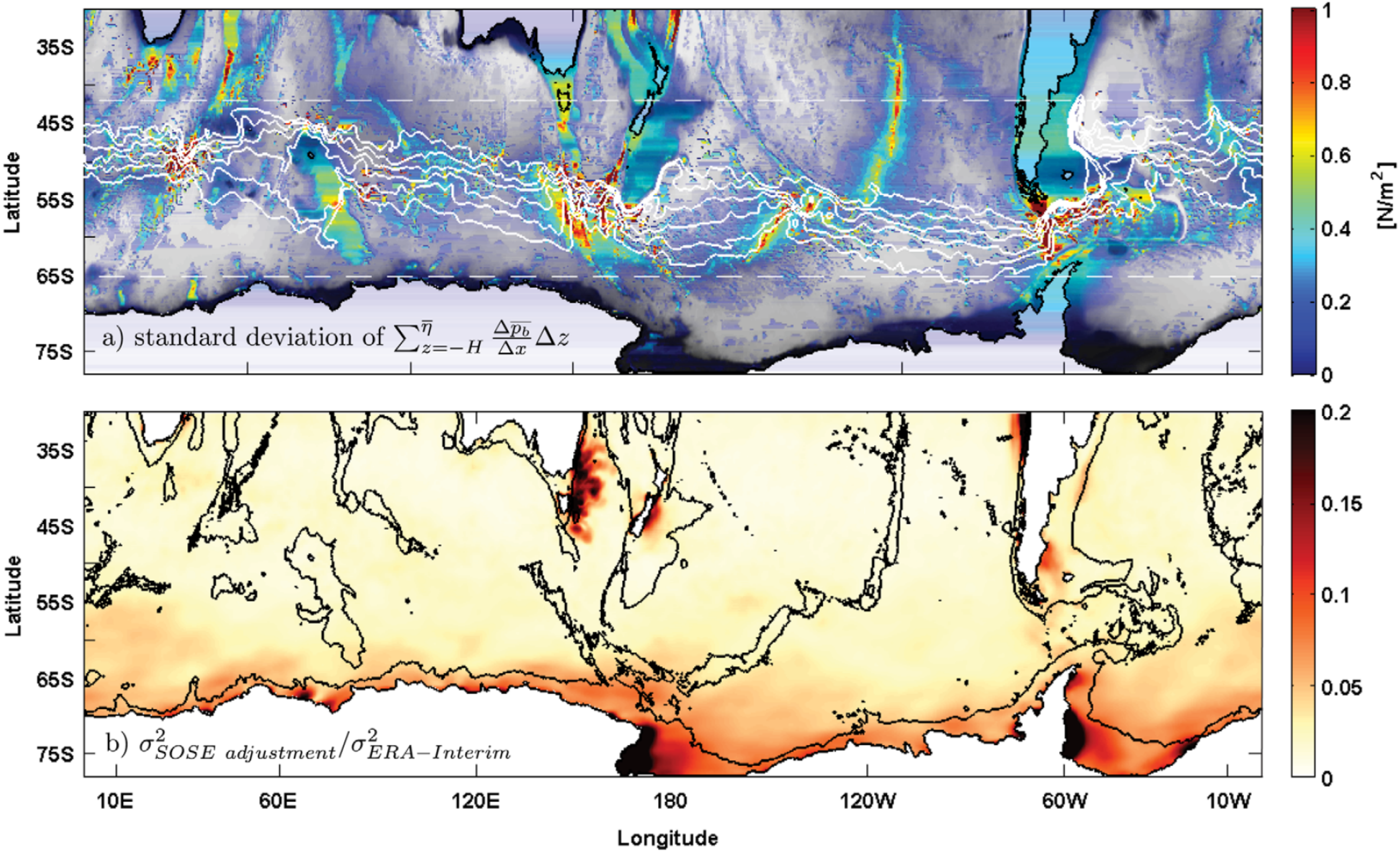


Fig. 10

Conclusions

- 95% of the zonal momentum input via wind stress at the surface is balanced by topographic form stress across ocean ridges, while the remaining 5% is balanced via bottom friction and momentum flux divergences at the northern and southern boundaries

- nearly 40% of topographic form stress occurs across South America, while the remaining 60% occurs across the major submerged ridges that underlie the ACC

- Shallow form stress in the top 3700 m balances most of the wind stress

- 88% of the variance in the 6 year form stress time series can be explained by the wind stress signal, suggesting that changes in the integrated wind stress signal are communicated via rapid barotropic response down to the level of bottom topography

Questions?