Shelf sea carbon accumulation rates are consistent with ocean current and atmosphere-ocean exchange inbalances

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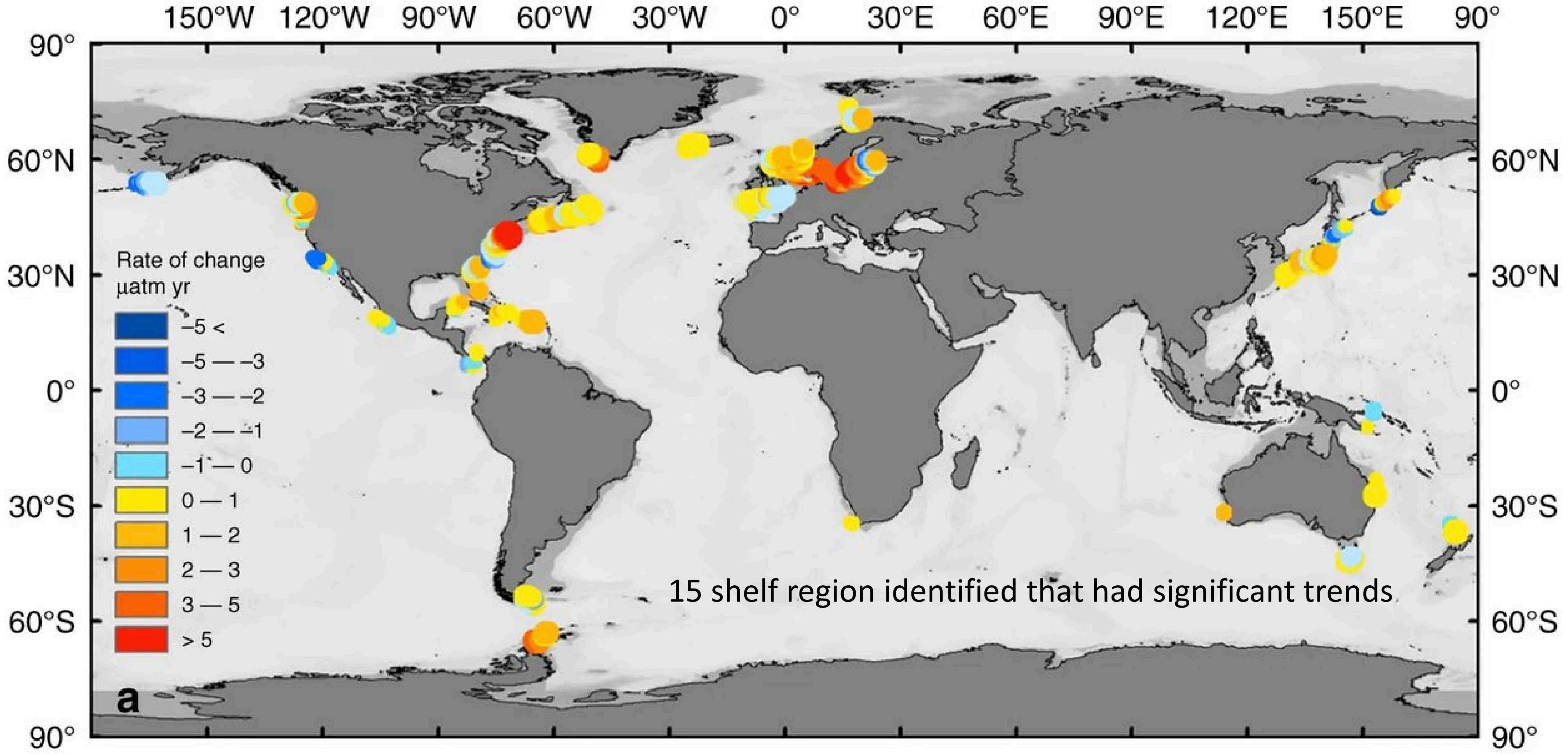
Shelf sea carbon sinks

- Oceanic CO_2 sink has so far acted as a brake on climate change.
- Shelf seas absorb carbon which is then exported to the deep ocean, but this absorption is also causing ocean acidification.
- Shelf seas are considered important CO_2 sinks and provide a range of ecosystem services e.g. food, well being, transport, recreation.

Shelf seas as variable but increasing CO_2 sinks

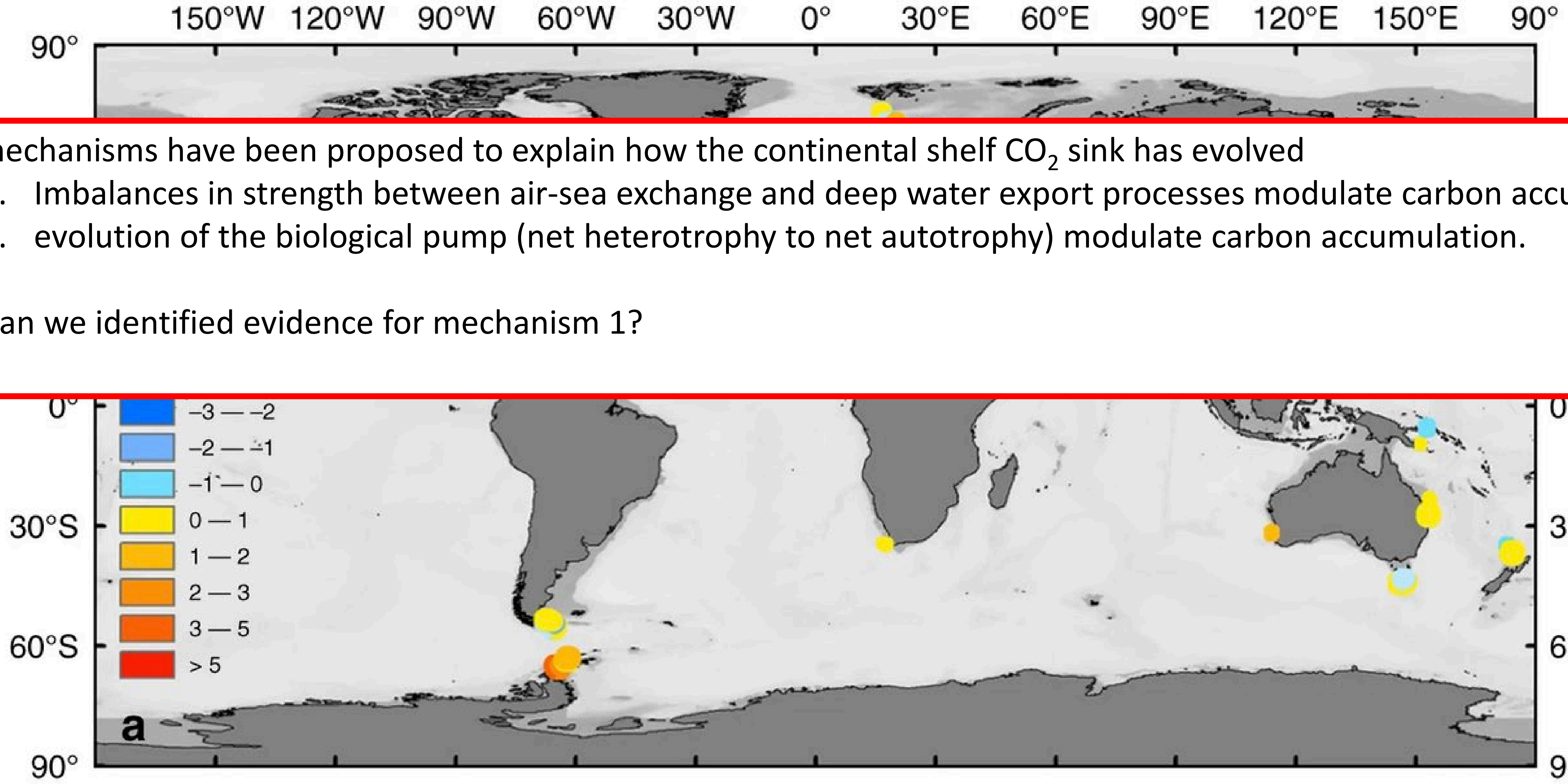


15 shelf region identified that had significant trends

Positive increase in $d\Delta pCO_2/dt$ implies a strengthening CO_2 sink (and increasing ocean acidification)

Laruelle *et al.*, 2018

Shelf seas as variable but increasing CO_2 sinks



Two mechanisms have been proposed to explain how the continental shelf CO_2 sink has evolved

1. Imbalances in strength between air-sea exchange and deep water export processes modulate carbon accumulation.
2. evolution of the biological pump (net heterotrophy to net autotrophy) modulate carbon accumulation.

Can we identified evidence for mechanism 1?

Positive increase in $d\Delta pCO_2/dt$ implies a strengthening CO_2 sink (and increasing ocean acidification)

Laruelle *et al.*, 2018

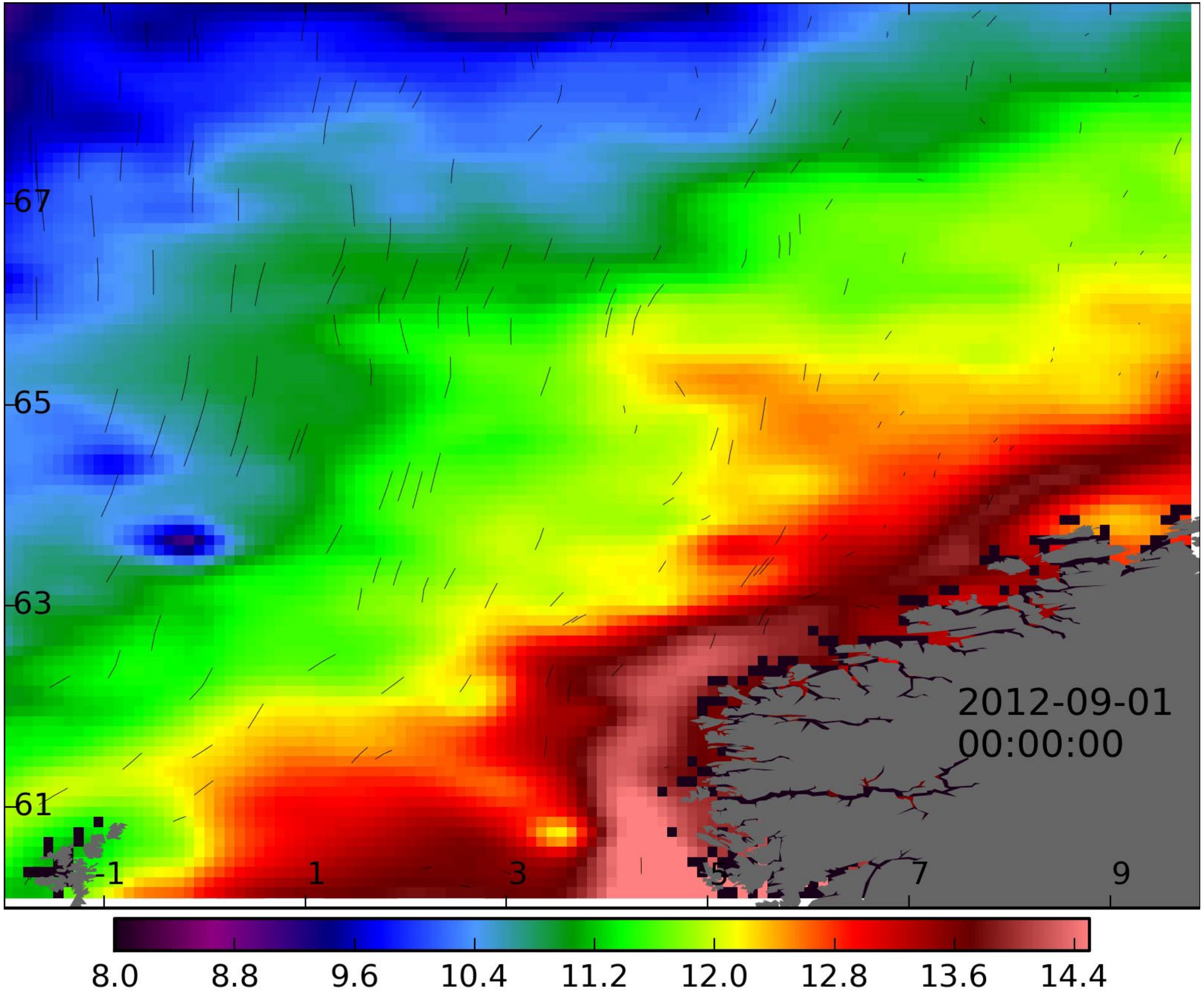
Data

Water flow
Copernicus service (GlobCurrent) re-analysis of Ekman and geostrophic currents at 0 m and 15 m (Chapron, 2015; Rio *et al.*, 2014).

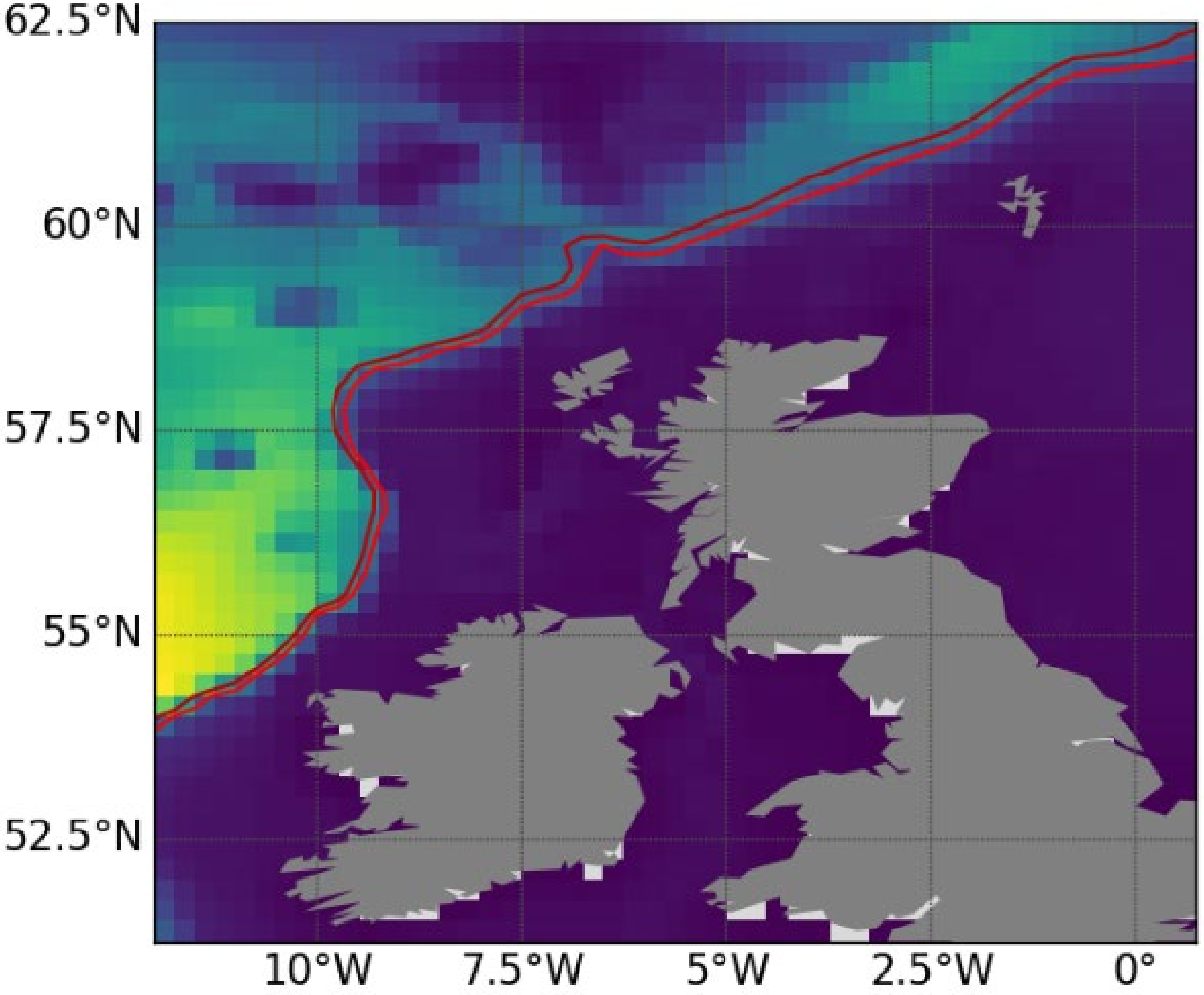
WaveWatch III model simulations for Stokes drift (Rascle and Ardhuin, 2013).

Air-sea exchange
k (Nightingale *et al.* 2000) using Globcurrent U10; OISST (Banzon *et al.*, 2016).

Bathymetry
GEBCO



Determining the shelf edge and normal vectors



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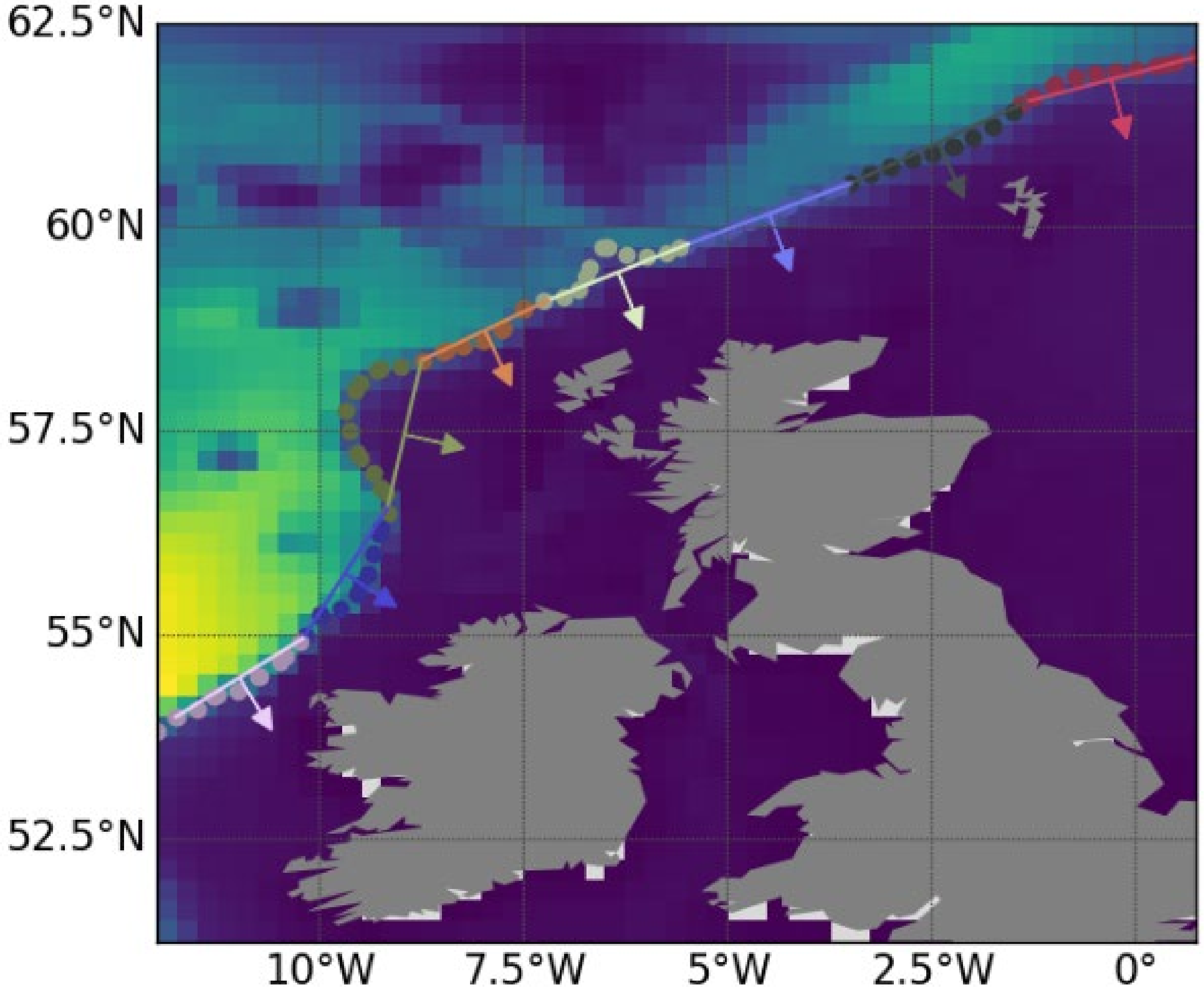
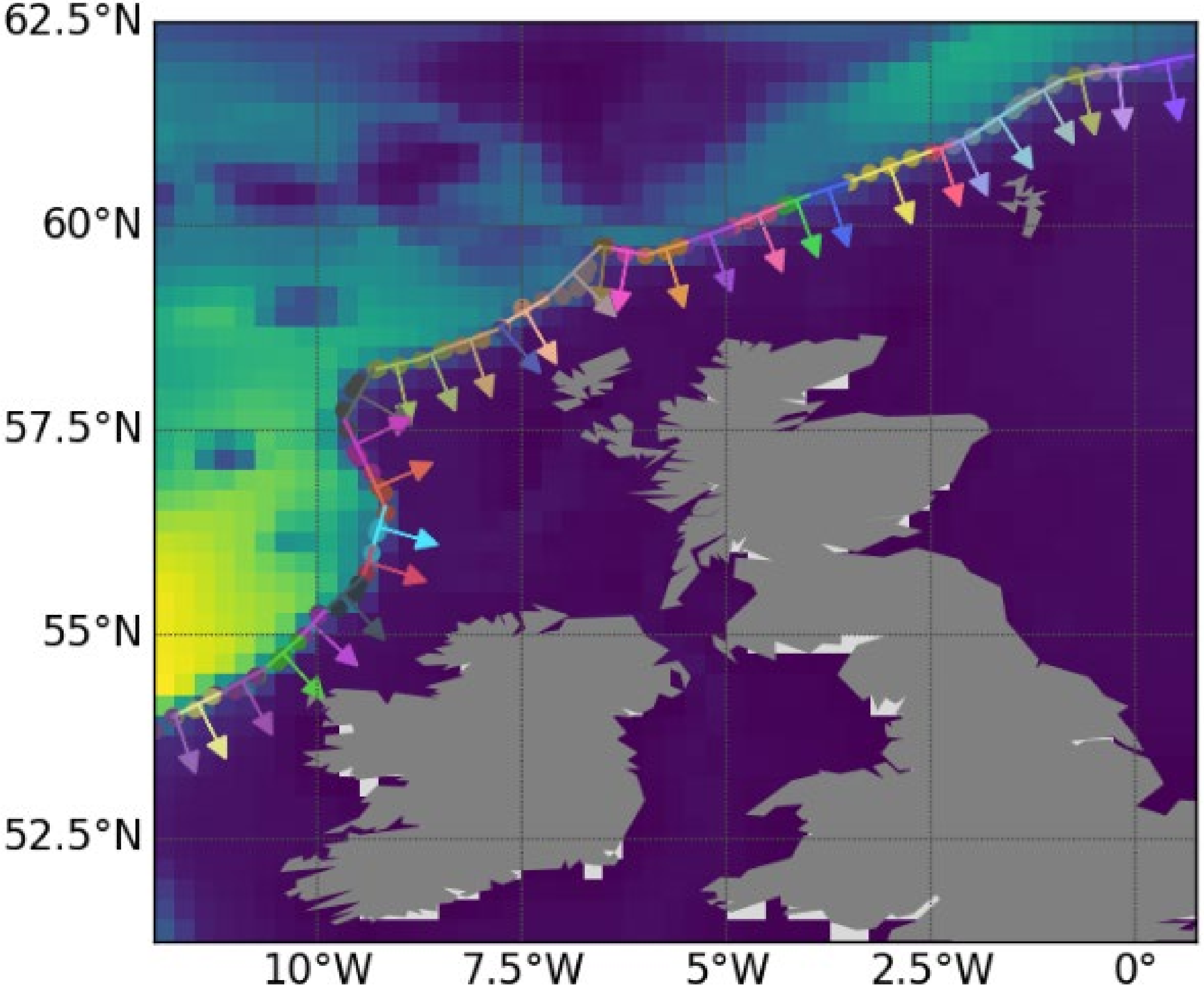
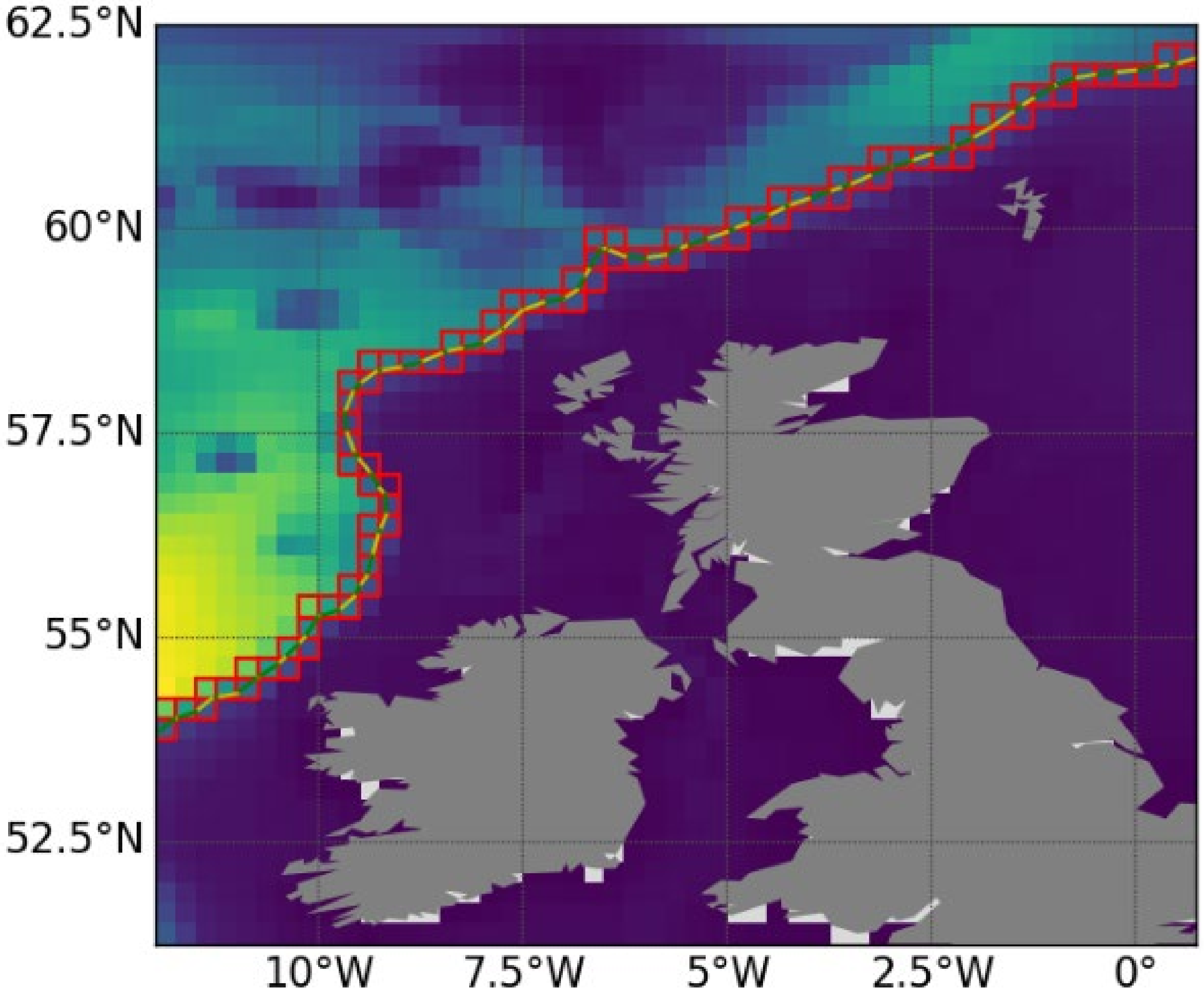
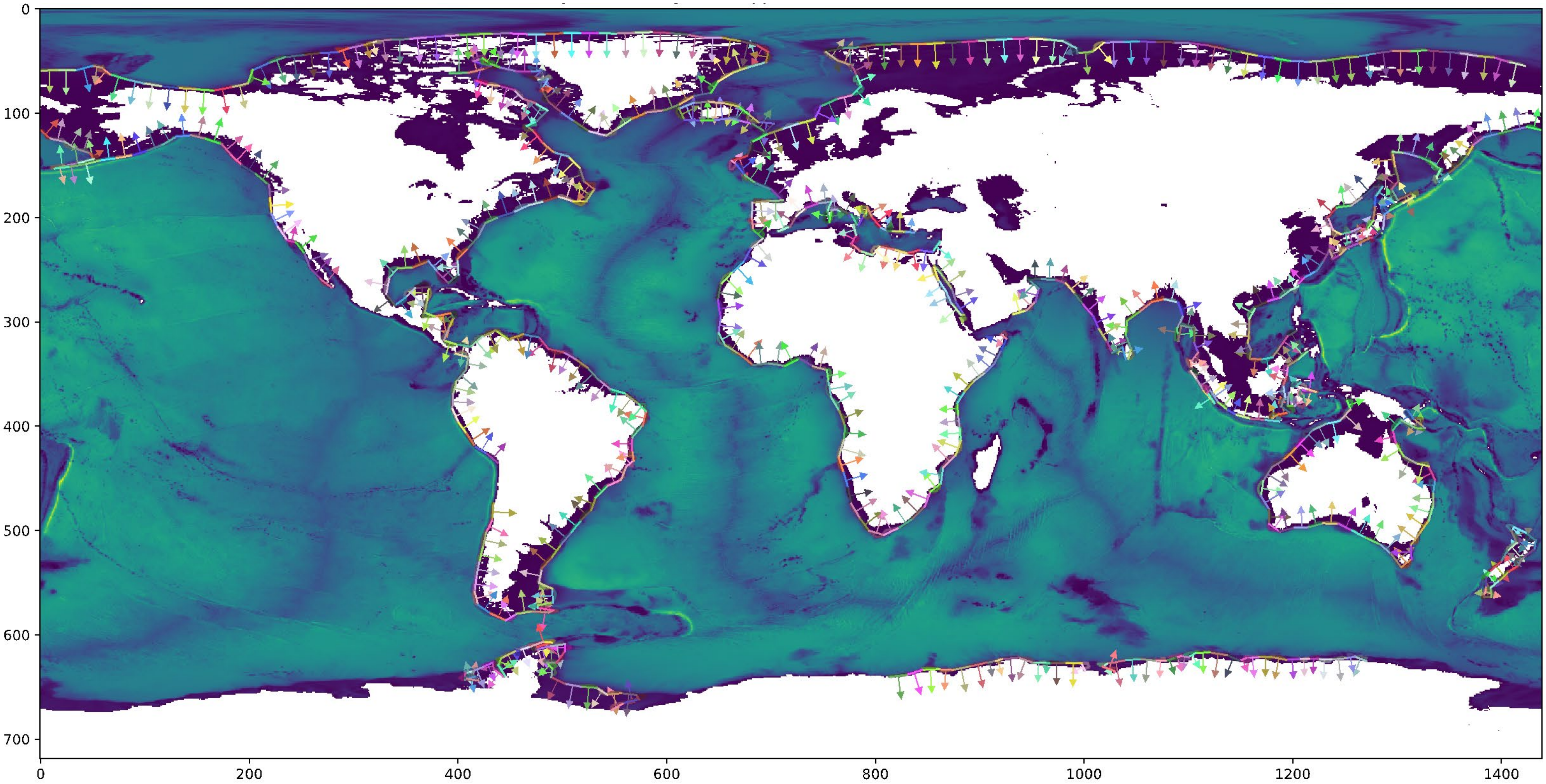


Determining the shelf edge and normal vectors



Determining the shelf edge and normal vectors




0
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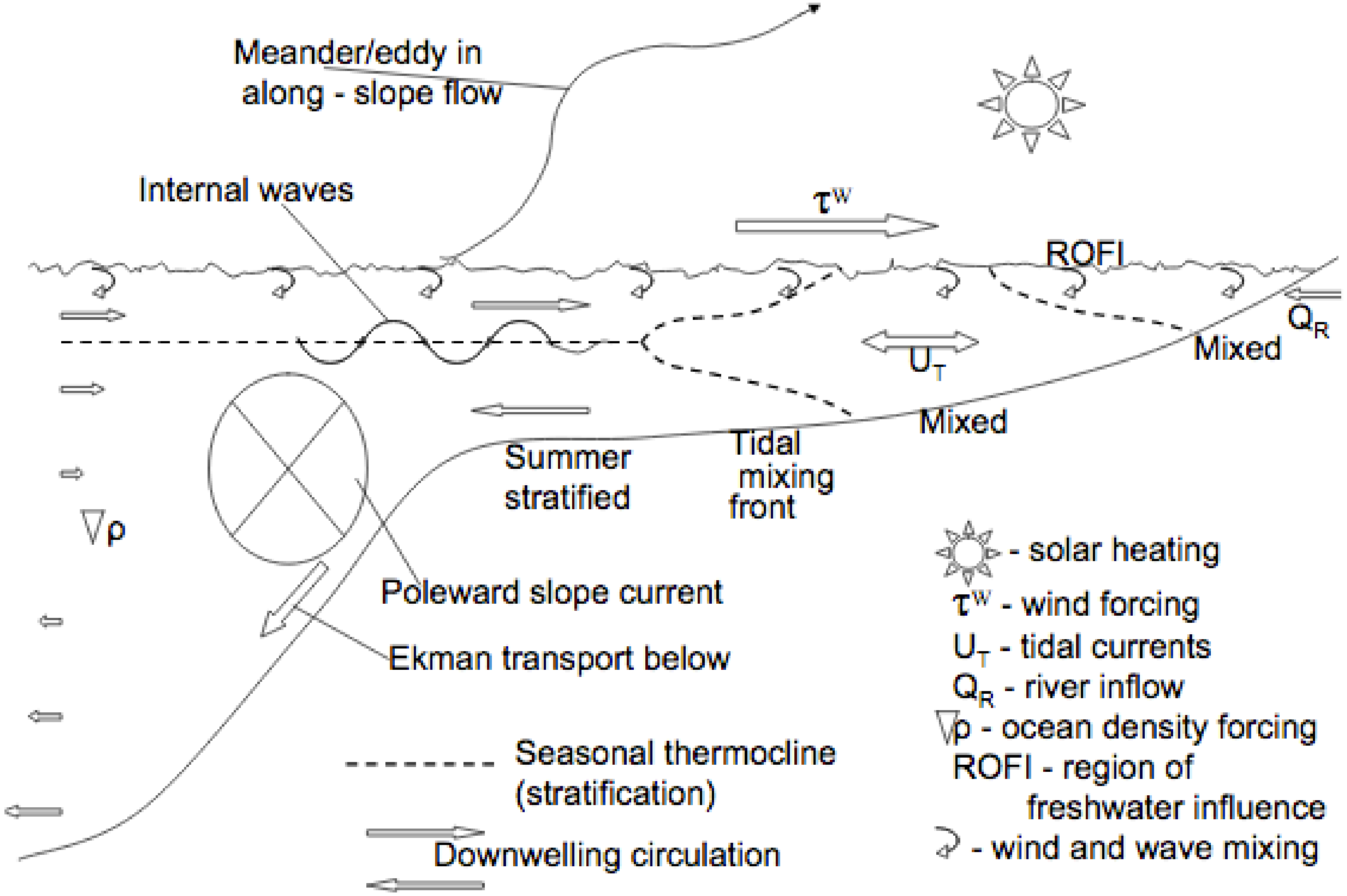
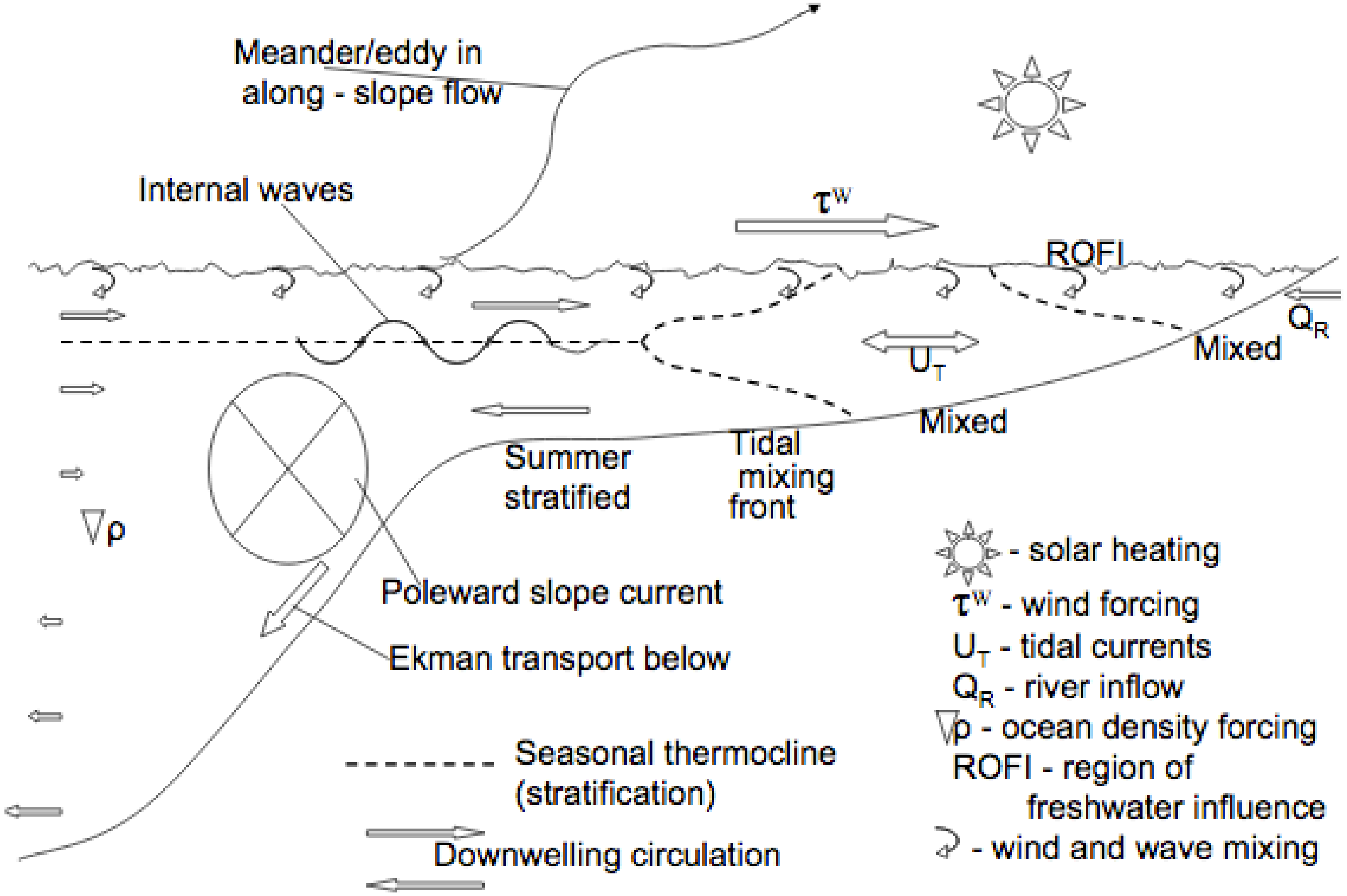
Estimating shelf sea transport and export



Schematic from Huthnance *et al.,* (2009)

Estimating shelf sea transport and export



C_E = 0 m Ekman component

$|\mathbf{n}(C_E + 45°)|$ is the estimate of the upper range of the net current strength crossing the shelf-edge within the mixed layer

Assume density within mixed layer is uniform.

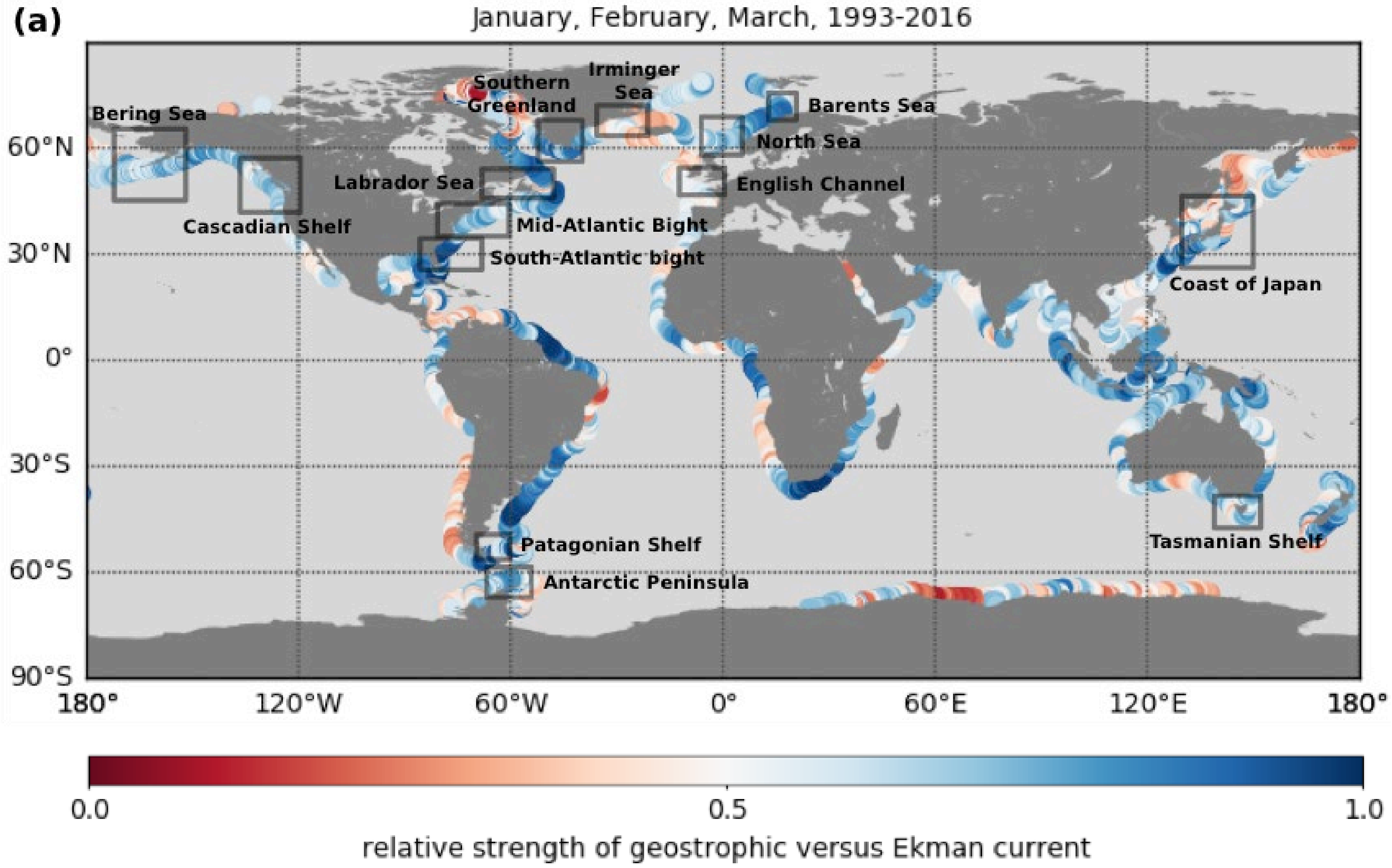
C_G = 0 m geostrophic component. $|\mathbf{n}(C_G)|$ should b a good proxy for all mixed layer.

d = dominance

$$d = \frac{|n(C_G)|}{|n(C_{E+45})| + |n(C_G)|}$$

Schematic from Huthnance *et al.,* (2009)

Relative dominance of geostrophic versus Ekman across shelf boundaries

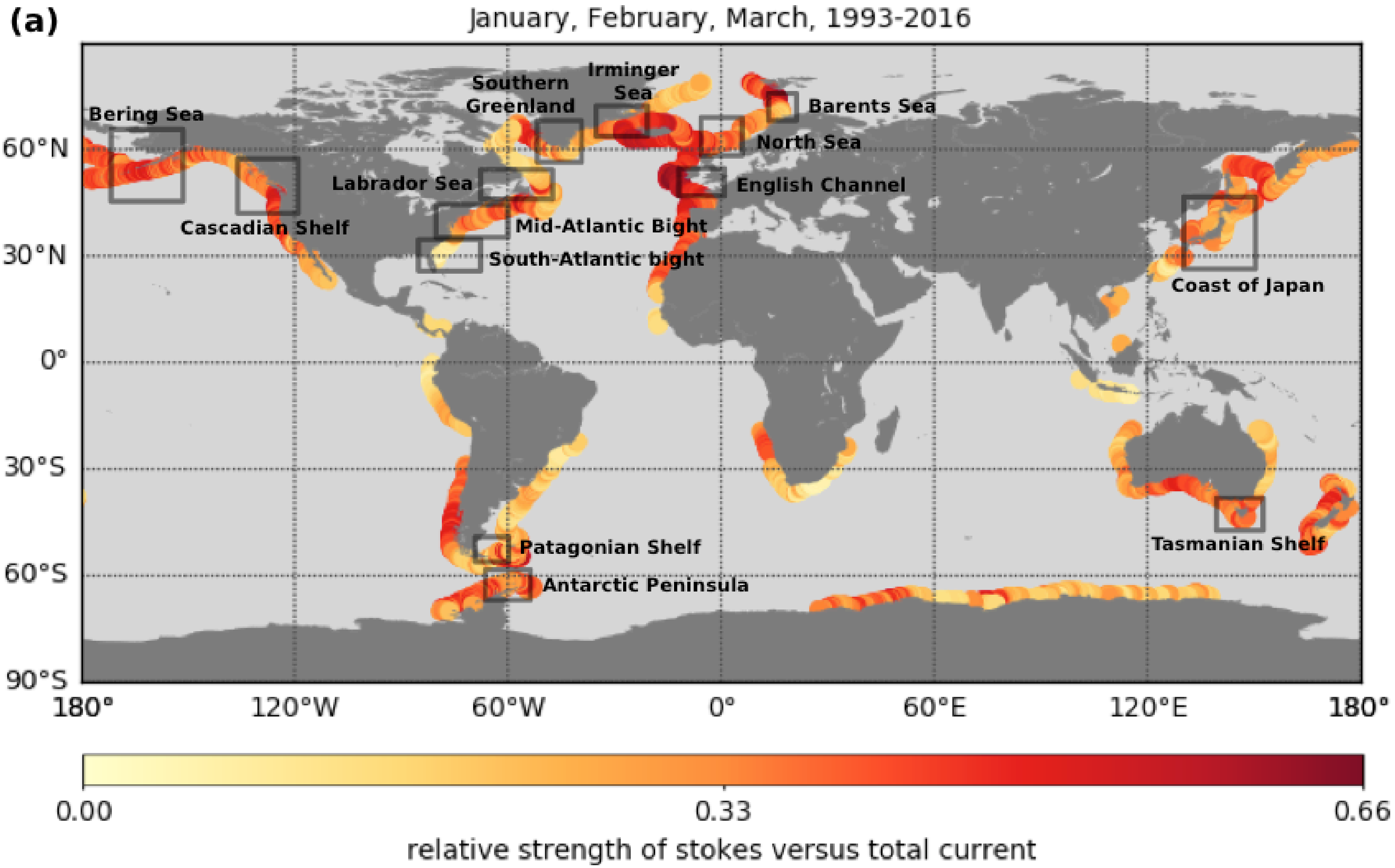


Relative dominance of Stokes versus total current across shelf boundaries

$$P_{Stoke} = \frac{|n(C_S)|}{|n(C_{E+45})| + |n(C_G)| + |n(C_S)|}$$

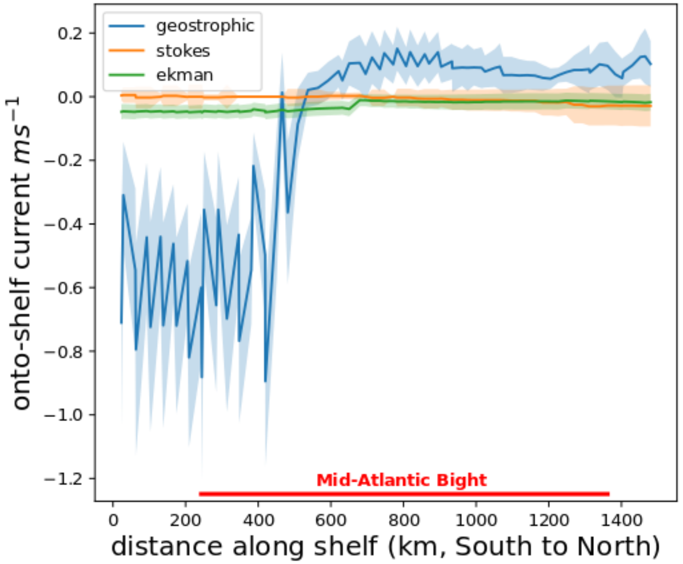
Maximum influence will occur within shallow mixed layers that exist during low wind, following Woodson (2013) criteria.

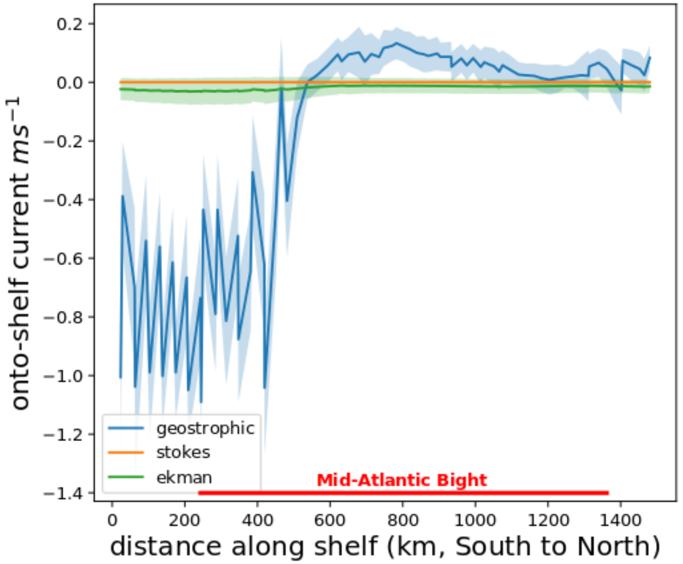
U^*, and H_S

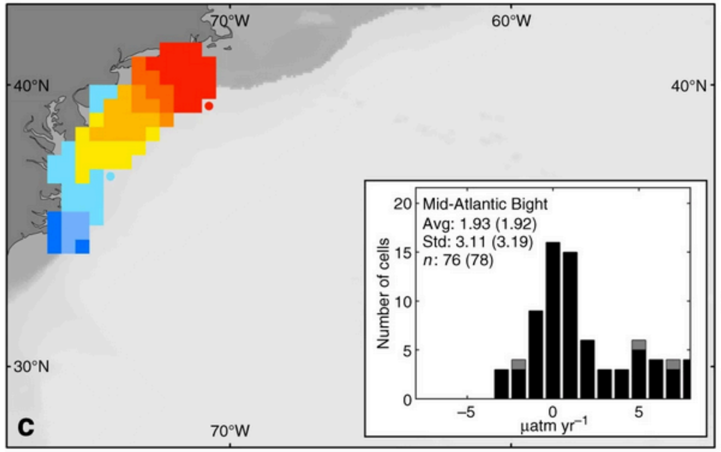


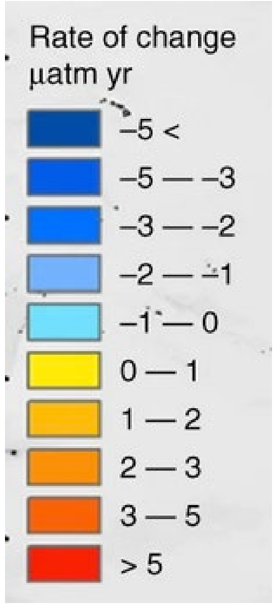
Cross-shelf exchange along the shelf edge

Mid Atlantic bight









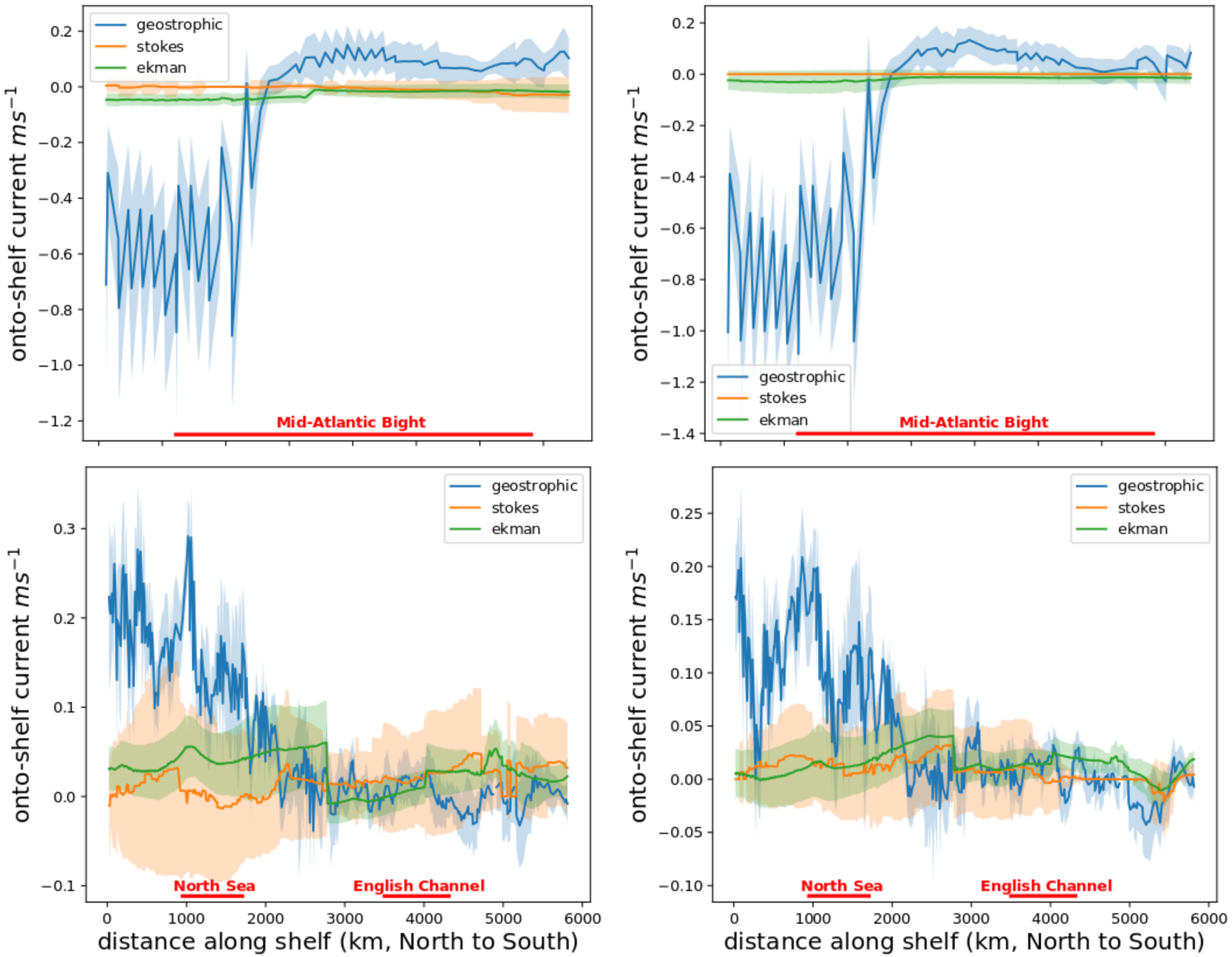
January to March

July to September

Cross-shelf exchange along the shelf edge

Mid Atlantic bight

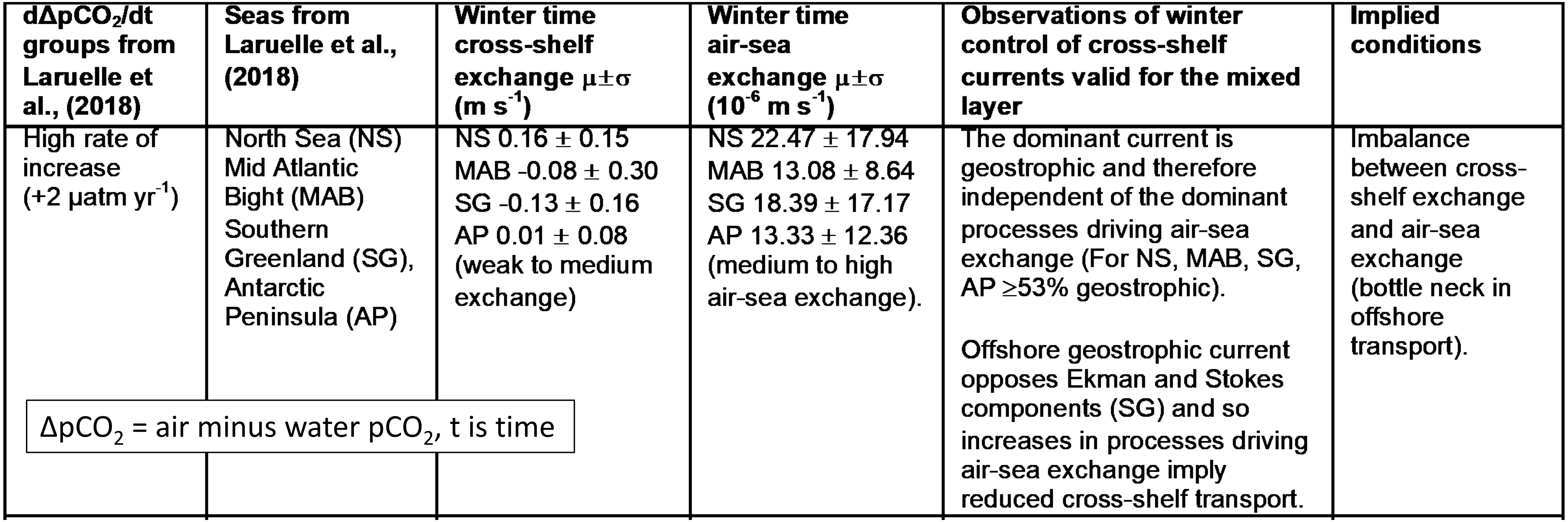
European shelf seas



January to March

July to September

Air-sea exchange versus cross-shelf control



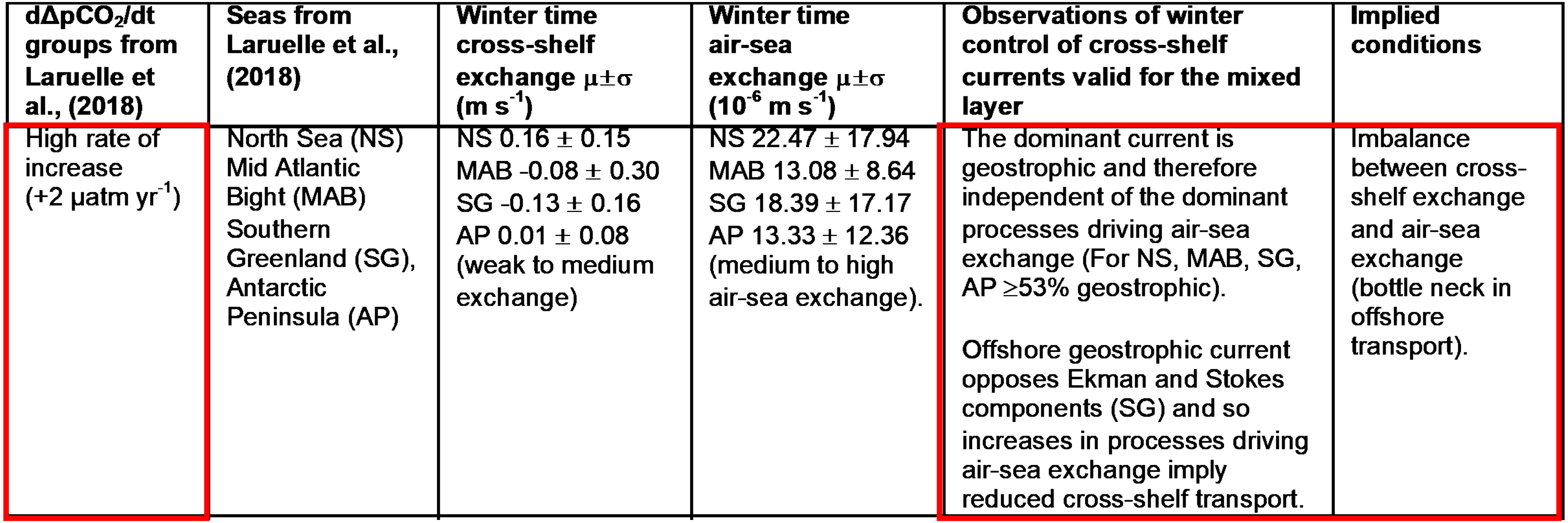
dΔpCO$_2$/dt groups from Laruelle et al., (2018)	**Seas from Laruelle et al., (2018)**	**Winter time cross-shelf exchange $\mu \pm \sigma$ (m s^{-1})**	**Winter time air-sea exchange $\mu \pm \sigma$ (10^{-6} m s^{-1})**	**Observations of winter control of cross-shelf currents valid for the mixed layer**	**Implied conditions**
High rate of increase (+2 µatm yr^{-1})	North Sea (NS) Mid Atlantic Bight (MAB) Southern Greenland (SG), Antarctic Peninsula (AP)	NS 0.16 ± 0.15 MAB -0.08 ± 0.30 SG -0.13 ± 0.16 AP 0.01 ± 0.08 (weak to medium exchange)	NS 22.47 ± 17.94 MAB 13.08 ± 8.64 SG 18.39 ± 17.17 AP 13.33 ± 12.36 (medium to high air-sea exchange).	The dominant current is geostrophic and therefore independent of the dominant processes driving air-sea exchange (For NS, MAB, SG, AP ≥53% geostrophic). Offshore geostrophic current opposes Ekman and Stokes components (SG) and so increases in processes driving air-sea exchange imply reduced cross-shelf transport.	Imbalance between cross-shelf exchange and air-sea exchange (bottle neck in offshore transport).

ΔpCO$_2$ = air minus water pCO$_2$, t is time

Winter time dΔpCO$_2$/dt gradients from Laruelle *et al.,* (2018)

Winter-time turbulent exchange and lower water temperatures are the dominant controller of annual atmosphere-ocean uptake of CO$_2$ within European shelf seas (Kitidis *et al.,* 2020).

Air-sea exchange versus cross-shelf control



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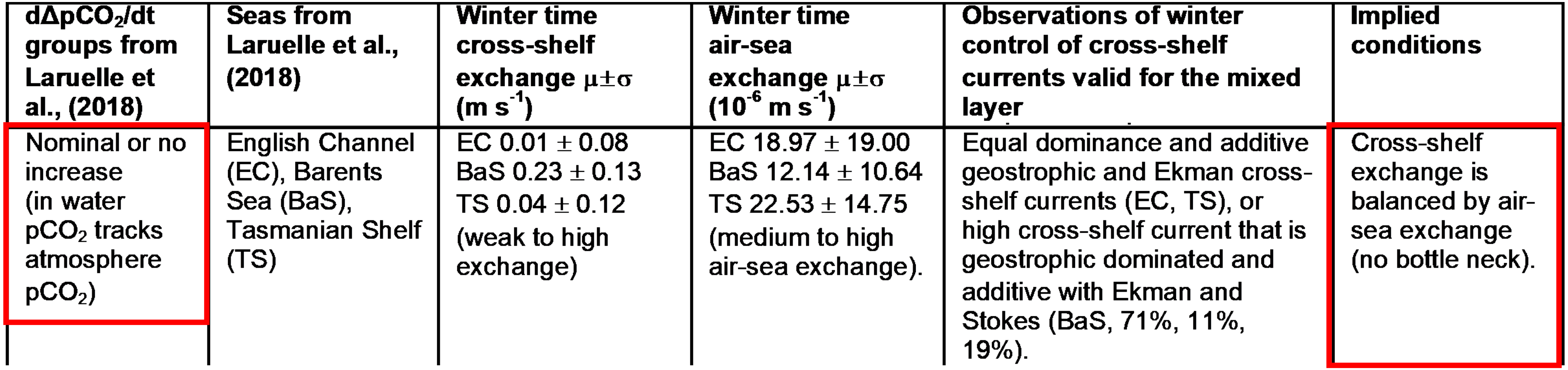
Positive increase in $d\Delta pCO_2/dt$ implies a strengthening sink of CO_2 (and increasing ocean acidification)

Air-sea exchange versus cross-shelf control

dΔpCO_2/dt groups from Laruelle et al., (2018)	**Seas from Laruelle et al., (2018)**	**Winter time cross-shelf exchange $\mu \pm \sigma$ ($m\ s^{-1}$)**	**Winter time air-sea exchange $\mu \pm \sigma$ ($10^{-6}\ m\ s^{-1}$)**	**Observations of winter control of cross-shelf currents valid for the mixed layer**	**Implied conditions**
Moderate rate of increase (e.g. +0.5 to 1.0 µatm yr^{-1})	Irminger Sea (IS), Labrador Sea (LS), Coast of Japan (CoJ), Cascadian Shelf (CS), South Atlantic Bight (SAB).	IS: -0.04 ± 0.09 LS 0.01 ± 0.18 CoJ 0.003 ± 0.17 CS -0.06 ± 0.14 (weak exchange) SAB -0.50 ± 0.56 (very high exchange)	IS: 17.19 ± 17.17 LS 21.89 ± 18.69 CoJ 18.72 ± 12.39 CS 12.19 ± 12.03 (medium to high air-sea exchange). SAB 5.47 ± 4.78 (low air-sea exchange)	The dominant cross-shelf current is geostrophic, and therefore independent of the dominant processes driving air-sea exchange (LS, CoJ ≥ 54% geostrophic). Surface current is offshore with high air-sea exchange (IS, CS) implying that a portion of the increased surface water carbon from high air-sea exchange is retained as no deep-water export. Very high offshore surface current combined with low air-sea exchange (SAB). No deep-water export.	Imbalance between cross-shelf exchange and air-sea exchange (bottle neck in offshelf transport).

Positive increase in dΔpCO_2/dt implies a strengthening sink of CO_2 (and increasing ocean acidification)

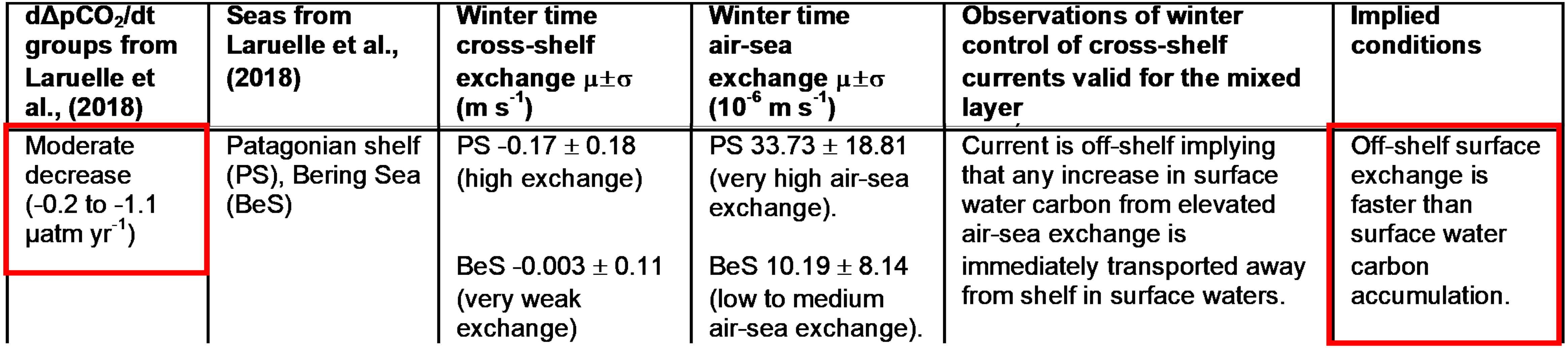
Air-sea exchange versus cross-shelf control



$d\Delta pCO_2/dt$ groups from Laruelle et al., (2018)	Seas from Laruelle et al., (2018)	Winter time cross-shelf exchange μ±σ (m s^{-1})	Winter time air-sea exchange μ±σ (10^{-6} m s^{-1})	Observations of winter control of cross-shelf currents valid for the mixed layer	Implied conditions
Nominal or no increase (in water pCO_2 tracks atmosphere pCO_2)	English Channel (EC), Barents Sea (BaS), Tasmanian Shelf (TS)	EC 0.01 ± 0.08 BaS 0.23 ± 0.13 TS 0.04 ± 0.12 (weak to high exchange)	EC 18.97 ± 19.00 BaS 12.14 ± 10.64 TS 22.53 ± 14.75 (medium to high air-sea exchange).	Equal dominance and additive geostrophic and Ekman cross-shelf currents (EC, TS), or high cross-shelf current that is geostrophic dominated and additive with Ekman and Stokes (BaS, 71%, 11%, 19%).	Cross-shelf exchange is balanced by air-sea exchange (no bottle neck).

nominal or no increase in $d\Delta pCO_2/dt$ implies a temporally constant sink

Air-sea exchange versus cross-shelf control



$d\Delta pCO_2/dt$ groups from Laruelle et al., (2018)	**Seas from Laruelle et al., (2018)**	**Winter time cross-shelf exchange $\mu \pm \sigma$ ($m\ s^{-1}$)**	**Winter time air-sea exchange $\mu \pm \sigma$ ($10^{-6}\ m\ s^{-1}$)**	**Observations of winter control of cross-shelf currents valid for the mixed layer**	**Implied conditions**
Moderate decrease (-0.2 to -1.1 µatm yr^{-1})	Patagonian shelf (PS), Bering Sea (BeS)	PS -0.17 ± 0.18 (high exchange) BeS -0.003 ± 0.11 (very weak exchange)	PS 33.73 ± 18.81 (very high air-sea exchange). BeS 10.19 ± 8.14 (low to medium air-sea exchange).	Current is off-shelf implying that any increase in surface water carbon from elevated air-sea exchange is immediately transported away from shelf in surface waters.	Off-shelf surface exchange is faster than surface water carbon accumulation.

decrease in $d\Delta pCO_2/dt$ implies a weakening sink

Conclusions

Imbalances in strength, between air-sea exchange and deep water export appear related to carbon accumulation in the 15 shelf seas with significant trends in winter-time pCO_2 gradient (as identified by Laruelle *et al.,* 2018).

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Conclusions

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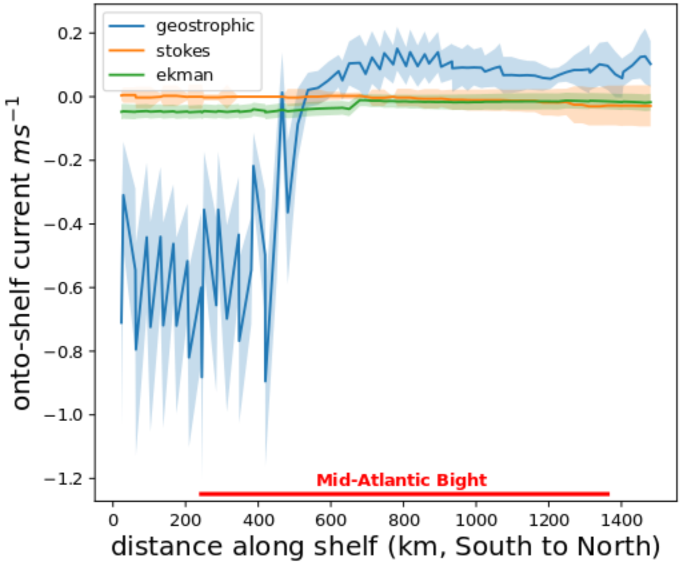
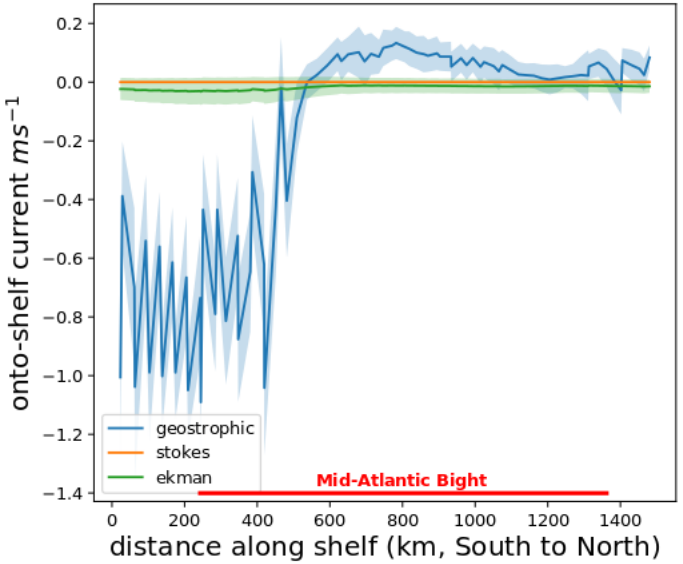
Shelf-seas exhibiting cross-shelf velocities within the mixed layer that are dominated by geostrophic flow (i.e. >50% geostrophic) will continue to accumulate carbon.

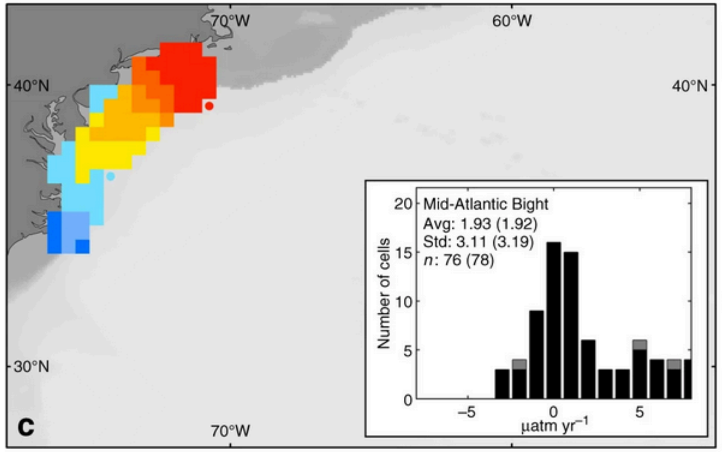
Shelf seas where cross-shelf velocities within the mixed layer are strongly influenced by wind and wave induced currents could continue to track atmospheric values.

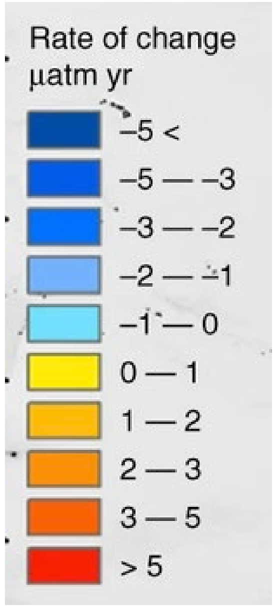
Cross-shelf exchange along the shelf edge

Mid Atlantic bight









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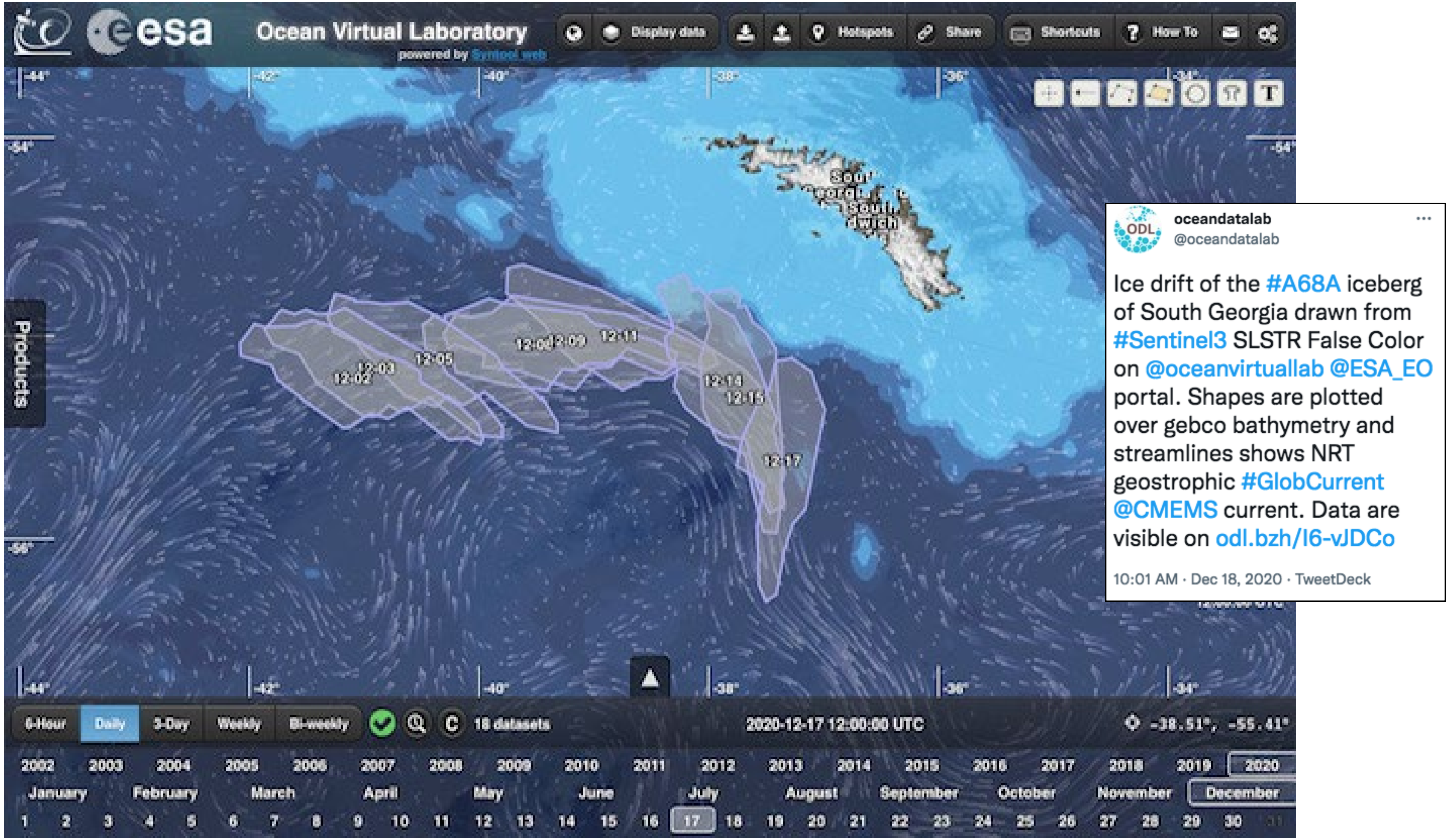

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Ice drift of the #A68A iceberg of South Georgia drawn from #Sentinel3 SLSTR False Color on @oceanvirtuallab @ESA_EO portal. Shapes are plotted over gebco bathymetry and streamlines shows NRT geostrophic #GlobCurrent @CMEMS current. Data are visible on odl.bzh/l6-vJDCo

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Case study for European shelf using NATL60 CJM165 simulations (geostrophic, Ekman, residual assumed ageostrophic, as percentage of simulated total).