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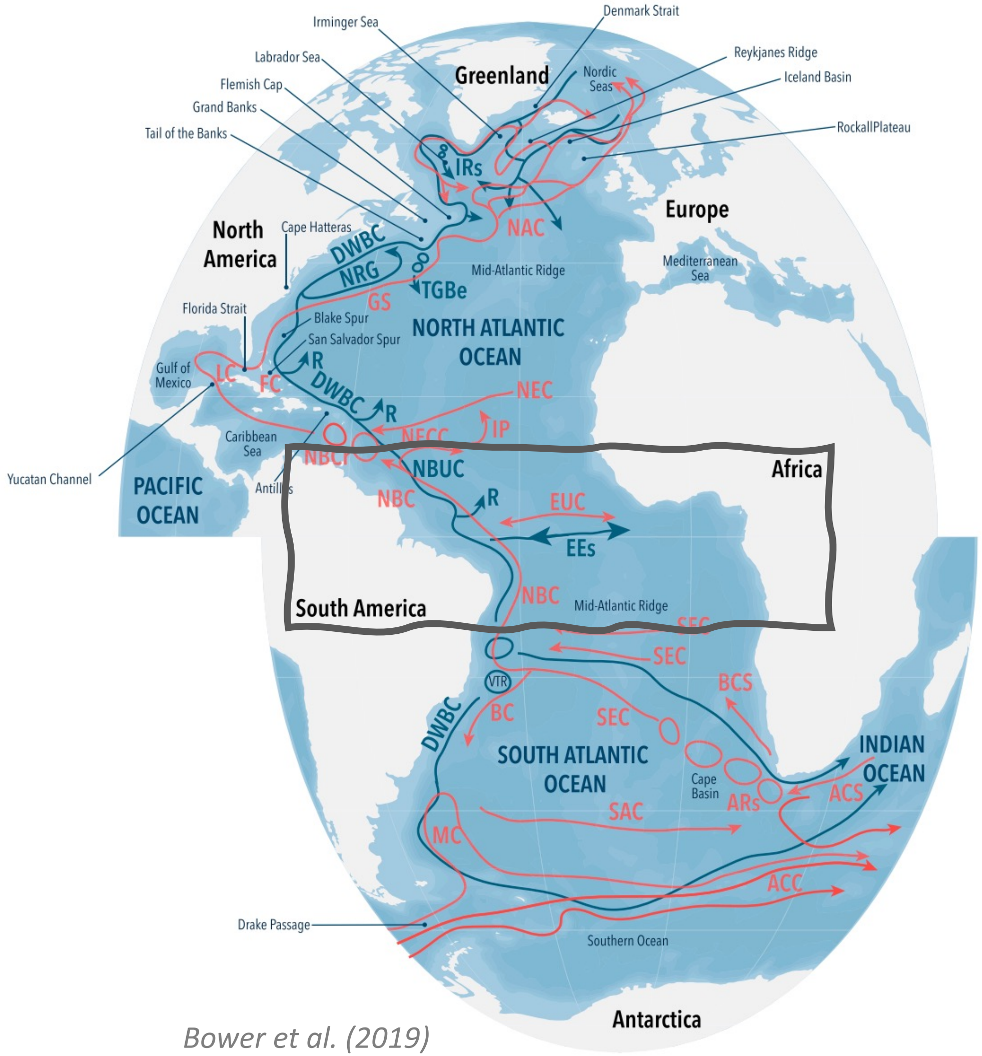
SCAN ME

Transports and pathways of the tropical AMOC return flow from Argo data and shipboard velocity measurements

Franz Philip Tuchen, Peter Brandt, Joke F. Lübbecke, Rebecca Hummels

(Journal of Geophysical Research: Oceans, 2022, 127, e2021JC018115, https://doi.org/10.1029/2021JC018115*)*

Tropical segment of the AMOC



Bower et al. (2019)

Tropical Atlantic:

- Both AMOC branches concentrated at the western boundary
- Western boundary circulation consists of :
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  - Wind-driven Circulation
    - Subtropical Cells (STCs)
    - Sverdrup compensation transport

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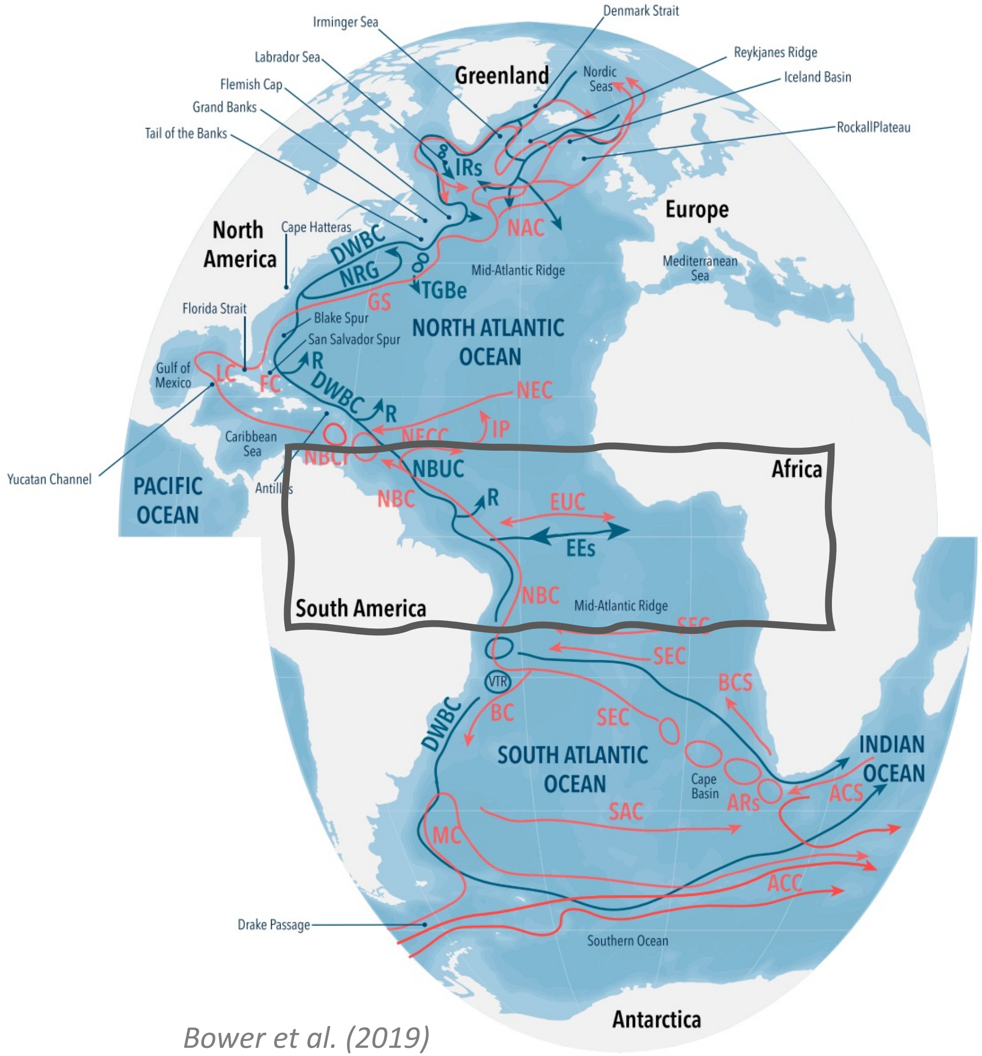

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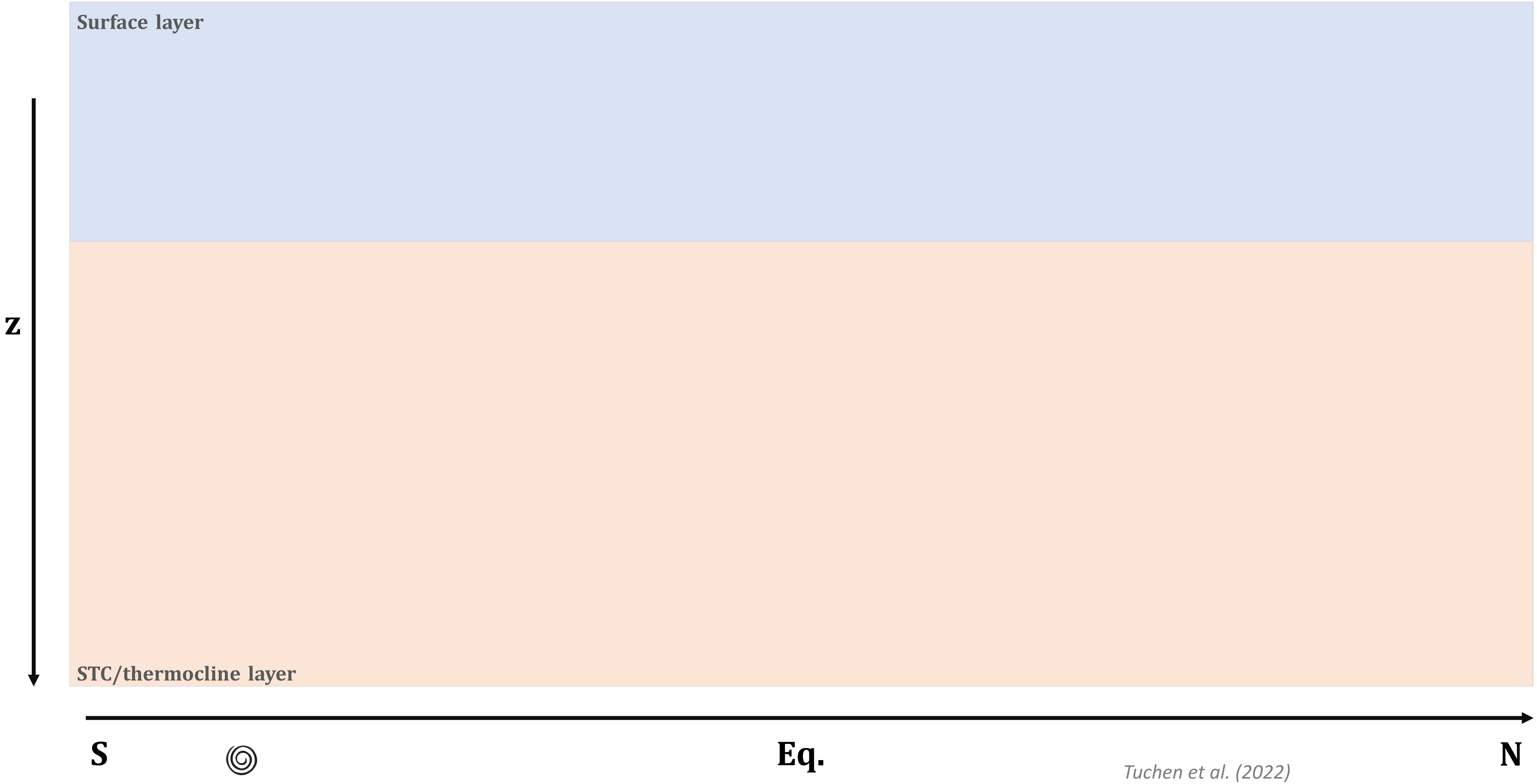

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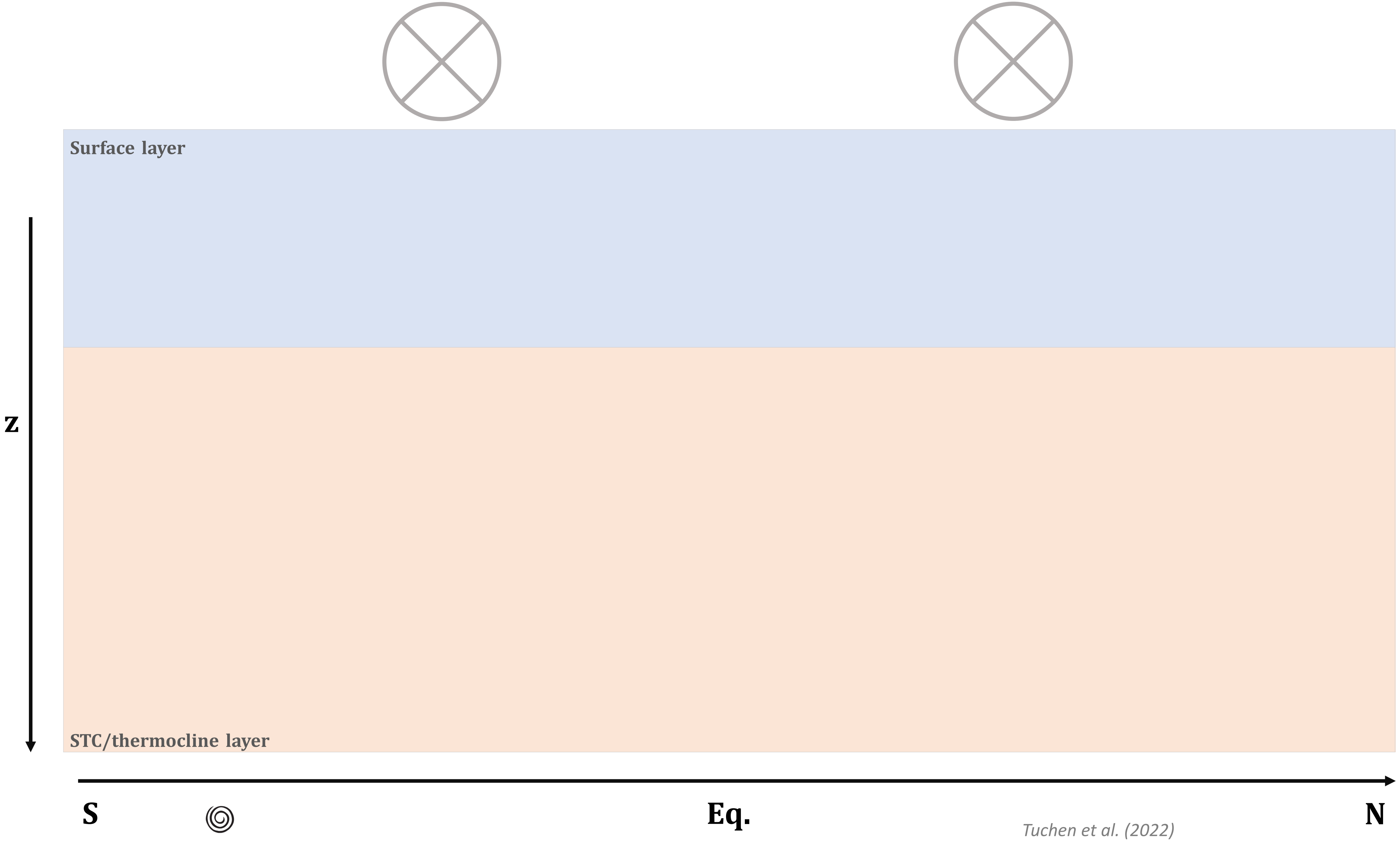

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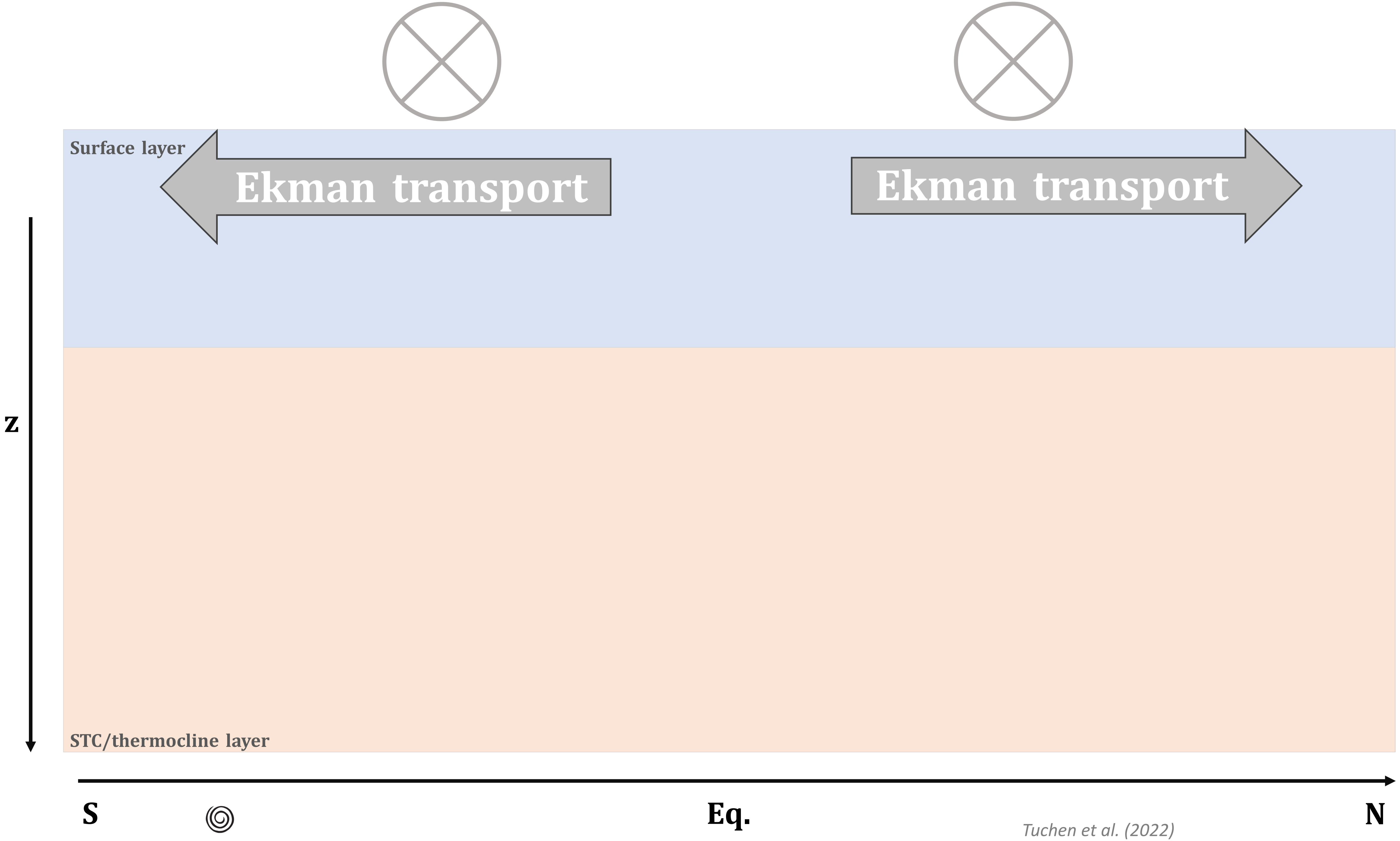

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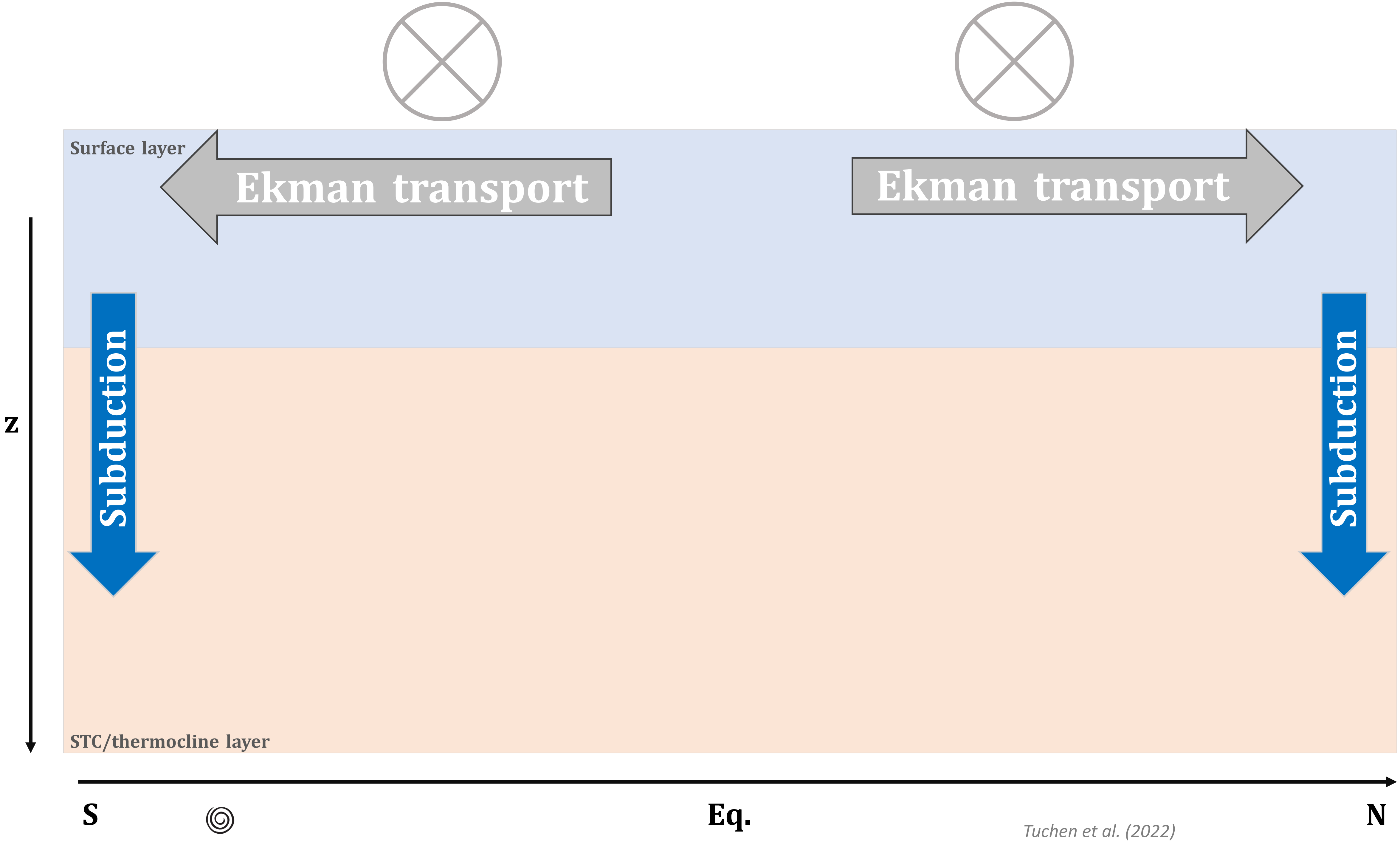

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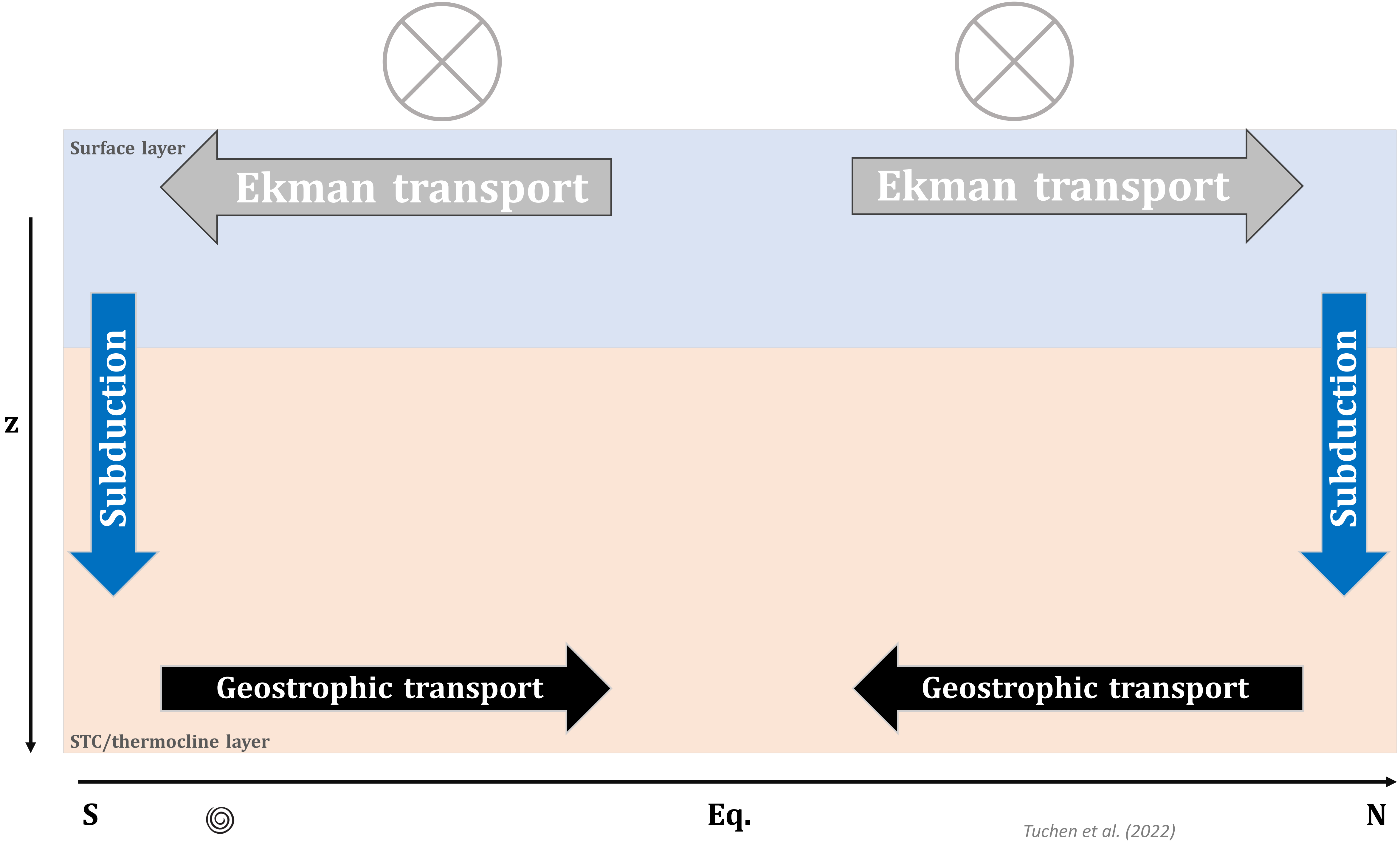
Surface layer
Ekman transport
Ekman transport
Subduction
Subduction
z
Geostrophic transport
Geostrophic transport
STC/thermocline layer
S
Eq.
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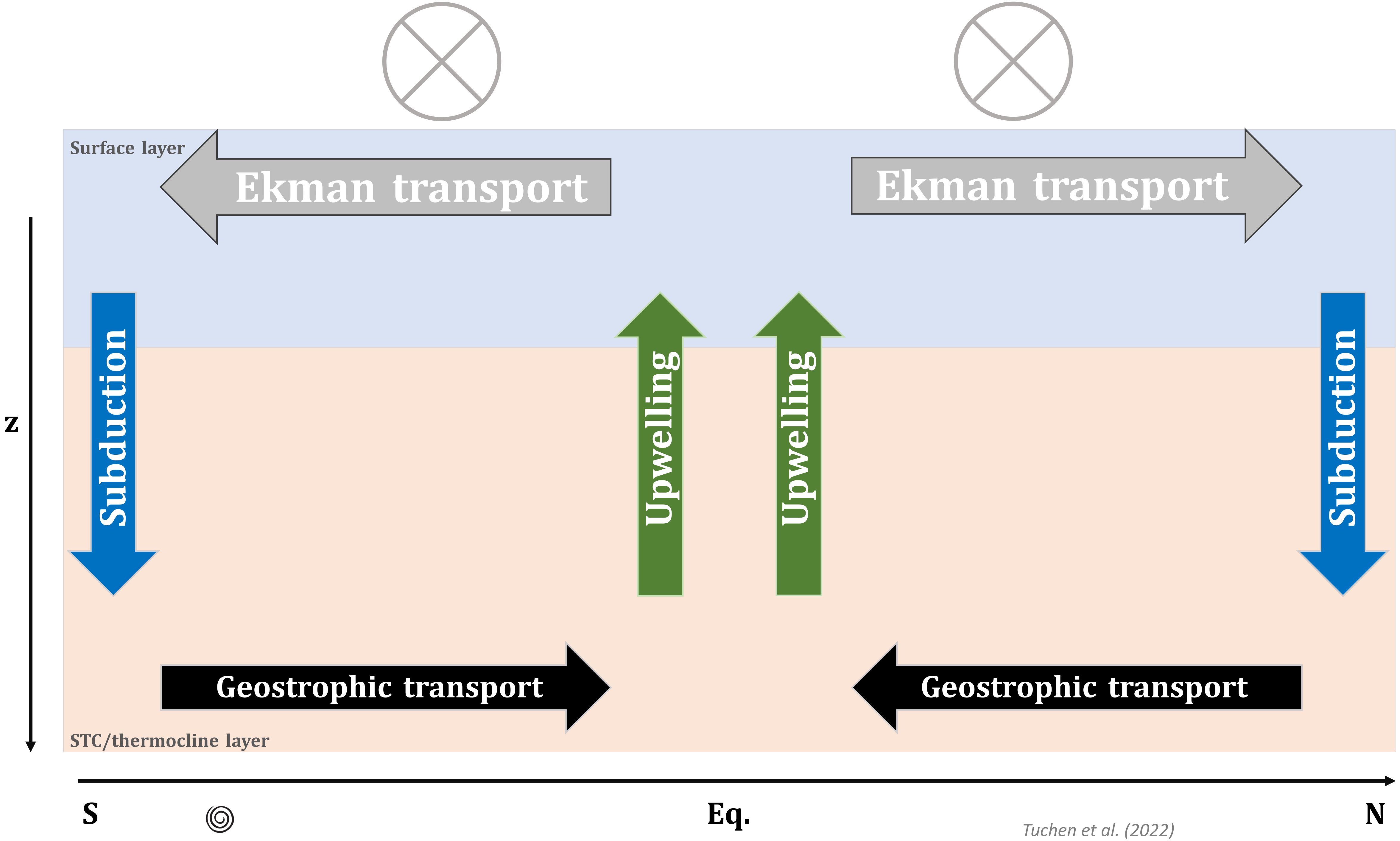

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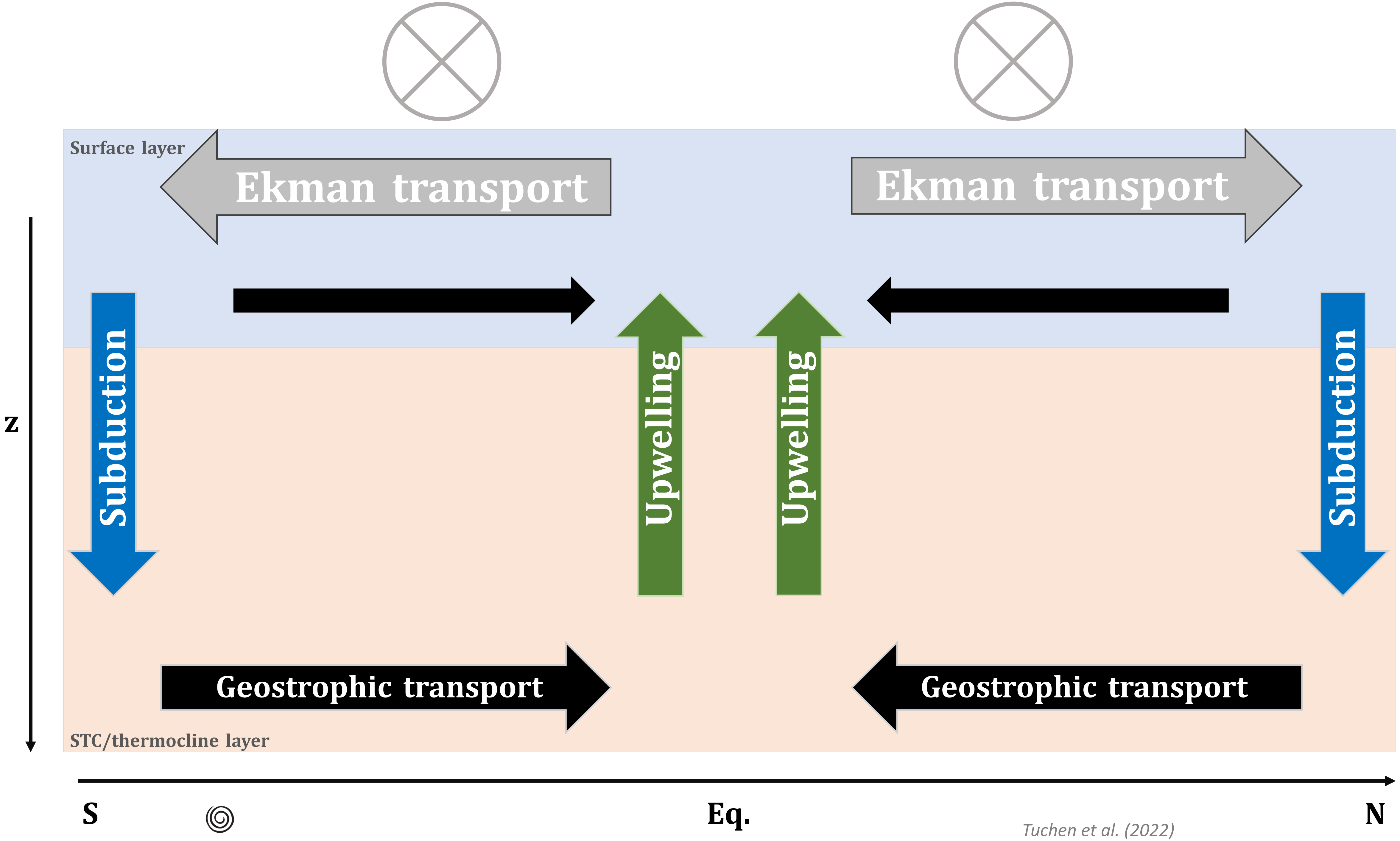
Surface layer
Ekman transport
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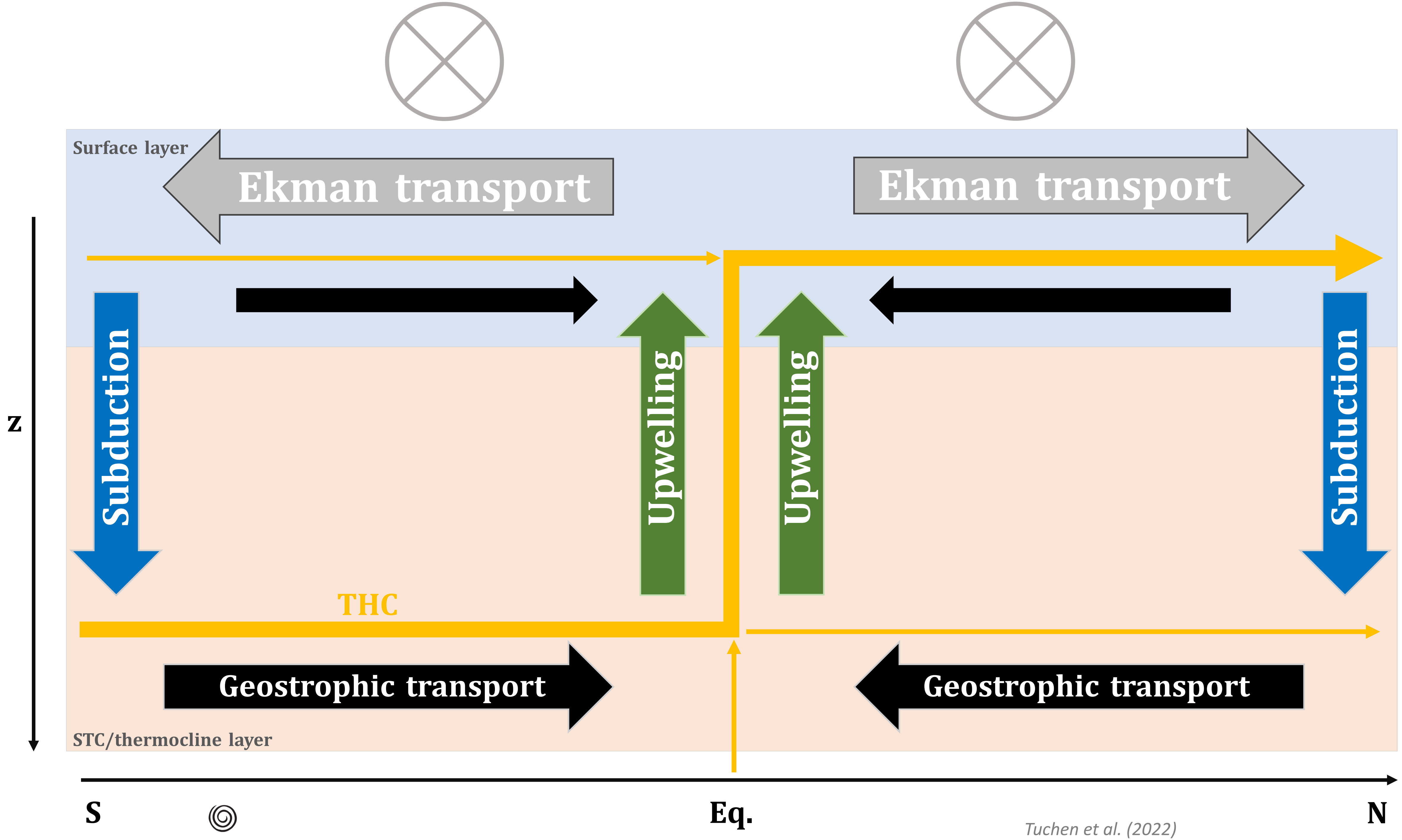

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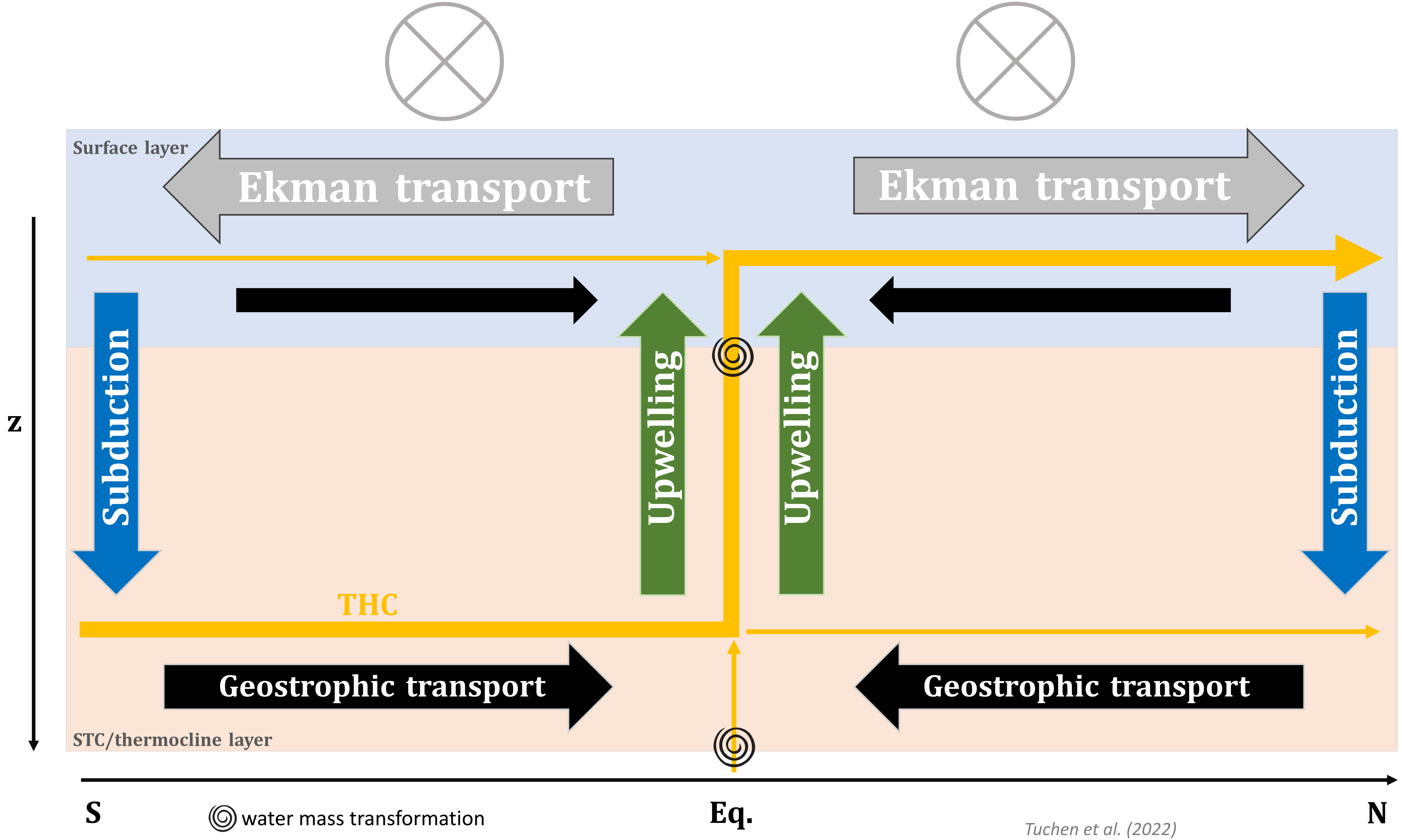

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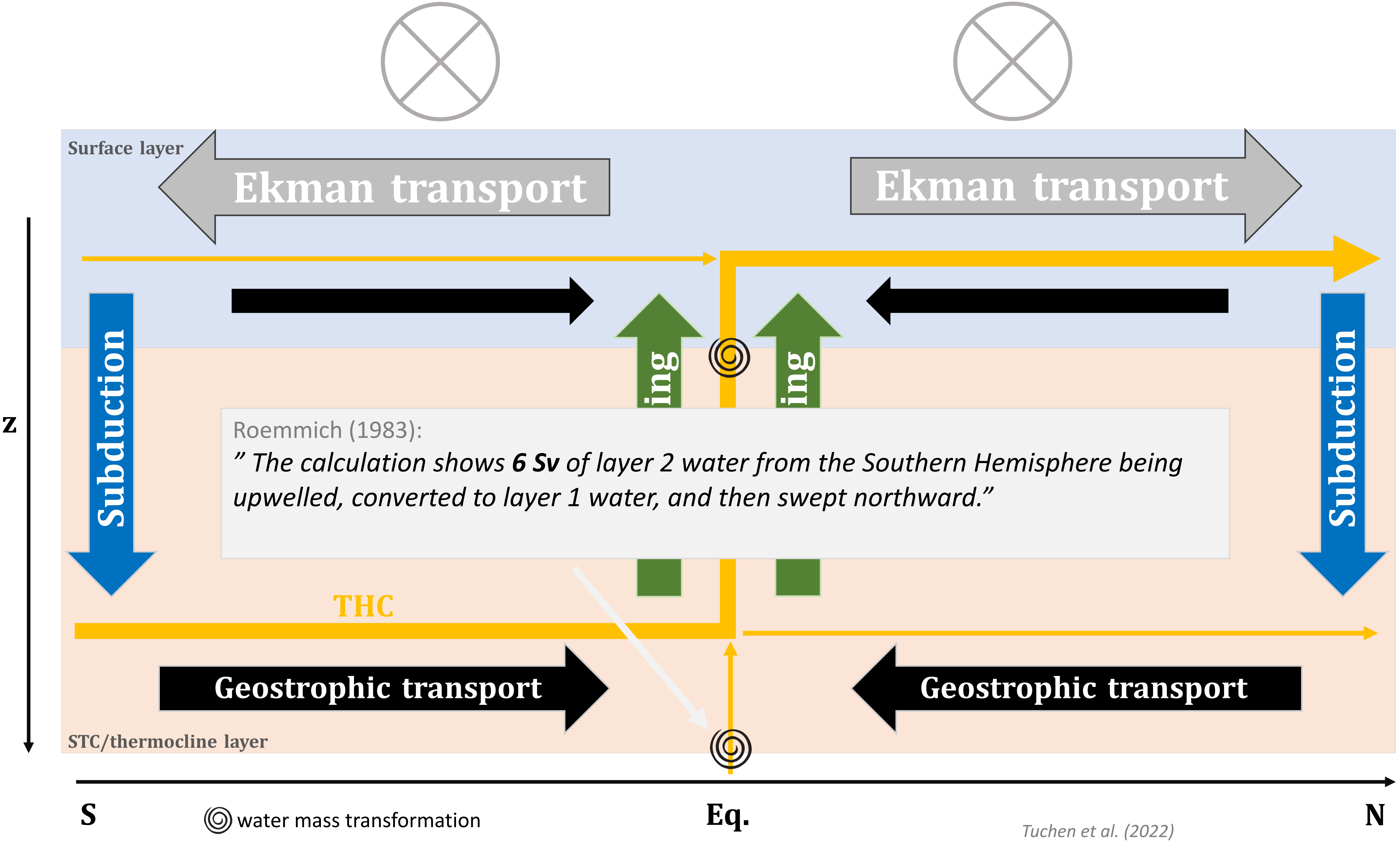

Roemmich (1983):

*" The calculation shows **6 Sv** of layer 2 water from the Southern Hemisphere being upwelled, converted to layer 1 water, and then swept northward."*

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Argo and ship section mean

- Revisiting and quantifying the diapycnal transport within the tropics into the STC layer from below
  - High-resolution (1/6°) Argo mean (Roemmich & Gilson, 2009)
  - Validation against repeated ship section along 11°S (Schott et al. 2005, Hummels et al. 2015)

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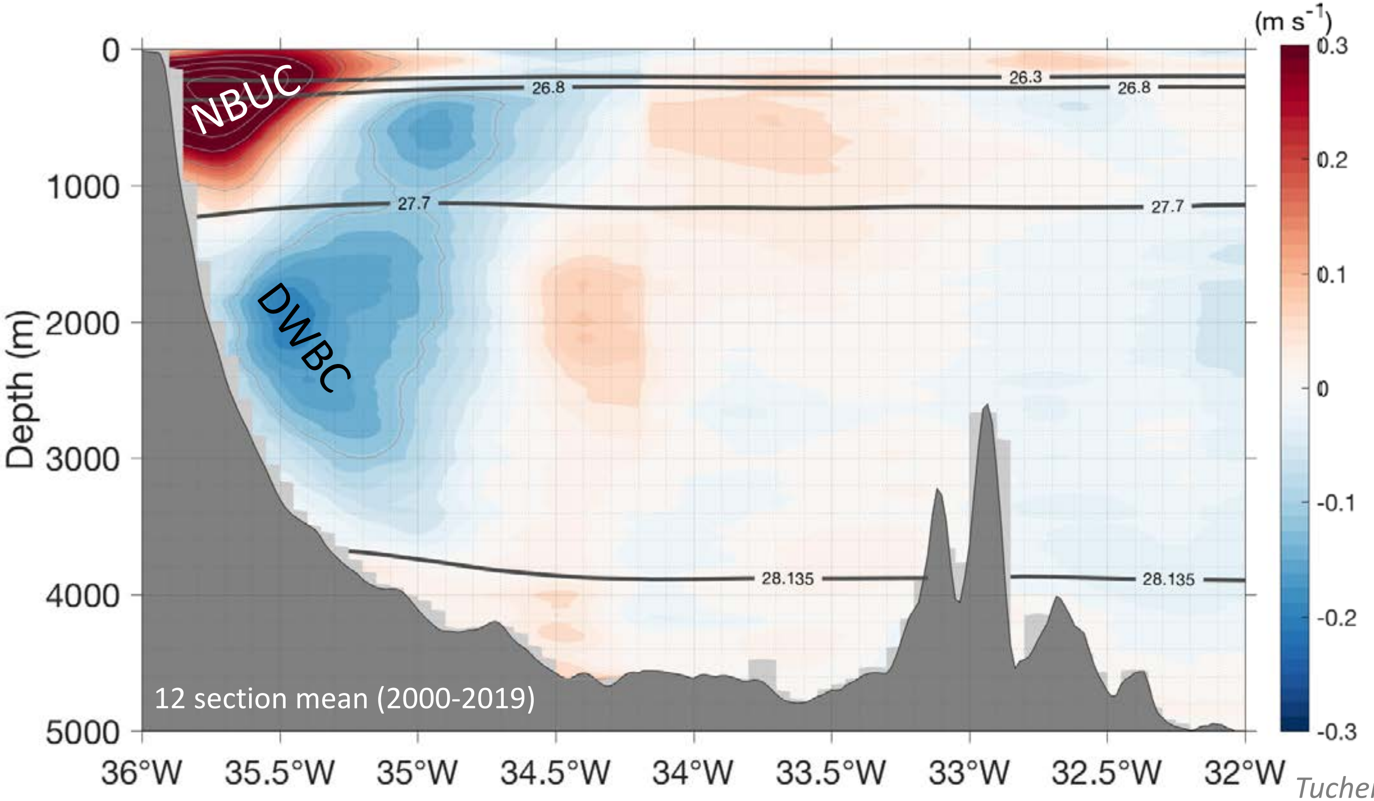

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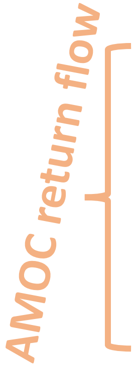
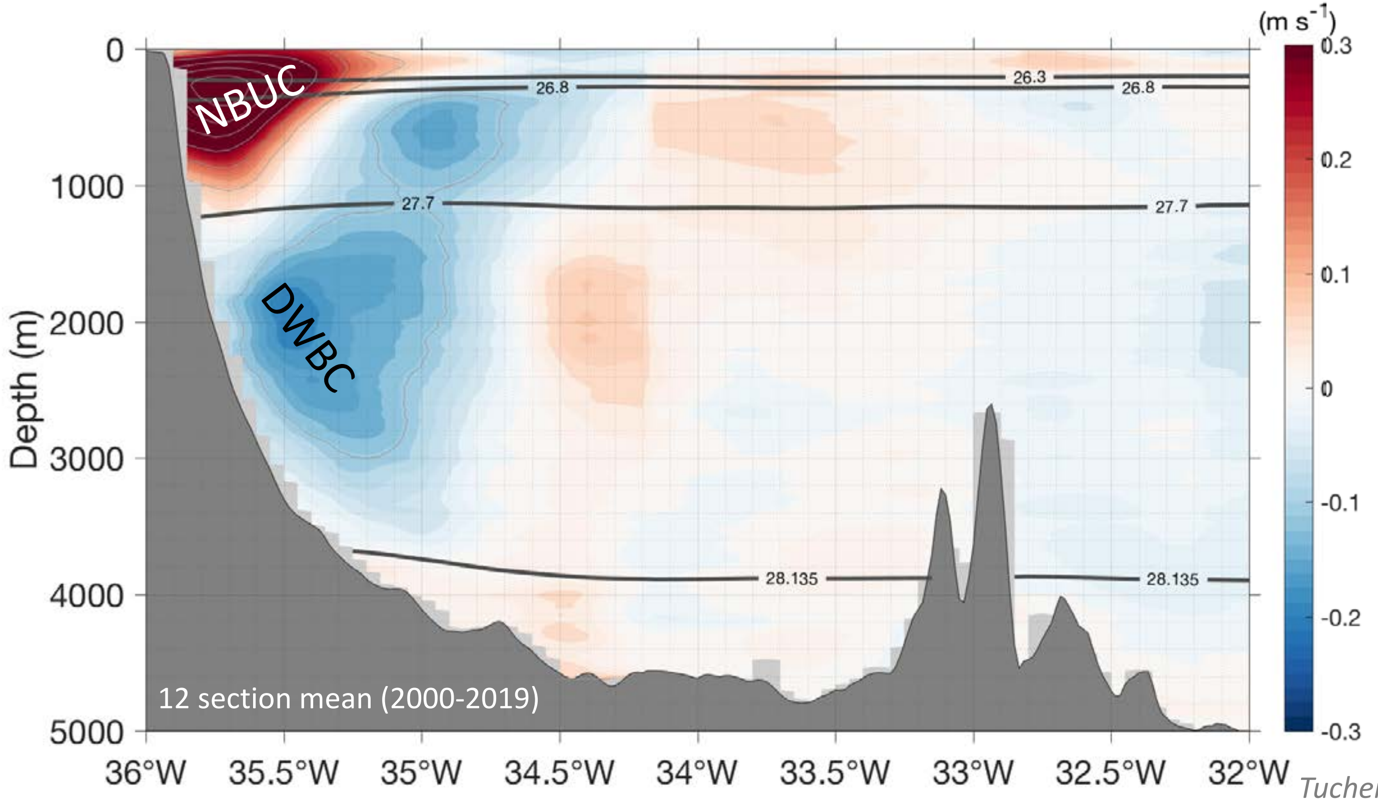


Water Mass Layer	Vertical Boundaries (γ_n)
Surface Layer	Surface to Ekman depth
STC/thermocline Layer	Ekman depth to 26.3
Lower CW	26.3 to 26.8
AAIW	26.8 to 27.7
NADW	27.7 to 28.135
AABW	28.135 to bottom



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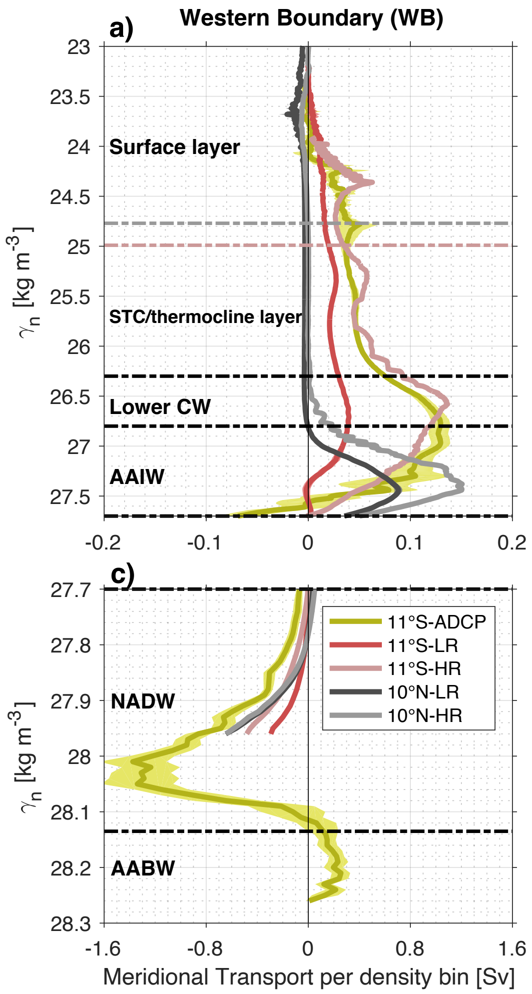
Argo data validation at 11°S



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- Substantial underestimation by lower-resolved (1°x1°) data
- Similar at 10°N, but no comparable reference

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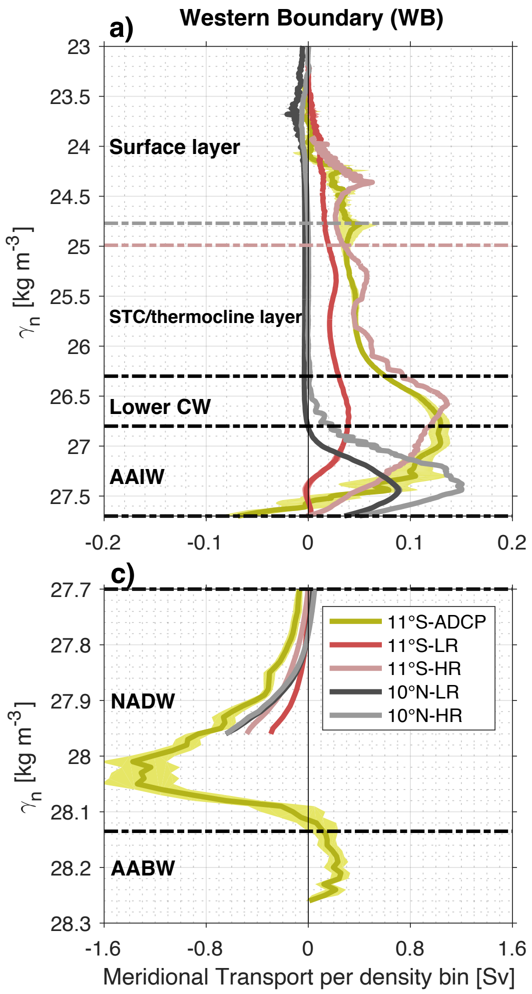

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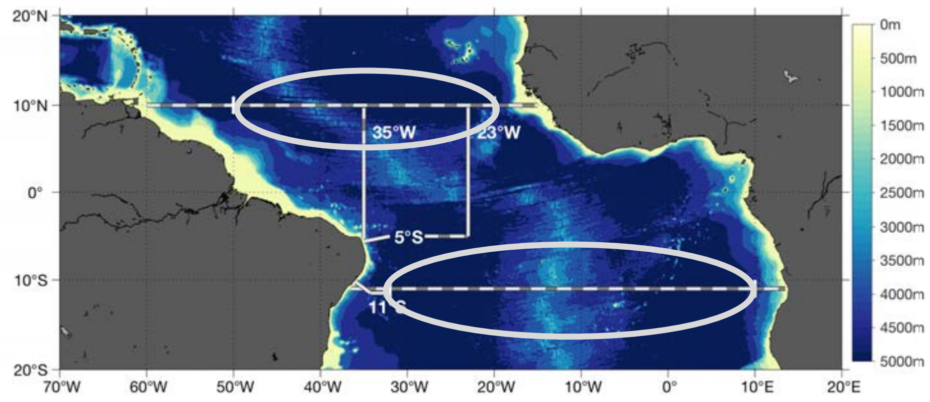

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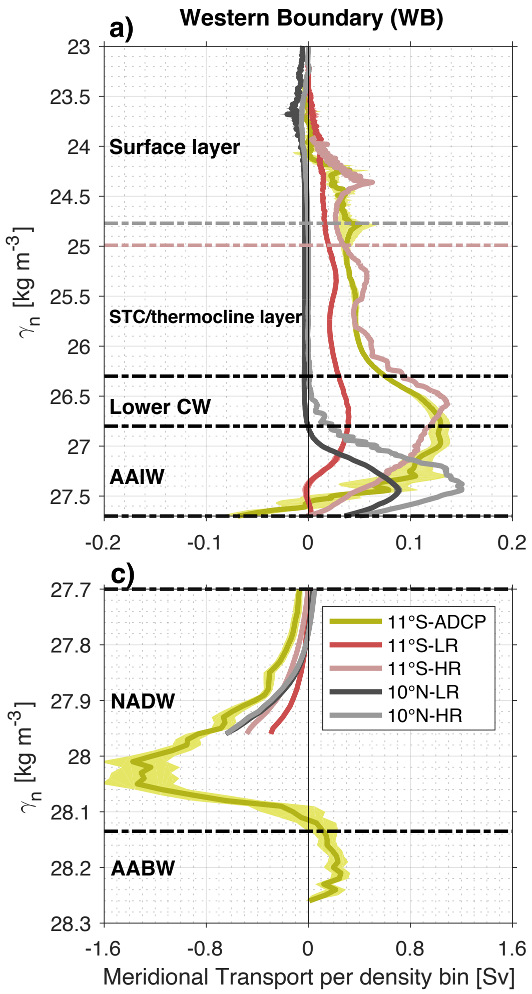

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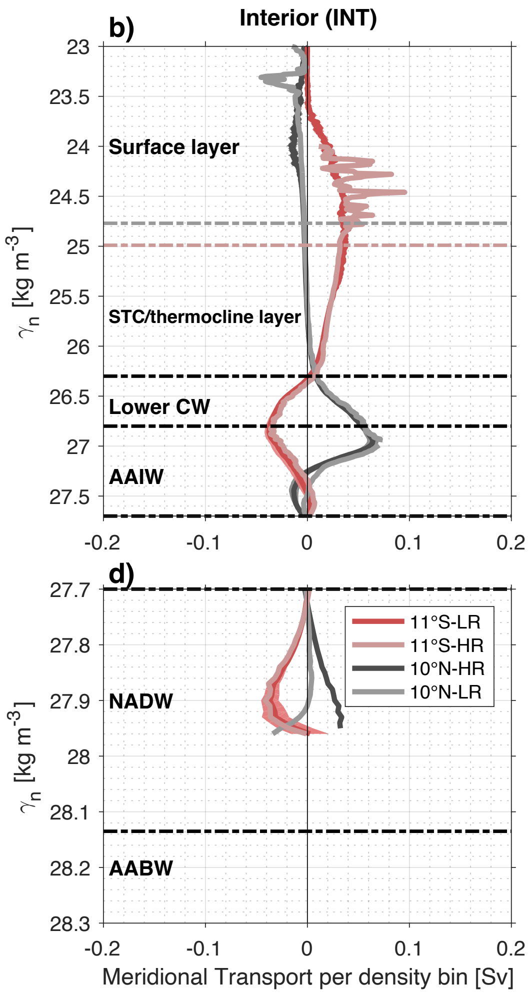
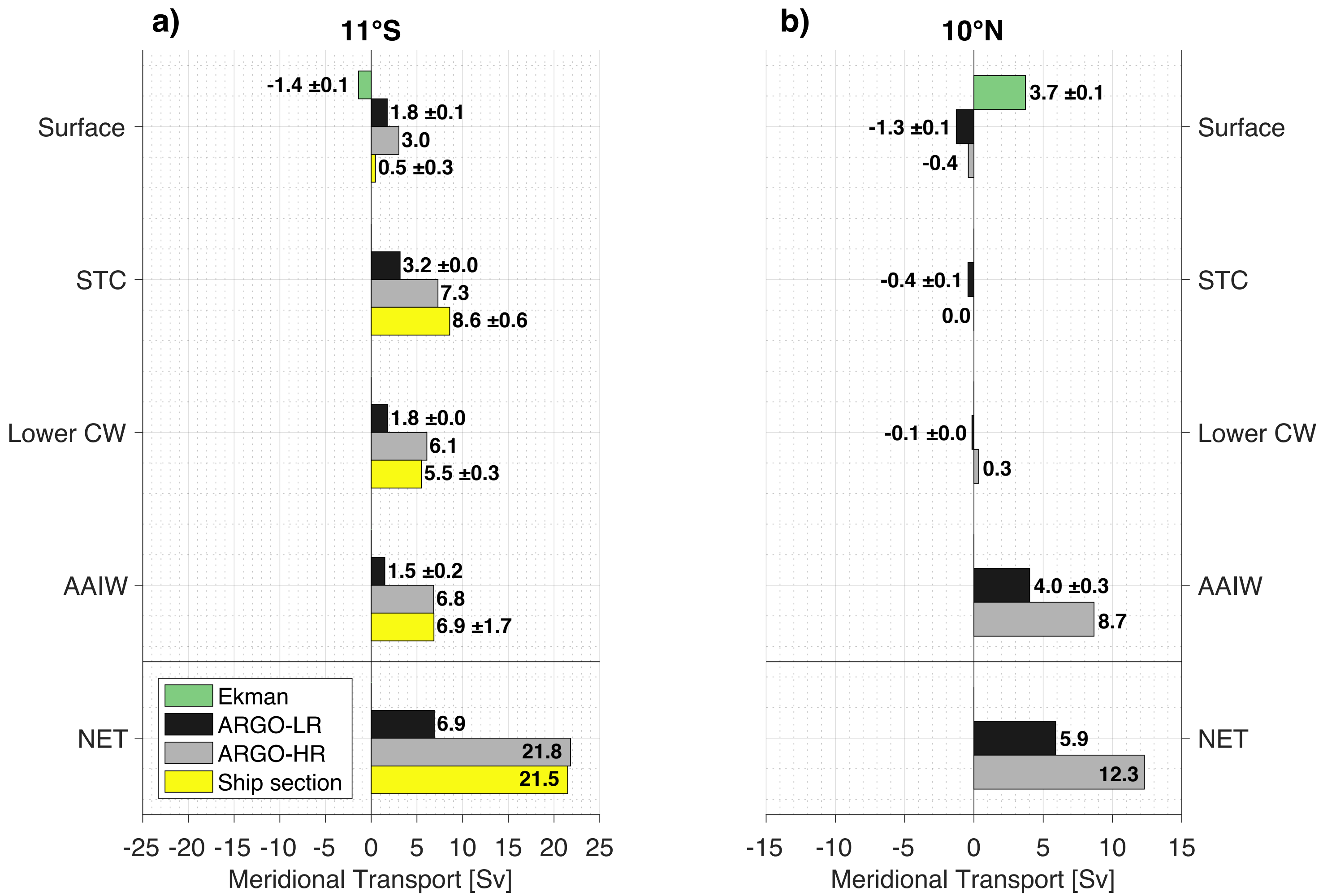


- Very good agreement between differently resolved Argo products
- Resolution more crucial at the western boundary

Western boundary transports



Western boundary transports

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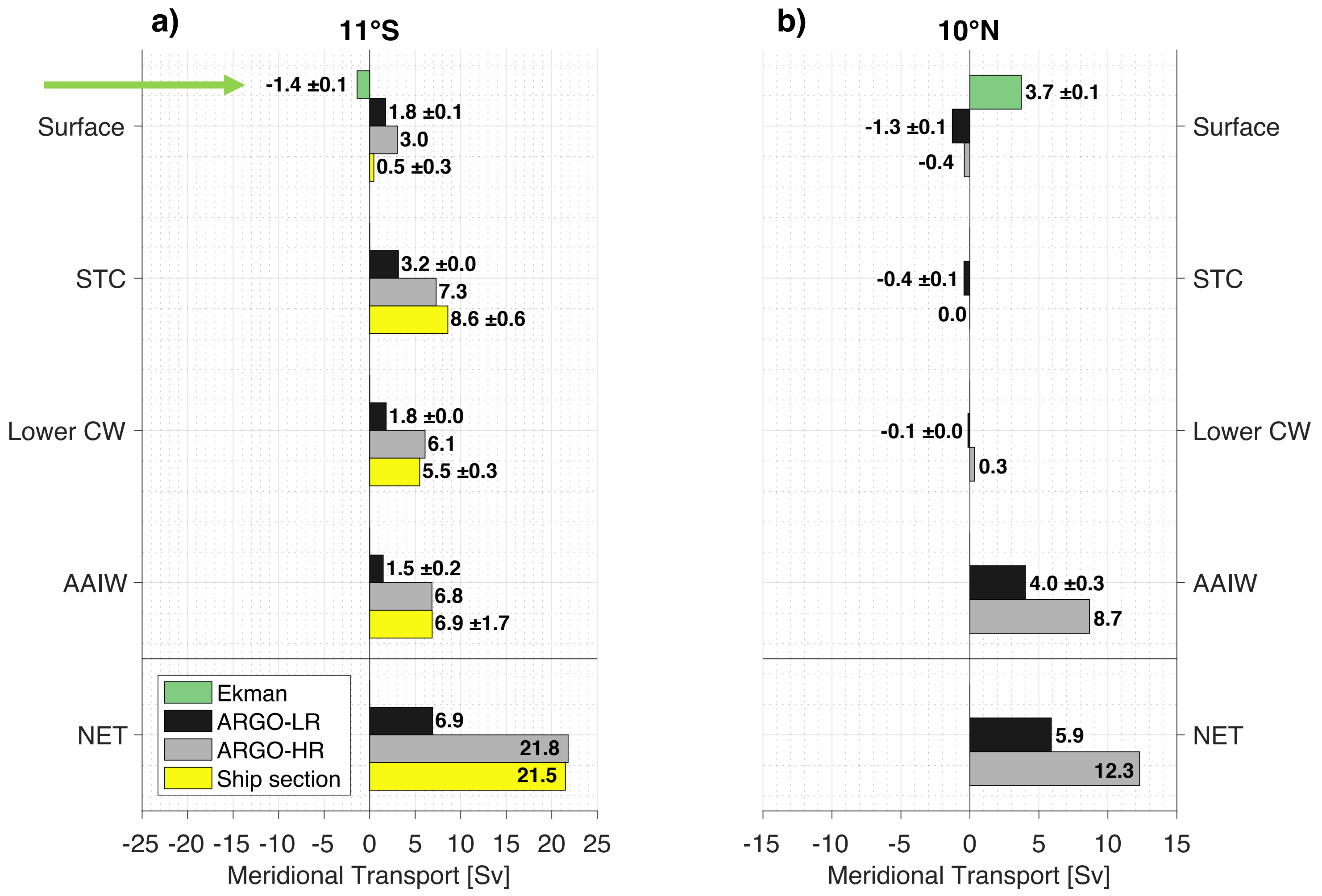

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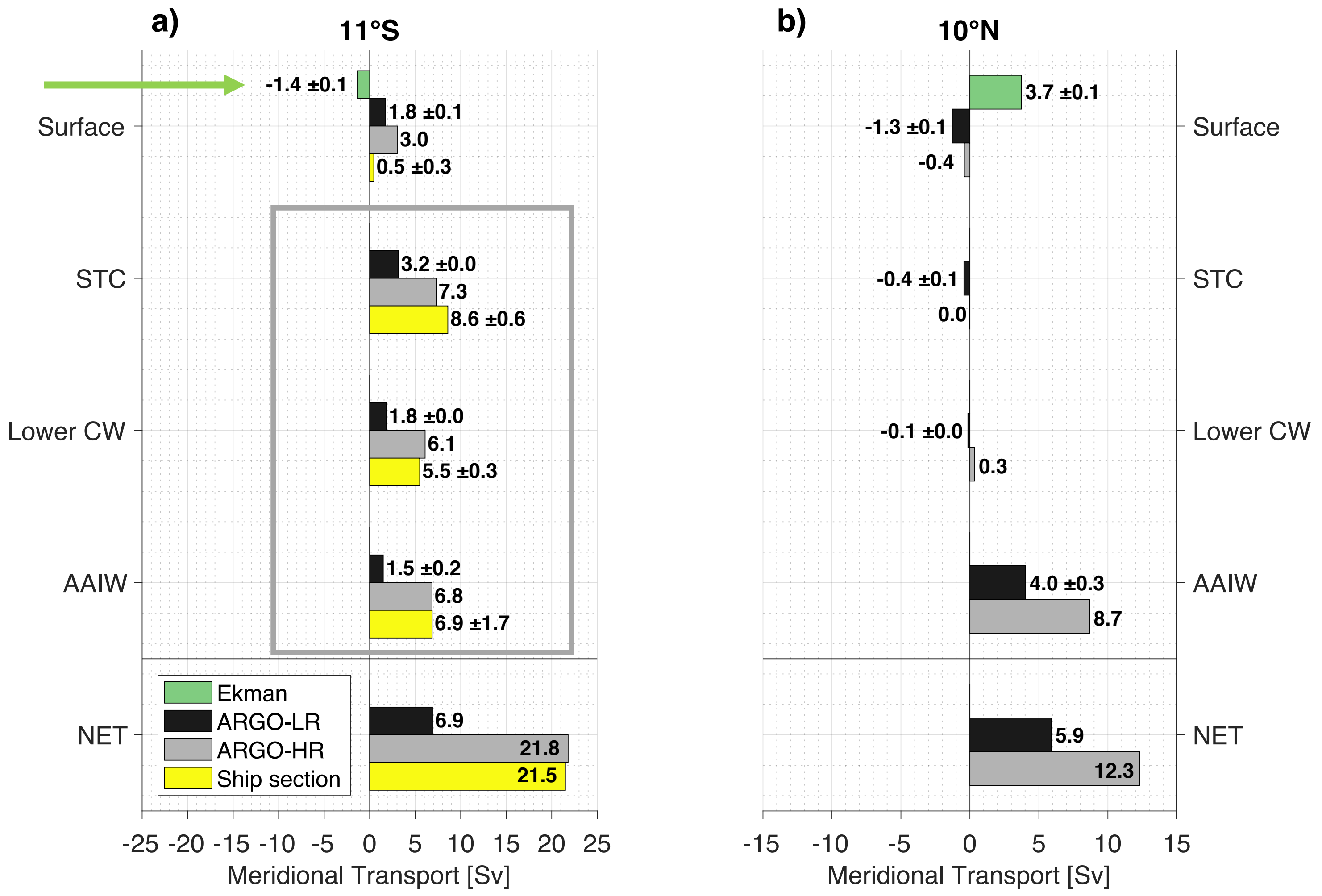

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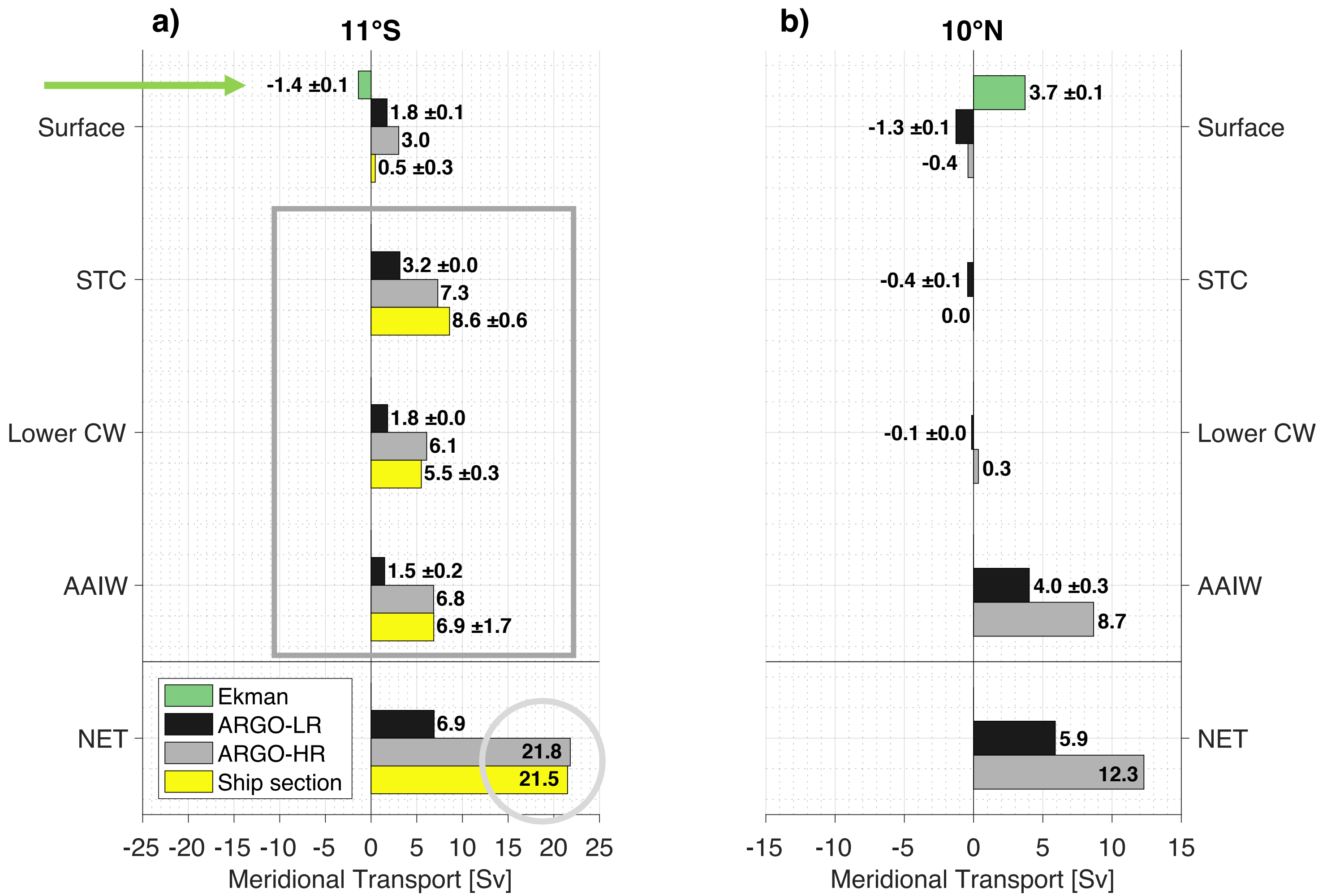

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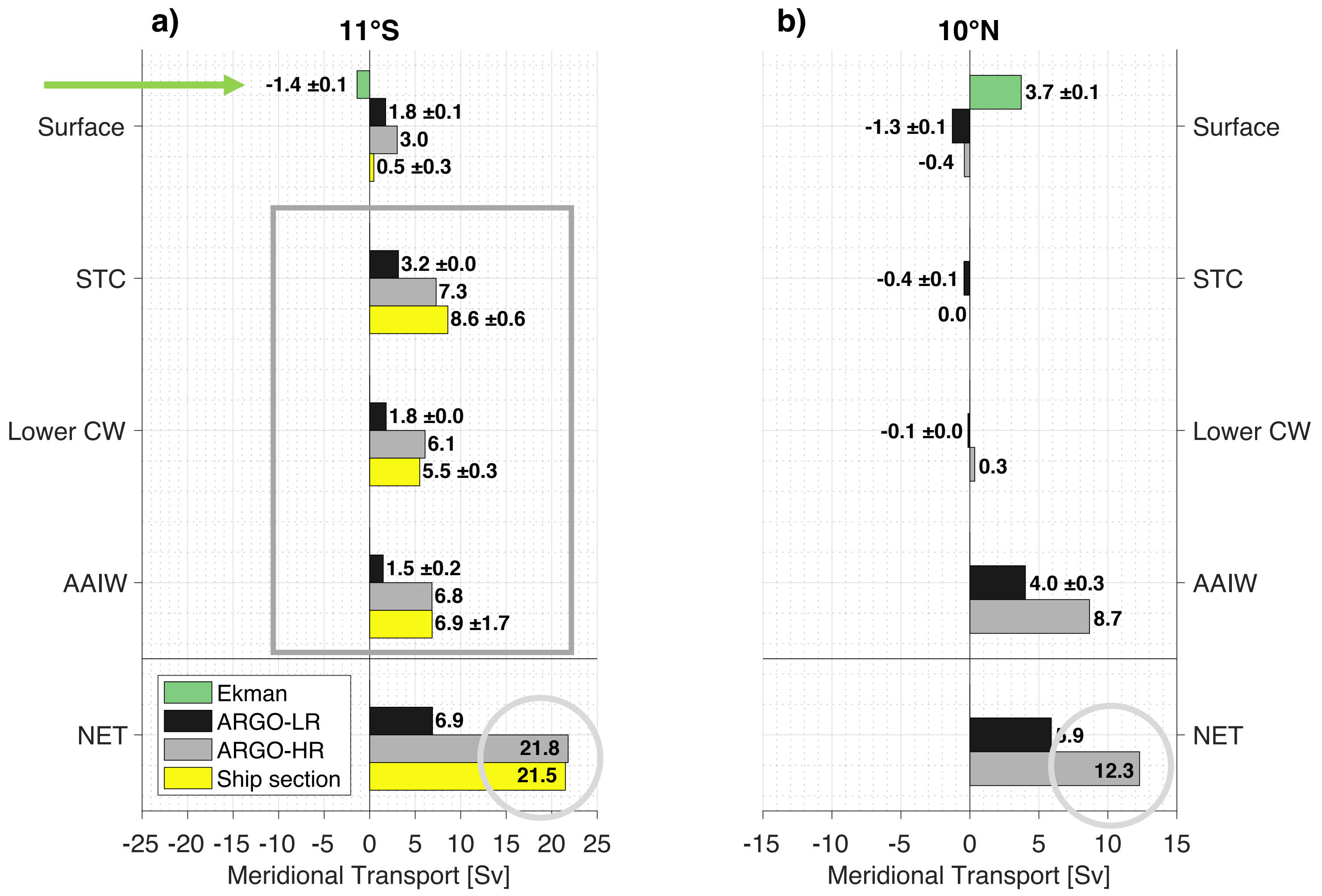

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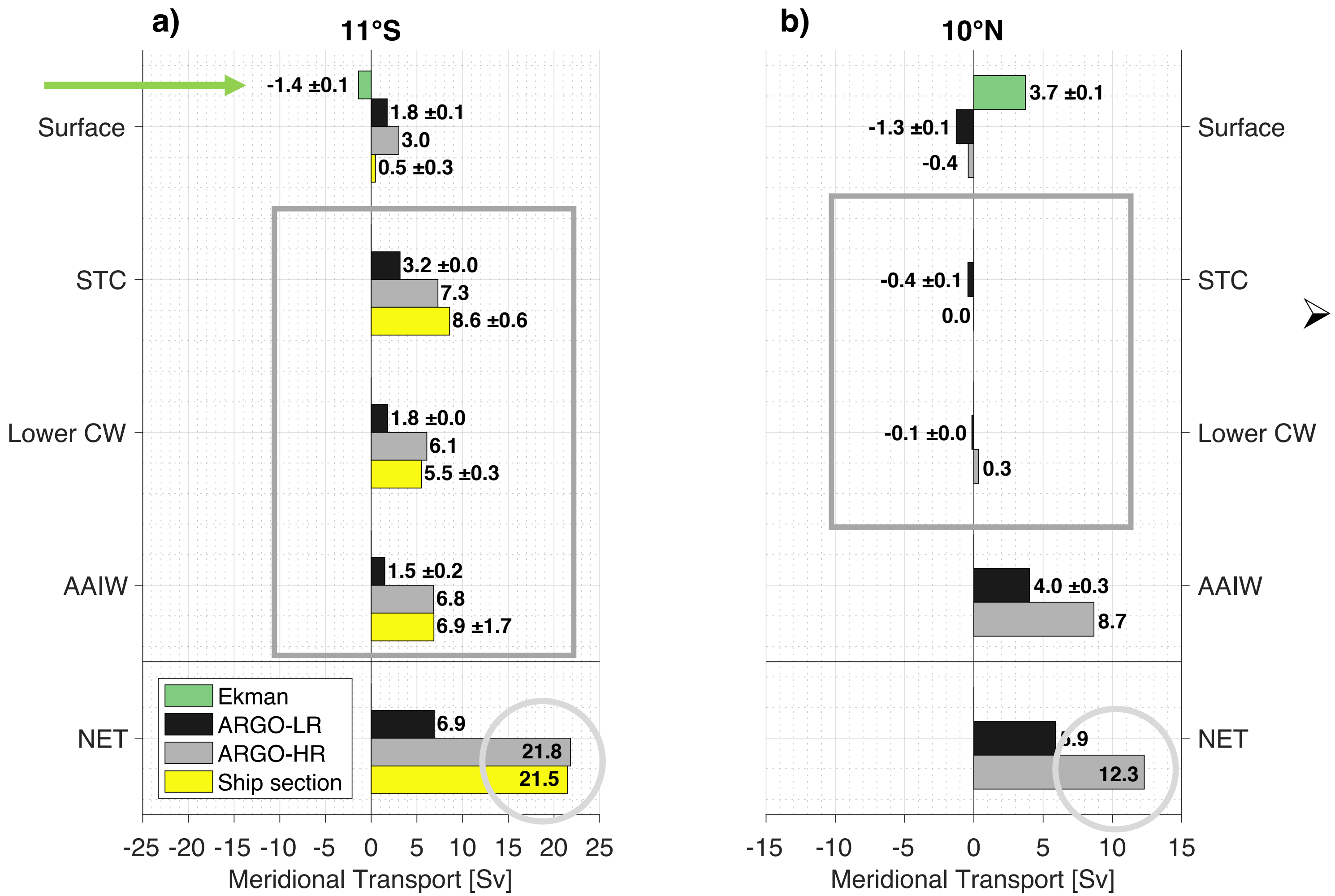
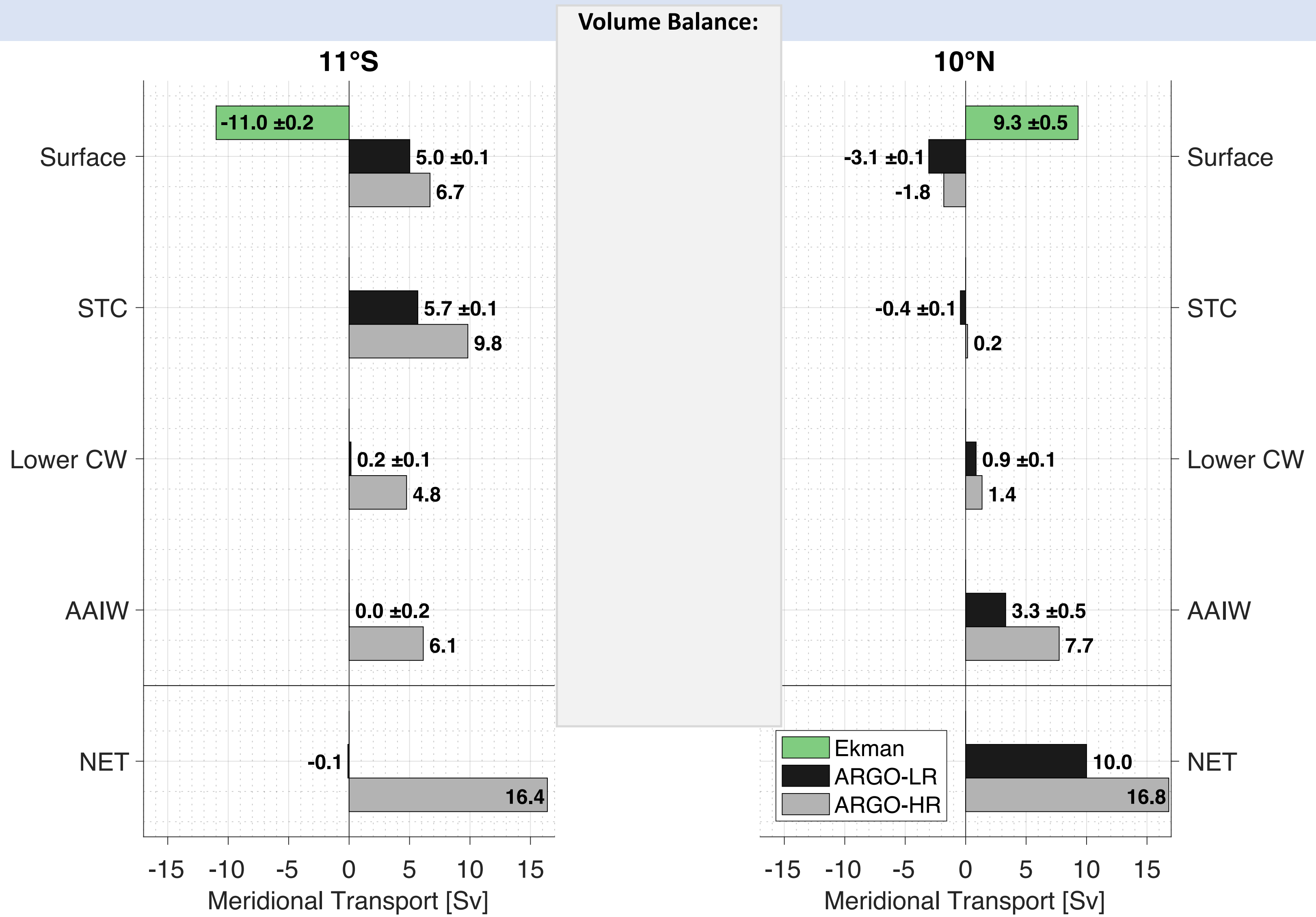


- Absence of STC and CW water?

Diapycnal transports between 10N/S



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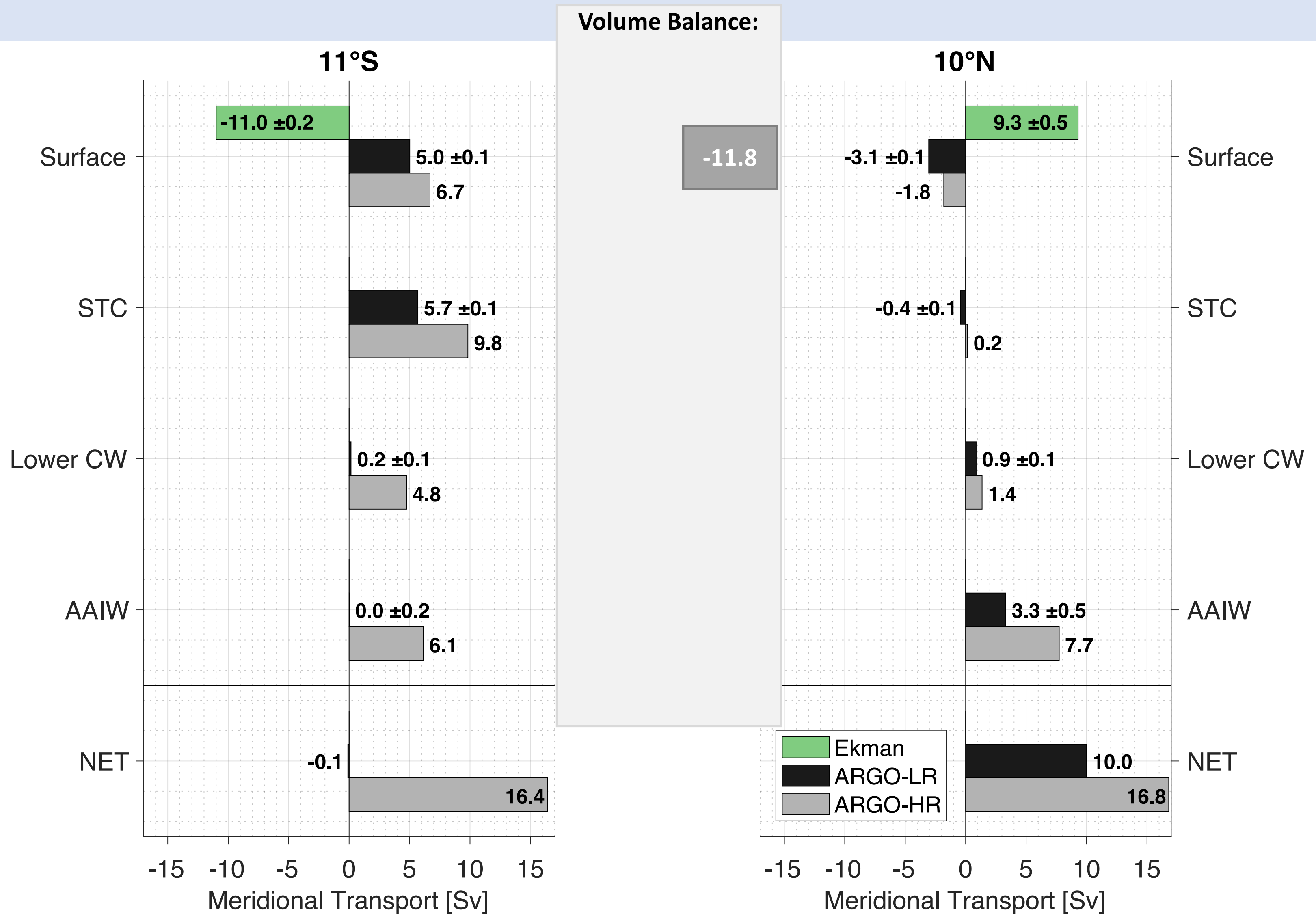

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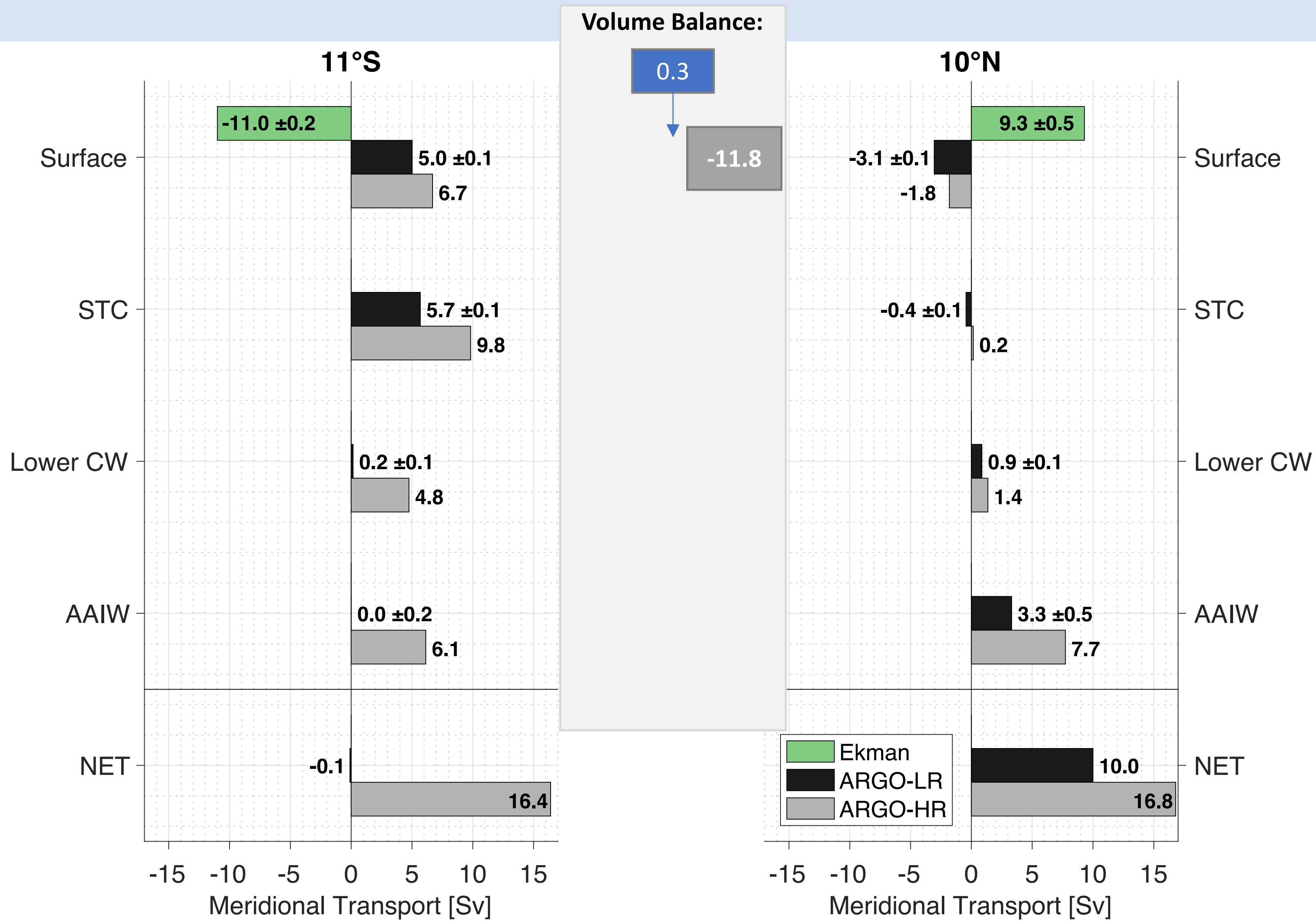

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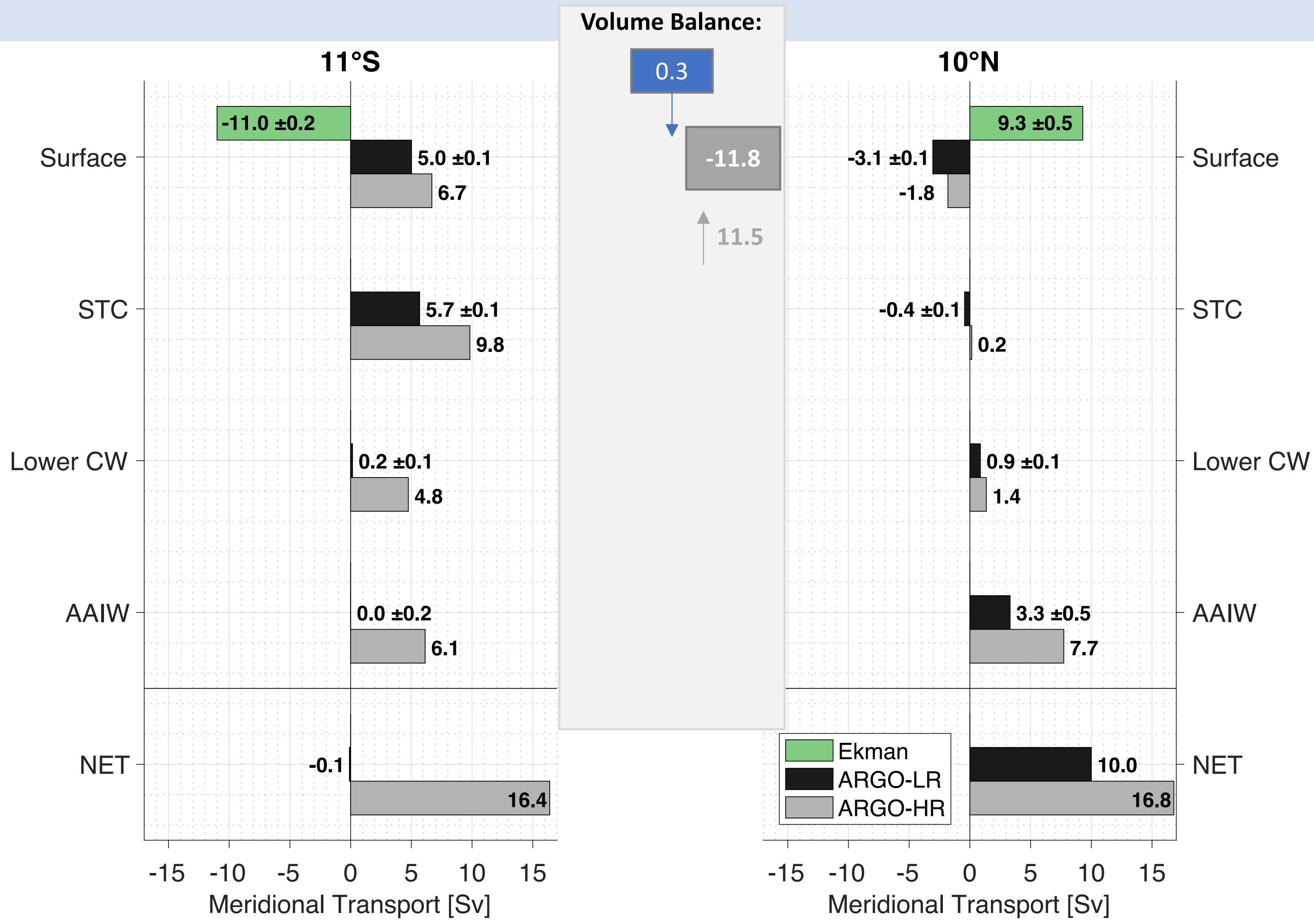

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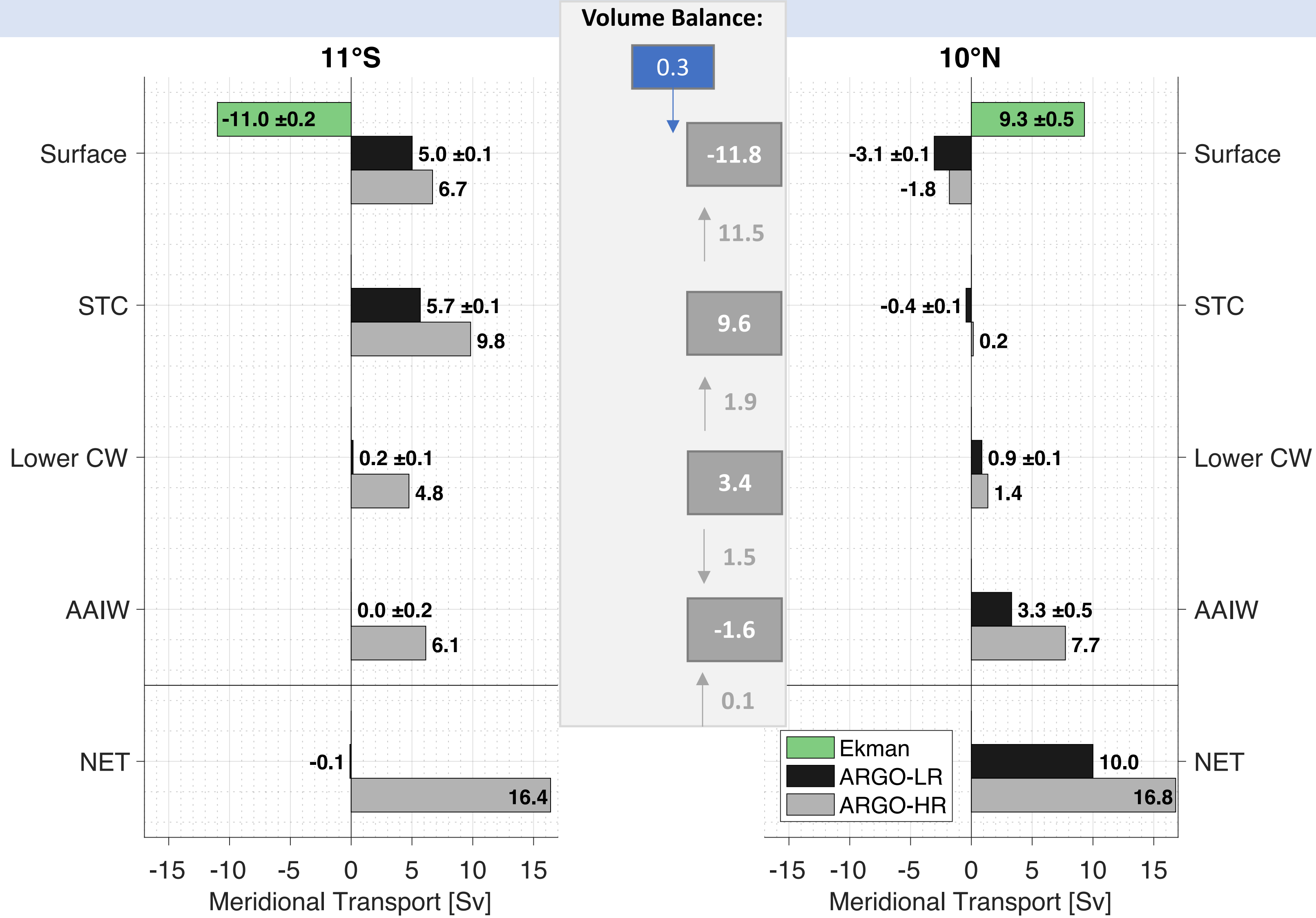

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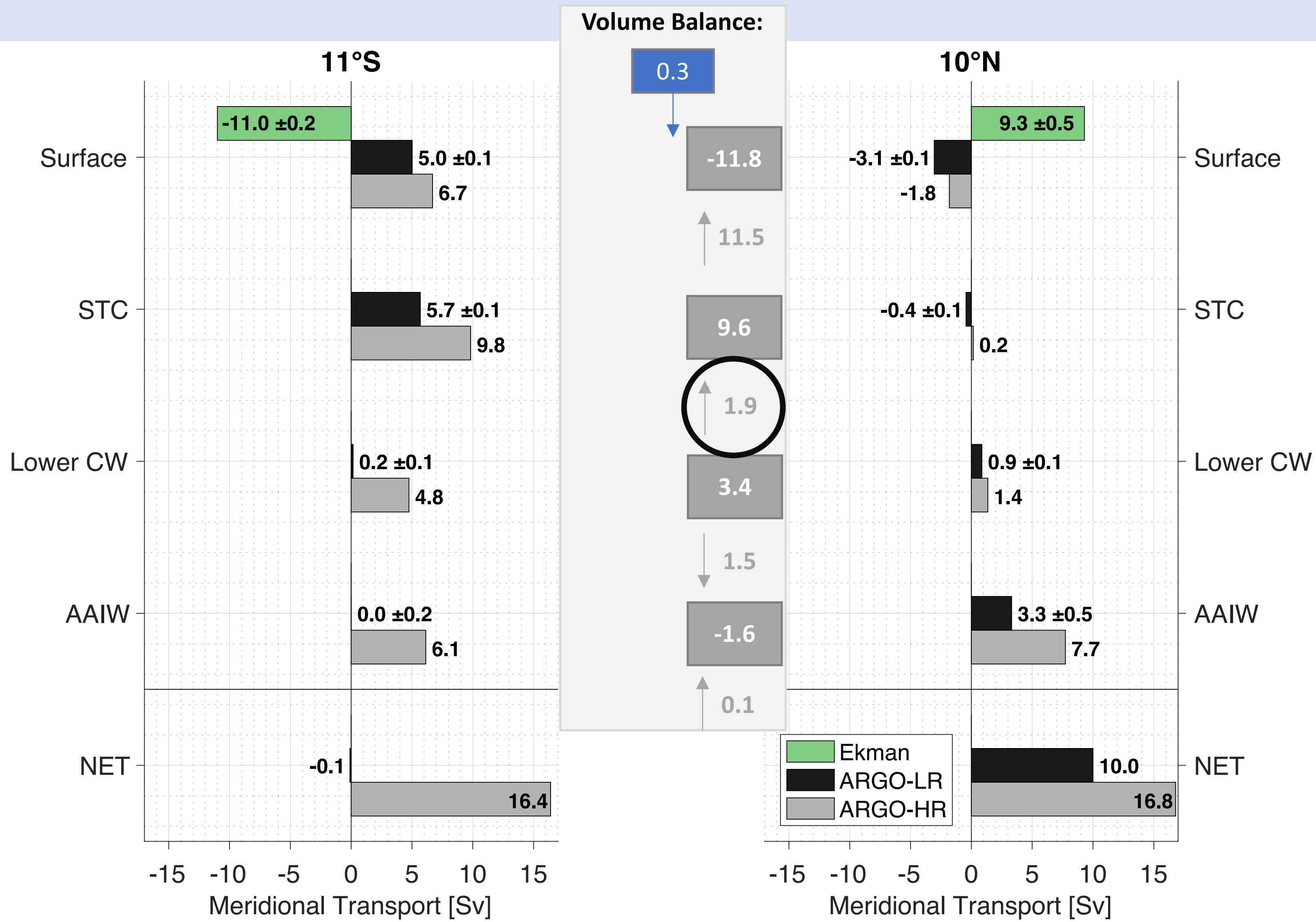

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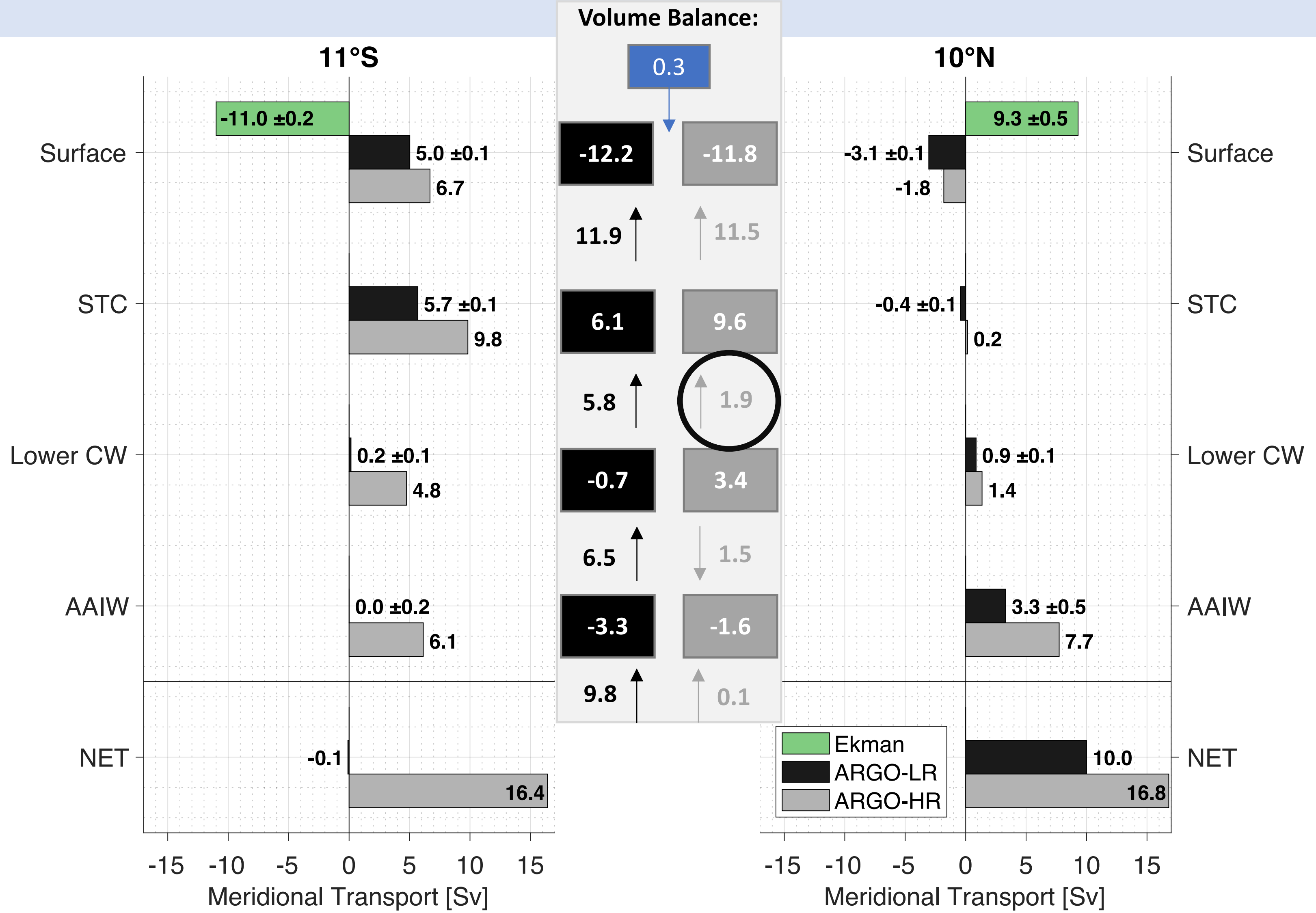

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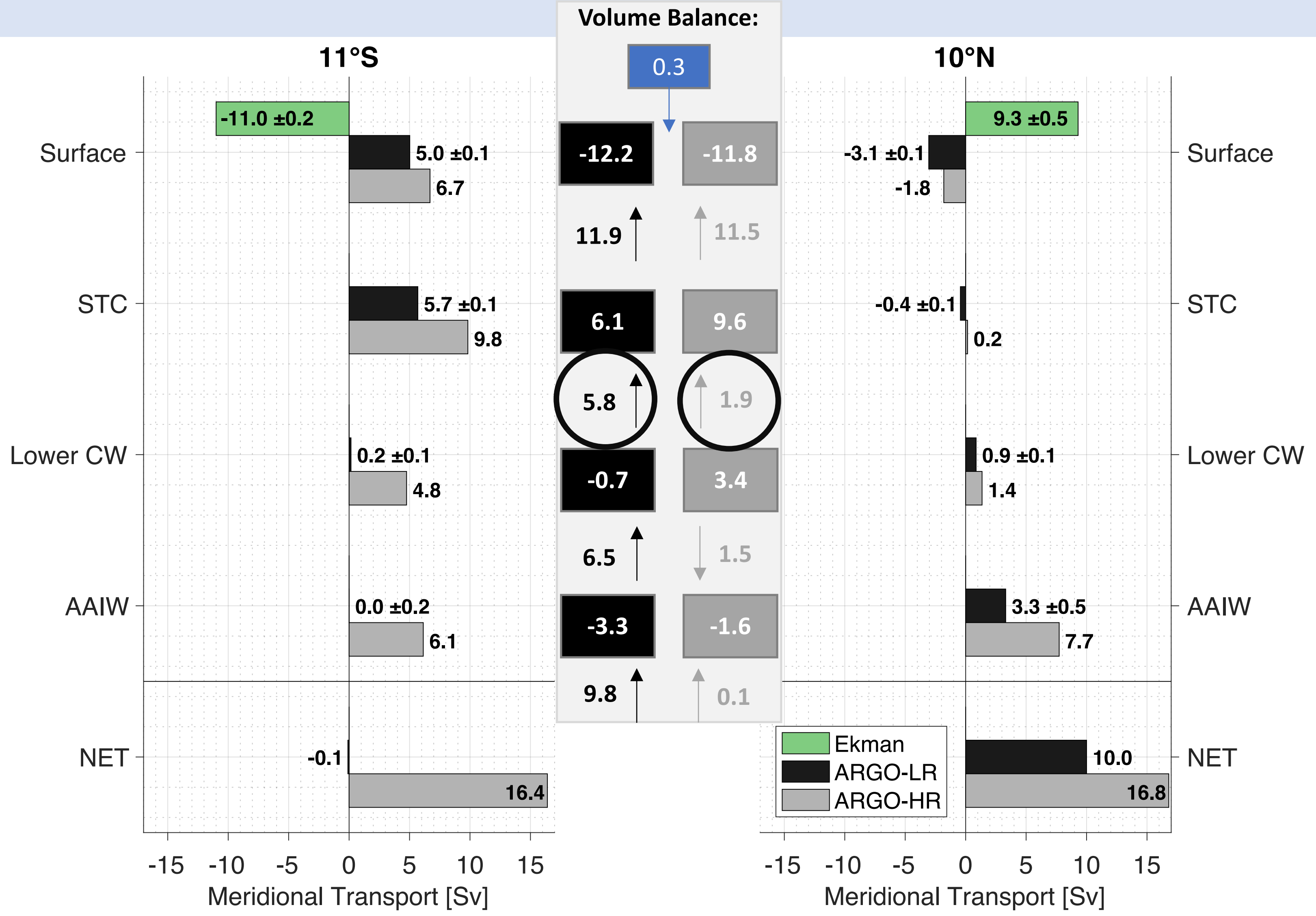
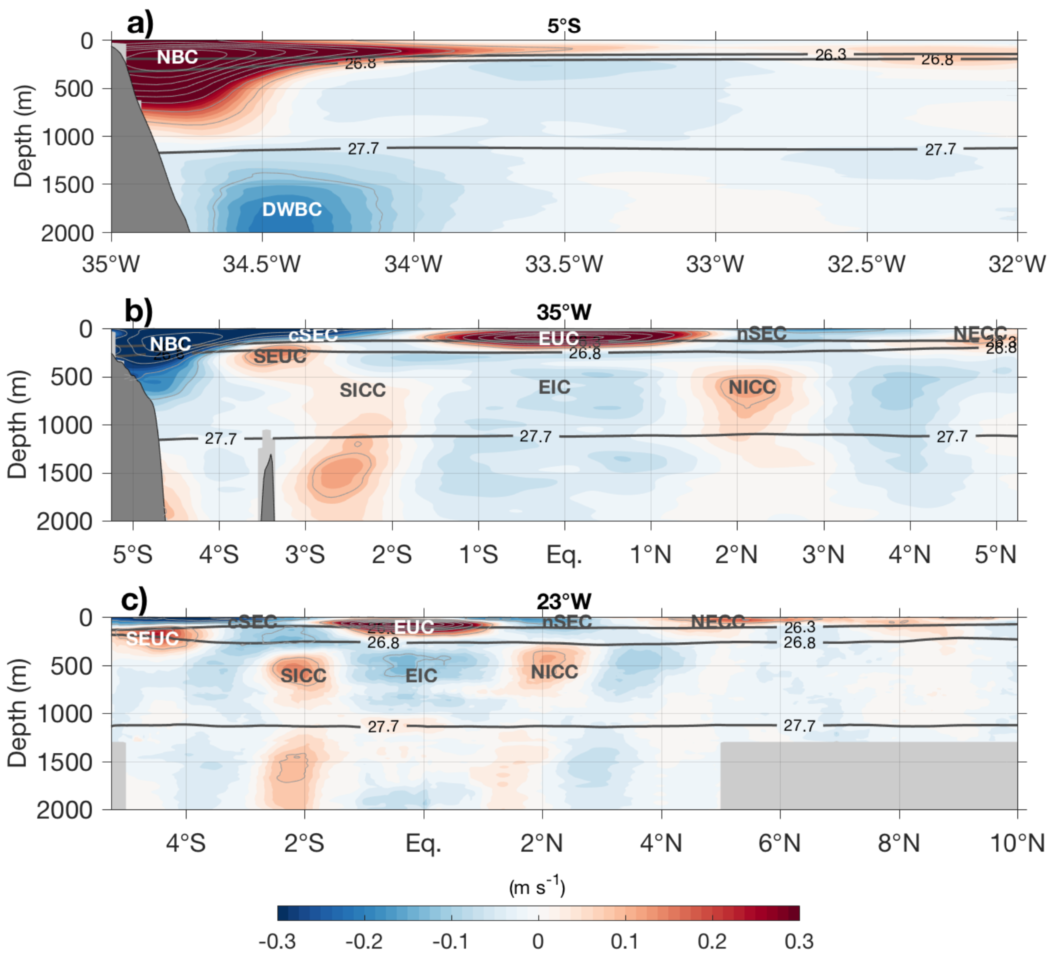
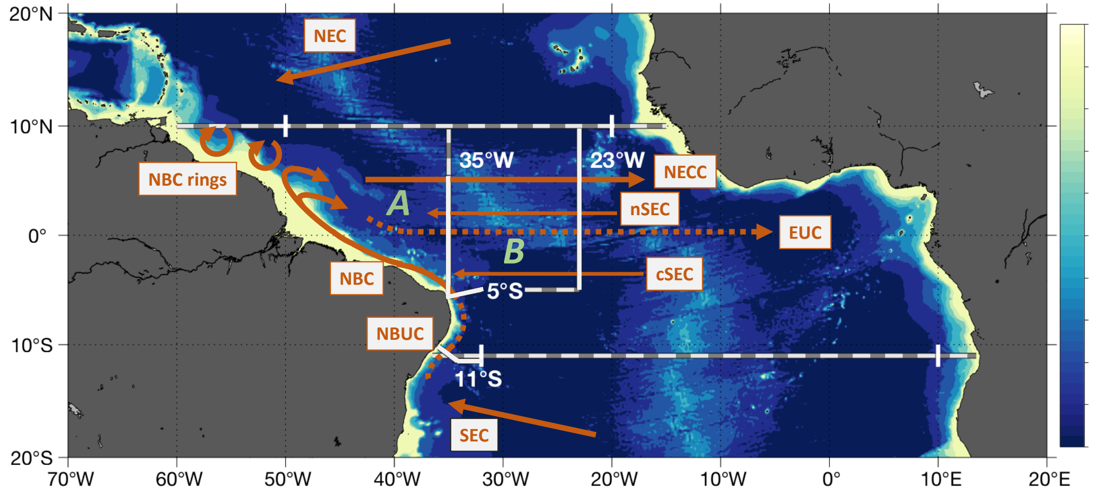


Transports and pathways

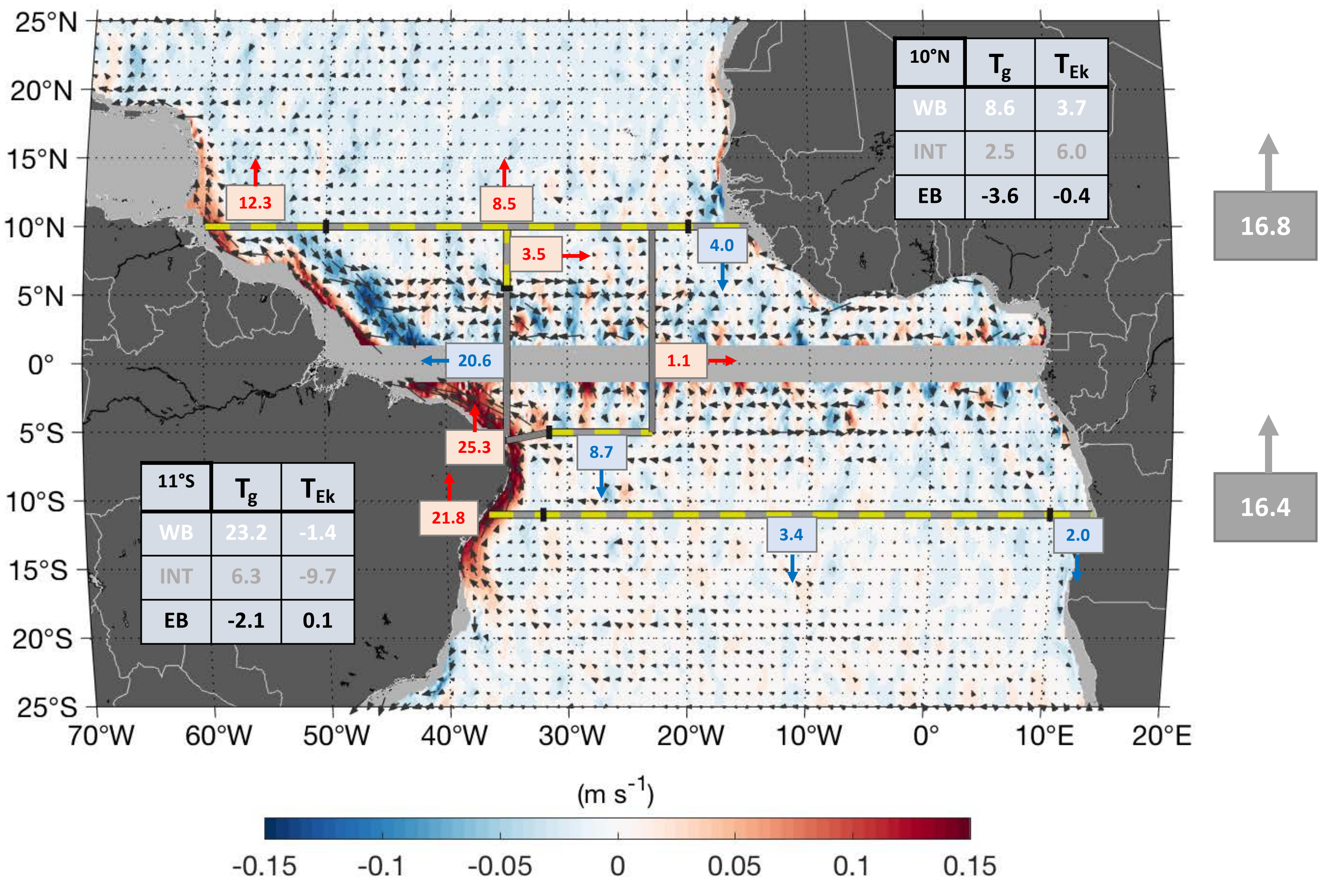




- Especially, close to the equator we rely on shipboard measurements (geostrophic balance does not hold)

AMOC return flow: Summary

Water Mass Layer
Surface Layer
STC/thermocline Layer
Lower CW
AAIW
NADW
AABW

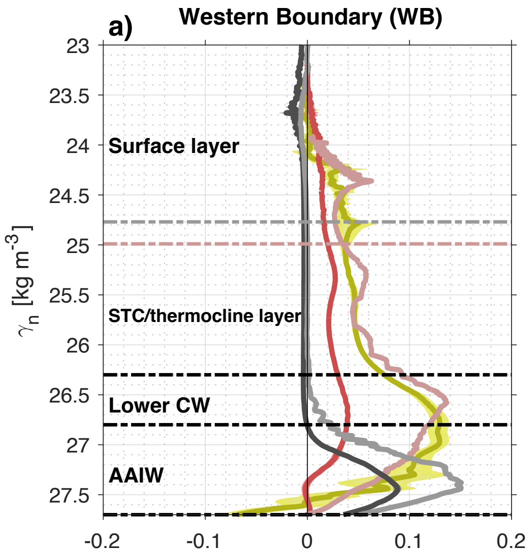


10°N	T_g	T_{Ek}
WB	8.6	3.7
INT	2.5	6.0
EB	-3.6	-0.4

11°S	T_g	T_{Ek}
WB	23.2	-1.4
INT	6.3	-9.7
EB	-2.1	0.1

Key Points

- Observed Atlantic western boundary mean transport of the upper 1,200 m at 11°S is realistically reproduced from high-resolution Argo data and satellite wind stress data
  (so far Argo products were struggling to reproduce the western boundary circulation)



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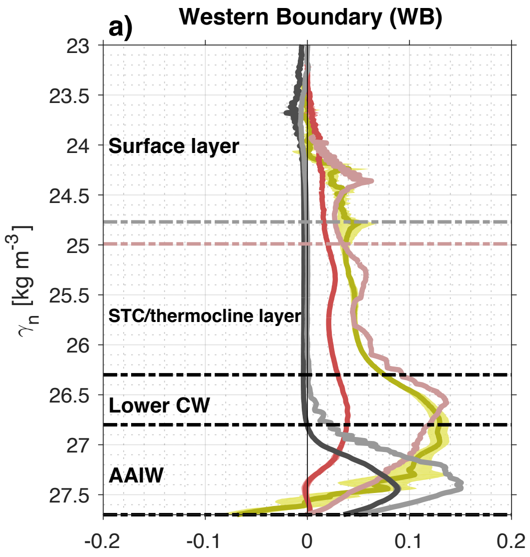
  (important term in STC estimates to close the transport budget and to address other uncertainties)



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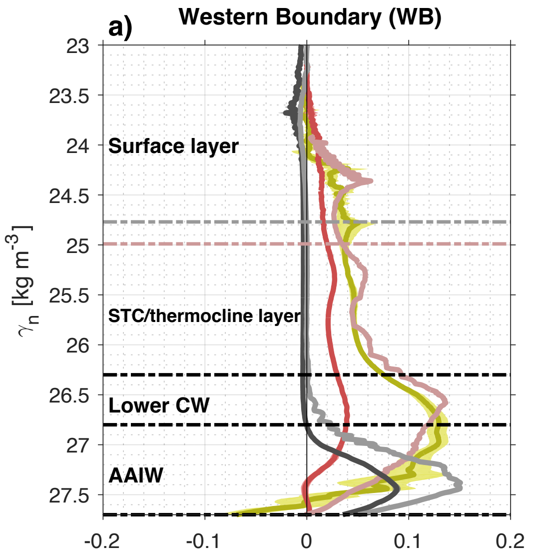

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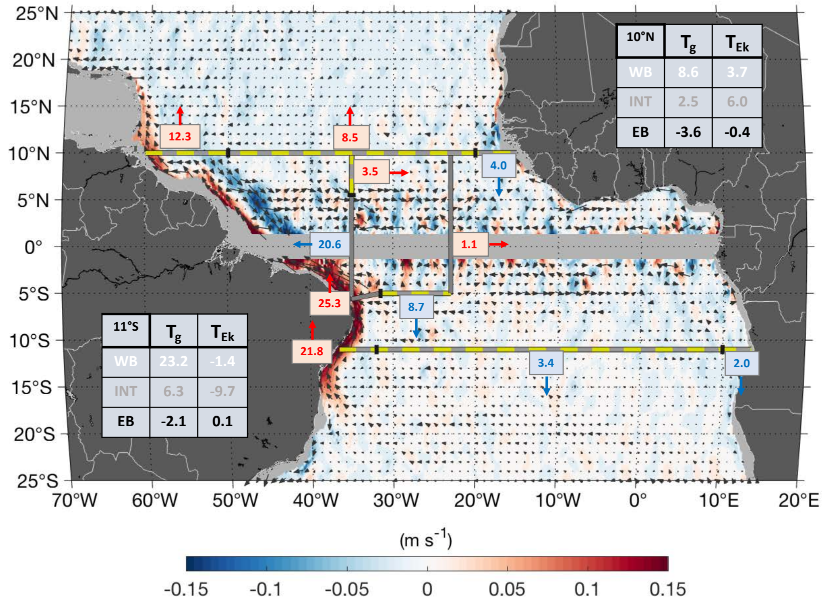

- Combining shipboard measurements with Argo data, an overview of the observed transports and pathways of the AMOC return flow is provided
  (so far this has been limited to (Lagrangian) model studies or drifter data at the surface)

Thank you for your attention

Questions:
franz.philip.tuchen@noaa.gov

- Thanks to all the scientists and technicians who collected the shipboard current velocity measurements along the four sections
- Thanks to the Argo program for providing the fundamental base for such studies

Supplemental figures and information

Transports and pathways

Water Mass Layer
Surface Layer
STC/thermocline Layer
Lower CW
AAIW
NADW
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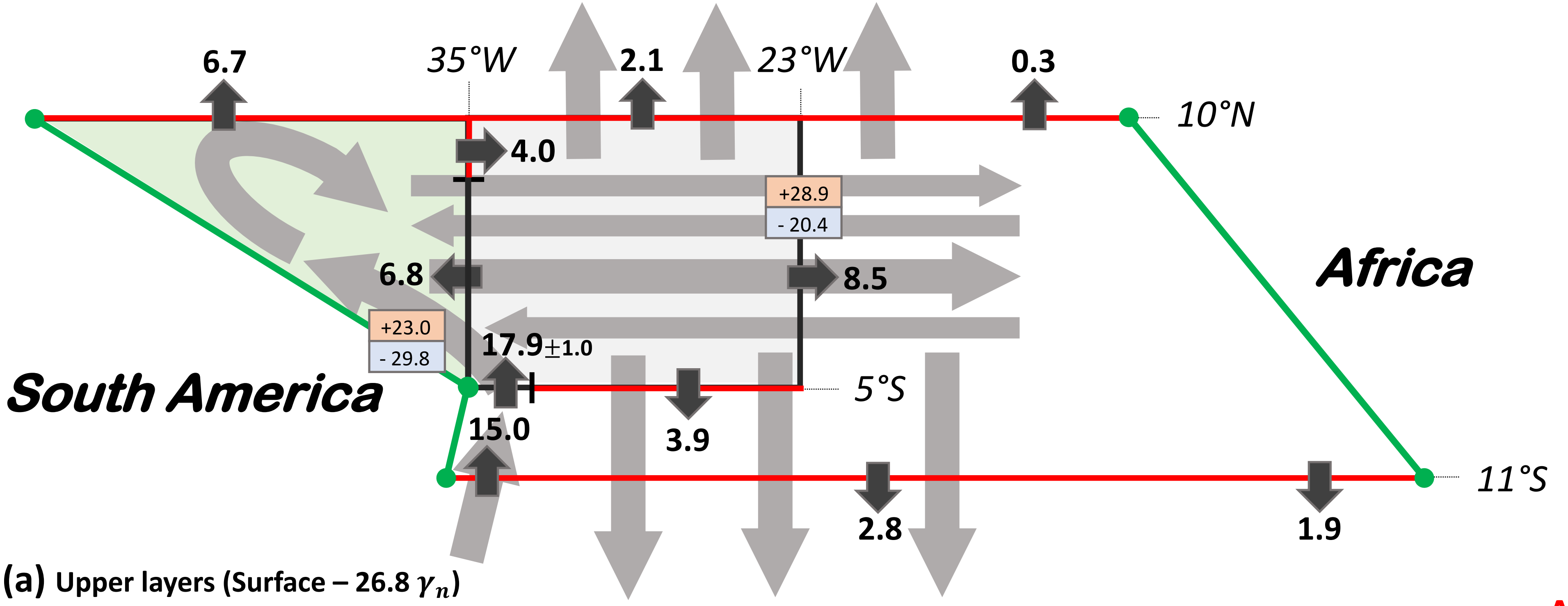
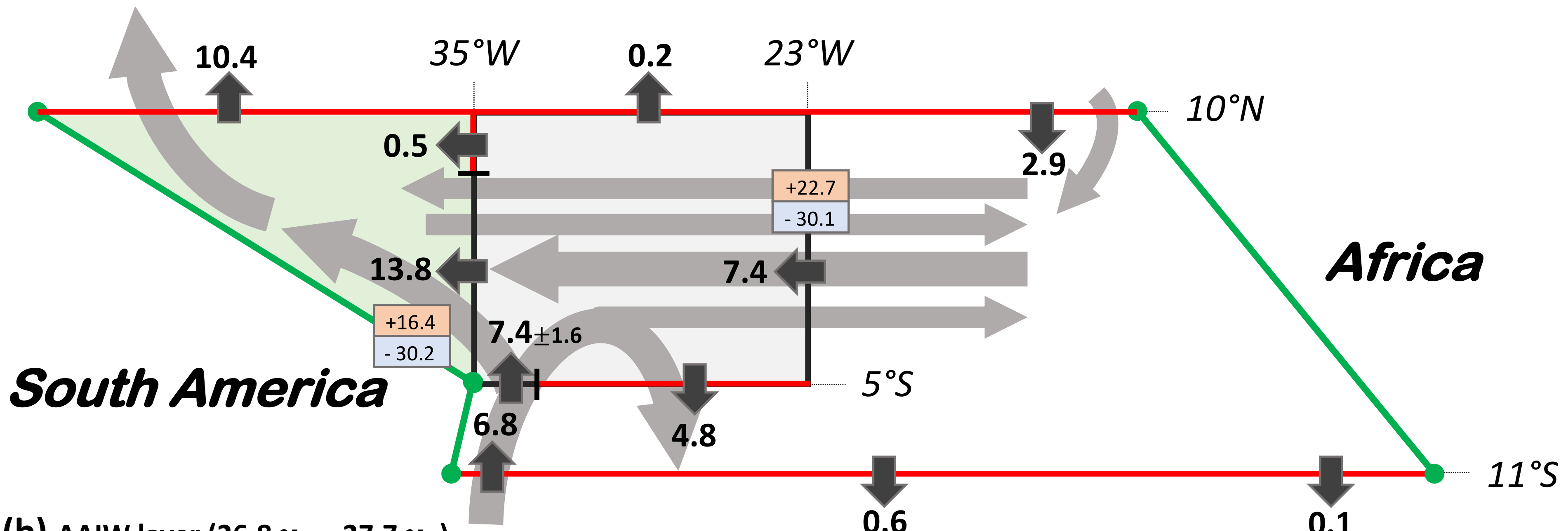


(a) Upper layers (Surface – 26.8 γ_n)

Argo data
Ship section data
Coastal boundary

Transports and pathways

Water Mass Layer
Surface Layer
STC/thermocline Layer
Lower CW
AAIW
NADW
AABW



(b) AAIW layer ($26.8\ \gamma_n - 27.7\ \gamma_n$)

Argo data
Ship section data
Coastal boundary

Diapycnal upwelling into the STC layer

TABLE 1. Hydrographic sections used for the calculations.

Latitude	Ship	Stations	Year	Month
24°15′S	*Crawford*	416–458	1958	October
8°15′S	*Crawford*	86–92, 94–120	1957	March
8°15′N	*Crawford*	154–184	1957	May
24°30′N	*Discovery* II	3587–3624	1957	October
27°23′N	*Atlantis*	5334–5343	1955	June

TABLE 2. Water masses, their isopycnal boundaries and the average depth of the isopycnals.

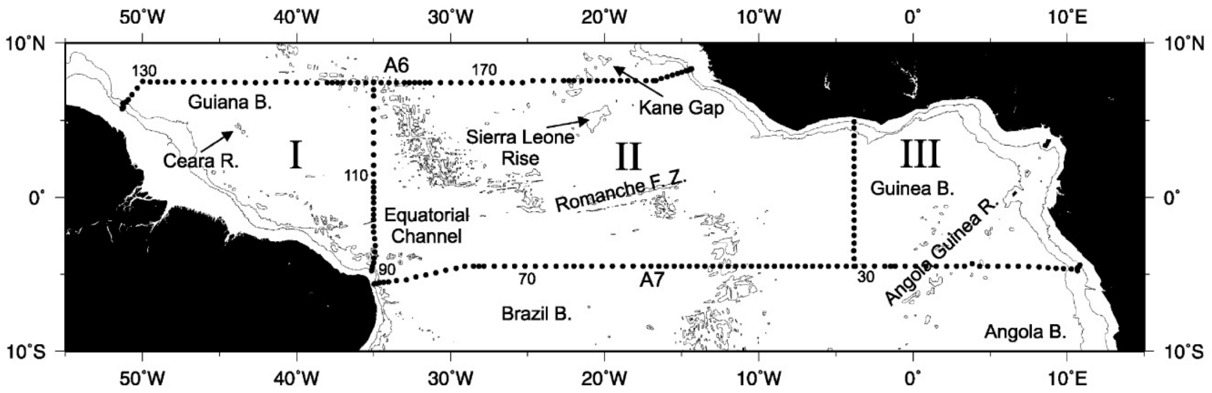
Layer	Water mass	Upper boundary	Lower boundary	Mean depth of interface (m)
1	Surface Water	Ocean surface	$\sigma_\theta = 26.2$	146
2	Surface Water	$\sigma_\theta = 26.2$	$\sigma_\theta = 26.8$	325
3	Antarctic Intermediate Water	$\sigma_\theta = 26.8$	$\sigma_\theta = 27.0$	437
4	Antarctic Intermediate Water	$\sigma_\theta = 27.0$	$\sigma_\theta = 27.4$	871
5	Upper Circumpolar Water	$\sigma_\theta = 27.4$	$\sigma_2 = 36.9$	1525
6	Upper North Atlantic Deep Water	$\sigma_2 = 36.9$	$\sigma_2 = 37.07$	2592
7	Lower North Atlantic Deep Water	$\sigma_2 = 37.07$	$\sigma_4 = 45.92$	4002
8	Lower Circumpolar Water	$\sigma_4 = 45.92$	ocean bottom	

Roemmich (1983):

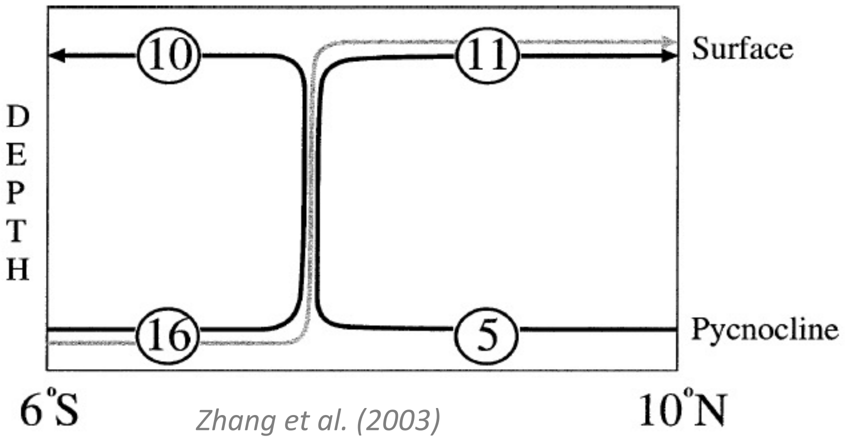
*” The calculation shows **6 x 10^6 m^3 s^{-1}** of layer 2 water from the Southern Hemisphere being upwelled, converted to layer 1 water, and then swept northward.”*

Lux et al. (2001):

”The equatorial Ekman divergence drives a conversion of Thermocline Water (24.58 ≤ $\sigma_0 < 26.75$) into Surface Water ($\sigma_0 < 24.58$) of ***7.5 x 10^6 m^3 s^{-1}*** ,…”



Further discussion on upwelling

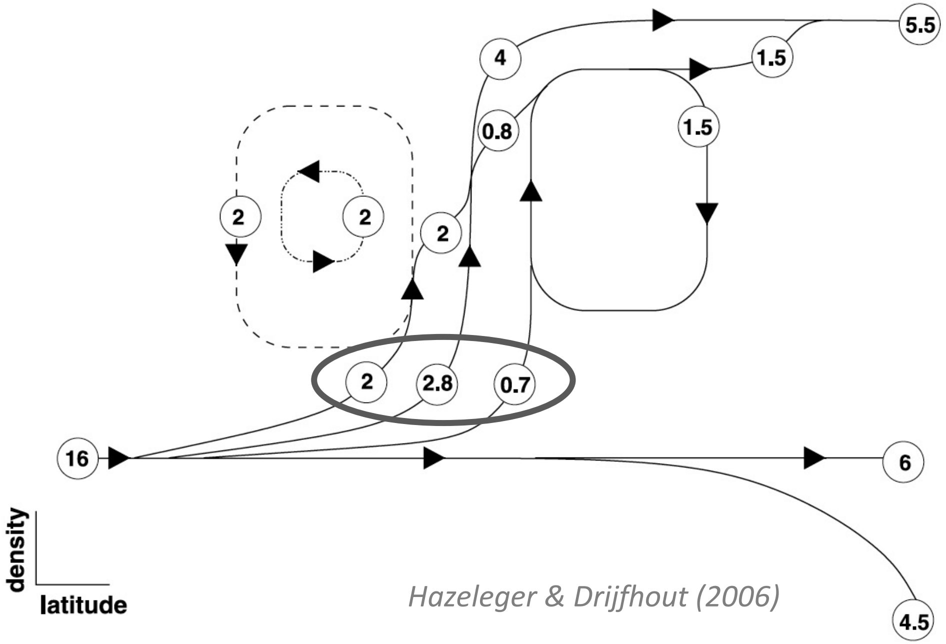


Zhang et al. (2003)

16 = **10** STC (**6** WB + **4** INT) + 6 THC upwelling (Roemmich 1983)

- High-resolution Argo data suggests smaller contribution by THC upwelling

- 5.5 Sv THC upwelling, **BUT** recirculation in the STCs



Hazeleger & Drijfhout (2006)

More on the Subtropical Cells …

JGR Oceans

RESEARCH ARTICLE
10.1029/2019JC015396

Key Points:

- Equatorward and poleward transports associated with the Atlantic Subtropical Cells are estimated from observations and reanalysis data
- Estimates show asymmetry in thermocline transports (three times more transport from the south) and symmetric flow divergence at the surface
- Transport budget reveals a residual of 3 Sv likely linked to the upper-layer flow of the Atlantic meridional overturning circulation

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The Atlantic Subtropical Cells Inferred from Observations

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Abstract The Atlantic Subtropical Cells (STCs) are shallow wind-driven overturning circulations connecting the tropical upwelling areas to the subtropical subduction regions. In both hemispheres, they are characterized by equatorward transport at thermocline level, upwelling at the equator, and poleward Ekman transport in the surface layer. This study uses recent data from Argo floats complemented by ship sections at the western boundary as well as reanalysis products to estimate the meridional water mass transports and to investigate the vertical and horizontal structure of the STCs from an observational perspective. The seasonally varying depth
the surface poleward flow and the thermo
isopycnal at depth. We find that the thern
hemisphere water mass transport (9.0 ± 1
from the northern hemisphere) and that t
Compared to the asymmetric convergence
surface layer is more symmetric, being 20
(Ekman minus geostrophy) in the surface
(5.5 ± 0.8 Sv at 10°S and 6.4 ± 1.4 Sv at 10
isopycnal is required in order to maintain

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RESEARCH ARTICLE
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Key Points:

- Observational transport time series of the Atlantic Subtropical Cells reveals dominant seasonal variability for horizontal branches
- On time scales longer than ~5 years, interior thermocline layer transport convergence modulates equatorial sea surface temperature anomalies
- Western boundary current and interior transport anomalies are partly compensating each other at thermocline level on all time scales

Supporting Information:

Observed Transport Variability of the Atlantic Subtropical Cells and Their Connection to Tropical Sea Surface Temperature Variability

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Abstract The shallow meridional overturning cells of the Atlantic Ocean, the subtropical cells (STCs), consist of poleward Ekman transport at the surface, subduction in the subtropics, equatorward flow at thermocline level and upwelling along the equator and at the eastern boundary. In this study, we provide the first observational estimate of transport variability associated with the horizontal branches of the Atlantic STCs in both hemispheres based on Argo float data and supplemented by reanalysis products.
ne layer transport convergence and surface layer transport divergence between 10°N and 10°S
ited by seasonal variability. Meridional thermocline layer transport anomalies at the western
ind in the interior basin are anti-correlated and partially compensate each other at all resolved
. It is suggested that the seesaw-like relation is forced by the large-scale off-equatorial wind
ges through low-baroclinic-mode Rossby wave adjustment. We further show that anomalies of
cline layer interior transport convergence modulate sea surface temperature (SST) variability
elling regions along the equator and at the eastern boundary at time scales longer than 5 years.
veaker (stronger) interior transport are associated with phases of higher (lower) equatorial SST.
ne scales, STC transport variability is forced by off-equatorial wind stress changes, especially by
e southern hemisphere. At shorter time scales, equatorial SST anomalies are, instead, mainly
ocal changes of zonal wind stress.

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Atlantic Equatorial Undercurrent intensification counteracts warming-induced deoxygenation

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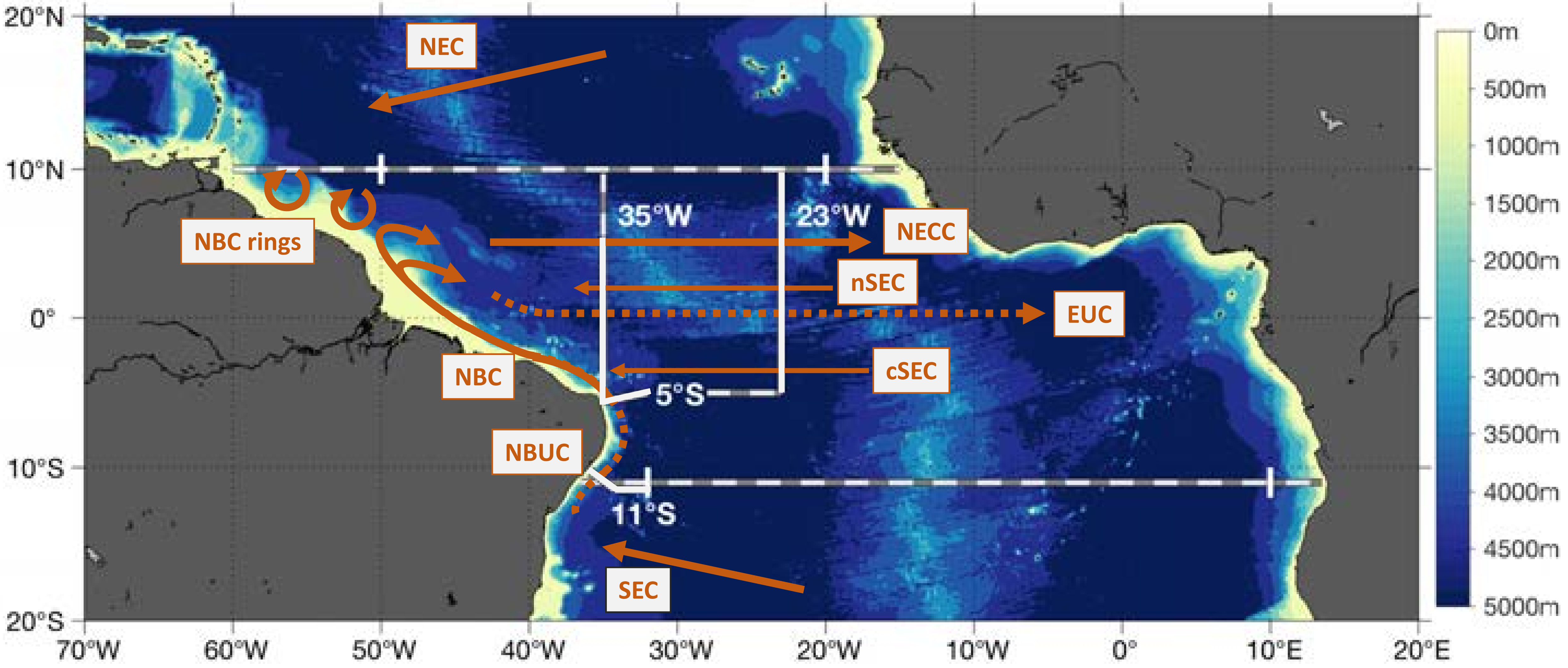
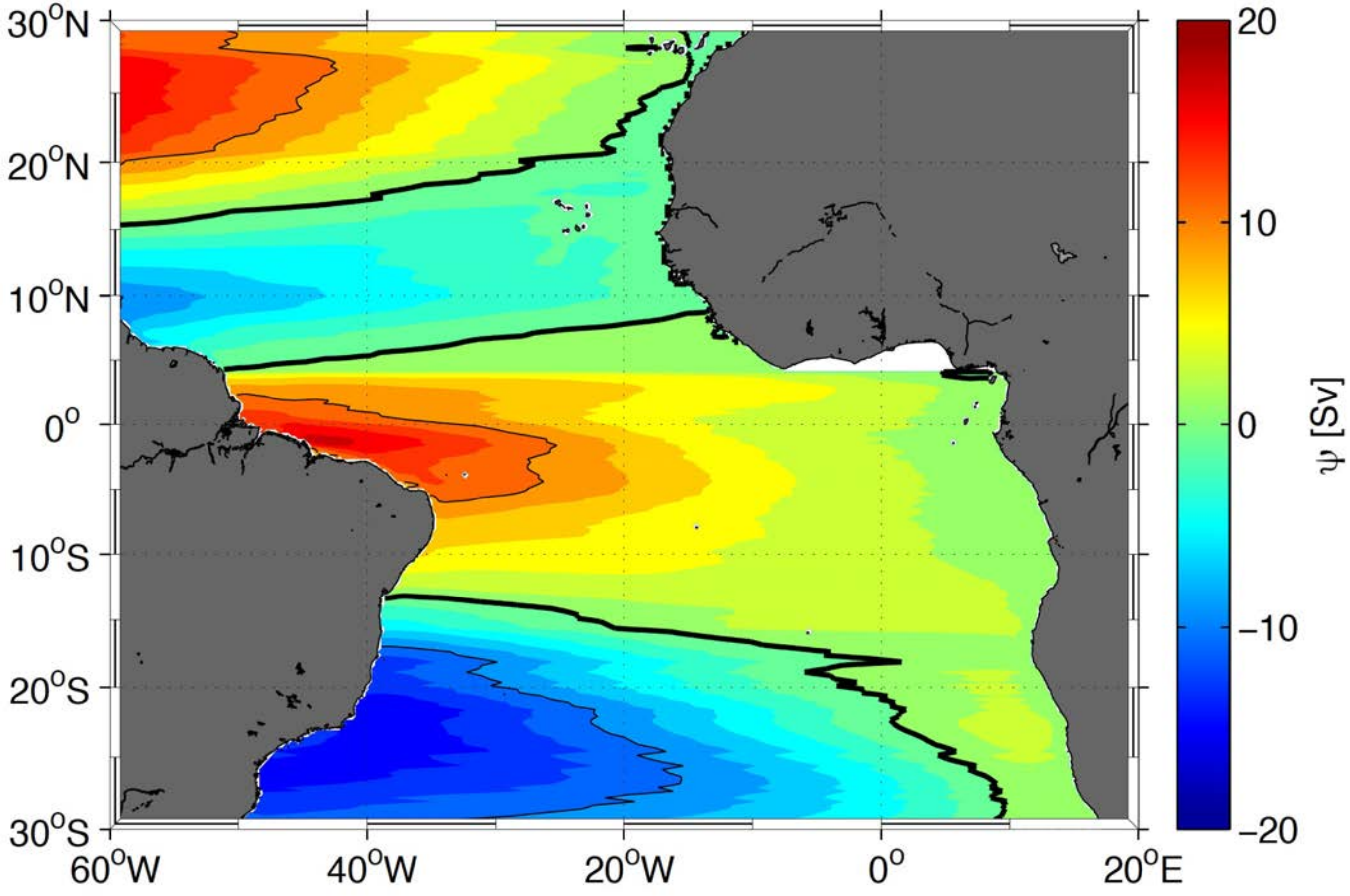
The tropical Atlantic upper-ocean circulation experiences multiannual to decadal changes associated with different climate modes and is simultaneously adjusting to climate warming. The most energetic current in the tropical Atlantic is the Equatorial Undercurrent (EUC), which flows eastwards along the Equator. On the basis of long-term moored observations, we show that the EUC strengthened by more than 20% from 2008 to 2018. The intensification of the EUC is associated with increasing subsurface oxygen concentrations and a thickening of the upper-ocean oxygenated layer in the equatorial Atlantic. These changes counteract climate-warming-induced deoxygenation in the region. The EUC strengthening is found to be mainly forced by trade wind changes in the western tropical North Atlantic. A 60-yr dataset reveals that the recent oxygen increase in the upper equatorial Atlantic is associated with multidecadal variability. This variability is characterized by low oxygen concentrations in the 1990s and early 2000s, and high oxygen concentrations in the 1960s and 1970s. The observed oxygen variability seems to be linked to a compression and expansion of the habitat of tropical pelagic fish, and must be accounted for when evaluating the possible consequences of deoxygenation for marine ecosystems and fisheries.

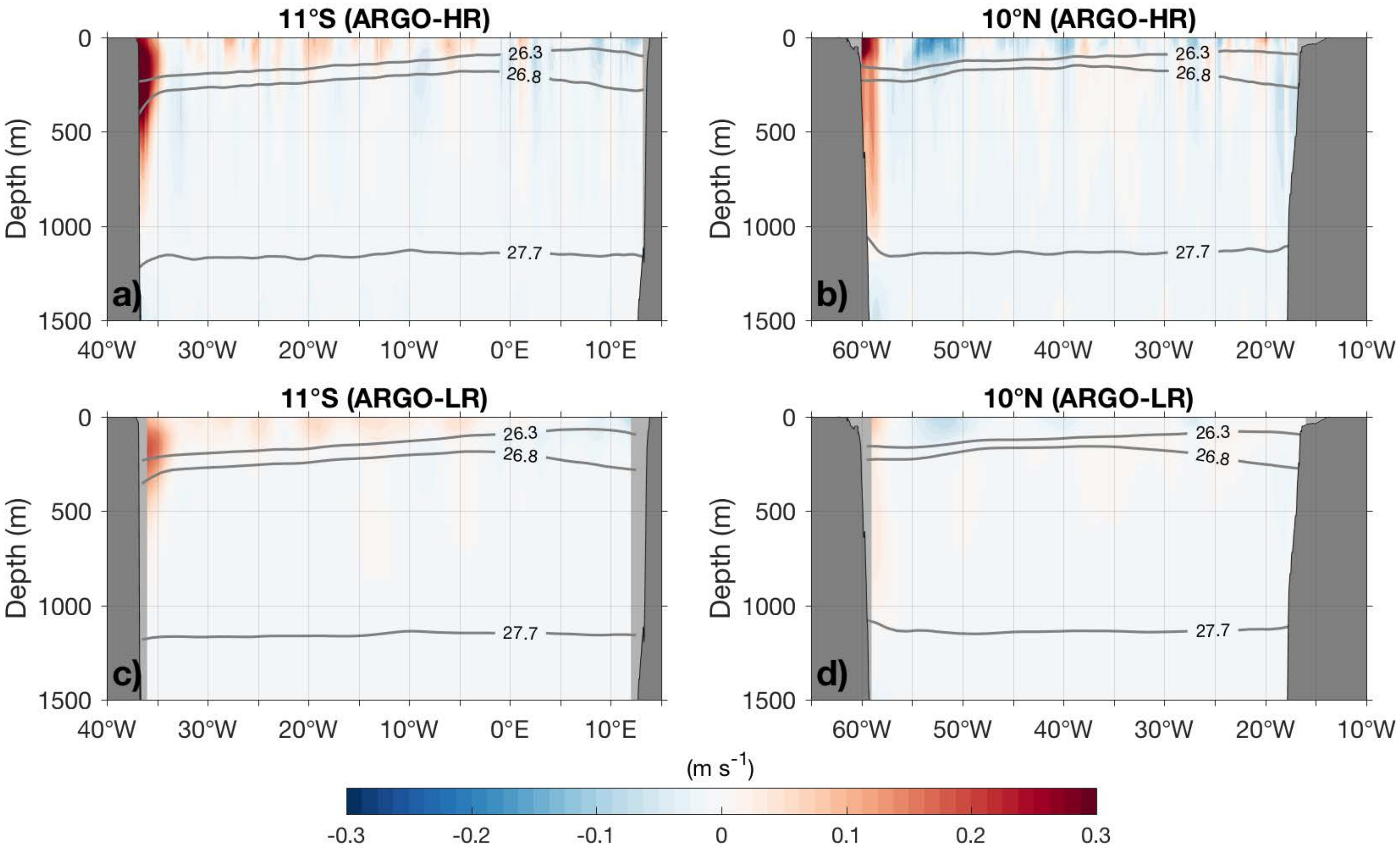
Tropical Atlantic current system



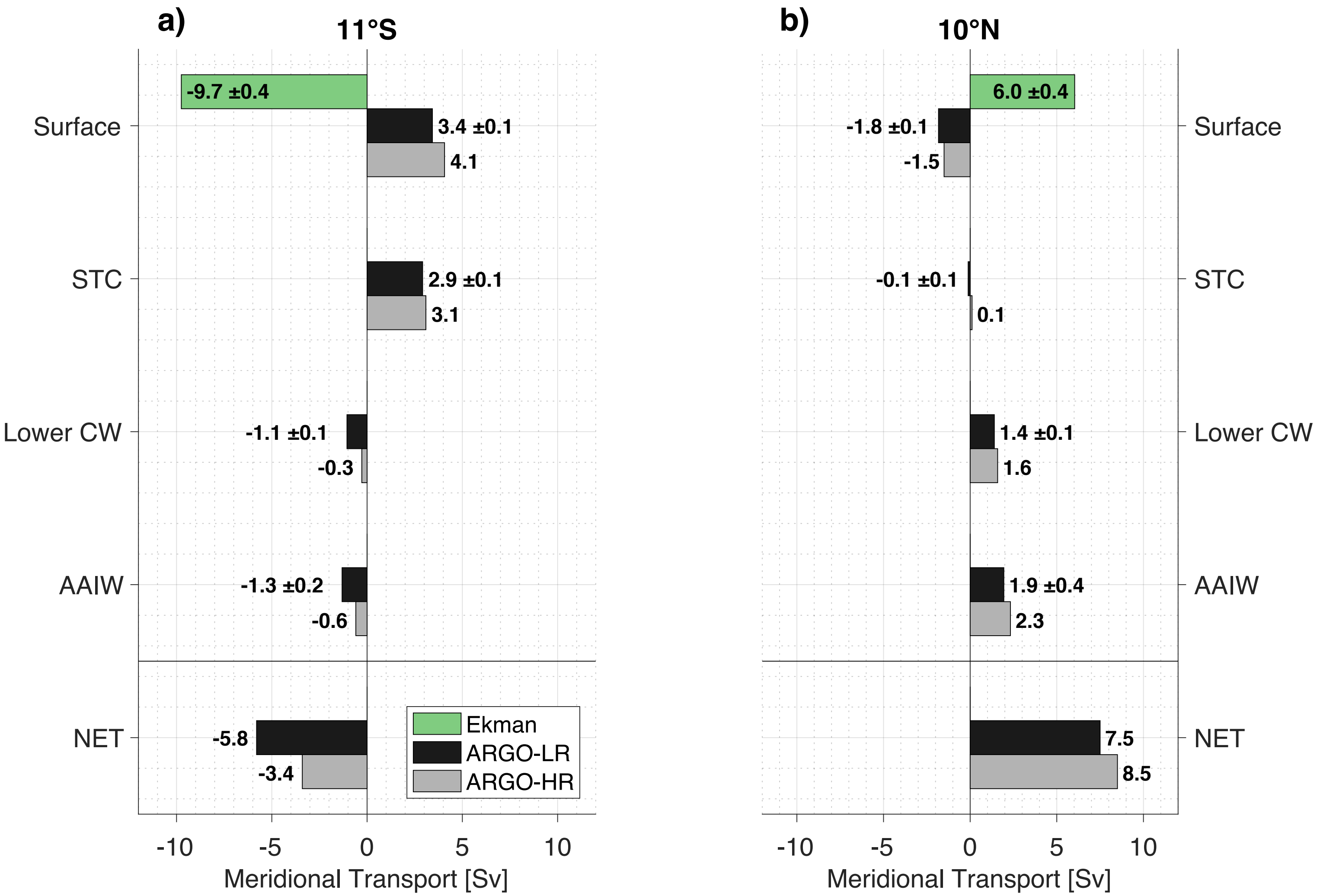
Sverdrup stream function



Argo sections



Interior layer transports



Eastern boundary layer transports