SUBSURFACE THERMOHALINE INTRUSIONS AT A MID-LATITUDE CONTINENTAL SHELF: DESCRIPTIVE CLIMATOLOGY AND DOUBLE DIFFUSION ROLE

Silva et al. [*in prep.*]

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OCEAN SCIENCES MEETING **2022**

Outline

- Introduction
- Motivation
- Part I - Descriptive climatology
- Part II - Underlying mixing processes
- Concluding remarks

Introduction

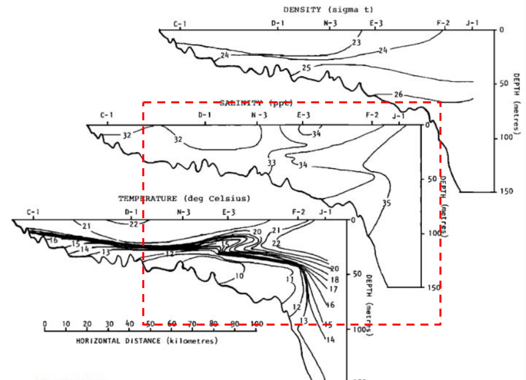
→ Intrusions are found in frontal zone and are related to strong lateral fluxes, enhanced vertical gradients, larvae exchange.
[Roden, 1964; Ruddick and Hebert, 1988; Ruddick and Richards, 2003; Beal, 2007; Wang and Jordi, 2011]

→ Intrusions are triggered by several processes

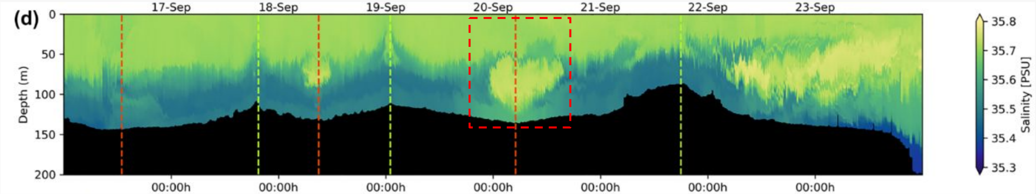
- cross-shelf horizontal density gradient [Welch, 1981]
- internal waves [Hopkins, Sharples and Huthnance, 2012]
- wind stress [González-Pola et al., 2005; Ruiz-Castillo et al., 2019]
- mesoscale activity [Li, Wang and Sun, 2012; Malan et al., 2021]

→Growth by:

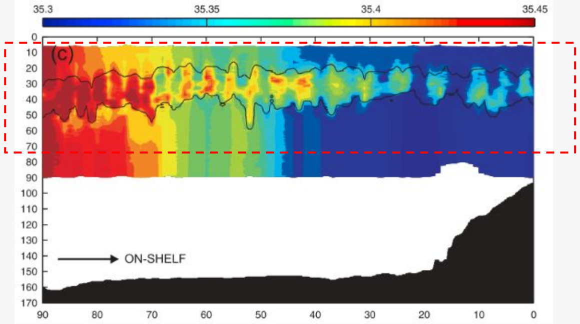
- Baroclinicity [Kuzmina and Rodionov, 1992; May and Kelley, 1997; 2002]
- Double diffusion [Stern, 1967; Ruddick and Turner, 1979]



Welch (1981)



Malan et al. (2020)



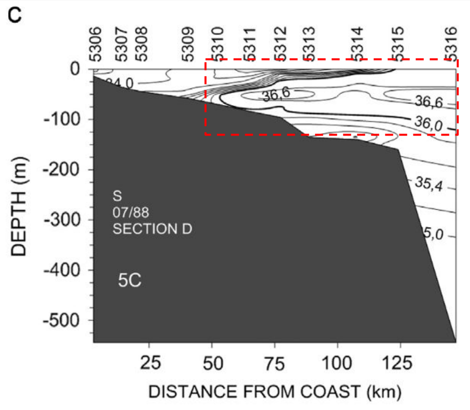
Hopkins, Sharpels and Huthnace (2012)

Ruddick and Kerr (2003). Oceanic thermohaline intrusions: theory. Progress in oceanography, 56(3-4). 483-497
Ruddick and Richards (2003). Oceanic thermohaline intrusions: observations. Progress in oceanography, 56(3-4), 499-527.
May and Kelley (2002). Contrasting the interleaving in two baroclinic ocean fronts. Dynamics of Atmosphere and Oceans, 36(1-3), 23-42.

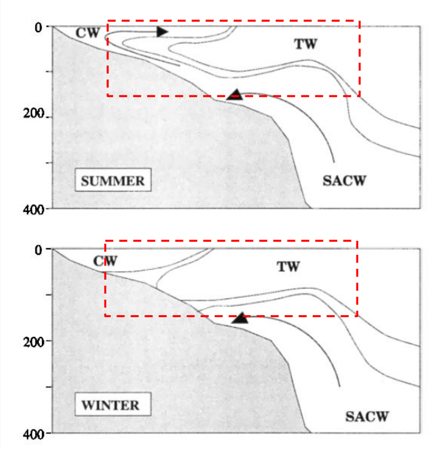
Subsurface thermohaline intrusions at a mid-latitude continental shelf

Motivation

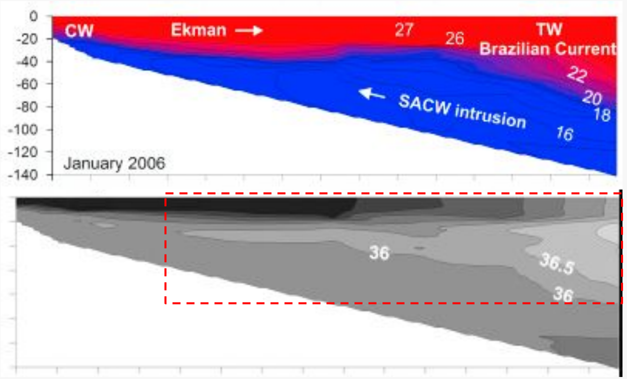
A "tongue shaped salty and warm" pattern was observed in several hydrographic section in 90' and 2000', but till date no further details was investigated regarding this phenomenon.



Castro (2014)



Campos et al. (2000)



Brandini et al. (2014)

Castro (2014). Summer/winter stratification variability in the central part of the South Brazil Bight. Continental Shelf Research, 89, 15-23.

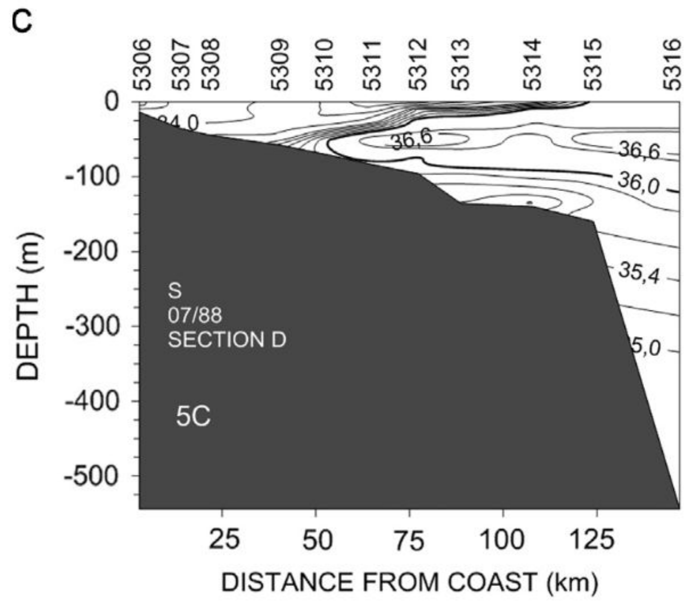
Campos et al. (2000). Shelf break upwelling driven by Brazil Current cyclonic meanders. Geophysical Research Letters, 27(6), 751-754.

Brandini et al. (2014). Deep chlorophyll maximum and plankton community response to oceanic bottom intrusions on the continental shelf in the South Brazilian Bight. Continental Shelf Research, 89, 61-75.

Scientific question and goals

- Are they recurrent?
- In which frequency do they occur?
- What are the common features?

- Can we evaluate the mixing processes?
- Is this mixing fast or slow?



Castro (2014)

Scientific question and goals

Part I - Descriptive climatology

- Are they recurrent?
- In which frequency do they occur?
- What are the common features?

Part II - Underlying mixing processes

- Can we evaluate the mixing processes?
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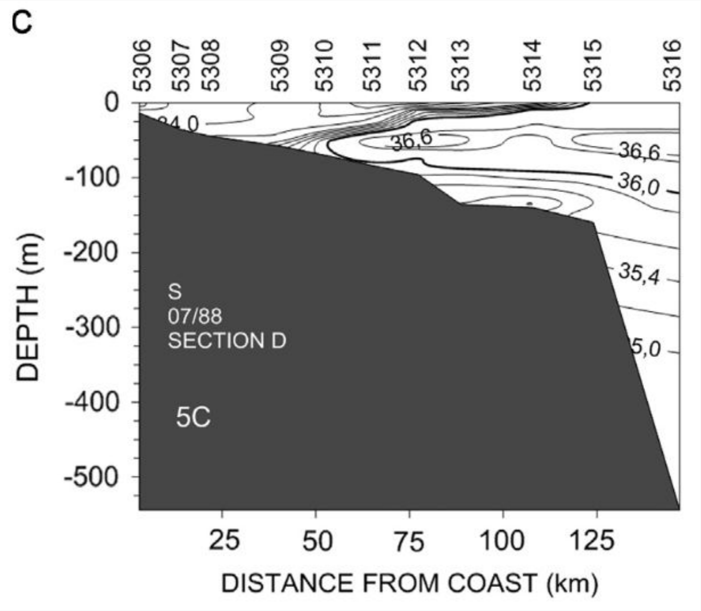

Castro (2014)

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Descriptive climatology

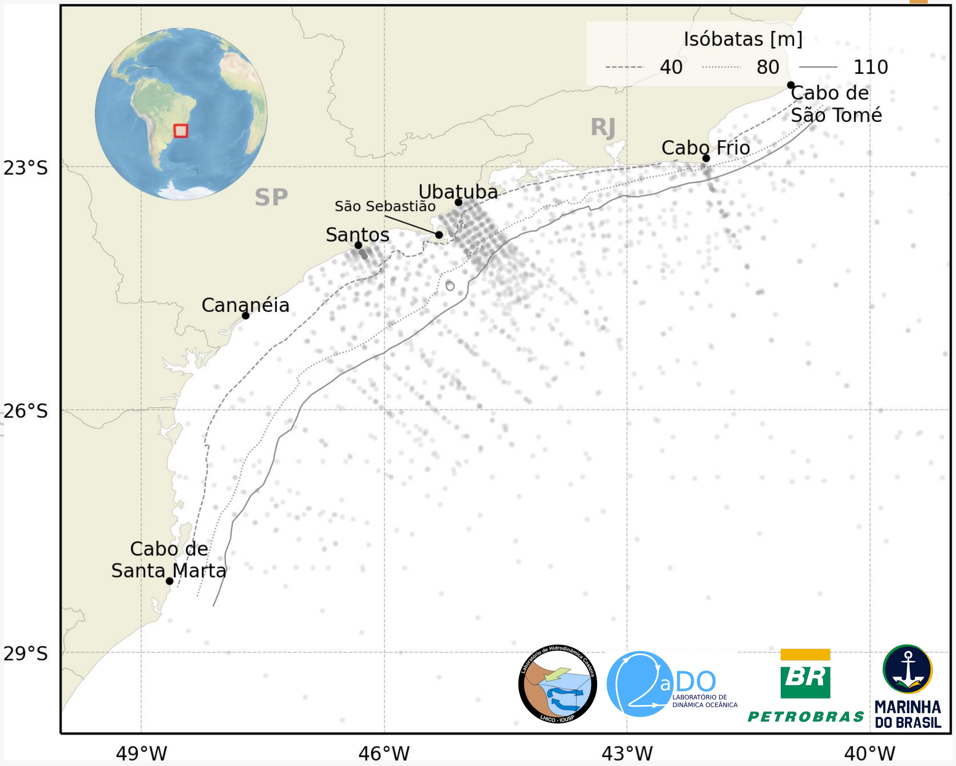
→ Historical dataset (~1100)

(BNDO + acervo IOUSP + Petrobrás/CENPES)

→ Detection algorithm on CTD casts

(Lentz, 2003)

- Thickness
- Salt anomaly
- Maximum salinity depth (core)



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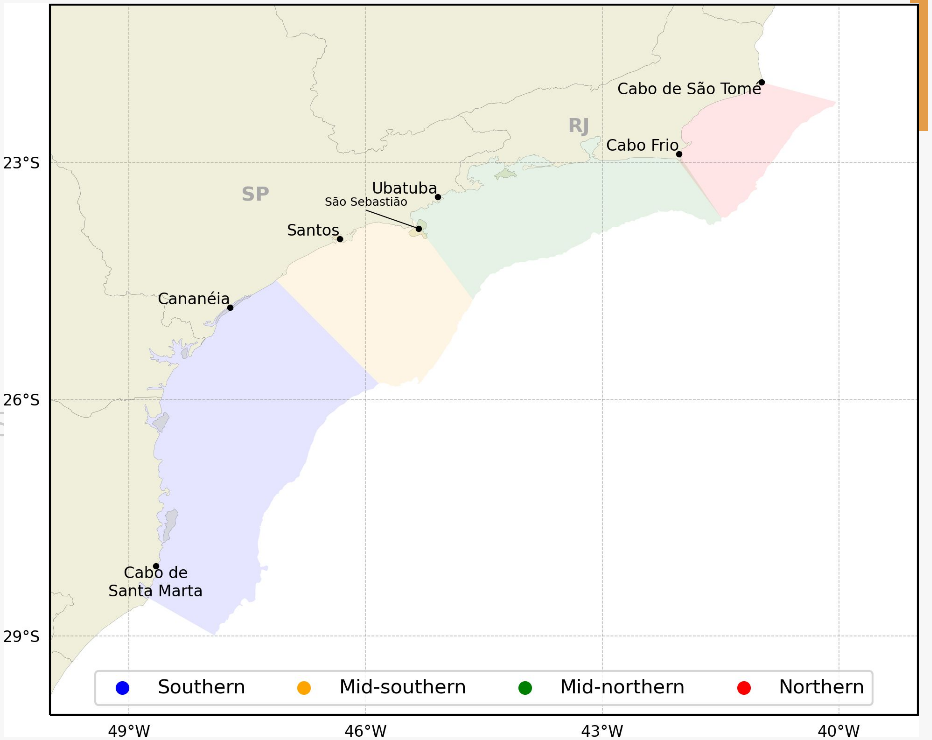

Subsurface thermohaline intrusions at a mid-latitude continental shelf

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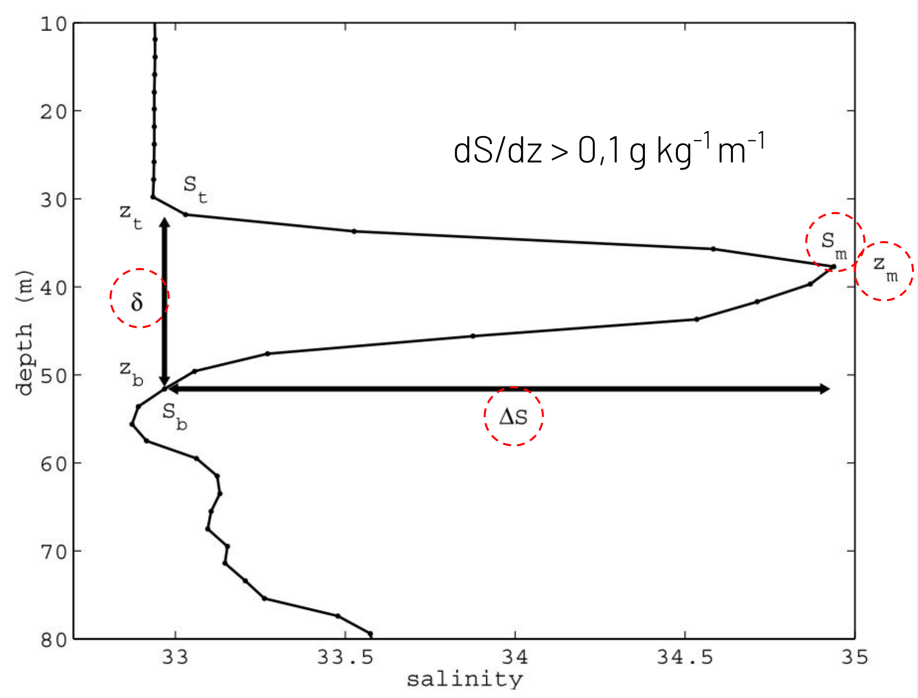


Lentz (2003)

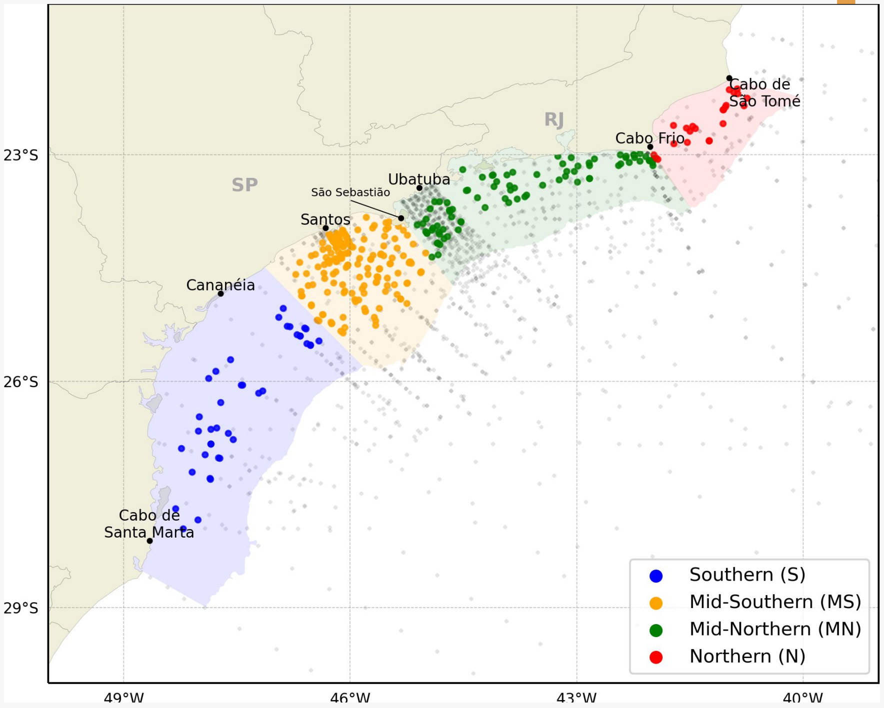
Lentz (2003). A climatology of salty intrusions over the continental shelf from Georges Bank to Cape Hatteras. Journal of Geophysical Research: Oceans, 108(C10).

Descriptive climatology

Spatial and temporal occurrences

→ 27% of intrusions identified

→ spread all over the continental shelf



Subsurface thermohaline intrusions at a mid-latitude continental shelf

Descriptive climatology

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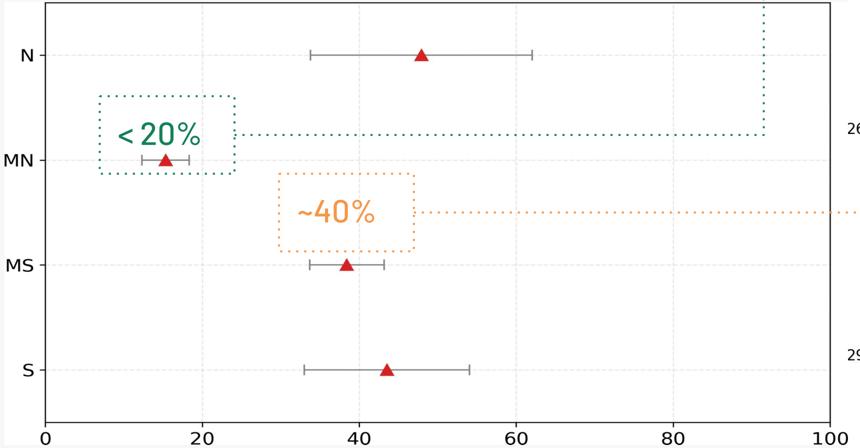
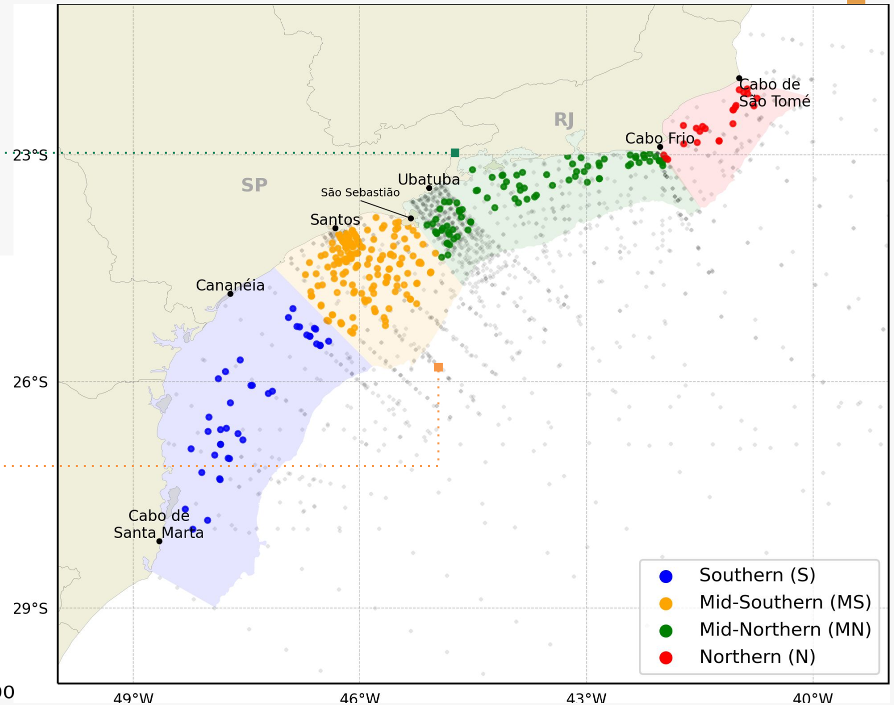
→ Spread all over the continental shelf

→ MS > MN [Mann-Whitney, @95% CL]





Descriptive climatology

General description

→ΔS: northernmost > southernmost

[Mann-Whitney Test, @95% CL]

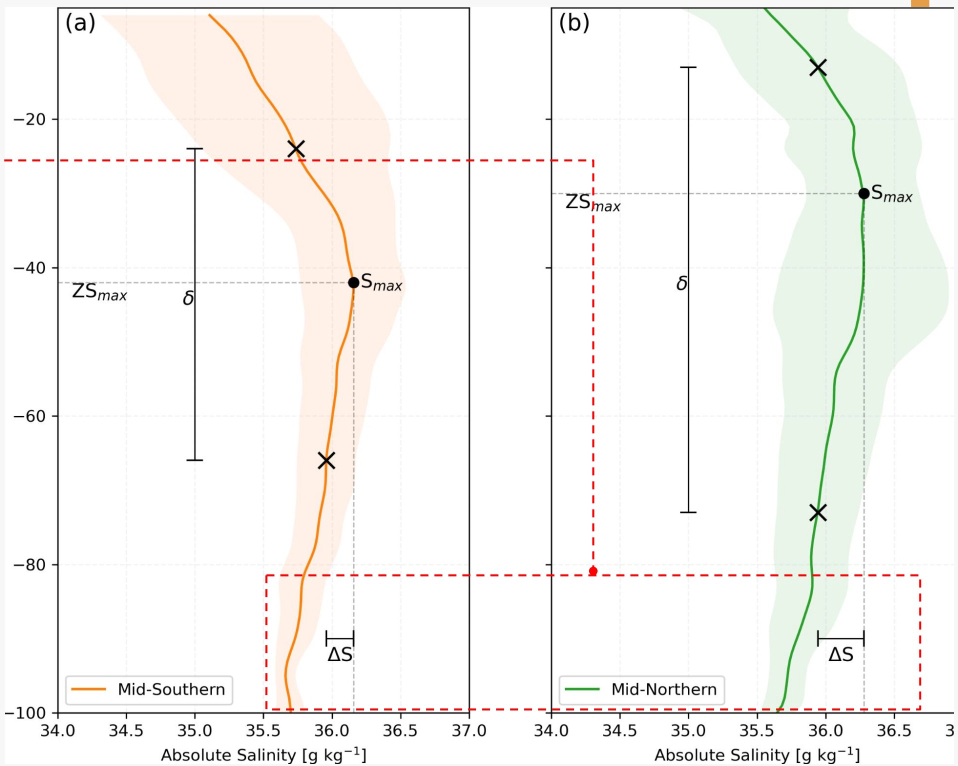
→ Z_{Smax}: deepening from North to South

[Mann-Whitney Test, @95% CL]

→ δ: inverse relationship between N^2 and δ

→ $R_{spearman}$ [-0.39; -0.18], @95%)

→ Similar relationship found by Lentz (2003)



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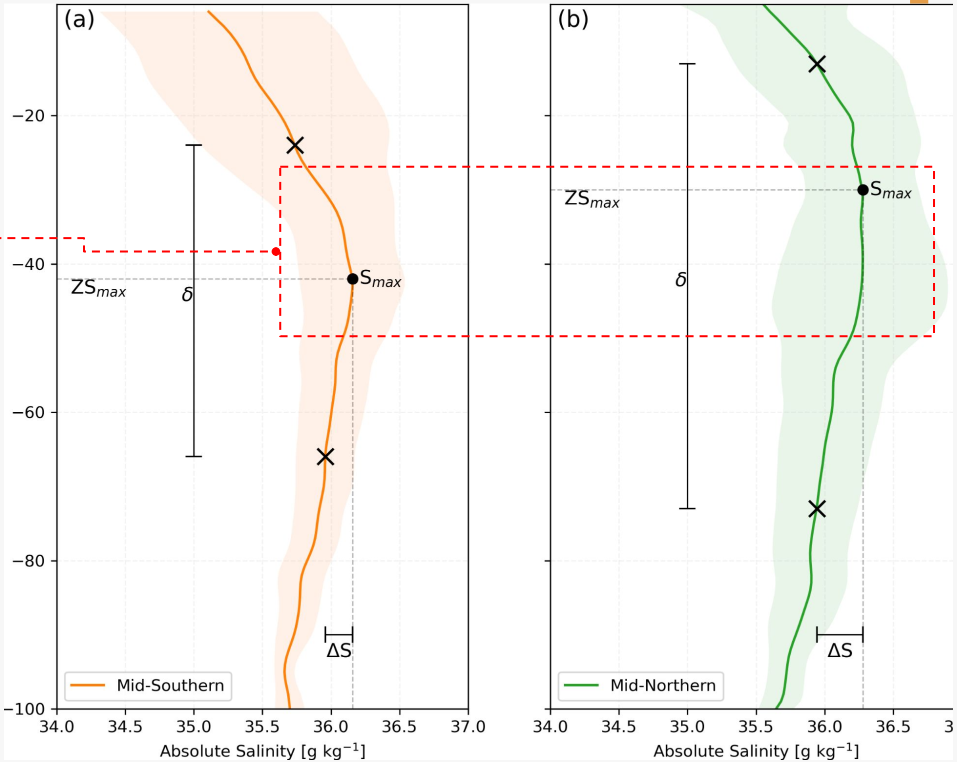

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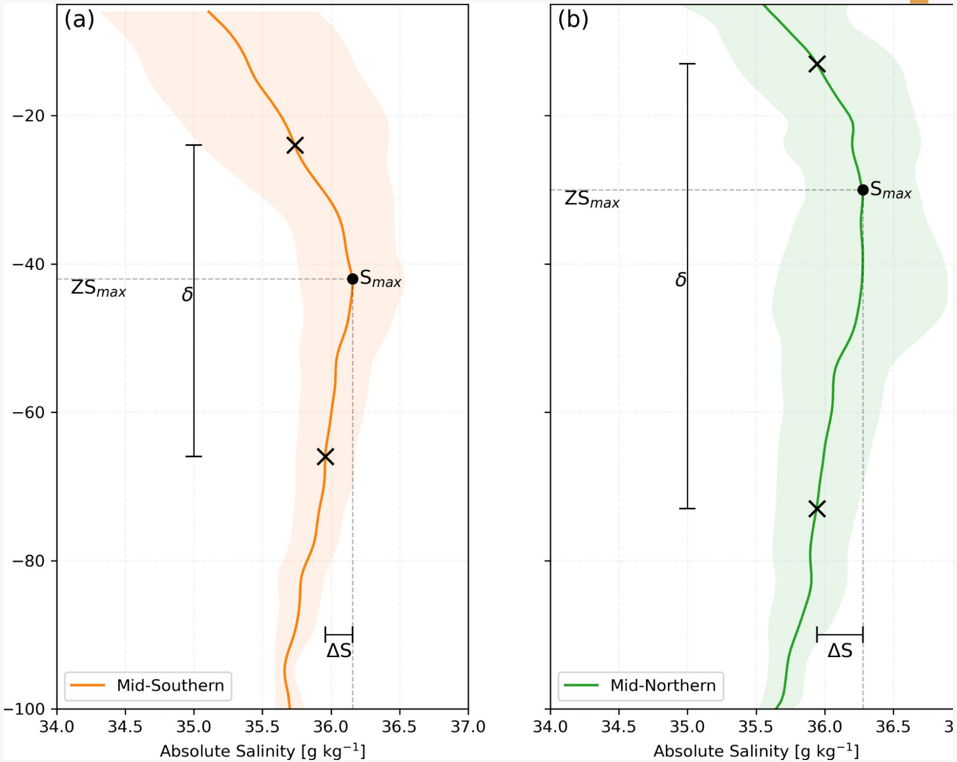
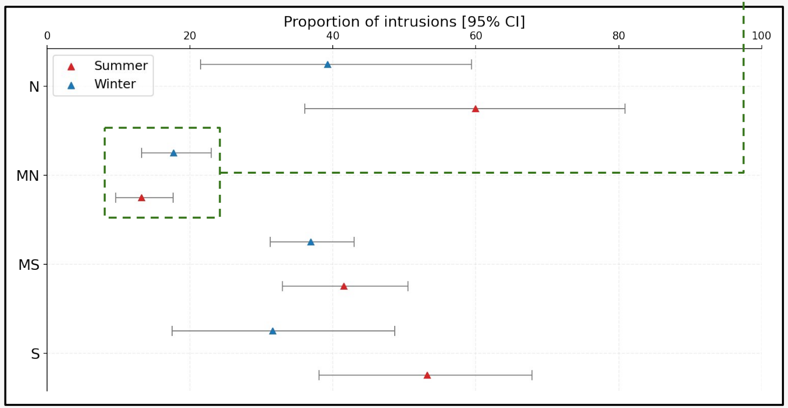


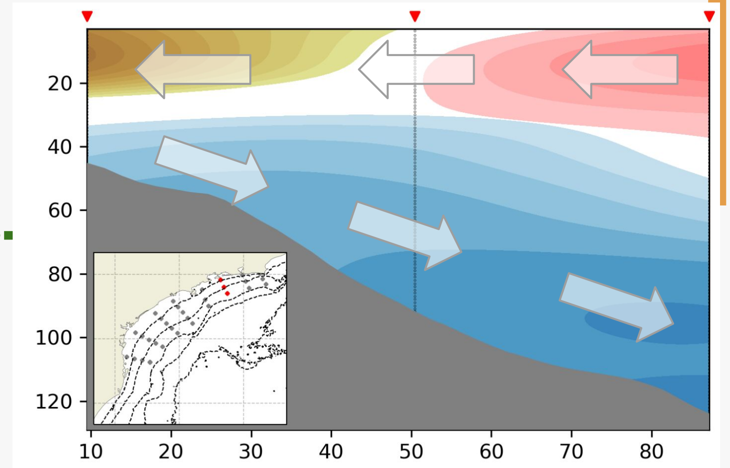
Descriptive climatology

Seasonal description

→ Mid-Northern (MN): winter > summer

→ Mid-Southern (MS): summer > winter





Water mass percentage in the cross-section, based on Mamayev's (1975) method

Downwelling favorable winds + increase in CW volume forces intrusions to subsurface depths in the MN region:

→ In winter, SACW retreat to the shelfbreak and the increase in CW volume force intrusions to subsurface depths.

→ In summer, intrusions are shallower due to the presence of SACW near the bottom which forces intrusions upwards.

[Castro, 2014; Cerda and Castro, 2014]

Cerda and Castro (2014). Hydrographic climatology of South Brazil Bight shelf waters between Sao Sebastiao (24ºS) and Cabo Sao Tome (22ºS). Continental Shelf Research, 89, 5-14.

Subsurface thermohaline intrusions at a mid-latitude continental shelf

Descriptive climatology

Seasonal description

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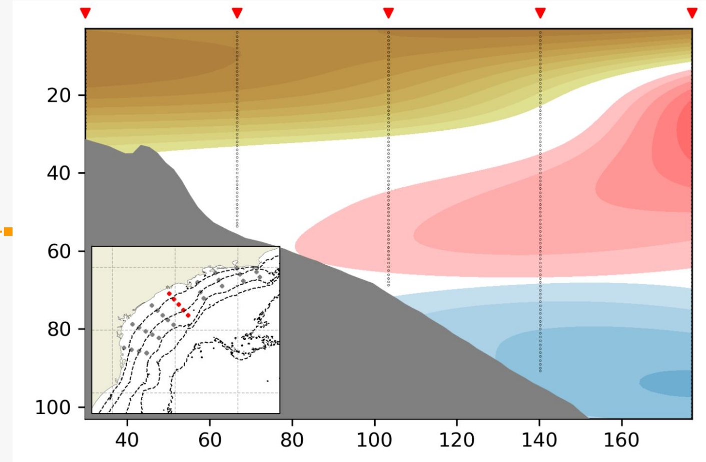

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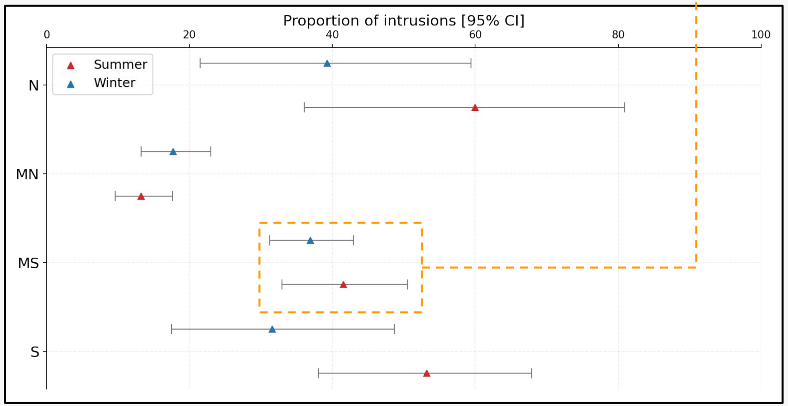

CW volume apparently dictates the intrusions seasonal frequency:

→ Winter: increase in CW volume fills the whole water column nearshore, not favoring the downwelling of TW
[Campos et al., 2000; Castro, 2014]

→ Summer: reduction of CW volume favors the occurrence of subsurface intrusions
[Marta-Almeida et al., 2021]

Marta-Almeida, M., Dalbosco, A., Franco, D., & Ruiz-Villarreal, M. (2021). Dynamics of river plumes in the South Brazilian Bight and South Brazil. Ocean Dynamics, 71(1), 59-80.

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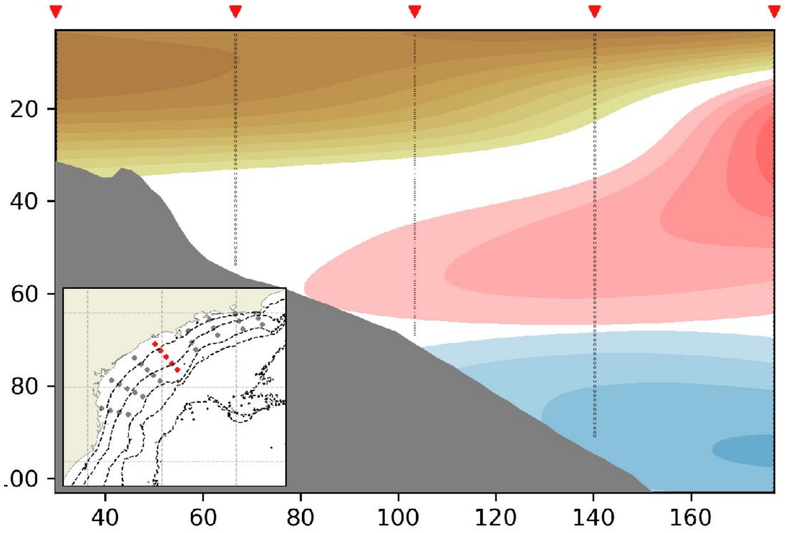
Underlying mixing processes



Why investigate double-diffusion?

→ Thermohaline structure created by an intrusion provides conditions to double diffusion processes.
[Toole and Georgi, 1981; Ruddick and Walsh, 1995]

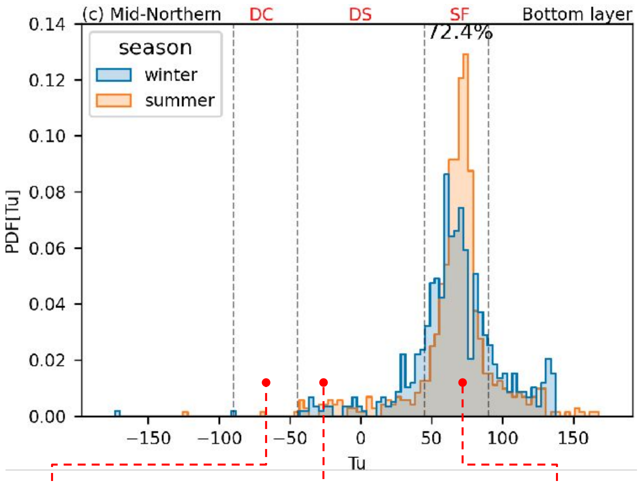
→ Double diffusion can be a driving mechanism, but also might act in the growth, steady-state and erosion stages of the intrusion.
[Toole and Georgi, 1981; Ruddick and Walsh, 1995, Beal, 2007]

→The inverse relationship between stratification and thickness found suggest the presence of double-diffusively driven intrusions.
[Ruddick and Turner, 1979; Lentz, 2003]

Toole and Georgi (1981). On the dynamics and effects of double-diffusively driven intrusions. Progress in Oceanography, 10(2), 123-145.

Beal, L. M. (2007). Is interleaving in the Agulhas Current driven by near-inertial velocity perturbations?. Journal of physical oceanography, 37(4), 932-945.

Underlying mixing processes



Diffusive convection
(-90 < Tu < -45)

Doubly stable
(-45 < Tu < 45)

Salt fingering
(45 < Tu < 90)

Why investigate double-diffusion?

→ Turner Angle (Tu) [Ruddick, 1983]

$$Tu = tg^{-1}\left(\frac{\alpha\Delta T - \beta\Delta S}{\alpha\Delta T + \beta\Delta S}\right)$$

Relative contribution of temperature and salinity in the vertical stability [Radko, 2013]

→ Possibility* of double diffusion processes

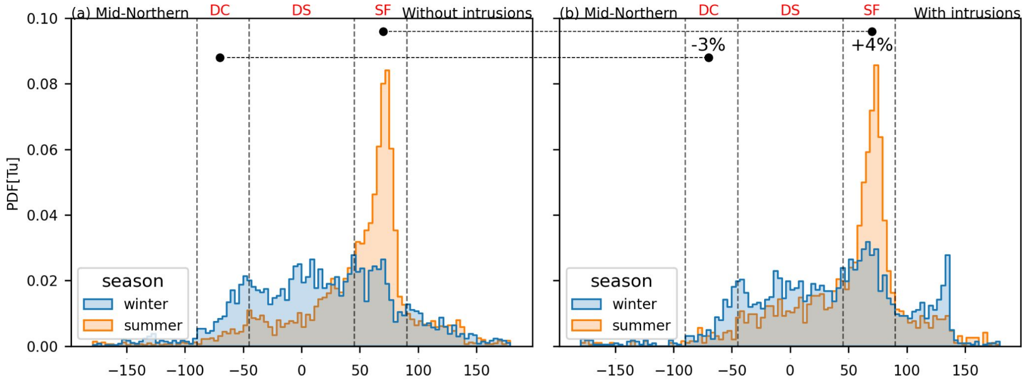
* Necessary but not sufficient condition [Radko, 2013]

→ Typically presented as probability density functions (pdf).

Radko, T. (2013). Double-diffusive convection. Cambridge University Press.

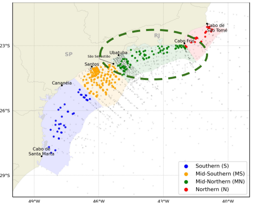
Subsurface thermohaline intrusions at a mid-latitude continental shelf

Underlying mixing processes



Intrusions destabilize the environment?

In the case of the **MN** region, intrusions does not change the Turner Angle distribution, whether in summer or winter.



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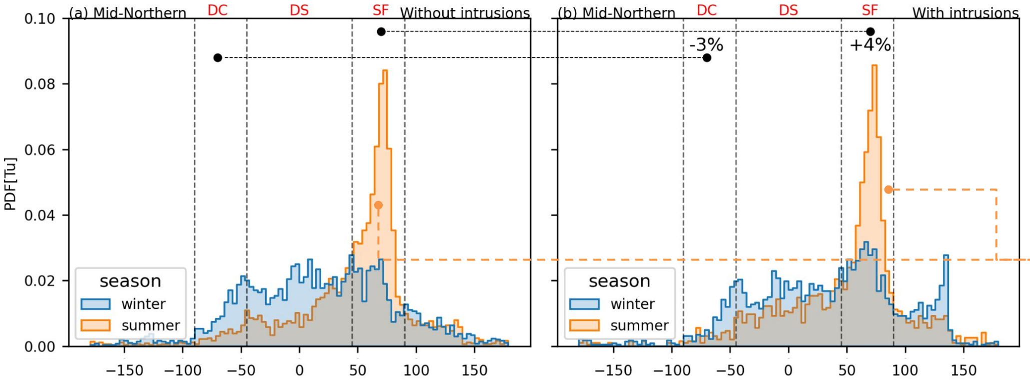
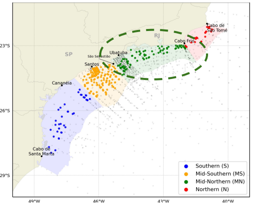


Intrusions destabilize the environment?

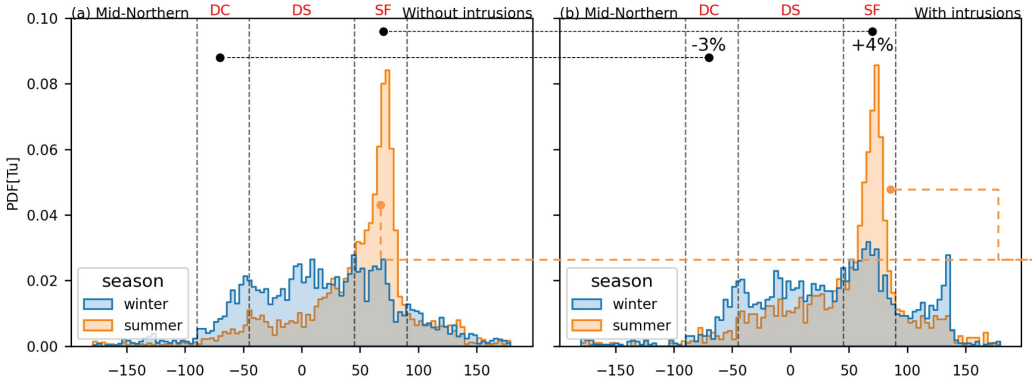
In the case of the **MN** region, intrusions does not change the Turner Angle distribution, whether in summer or winter.

Unstable to salt fingering with or without intrusions, in summer, probably due to a narrow shelf and small continental runoff in this area, which allows a greater influence of oceanic waters, creating conditions for salt fingering. [Castro, 2014; Cerda and Castro, 2014]



Subsurface thermohaline intrusions at a mid-latitude continental shelf

Underlying mixing processes



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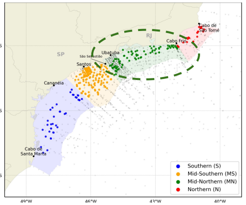
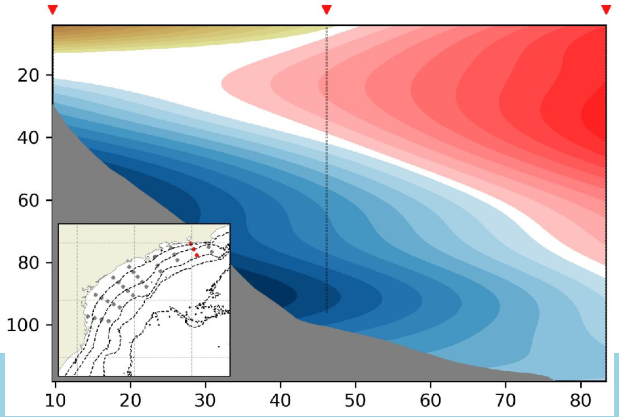


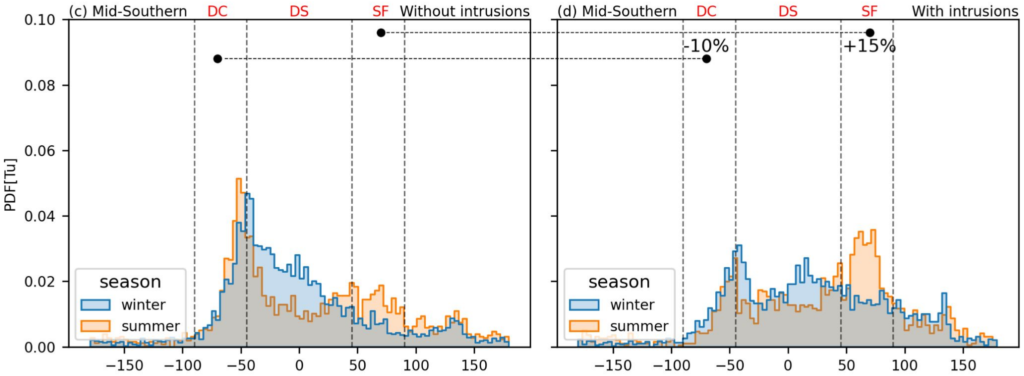


salty and warm waters (TW) overlaying cold and relatively fresher waters (SACW)
[Voorhis et al., 1976; Posmentier and Houghton, 1979]

Voorhis, A. D., Webb, D. C., & Millard, R. C. (1976). Current structure and mixing in the shelf/slope water front south of New England. Journal of Geophysical Research, 81(21), 3695-3708.

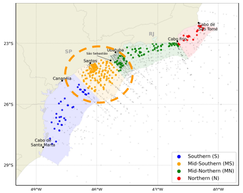
Subsurface thermohaline intrusions at a mid-latitude continental shelf

Underlying mixing processes



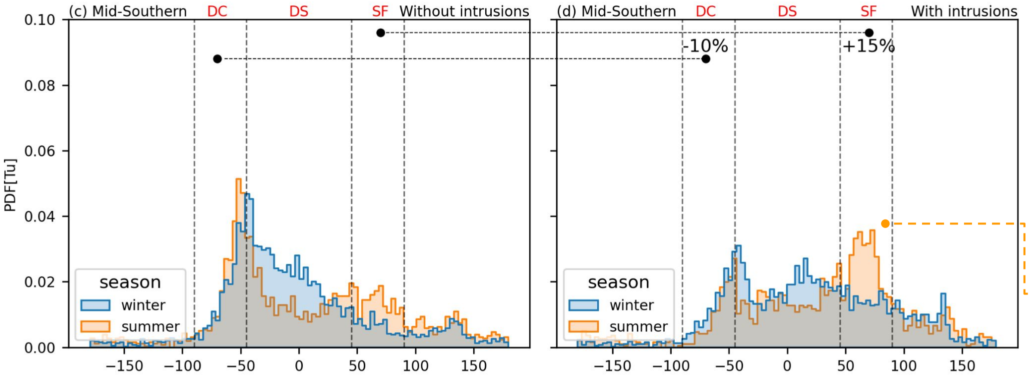
Intrusions destabilize the environment?

The **MS** contrast with MN, by presenting a Turner Angle distribution skewed to the diffusive convection range without intrusions.



Subsurface thermohaline intrusions at a mid-latitude continental shelf

Underlying mixing processes



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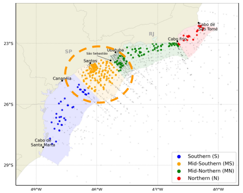
Intrusions destabilize the environment in favor of salt fingering in summer and winter keeps skewed to the diffusive convection range.



Subsurface thermohaline intrusions at a mid-latitude continental shelf

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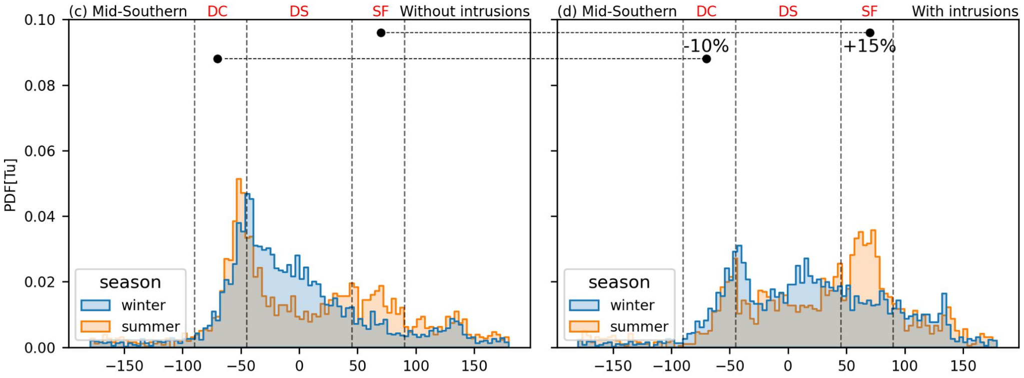
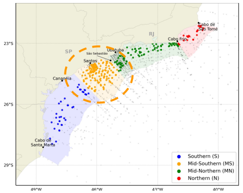
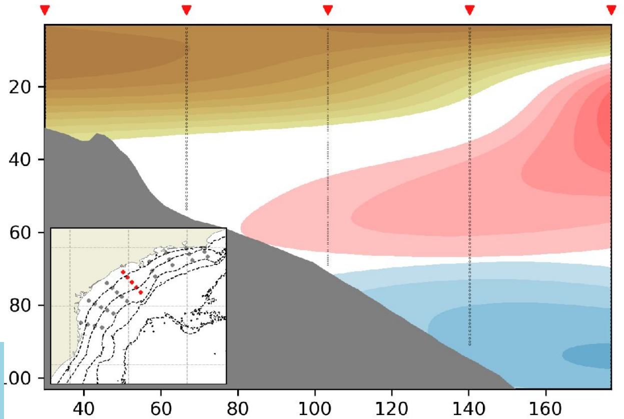






Intrusions destabilize the environment?

The **MS** contrast with MN, by presenting a Turner Angle distribution skewed to the diffusive convection range without intrusions.

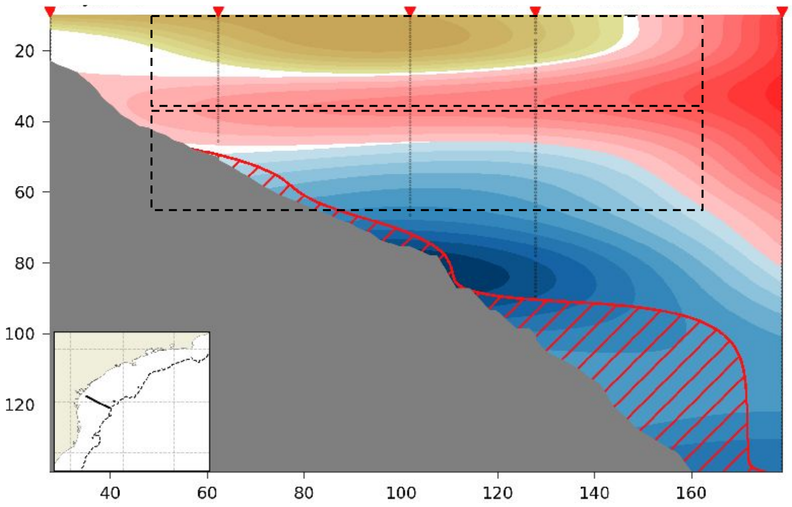
Intrusions destabilize the environment in favor of salt fingering in summer and winter keeps skewed to the diffusive convection range.

The region has the presence of a low-salinity strip nearshore throughout the year (Coastal Water) which influences the distribution:

→ Winter: increased CW volume, more diffusive convection
[Marta-Almeida et al., 2021]

→ Summer: reduced CW volume + SACW intrusion near-bottom, result in more salt fingering probability
[Campos et al., 2000; Marta-Almeida et al., 2021]

Underlying mixing processes



Intrusions destabilize the environment?

→ co occurrence of both forms of double diffusion **suggests** an important role of double diffusion in growth, stability or erosion.
[Ruddick and Walsh, 1995; May e Kelley, 2002; Ruddick e Richards, 2003; Bael, 2007]

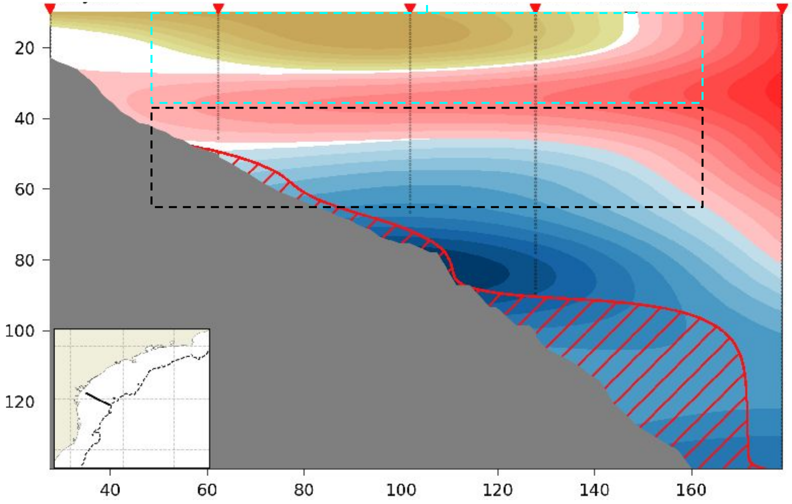
→ Top layer: diffusive convection
[Radko, 2013]

→ Bottom layer: salt fingering
[Voorhis et al., 1976; Posmentier and Houghton, 1979]

→ Evaluate the Turner Angle pdf only for top and bottom layers of the intrusion.

Ruddick, B., & Walsh, D. (1995). Observations of the density perturbations which drive thermohaline intrusions. Washington DC American Geophysical Union Geophysical Monograph Series, 94, 329-334.

Underlying mixing processes



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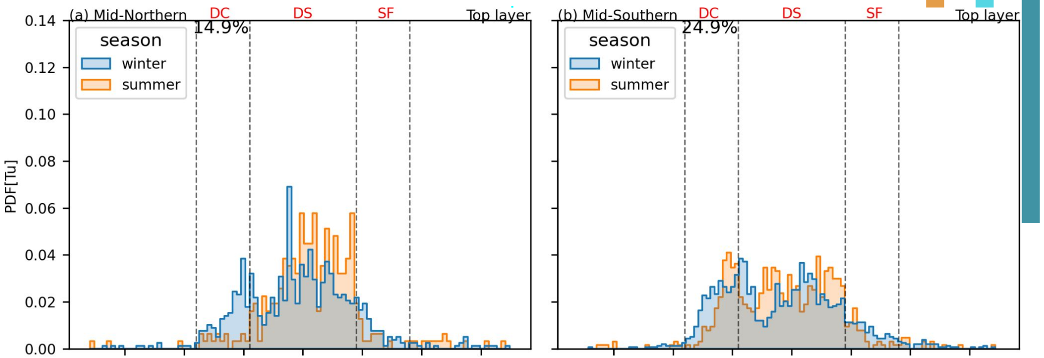


Top layer is doubly stable in **MN**, but with a second peak in winter within the diffusive convection range:

→ increase in the CW volume in this season

[Cerda and Castro, 2014]

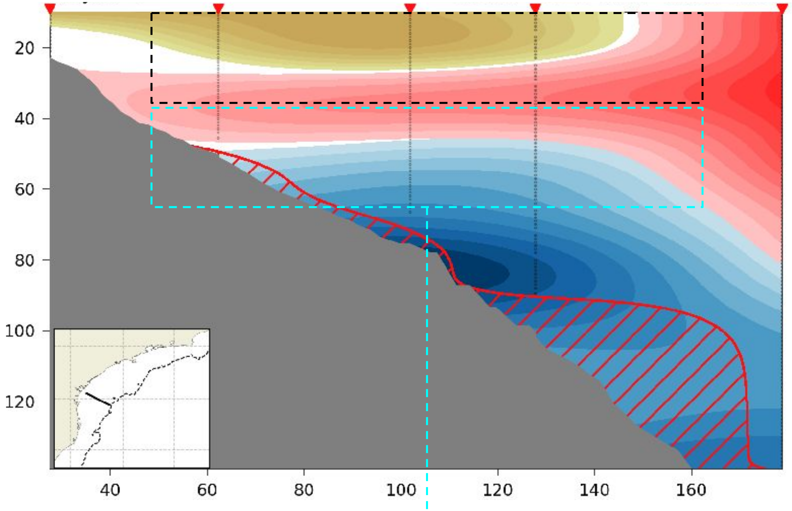
The **MS** has a bimodal distribution, with a peak in the doubly stable and slightly skewed to the diffusive convection (~25%) throughout the year.

→ quasi-permanente low-salinity strip nearshore.

[Castro, 1996; Marta-Almeida et al., 2021]

Subsurface thermohaline intrusions at a mid-latitude continental shelf

Underlying mixing processes

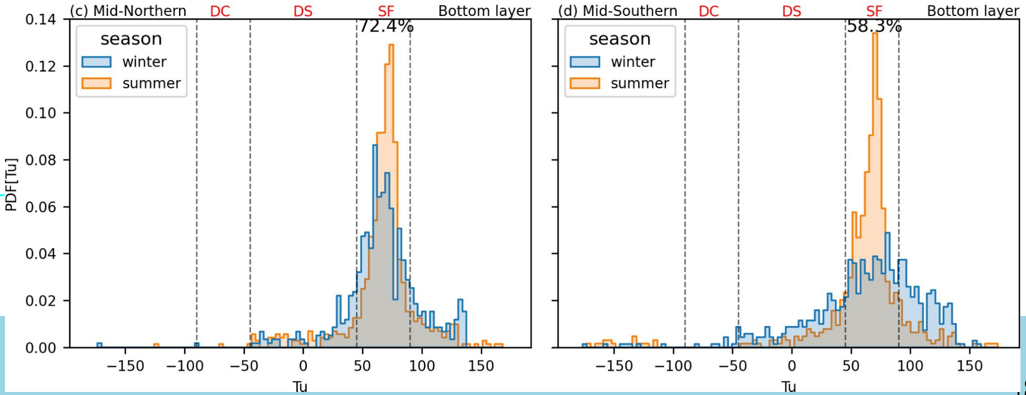


Intrusions destabilize the environment?

The **bottom layer** is susceptible to salt fingering processes in both **MN** and **MS** throughout the year, since there will be salty and warm water above cold and relatively fresher water.

Winter has lower probability of salt fingering, which might be an influence of the increase in the CW volume.

[Cerda and Castro, 2014; Marta-Almeida et al., 2021]



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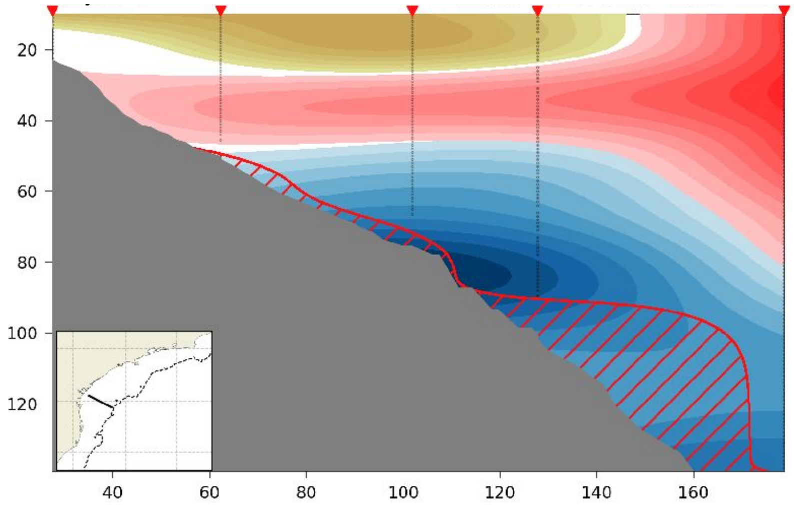
Concluding remarks

The main founding in this work were:

→ We know that intrusions have different properties along the shelf, varying based on the volume of the Coastal Water in the region.

→ The evidences points to not double-diffusively driven intrusions, since the environment supports double diffusion independently of intrusion.

→ However, we cannot reject the double diffusion role completely, since it can be important during the growth, stability and erosion of the intrusions, as supported by the possibility of co occurrence of both forms of double diffusion in the intrusion.



Thank you!

OCEAN SCIENCES MEETING 2022

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Underlying mixing processes

Are these intrusions double-diffusively driven?

→ The pdf[Tu] considering the whole water column suggest that the SBB is always unstable to double diffusion, indepently of intrusions.

	Theory[a]	**Observed**
Thickness	$O(10^0\ \mathrm{m})$	$O(10^1\ \mathrm{m})$
Cross-front velocity	$O(10^{-1}; 10^0\ \mathrm{mm\ s^{-1}})$	$O(10^2\ \mathrm{mm\ s^{-1}})$

[a]Ruddick and Turner (1979).

→ All things considered, double diffusion might take no action in triggering intrusions, but it can be an important process in other stages of an intrusion.
[Ruddick et al., 1985;Schmitt, Lueck and Joyce, 1986; May and Kelley, 2002; Beal, 2007]

Underlying mixing processes

What is the role of double diffusion?

→ the possible coexistence of both forms of double diffusion suggest an influence of these processes on the vertical mixing.
[Ruddick and Richards, 2003]

→ And what about the shear-driven turbulence?

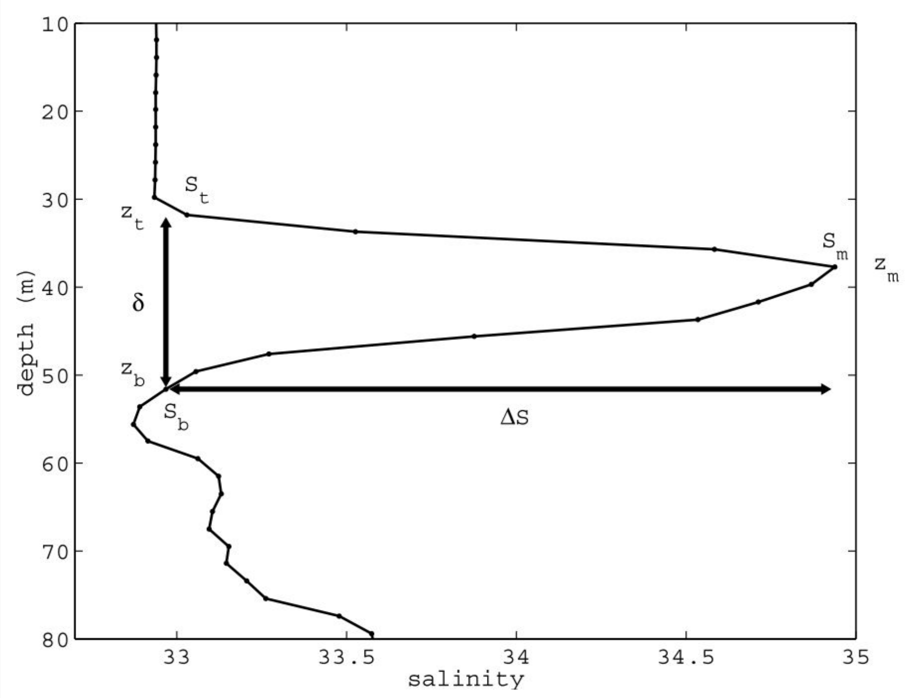
→ Adapted Bulk Richardson number:

$$Ri_b = \frac{< N^2 >_\rho H_I}{U^2}$$

→ Ri_b always higher than the critical Ri of 0.25 [Miles, 1961]

		Inner*	Mid*	Outer*
Mid-Northern	**Summer**	2.08	3.55	5.63
	Winter	3.18	3.71	5.07
Mid-Southern	**Summer**	2.66	4.15	8.65
	Winter	2.14	3.89	7.12

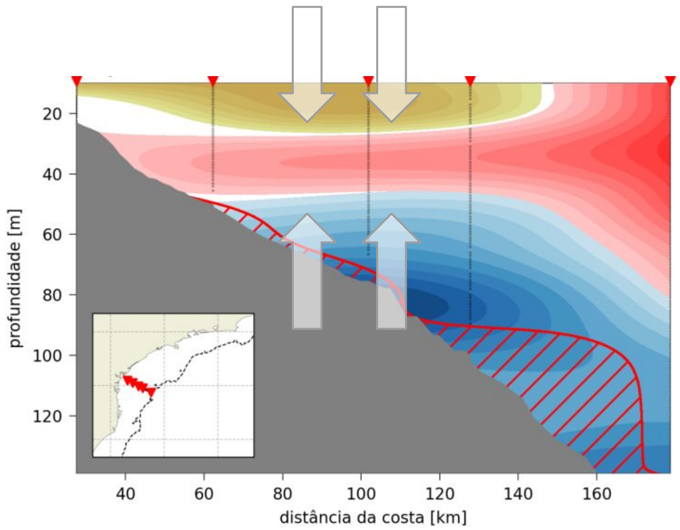
*Cross-shelf compartmentalization based on Castro (2014).



$$S_{max} - S(\boxed{z = z_{t,b}}) = 0.75(S_{max} - S_{min})$$

Relação inversa entre N^2 e H fornece argumentos para utilizar a formulação de Ruddick e Turner (1979) para calcular a espessura (H) da intrusão com base em:

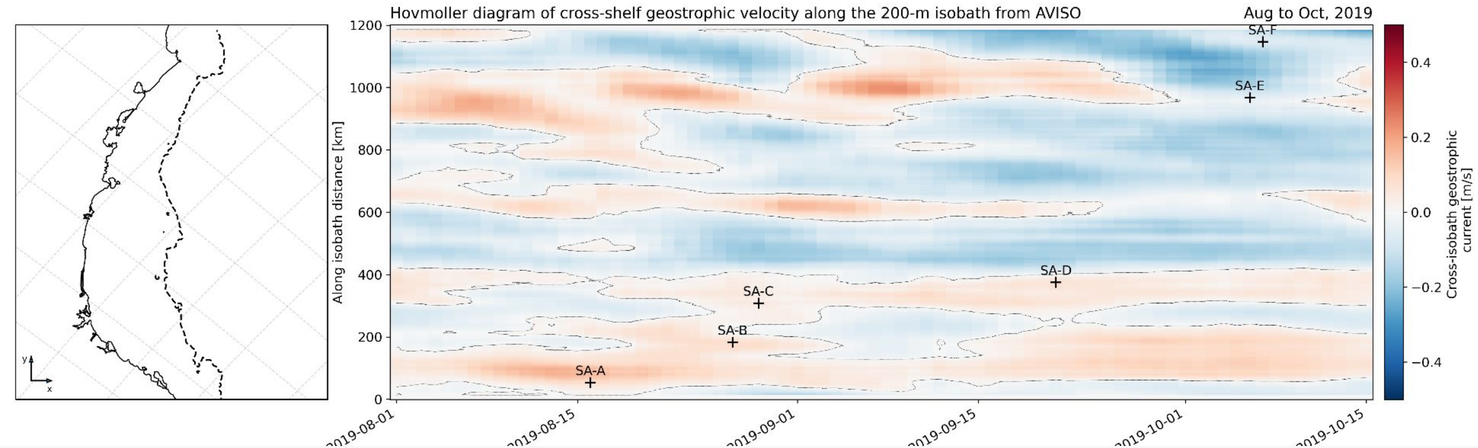
$$H = \frac{3(1-\gamma)g\beta\Delta S}{2 \quad N^2}$$

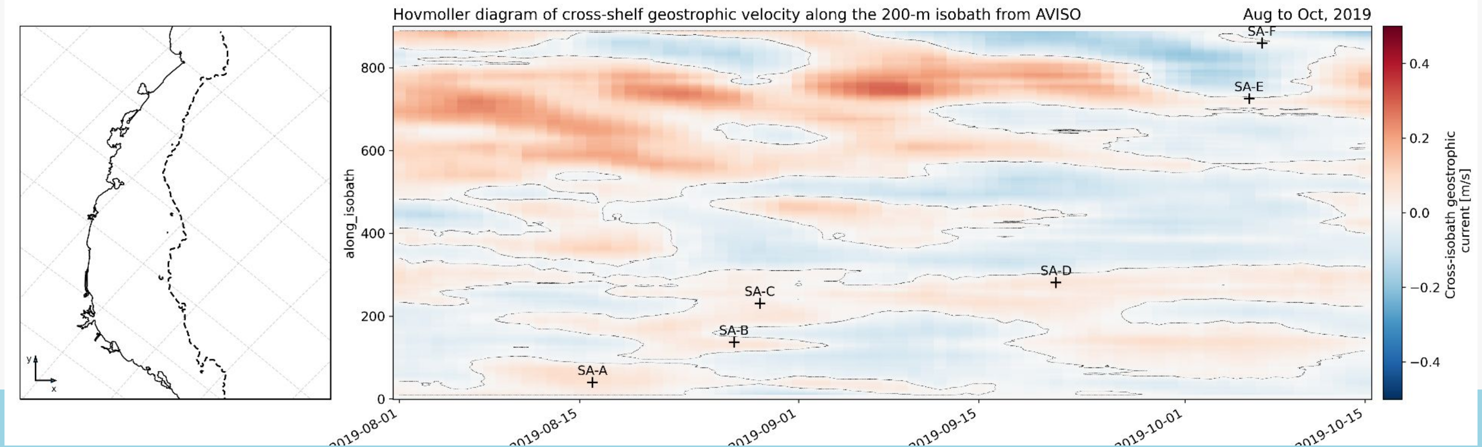


No entanto, ao usar essa equação obtivemos espessuras com 1 ordem de grandeza menor que as observadas no conjunto histórico.

O que podemos concluir disso é que talvez a dupla difusão realmente não seja um agente gerador de intrusões.

Nota: Ruddick e Turner (1979) utilizam a teoria da instabilidade linear.


Hovmoller diagram of cross-shelf geostrophic velocity along the 200-m isobath from AVISO
Aug to Oct, 2019
Along isobath distance [km]
0
200
400
600
800
1000
1200
2019-08-01
2019-08-15
2019-09-01
2019-09-15
2019-10-01
2019-10-15
SA-A
SA-B
SA-C
SA-D
SA-E
SA-F
Cross-isobath geostrophic current [m/s]
0.4
0.2
0.0
−0.2
−0.4
y
x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