Identification and quantification of North Atlantic Deep Water pathways

P. Miron[1], M. J. Olascoaga[1], F. J. Beron-Vera[1], K. L. Drouin[2], M. S. Lozier[3]

[1] Rosenstiel School of Marine and Atmospheric Sciences, University of Miami

[2] Earth and Ocean Sciences Department, Nicholas School of the Environment, Duke University

[3] Earth and Atmospheric Sciences Department, Georgia Institute of Technology

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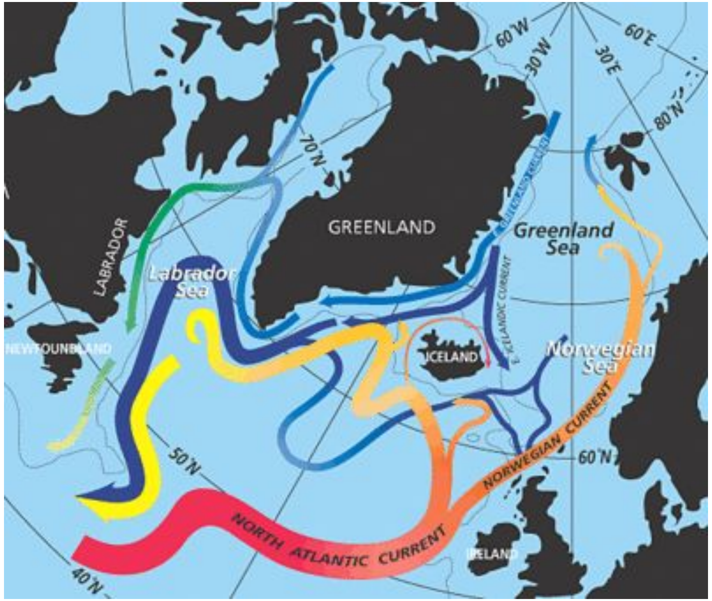
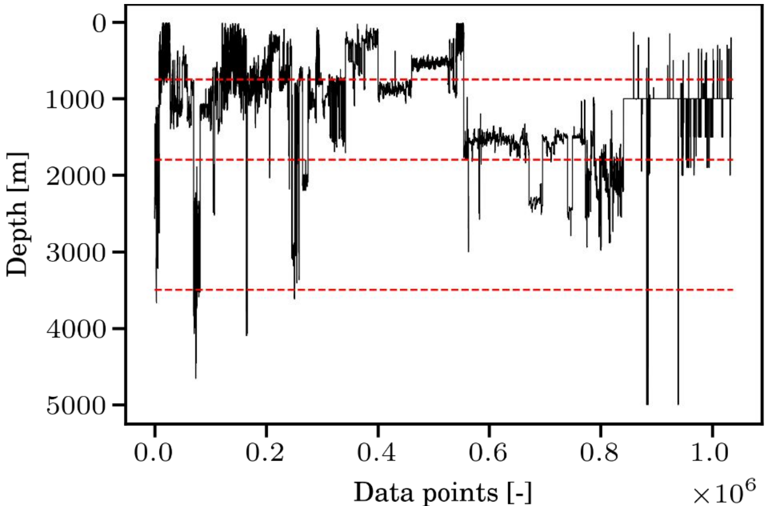
Introduction

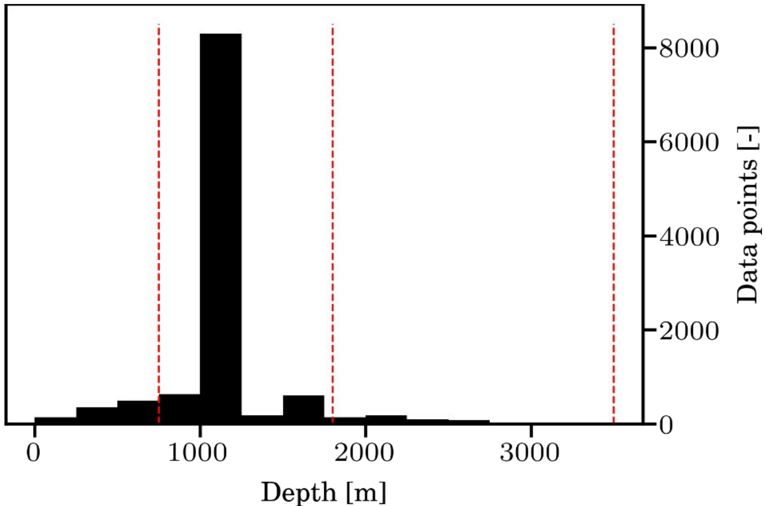
- Traditional view (citation): North Atlantic Deep Water (NADW) flows equatorward along the Deep Western Boundary Current (DWBC)
    - **Upper layer:** Labrador Sea Water (LSW) formed by open-ocean deep convection in the Labrador and Irminger Seas
    - **Lower layers:** Iceland–Scotland Overflow Water & the Denmark Strait Overflow Water formed north of the Greenland–Iceland–Scotland Ridge.
- Recent observations challenge this view: Multiple interior pathways (not shown in figure!)
- Consequential for the Atlantic Meridional Overturning Circulation



Lagrangian data sets (RAFOS & Argo) in the North Atlantic

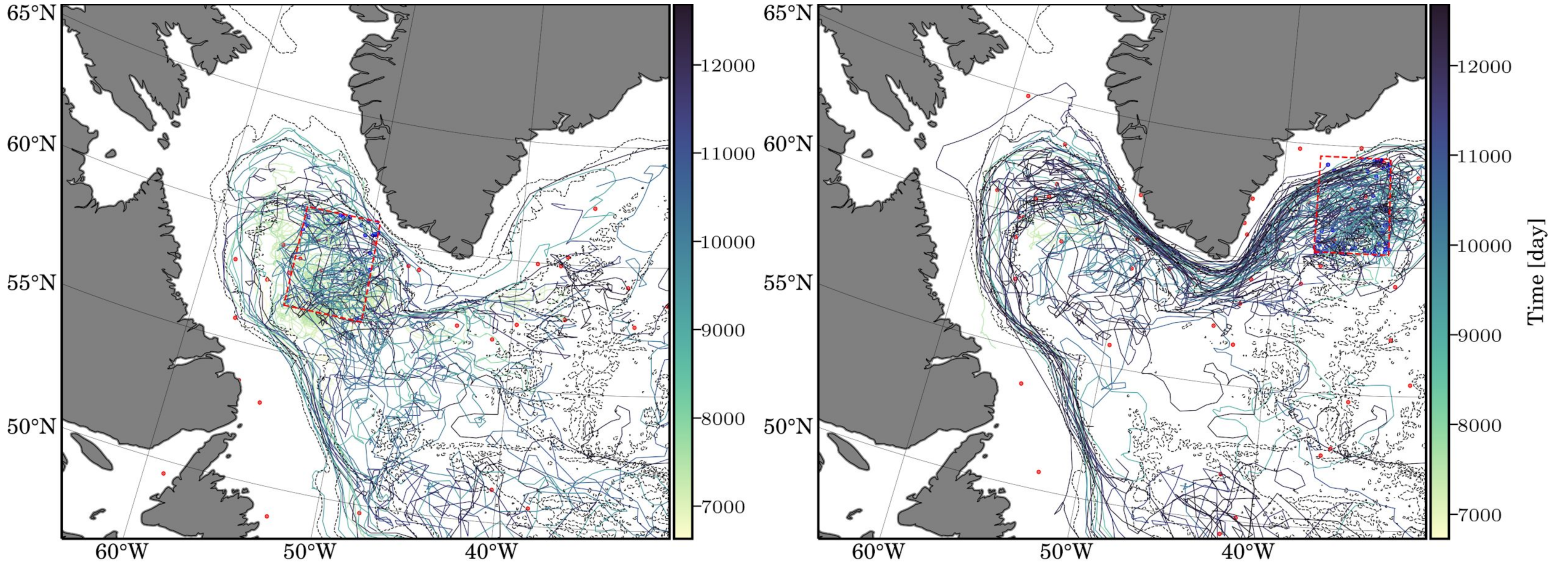
- Upper layer 2037 float trajectories between [750, 1800] m
  - includes 1478 Argo floats park at 1200 m
- Lower layers 302 float trajectories between]1800, 2500] m
  - includes 35 Argo floats park at 2000 m





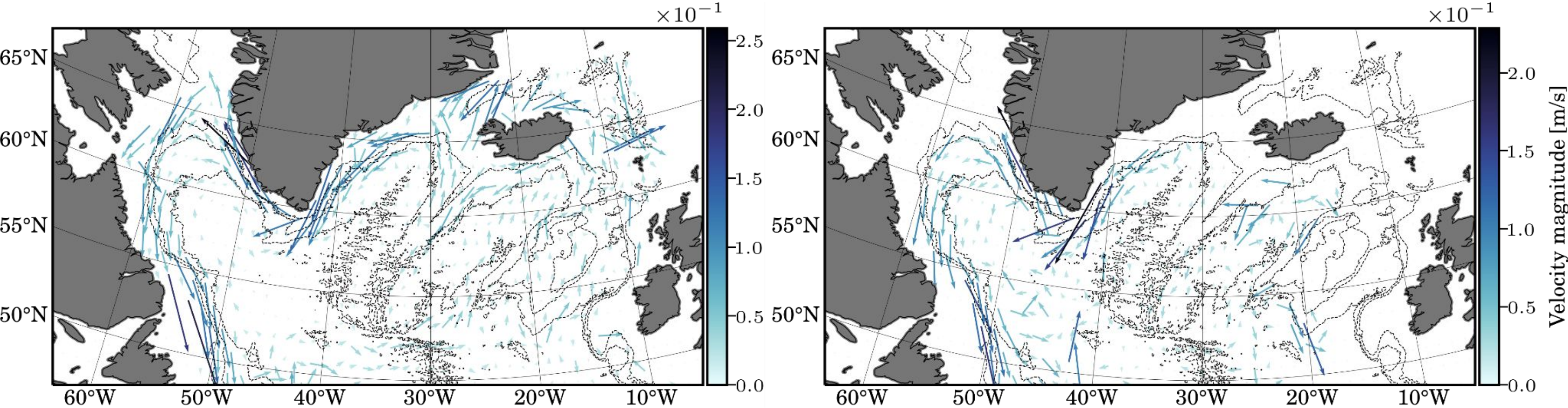
How to identify pathways from observations data sets?

- Follow floats from launch locations (Zou S. et al., 2020; Bower A. et al, 2019)
  - Limited float trajectory lengths so can't observe pathways between remote locations
  - Only 97 Argo floats crossed the Labrador Sea and reached 53°N (see, Georgiou S. et al., 2020)



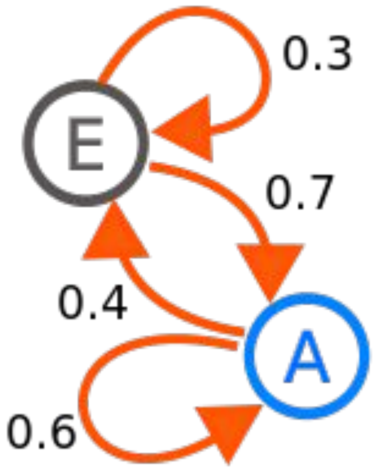
How to identify pathways from observations data sets?

- The construction of an Eulerian velocity fields
  - Loss of resolution (spatial & temporal) due to low coverage and data density
  - Only boundary current is “resolved”

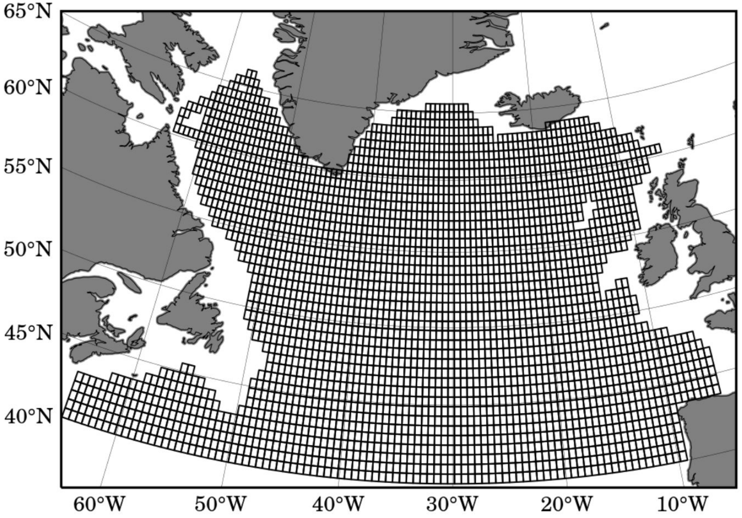


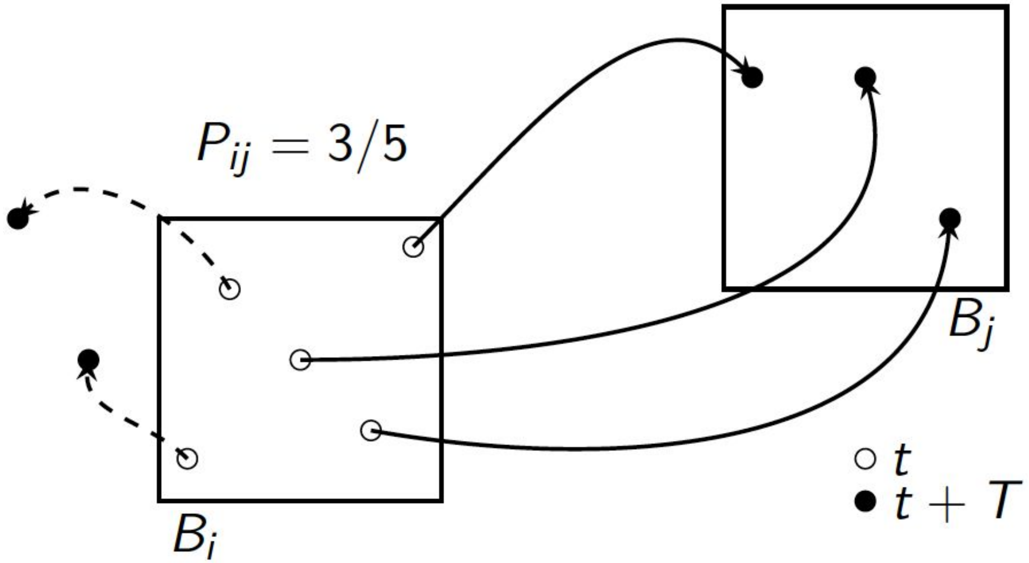
Markov Chain

- Stochastic model where future events only depend on the current states
- Obtained the Markov chain model by discretizing the Lagrangian dynamics as described by observations assuming an advection-diffusion process
- Evolution of probability densities rather than individual trajectories



Transition matrix

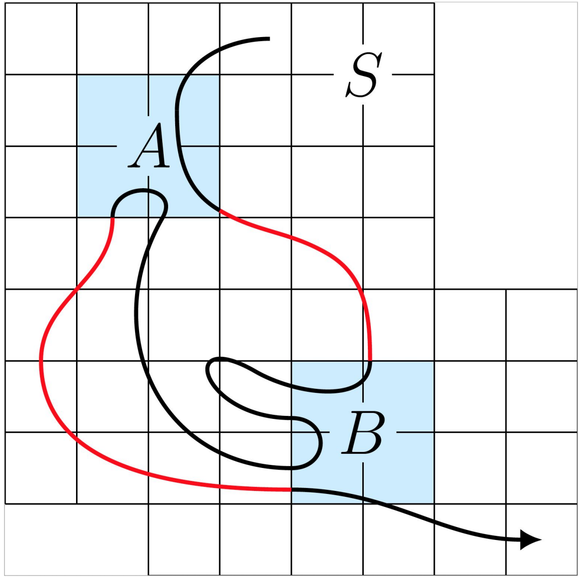




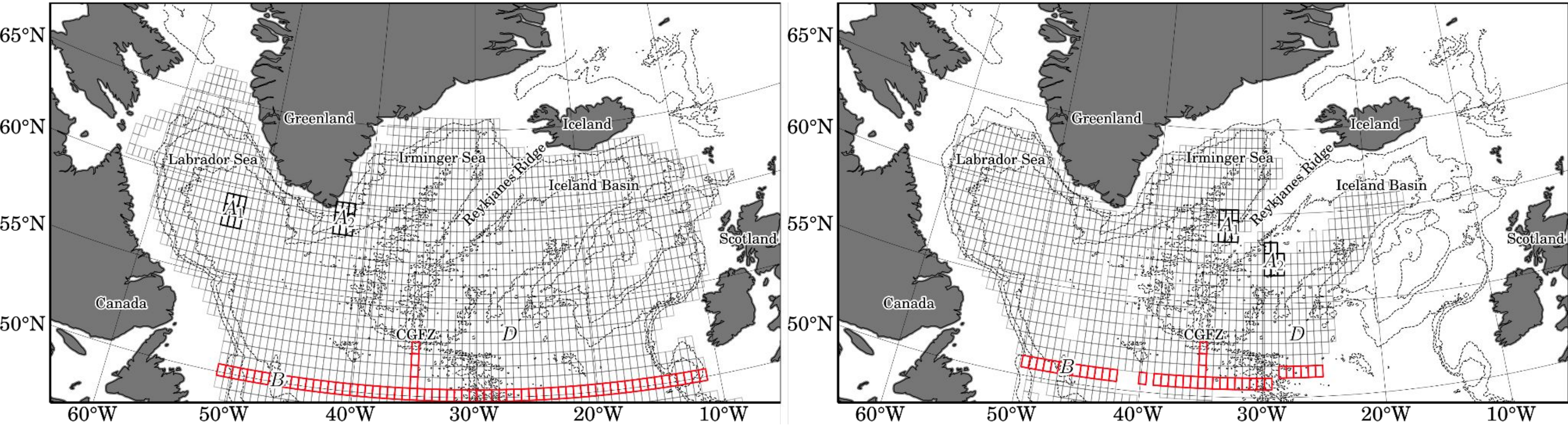
$$P_{ij} \approx \frac{\#\text{ points in } B_i \text{ at } t \text{ that evolve to } B_j \text{ at } t+T}{\#\text{ points in } B_i \text{ at } t}$$

Transition Path Theory

- Developed to identify and understand rare events
  - Chemical reactions (reactants & products)
  - Ocean pathways!
- Reaction events: transition from source **A** to target **B**
- Reactive trajectories : pieces of trajectory that connects directly **A** to **B**



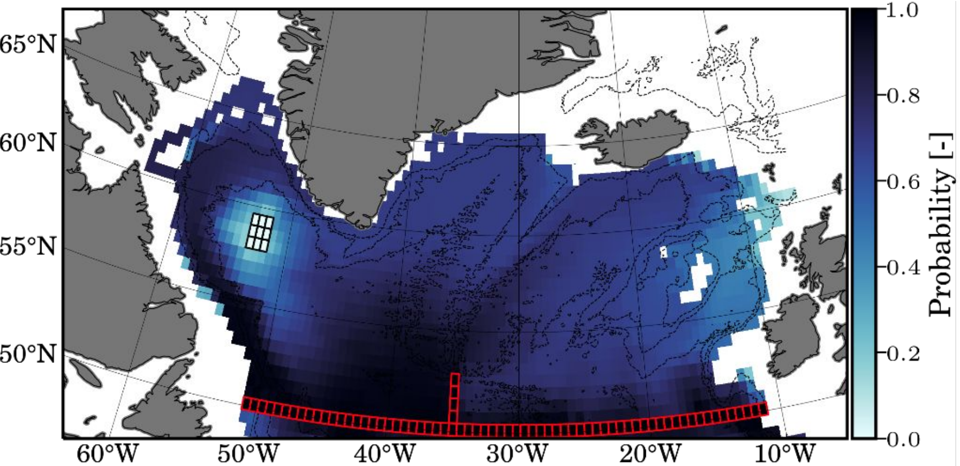
Domain, sources and targets

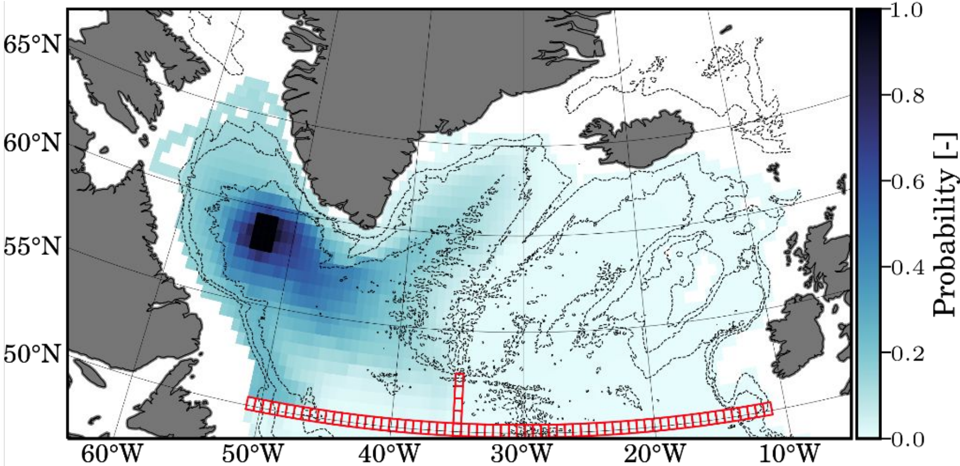


Transition Path Theory

Committors are the basis of the theory and they represent the probability to reach **B** before **A** (or vice versa in backward time).

$$q_i^+ := \Pr(\tau_B^+ < \tau_A^+ \mid X_0 = i) \qquad q_i^- = \Pr(\tau_A^- > \tau_B^- \mid X_0 = i)$$

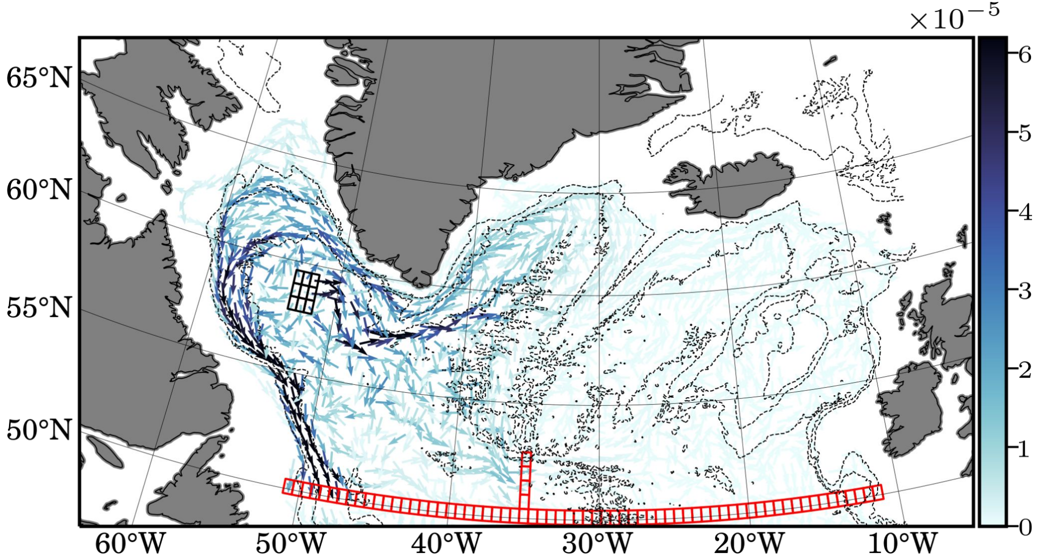




Transition Path Theory

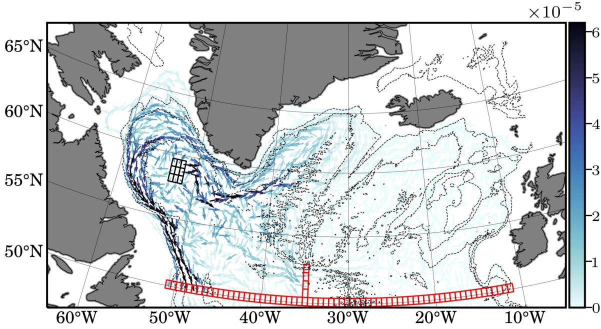
The current of reactive trajectories show the most likely transition channel from **A** to **B** (using both forward and backward commitors).

$$f_{ij}^{AB} = \Pr(X_0 = i, X_1 = j, \tau_A^- > \tau_B^-, \tau_B^+ < \tau_A^+) = q_i^- p_i P_{ij} q_j^+$$



Transition Path Theory

- Rate of reactive trajectories leaving **A** or entering **B** (per time step T). Can be given the interpretation of 'flux' or 'transport' (upon multiplication by time step T, and the area covered and height of a layer)



$$k^{A\to} = \sum\nolimits_{i\in S, j\in B} f_{ij}^{AB} = 4.2 \times 10^{-4}$$

- Mean duration of all reactive trajectories are obtain by dividing the probability of being reactive by the transition rate.

$$t^{AB} = \frac{\sum_{j\in C} q_i^- p_i q_i^+}{k^{AB}} (T/365) = 3.02 \text{ years}$$

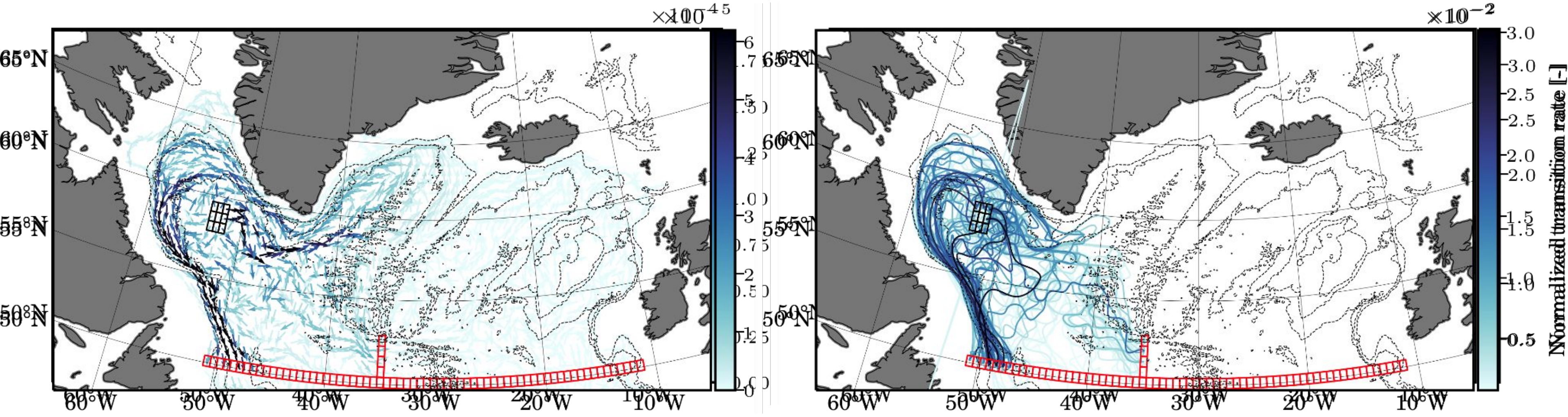
Location of sources and targets

Identification and quantification of North Atlantic Deep Water pathways:

- Sources
  - Locations of open-ocean deep convection
  - Deep water formation sites
- Target (50°N)
  - South of the Labrador Sea
  - North of the deepening of NAVD so we can target the upper and lower layer with current float trajectories
- Vertical portion of the Target (33°W)
  - Mid North-Atlantic Ocean
  - Quantification of interior pathways

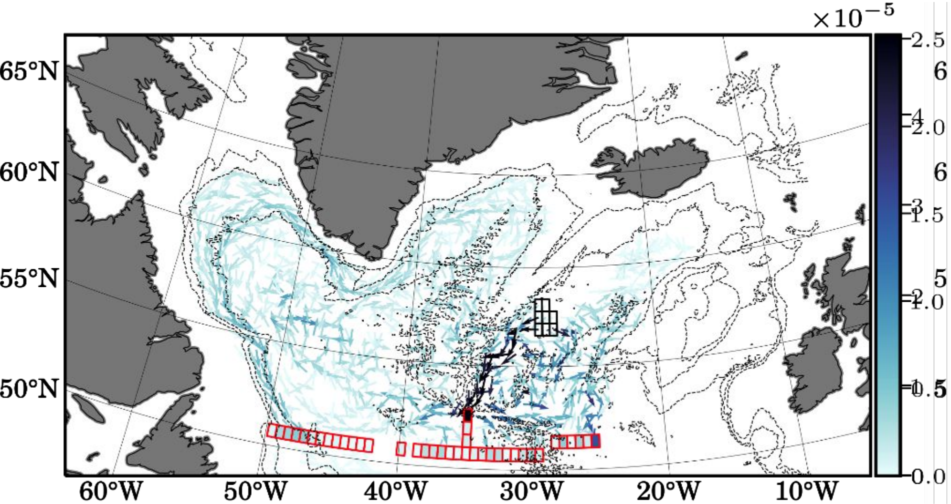
Reactive Current (Upper layer)

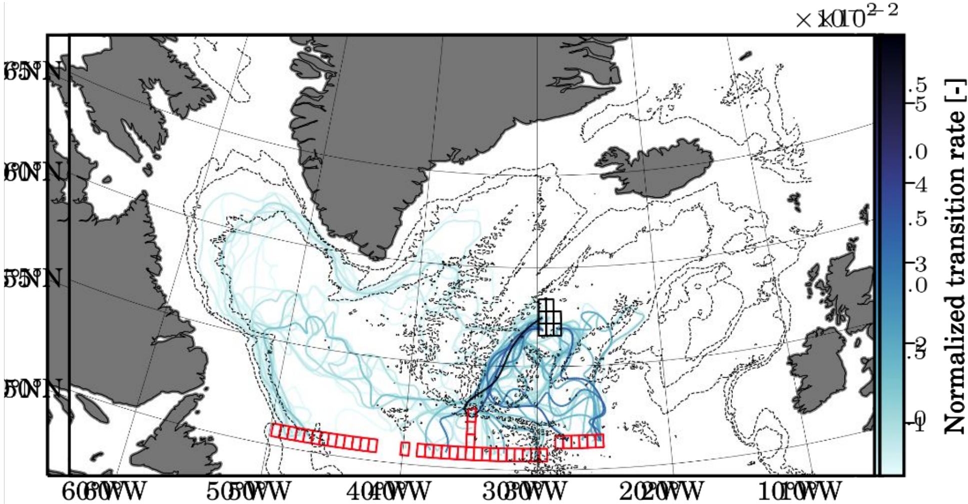
- Recirculation from the Labrador to Irminger Sea
- Irminger Sea pathways are more direct and follow the boundary current
  - Two branches in the Labrador Sea over 2000-3000 m bathymetry lines



Reactive Current (Lower layers)

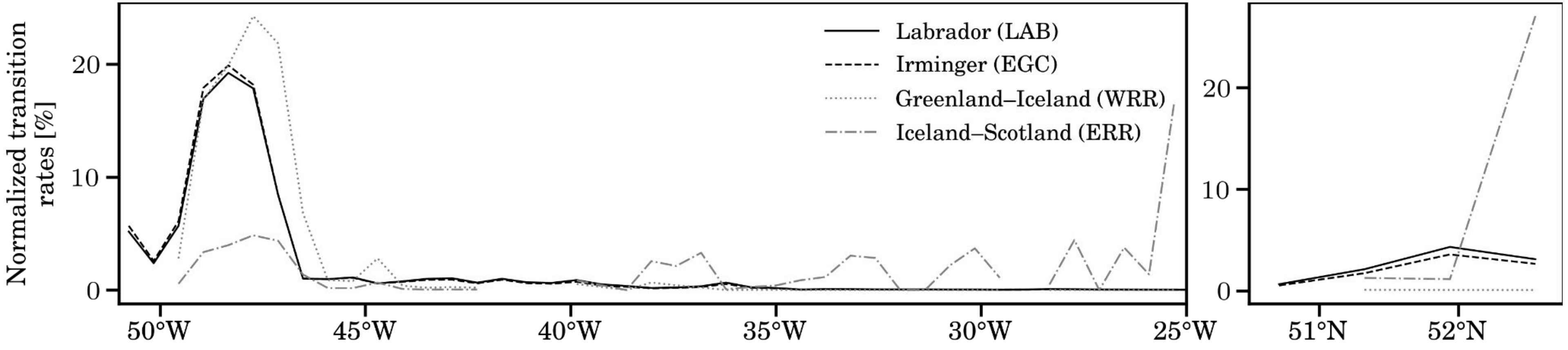
- Flow more organized than what naked-eye inspection of trajectories suggests
- Two connections to the target from east and west of the Reykjanes Ridge
- Less pathways reach the interior of the North Atlantic





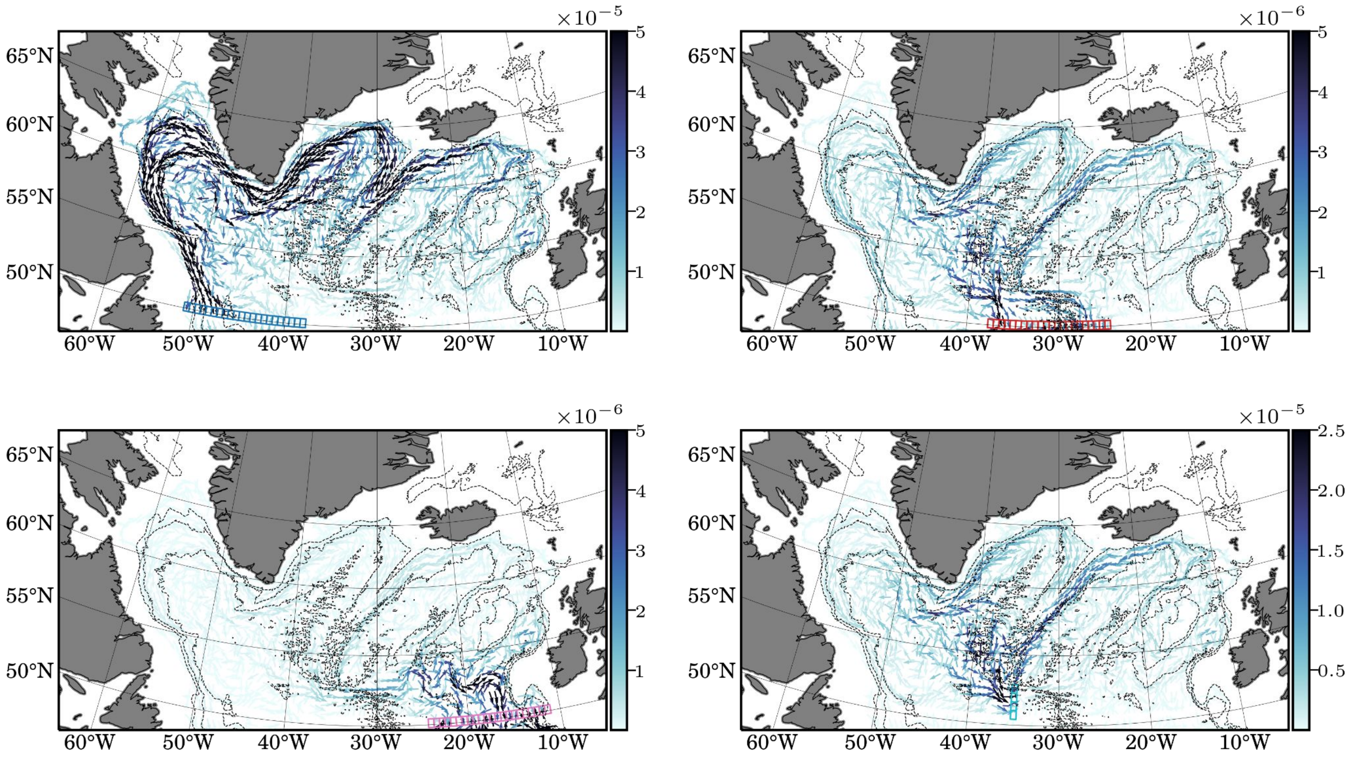
Pathways exiting the Labrador Sea

- Pathways through the DWBC (west of 45°W)
  - Upper layer: Labrador 78.7% and Irminger 81.8%
  - Lower layers: Iceland 94.1% and Denmark 18.8%
- Internal pathways (vertical part of the target)
  - Upper layer: Labrador 10.1% and Irminger 8.4%
  - Lower layers: Iceland 0.2% and Denmark 29.4%



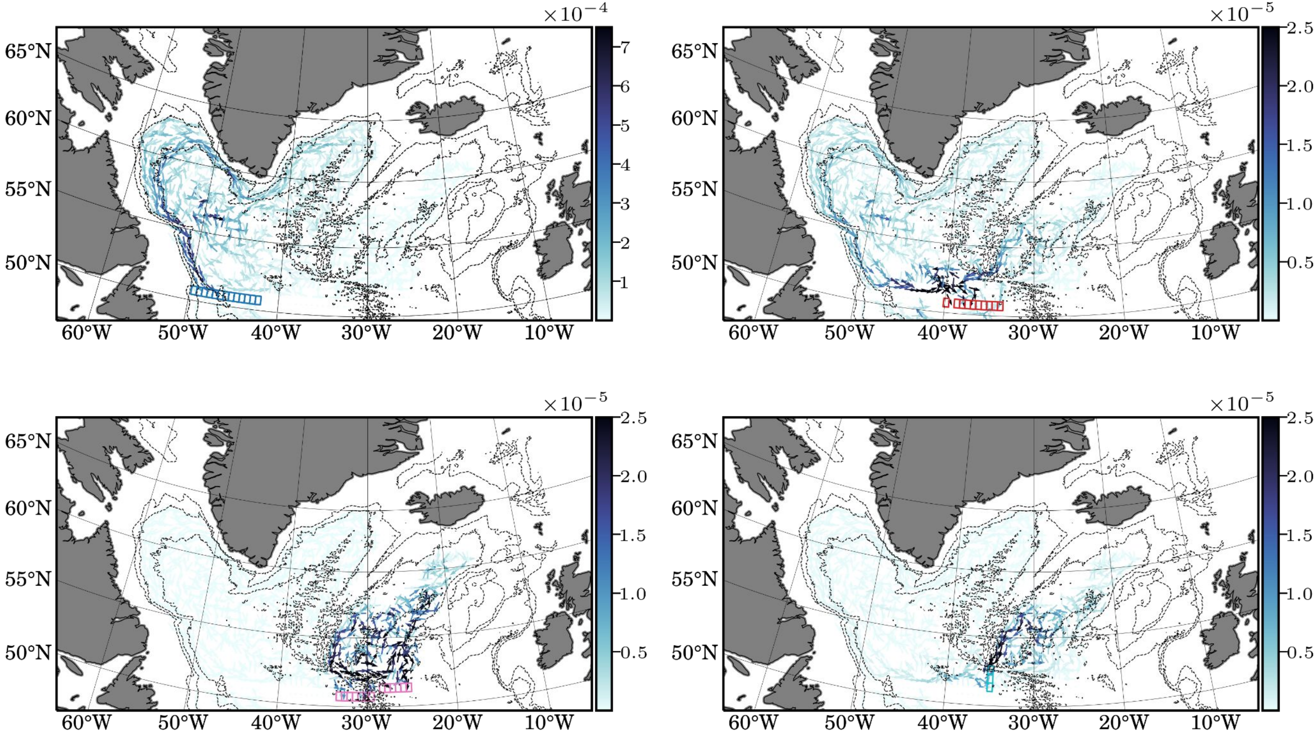
Transition rate to target's sections (Upper L)

- Most bins of the domain converge to the westernmost section of the target.
- Interior pathways come from South (Fleming Cap) and Reykjavík Ridge



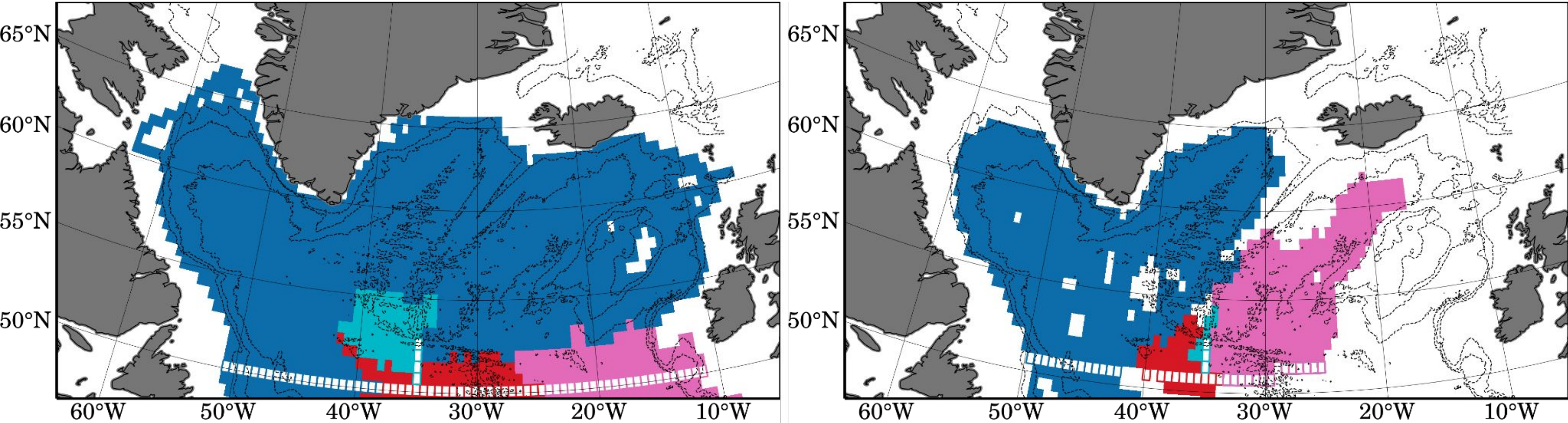
Transition rate to target's sections (Lower L)

- Clear separation at the Reykjanes Ridge
- Interior pathways mostly come from the South recirculating after Fleming Cap and the Newfoundland Ridge



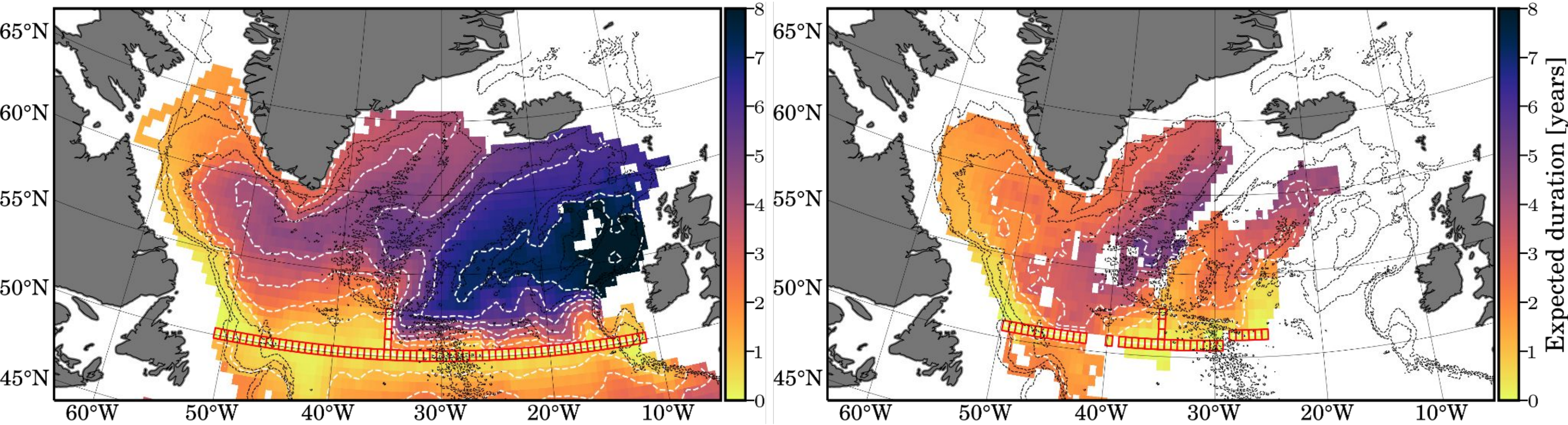
Regions reaching target's sections

- Bins are colored according to the most probable target's section to converge too (i.e. basins of attraction of each section)
- Most of the pathways reach the westernmost section of the target
- Whole domain connected in the upper layer while the lower layers splits in two



Mean duration pathways to target at 53°N

- Cyclonic motion(s) in both layers
- Less probability of looping around the Reykjanes Ridge for the Denmark Strait Overflow Water
- Reach the target in 2–3 yrs from Labrador Sea and 3–5 yrs Irminger Sea



Conclusions

- Existence of interior pathways but with much smaller probabilities
- The NADW flows out of the Labrador is largely accomplished in the form of a Deep Western Boundary Current (DWBC) consistent with traditional abyssal circulation theory
- Comparison between the upper and lower branches
  - The upper branch shows recirculation from the Labrador Sea to the Irminger Sea
  - Both the upper and lower branch detach at the Flemish Cap
  - The lower branch also detaches south of the Reykjanes Ridge

References

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Thank you

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- nonlinear.rsmas.miami.edu
- github.com/philippemiron
- @philippemiron

Paper is coming soon ...

README.md

pygtm : a python Geospatial Transition Matrix toolbox

launch binder | hits 349

Folders

- tutorials/: Jupyter notebook examples to help interacting with the toolbox
- tests/: Unit tests

Used in the following Publications

- Identification and quantification of North Atlantic Deep Water pathways, P. Miron, F.J. Beron-Vera, M.J. Olascoaga, K.L. Drouin and M.S. Lozier, Preprint, Preprint, 2021
- Influence of the Loop Current on the Gulf of Mexico connectivity, P. Miron, TBD
- Transition paths of marine debris and the stability of the garbage patches, P. Miron, F.J. Beron-Vera, L. Helfmann and P. Koltai, Chaos: An Interdisciplinary Journal of Nonlinear Science, 2021, link soon
- Markov-chain-inspired search for MH370, P. Miron, F. J. Beron-Vera, M. J. Olascoaga and P. Koltai, Chaos: An Interdisciplinary Journal of Nonlinear Science, 2020, link
- Lagrangian geography of the deep Gulf of Mexico, P. Miron, F. J. Beron-Vera, M. J. Olascoaga and G. Froyland, Journal of Physical Oceanography, 2018, link
- Connectivity of Pulley Ridge with remote locations as inferred from satellite-tracked drifter trajectories, M. J. Olascoaga, P. Miron, C. Paris, P. Pérez-Brunius, R. Pérez-Portela, R. H. Smith and A. Vaz, Journal of Geophysical Research, 2018, link
- Lagrangian dynamical geography of the Gulf of Mexico, P. Miron, F. J. Beron-Vera, M. J. Olascoaga, P. Pérez-Brunius, J. Sheinbaum and G. Froyland, Scientific Reports, 2017, link

Contributors

- Philippe Miron
- Luzie Helfmann
  - *pygtm/tpt.py* is based on this repo