High latitude mesoscale eddy characterization from SWOT altimetry

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Motivations & Context

Mesoscale eddies are key drivers of global ocean physics and biology.

At high latitudes (poleward of 50°N/S), they play an outsized role in:

- air-sea heat exchange, deep-water formation, and poleward heat transport—critical for global climate dynamics;
  (Chelton et al. 2011, Thompson et al. 2014, Manucharayan et al. 2022)
- primary production and species distribution;
  (Cotte et al. 2007, Keppler et al. 2024)
- and sea-ice melt, accelerating retreat by transporting warm water poleward.
  (Dufour et al. 2015, Si et al. 2023)

Yet, a critical gap persists, conventional satellite altimetry—with effective resolution O(50) km—fails to resolve high-latitude eddies, which are smaller (10–50 km) than their mid-latitude counterparts.
This leaves polar and subpolar regions mesoscale activity poorly understood.
(Frenger et al. 2015, Ballarotta et al. 2019)

We take advantage of SWOT capabilities to develop a novel eddy characterization methodology and bridge this gap:

- we apply an eddy-detection algorithm directly to the native SWOT data (L3 2-km KaRIn filtered SLA over the full calendar year 2024);
- the method is validated against *in situ* data in the Labrador Sea;
- it enables the first comprehensive characterization of mesoscale eddies at high latitudes—revealing their spatial distribution and properties.

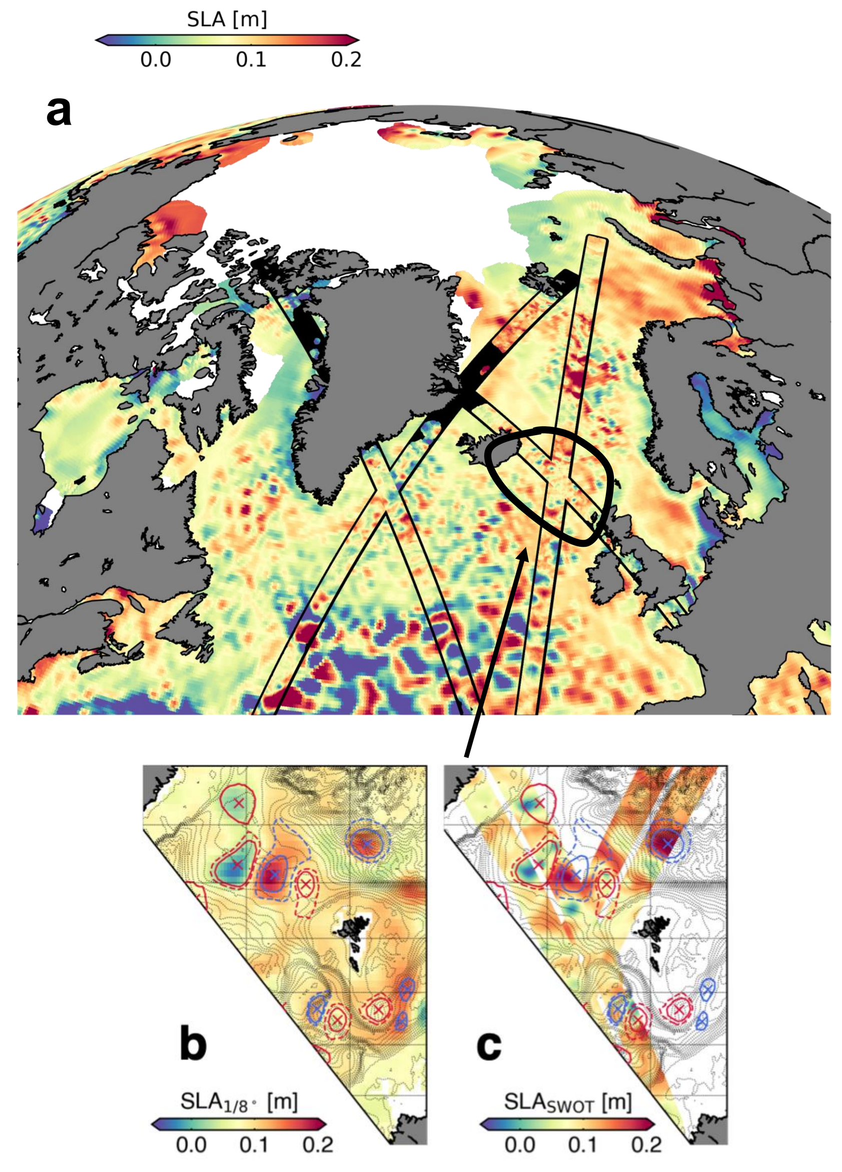


Fig. 1: Comparison between conventional gridded altimetry and SWOT altimetry. (a) SLA from both 1/8° AVISO and SWOT 2-km products.
(b) Detection of mesoscale eddies (contours) from 1/8° AVISO SLA (color) on the 10/06/2023.
(c) SWOT KaRIn 2-km SLA (filtered) in passes #5 and #16 on the same day than (b), the eddy detection from AVISO is superimposed.

Methodology

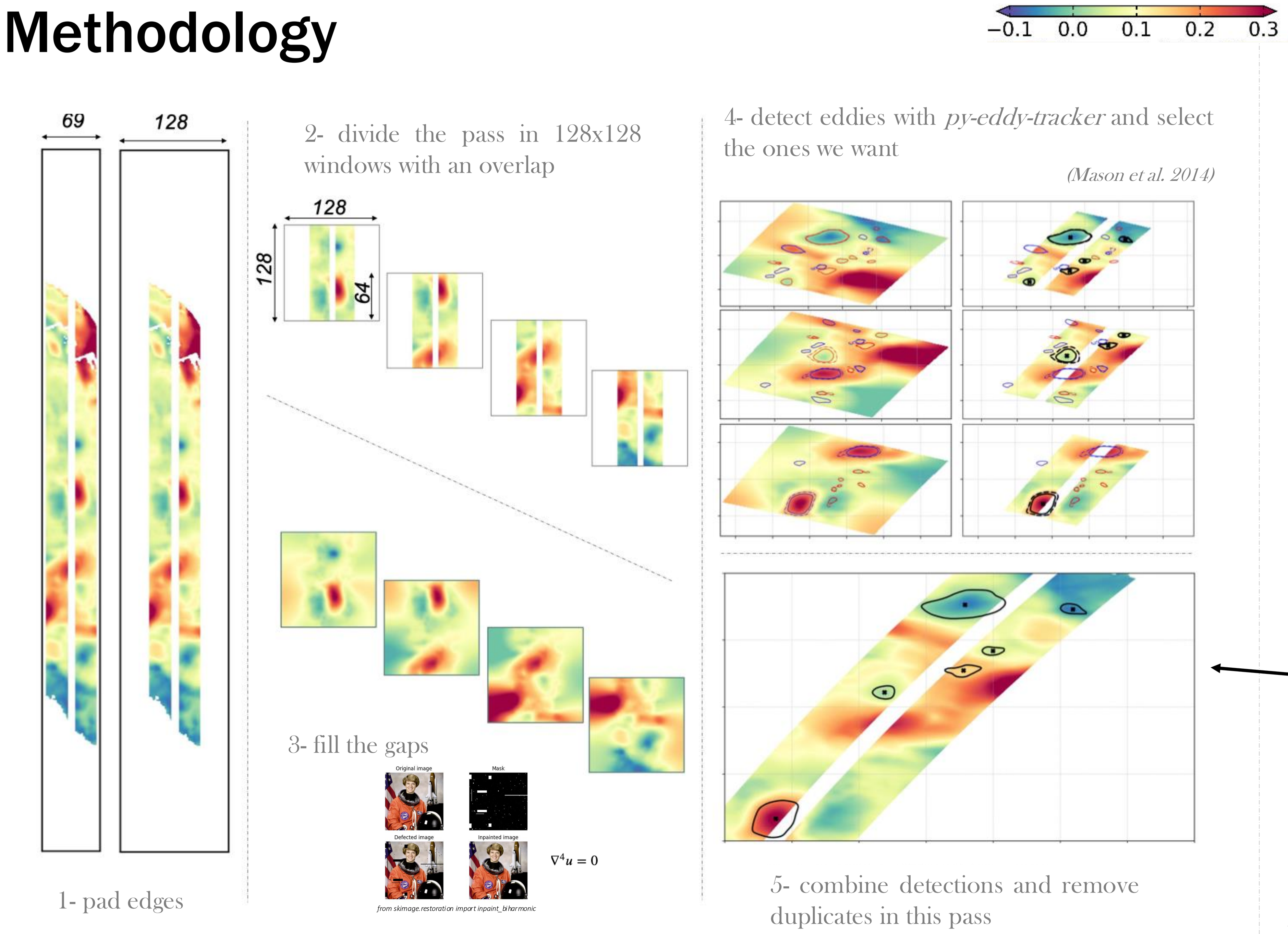


Fig. 2: Example of the detection methodology in pass #563, and cycle 10. The color shows SLA, and it is primarily obtained from L3 2-km KaRIn filtered SLA data (produced and made freely distributed by the AVISO and DUACS teams as part of the DESMOS Science Team project).

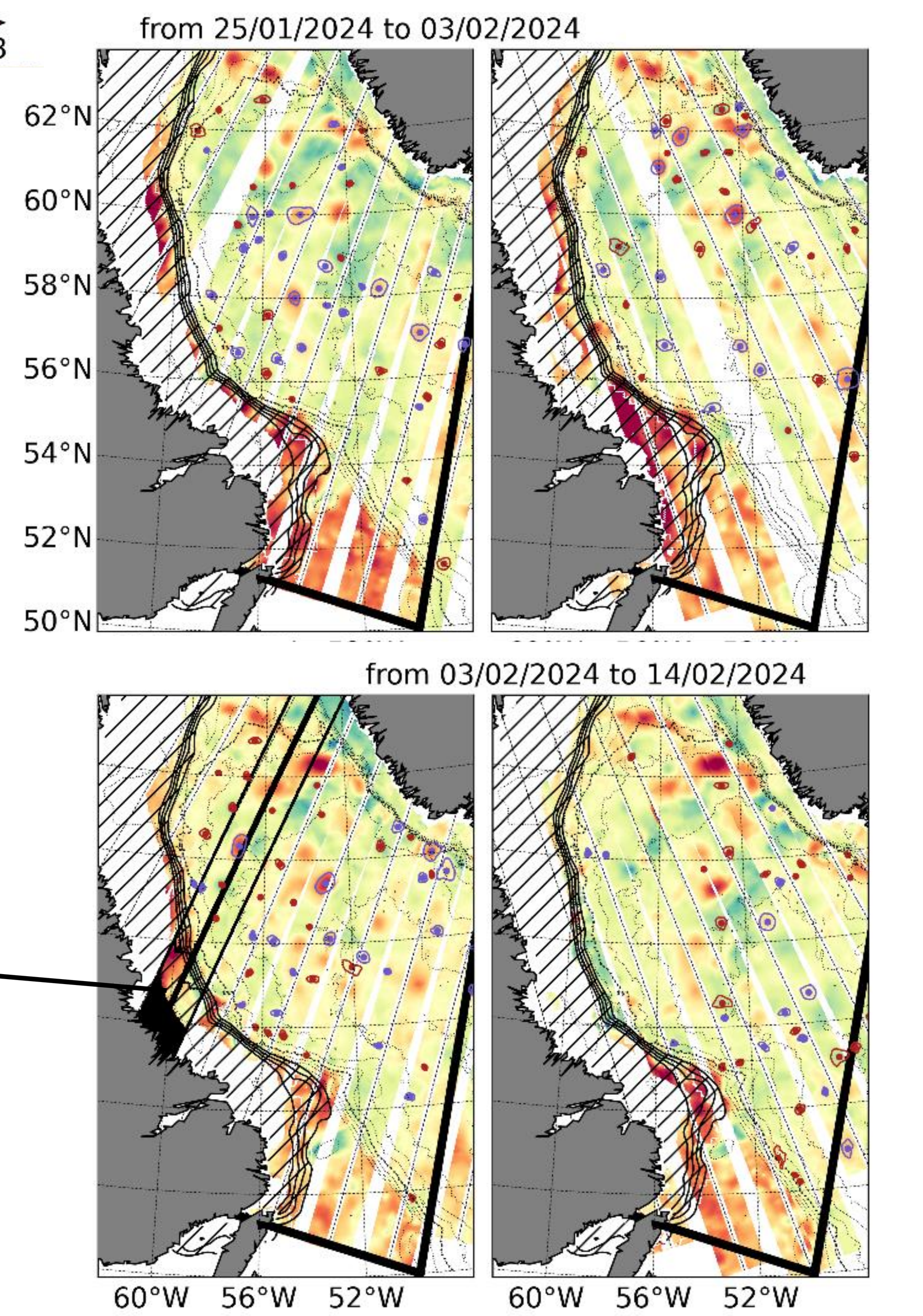
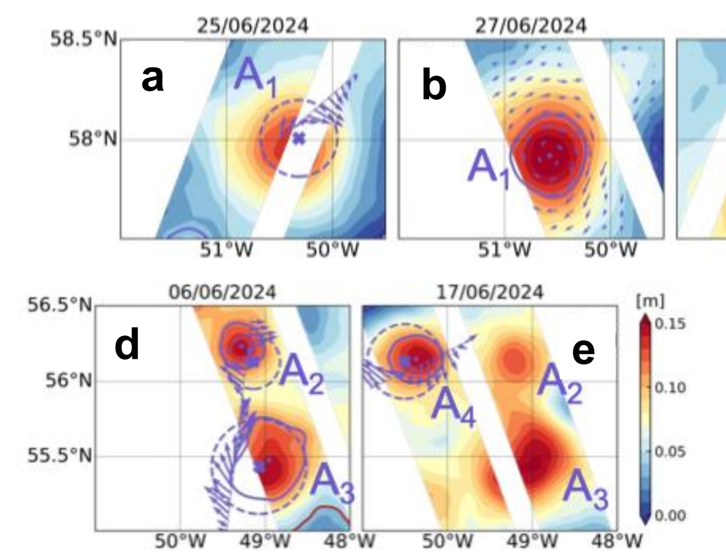


Fig. 3: Mesoscale eddy detection in the Labrador Sea from non-interpolated SWOT data for cycle 10; blue (resp. red) contours (resp. dots) indicate anticyclonic (resp. cyclonic) eddy contours of maximum velocity (resp. centers).

In situ assessment



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	A_1	A_2	A_3	A_4
V_{max}^{SWOT}	0.41	0.21	0.17	0.28
V_{max}^{ADCP}	0.66	0.25	0.28	0.29
R_{max}^{SWOT}	21.4	16.2	28.8	18.4
R_{max}^{ADCP}	19.0	16.8	29.2	23.1

Fig. 4: (a–e) SLA from SWOT, over which detected eddies are mapped. In panels (b, d, e), solid lines indicate the maximum azimuthal velocity contours of SWOT-detected eddies, and dots mark their centers. In panels (a, d, e), crosses indicate the centers of eddies identified during MSM129, with circles marking their radii; arrows show the surface velocity from the SADCP, used for the *in situ* eddy identification along the ship's trajectory.
Eddies A_{1-4} correspond to the four observed structures. Their maximum velocity (in m s^{-1}) and radius (in km) are summarized in panel (f) for both SWOT detections and SADCP identifications.

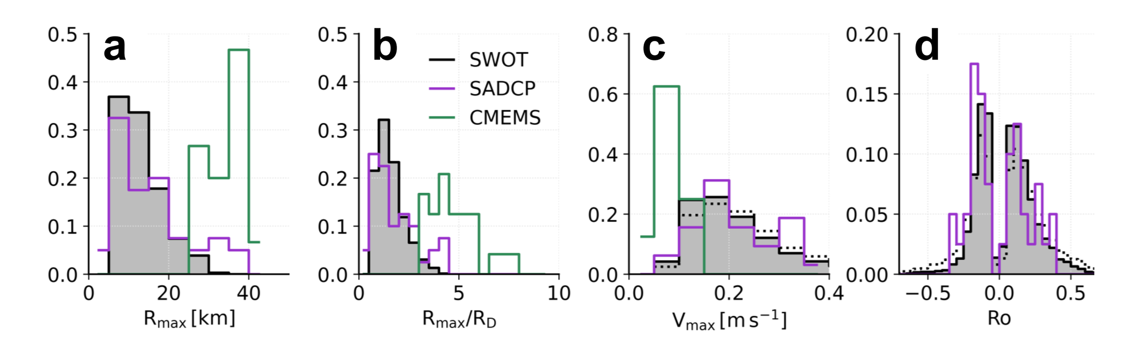

Fig. 5: Probability distribution of eddy statistics detected by SWOT (gray bars, solid black lines) in comparison with ADCP (purple) and CMEMS gridded product (green). (a) Distribution of radius of maximum azimuthal velocity R_{max}. (b) Distribution of R_{max} normalized by the first baroclinic deformation radius R_D. (c) Distribution of maximum azimuthal velocity V_{max}. (d) Distribution of the Rossby number Ro of detected eddies.

To validate our SWOT-based eddy detections, we compared them with independent *in situ* observations from the MSM129 cruise in the Labrador Sea, where 4 eddies were sampled using a Shipboard Acoustic Doppler Current Profiler (SADCP). The characteristics of these 4 eddies is determined using Bendinger et al. 2025's methodology.

→ There is a strong agreement in eddy location, radius, and velocity confirming the reliability of our detection method for SWOT's 2-km resolution data (Fig. 4).

SWOT-derived eddy distributions is further compared with a comprehensive *in situ* eddy dataset in the Labrador Sea (~40 mesoscale eddies characterized from 3 *in situ* surveys, Bendinger et al. 2025).

→ The distributions of key eddy properties revealed excellent alignment between SWOT and *in situ* statistics (Fig. 5).

→ This validation not only confirms the reliability of our detection method but also demonstrates SWOT's unprecedented accuracy in resolving high-latitude eddies.

Mesoscale eddy hotspots and deserts in polar and subpolar oceans

We apply the methodology to all high latitude areas, poleward of 50°N/S.
This gives maps of eddy density derived directly from SWOT's 2-km swaths, uncovering mesoscale patterns invisible to traditional altimetry.

This census reveals a heterogeneous eddy field: intense activity along gyre boundaries, boundary currents, and topographic slopes, highlighting **mesoscale eddy hotspots**—such as the Norwegian Sea, East Greenland Shelf, Kerguelen Plateau, and Antarctic continental slopes—while confirming **mesoscale eddy deserts** in quiescent regions (*e.g.,* Weddell Sea interior). SWOT's resolution eliminates ambiguity, distinguishing true dynamical quiescence from observational gaps (Fig. 6).
Mesoscale eddies can be characterized within the Seasonal Ice Zone (SIZ), where their properties were previously unconstrained. For instance, during ice-free periods, eddy densities along the Greenland Shelf and Baffin Bay rival those of the North Atlantic.

This census provides the first observationally based reference to evaluate eddy representation in climate models. It also supports operational applications, such as guiding *in situ* campaigns (in prevision of *e.g.,* Antarctica InSync, 5th International Polar Year, etc.) and future wide-swath altimeter missions.

In support of these efforts, the detection used to compute eddy density shall be provided a foundation for future SWOT-based monitoring efforts, regional process studies, and coupled physical–biogeochemical investigations aimed at capturing the evolving role of eddies in a warming climate.

eddy detection from SWOT
year 2024
all ice-free areas >50°N/S
SWOT L3_LR_SSH filtered SLA v2.0.1
de Marez et al. 2026a,b (in review)

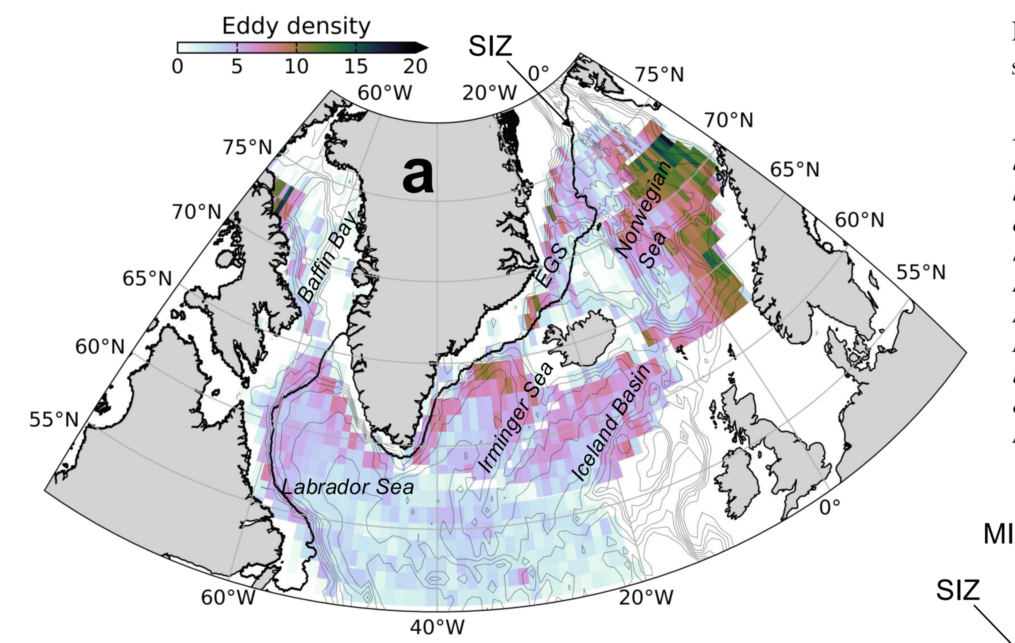

Fig. 6: Eddy density north of 50°N in the Atlantic sector (a) and south of 55°S (b) for 2024.

Eddy density is the number of eddy centers detected per 1°x1° bins (in the north hemisphere and 2°x2° bins in the south hemisphere) during the whole study period. Note that the eddy detection procedure ensures that eddies are not detected multiple times during one cycle, but because eddies are not tracked, they can be re-detected each cycle if they are still observable. The eddy density is normalized by the area in km² of each bin to render for the decrease in size of bins with latitude. It is also multiplied by an "ice coverage" factor to accounts for the under-representation of seasonally ice-covered areas during the year of detection and ensures that apparent eddy deserts are not artifacts of missing data caused by ice.