



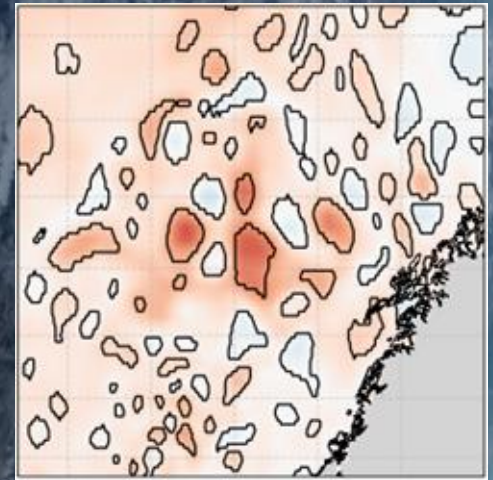
Data-Driven Eddy Detection from Wide-Swath Altimetry

Matteo Broccoli¹, Andrea Cipollone¹, Antonio Bonaduce²,
Roshin P. Raj², Elisa Carli³, Marie-Helene Rio³

¹ CMCC Foundation - Euro-Mediterranean Center on Climate Change, Bologna, Italy

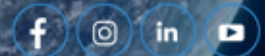
² Nansen Environmental and Remote Sensing Center and Bjerknes Center for Climate Research, Bergen, Norway

³ European Space Agency (ESA-ESRIN), Rome, Italy



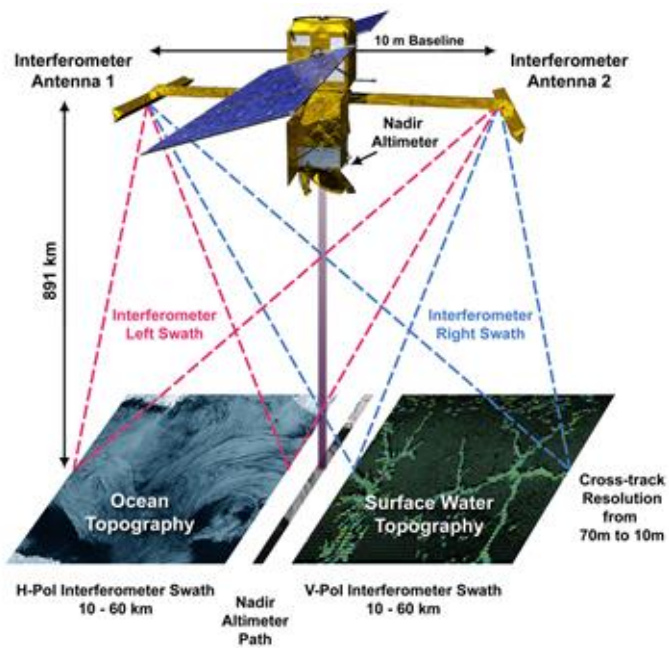
WATER – Wide-swath AlTimetry for Eddy Reconstruction, funded by the European Space Agency
Views expressed here can in no way be taken to reflect the official opinion of the European Space Agency

5th ECMWF-ESA Machine Learning Workshop, Bologna 13-17 April 2026



Conventional satellite altimetry (1993 -)

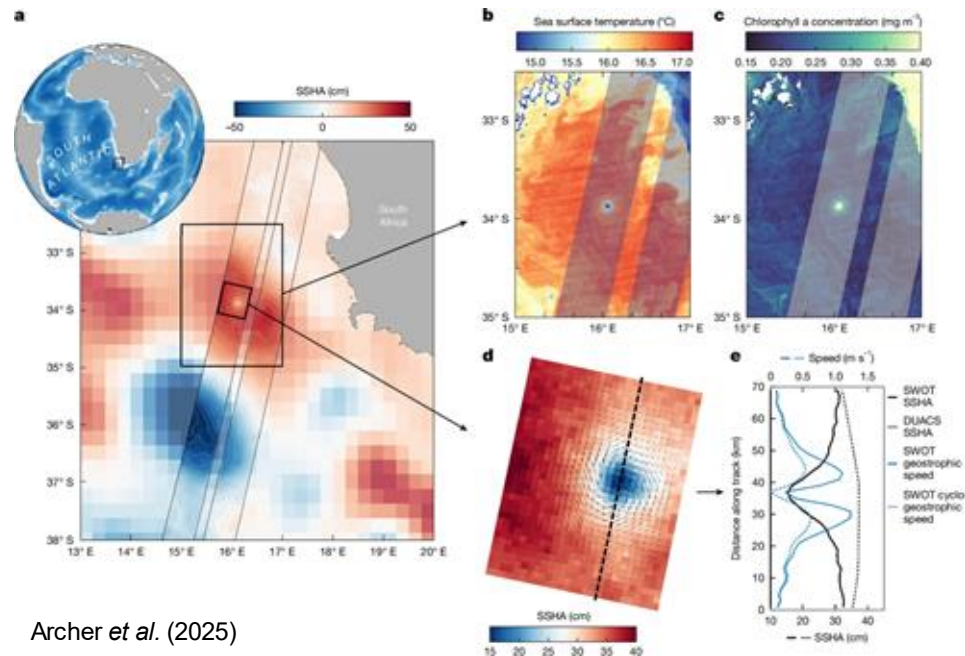
- 1D point observation at the nadir
- Measurements from multiple satellites interpolated to create 2D global maps



Credits: NASA/CNES

Wide-swath satellite altimetry: SWOT mission (2022 - 2025)

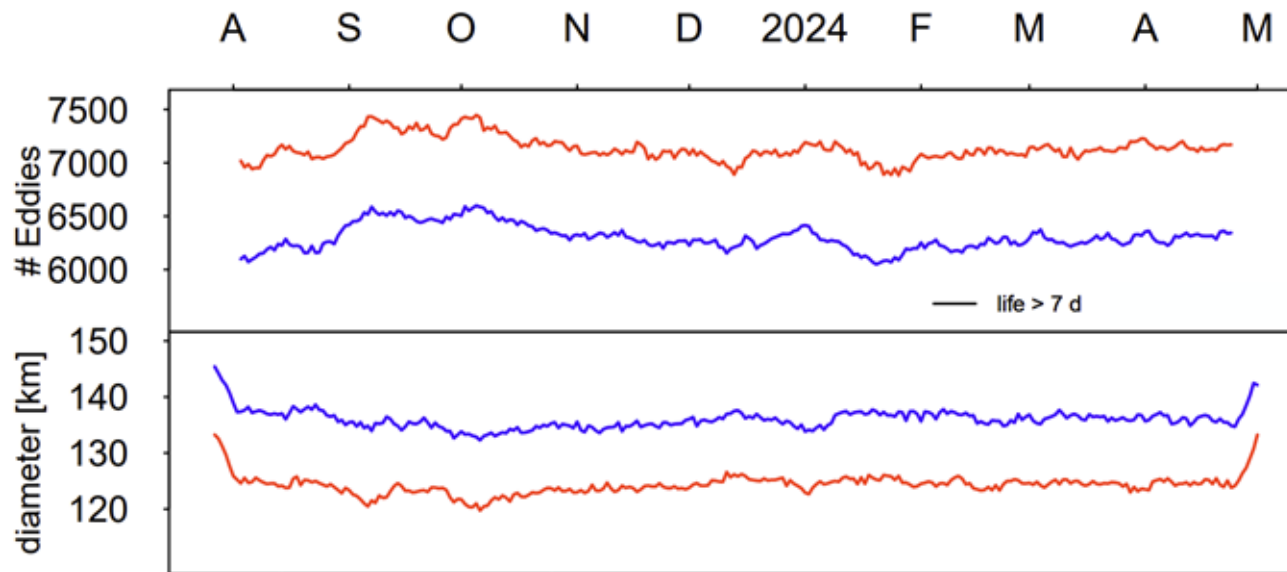
- 120-km-wide 2D swathes
- Ocean structures observed with increased accuracy even without interpolation



Archer *et al.* (2025)

Wide-Swath and Ocean Eddy

Bonaduce *et al.*, in preparation (2026)

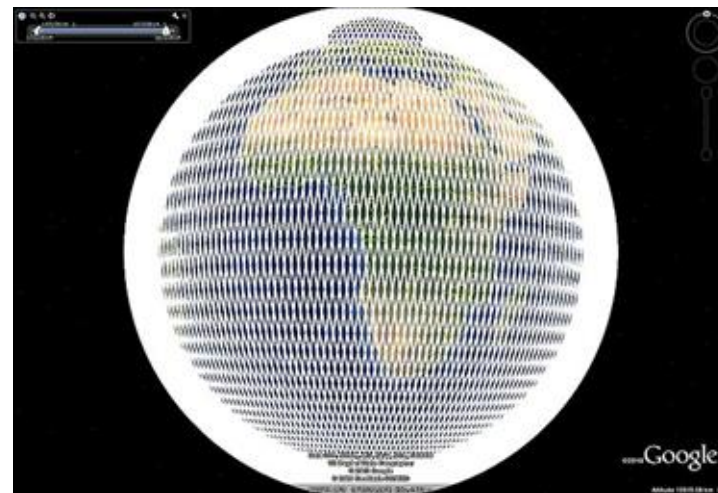


- Eddy population detected from **SWOT-enriched** and **conventional** altimetry maps from July 2023 to April 2024
- Number (top) and size (bottom) of eddy with lifetime larger than 7 days

However...

- SWOT orbit is 21 days long
 - Observing ocean dynamics on shorter timescales still depends on interpolated data
- Loss of SWOT fine-scale information due to gridding techniques that produce SSH maps
- Residual noise from SWOT data processing algorithms might still be present in swaths
- Limited timeseries available
 - e.g., L4 SWOT-enriched SSH maps available from 2023/07/27 to 2024/05/01

→ Extended to 2025/12/31

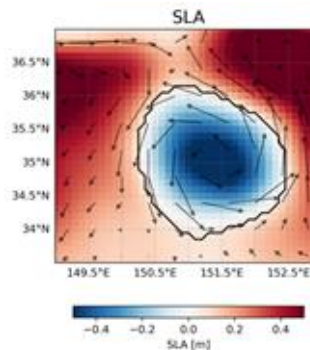


SWOT orbit (full 21 days), credits: AVISO

How much do we benefit from SWOT-enriched SSH maps for data-driven eddy detection?

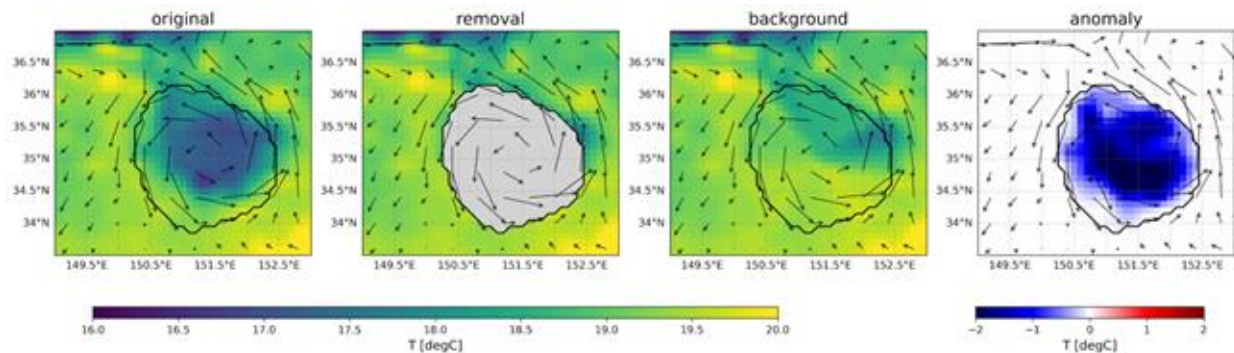
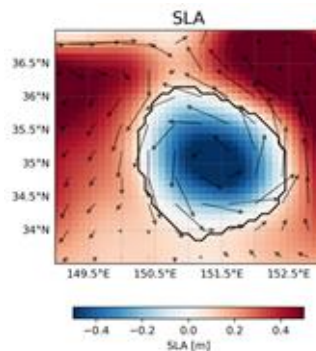
Cipollone *et al.* (2017); Bonaduce *et al.* (2021), (2025), in preparation (2026)

1. Geometrical constraint
 - local anomaly of SSH
2. Dynamical constraint
 - existence of a rotation within



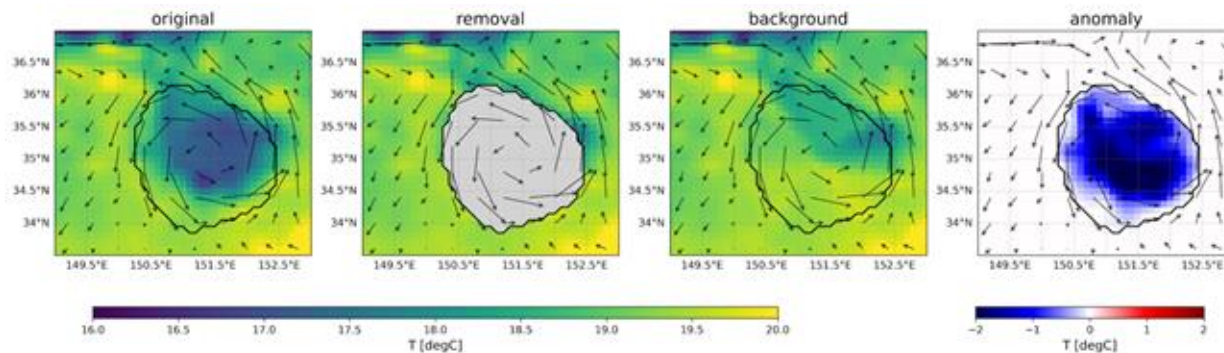
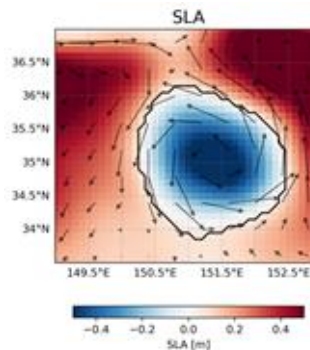
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3. Thermodynamic constraint ('active' eddy)
 - local anomaly of SST w.r.t. environment



Cipollone *et al.* (2017); Bonaduce *et al.* (2021), (2025), in preparation (2026)

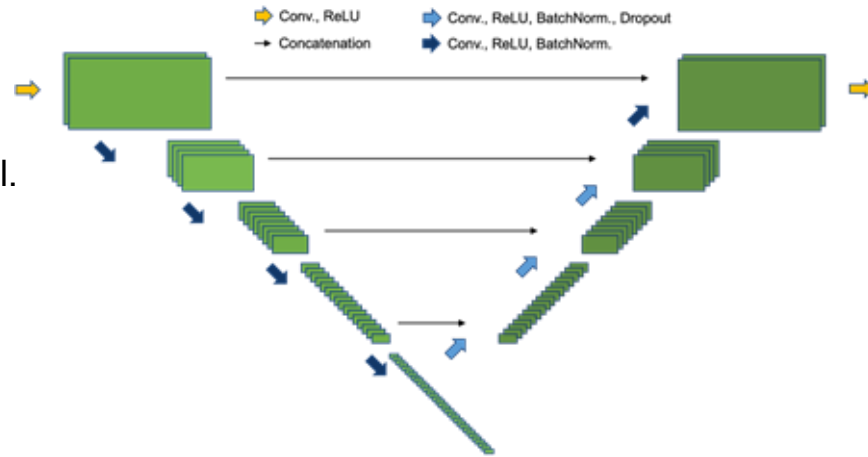
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- SST filtering eliminates spurious patterns in altimetry products
- Dynamical algorithm yields detection maps employed for training data-driven algorithm

Data-Driven Eddy Detection

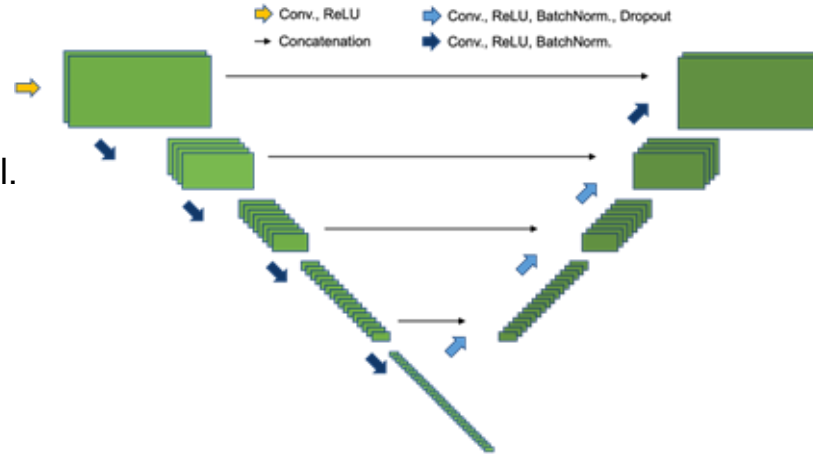
- nadir or SWOT
 - SLA
 - u_gosa, v_gosa
 - surface phase vel.
- ESA CCI
 - SST



- eddy detection mask
- spatial SST anomaly

Data-Driven Eddy Detection

- nadir or SWOT
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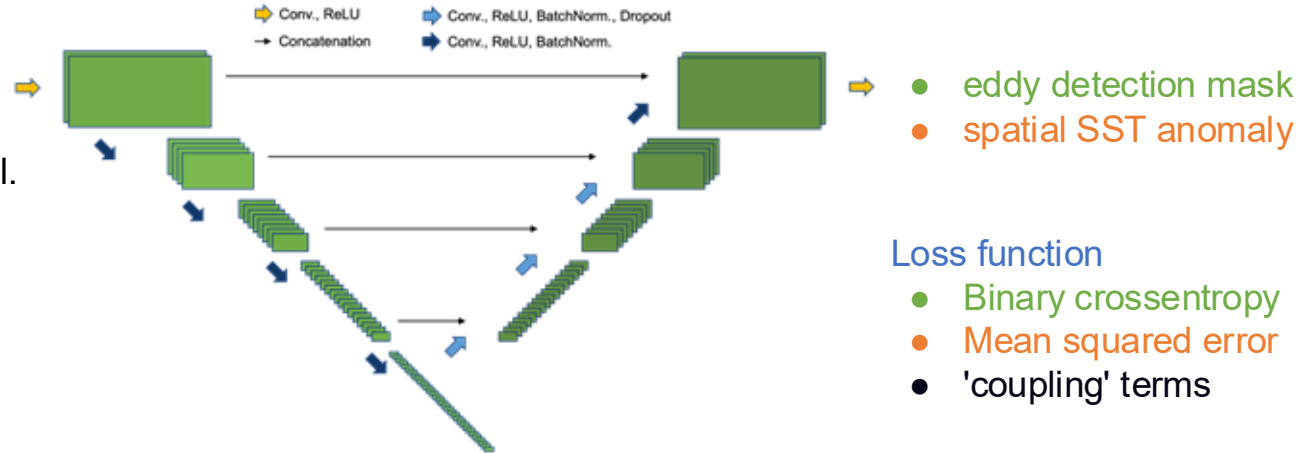


- eddy detection mask
- spatial SST anomaly

Loss function

- Binary crossentropy
- Mean squared error
- 'coupling' terms

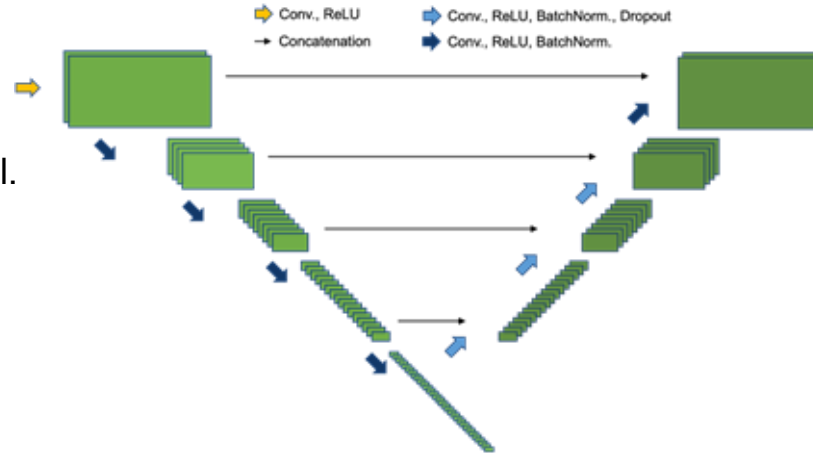
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Training data:

- Global L4 0.10°-resolution maps
- Detections of the dynamical algorithm as target
- timeseries:
 - Jan '22 - May '24 conventional altimetry
 - Jul '23 - May '24 SWOT-enriched altimetry

- nadir or SWOT
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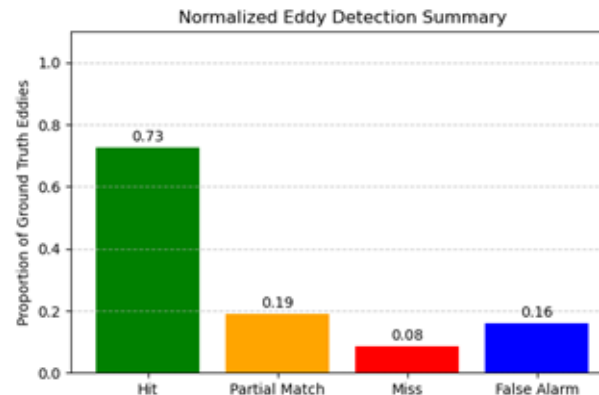
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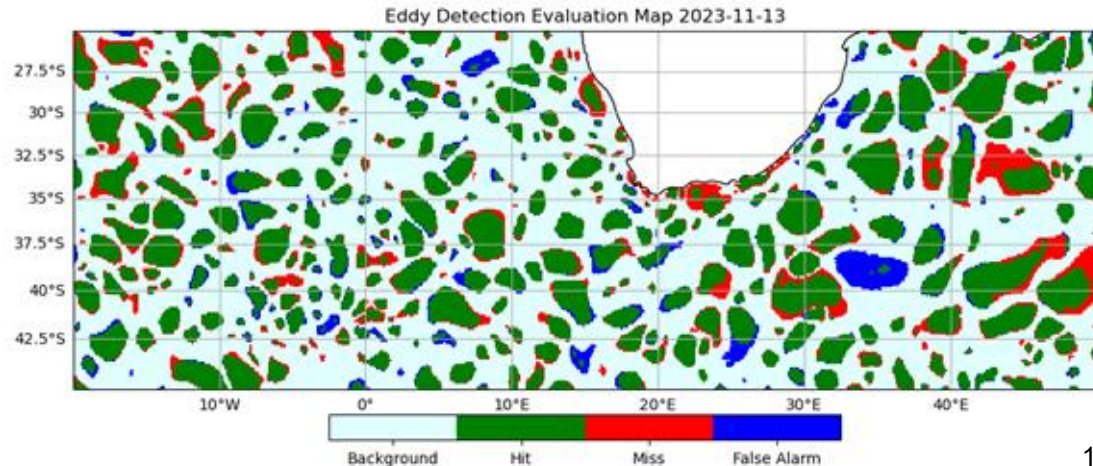
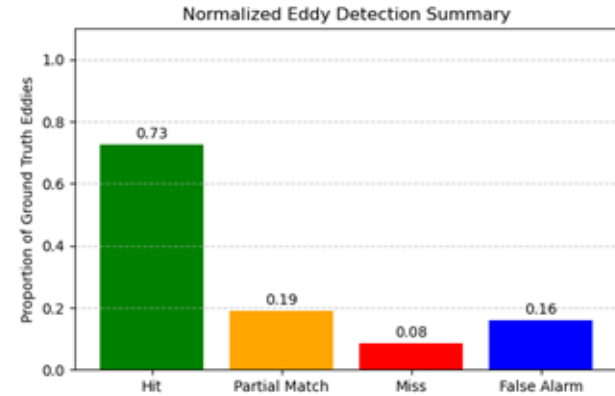
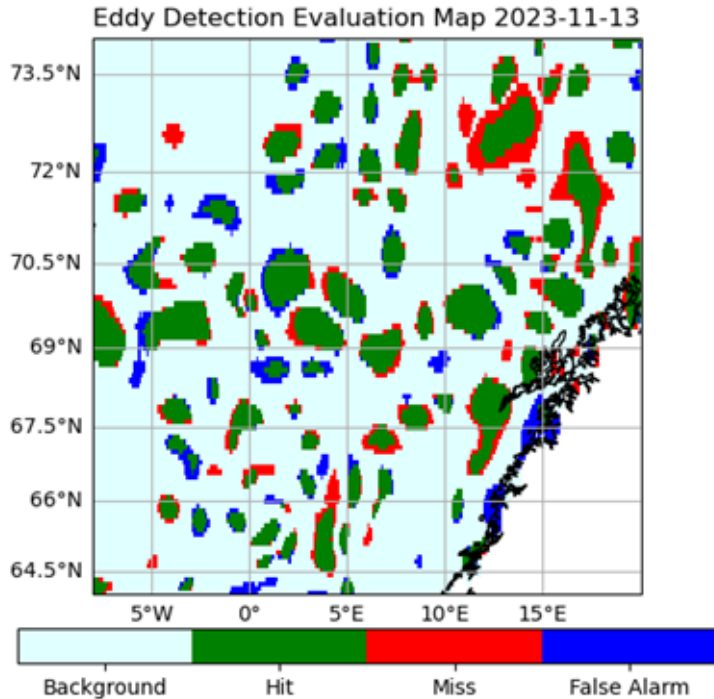
Why should we do this?

- Provide better detection than dynamical system
- possible via multimodal input (altimetry + SST)
- Extend benefits of SWOT-enriched detection to whole conventional altimetry timeseries

Results on conventional altimetry maps

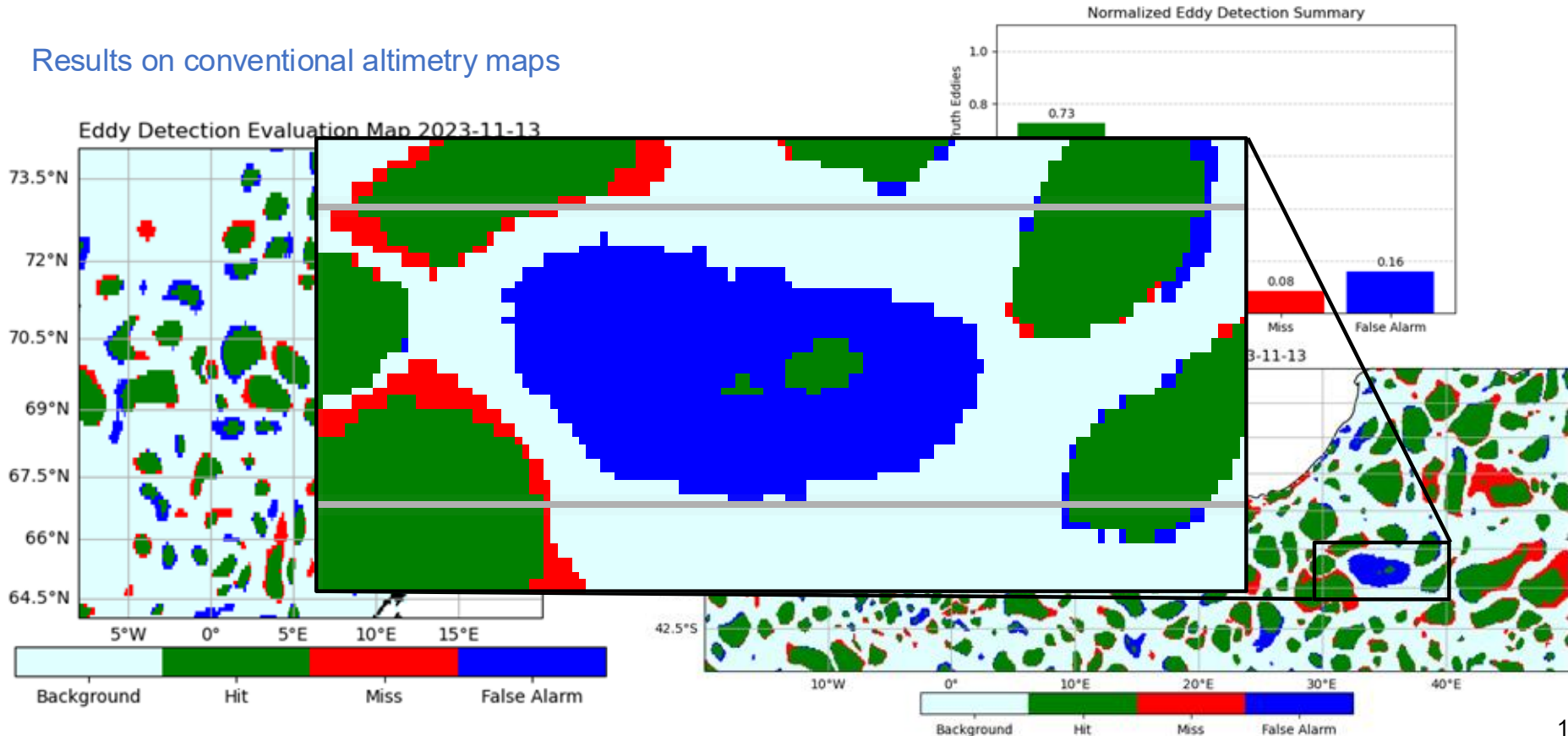


Results on conventional altimetry maps

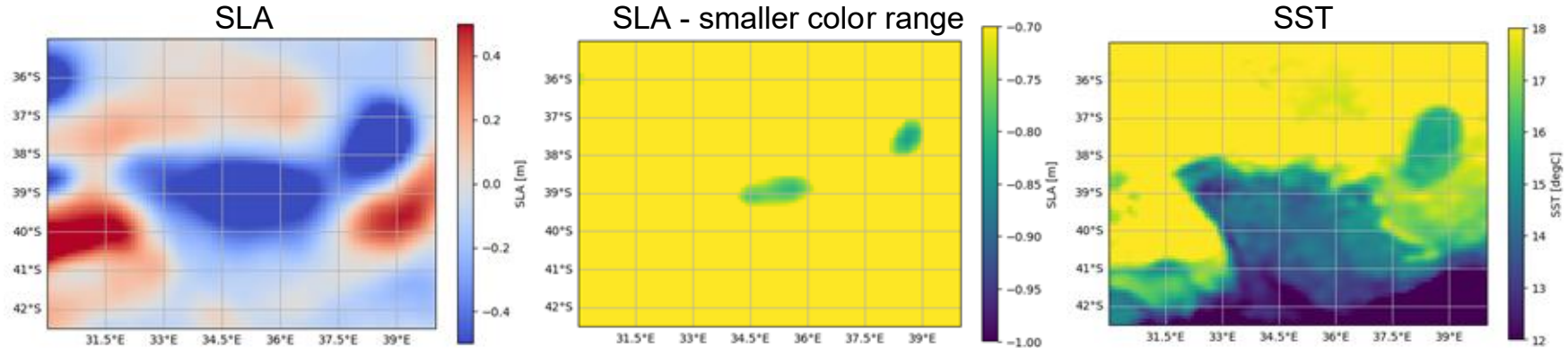


Data-Driven Eddy Detection

Results on conventional altimetry maps

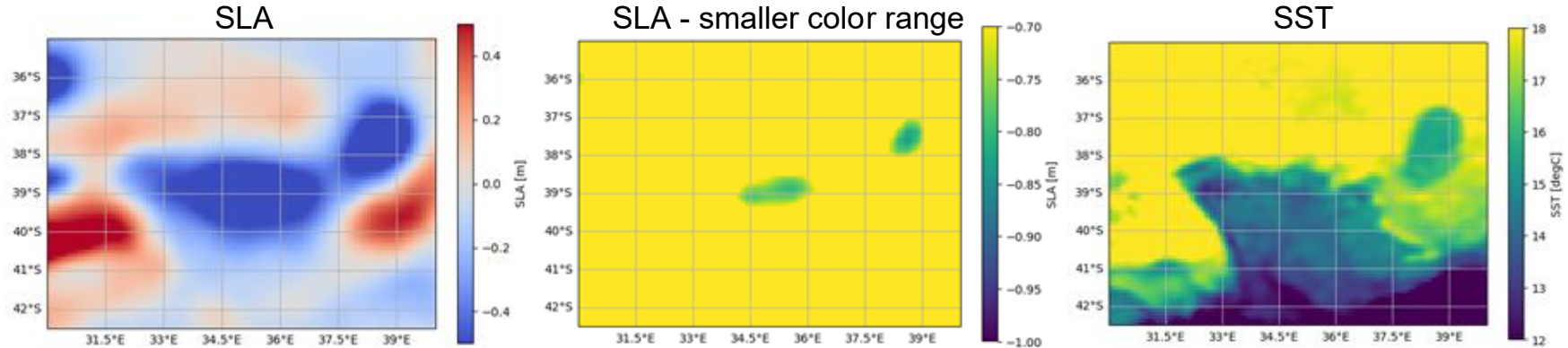


Data-Driven Eddy Detection



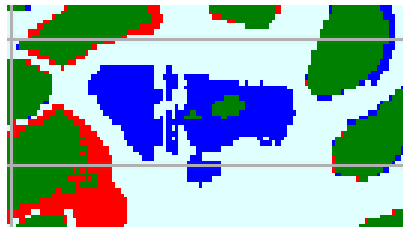
Arguably two different eddies..!

Data-Driven Eddy Detection

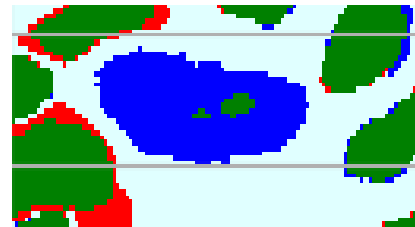


Arguably two different eddies..!

And we can check the impact of the SST:



No SST in training



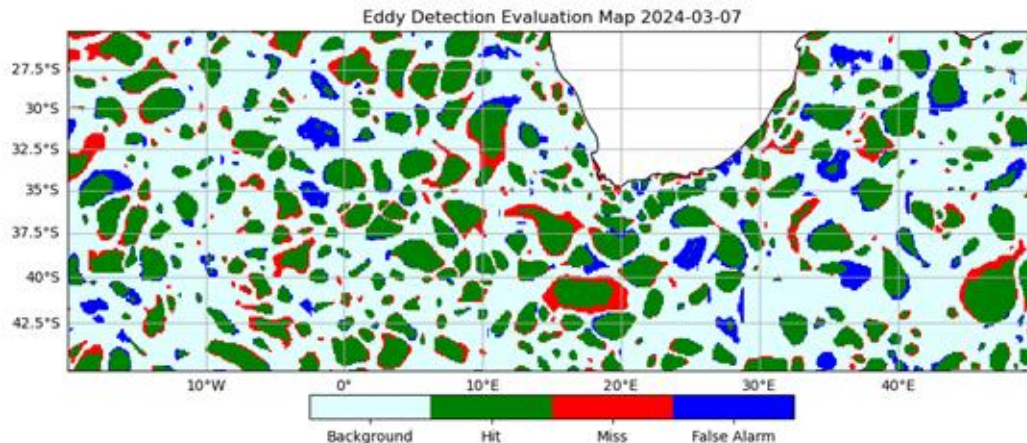
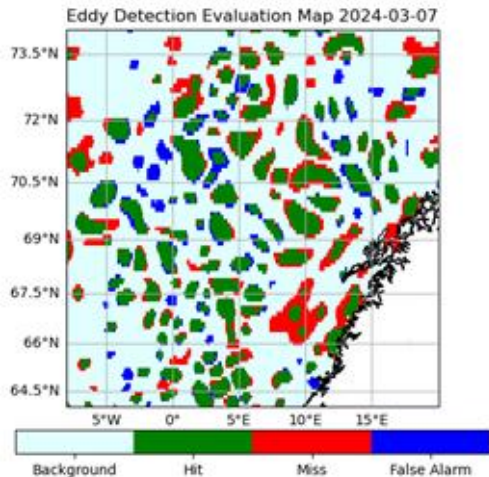
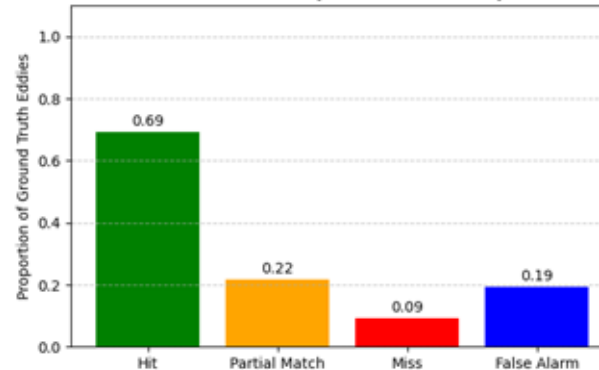
SST in training

Data-Driven Eddy Detection

with SWOT-enriched altimetry maps

- Less than a year of data (~9 months)
- Training from scratch produces lower score than on conventional altimetry
 - Fine-tune model pre-trained on conventional altimetry

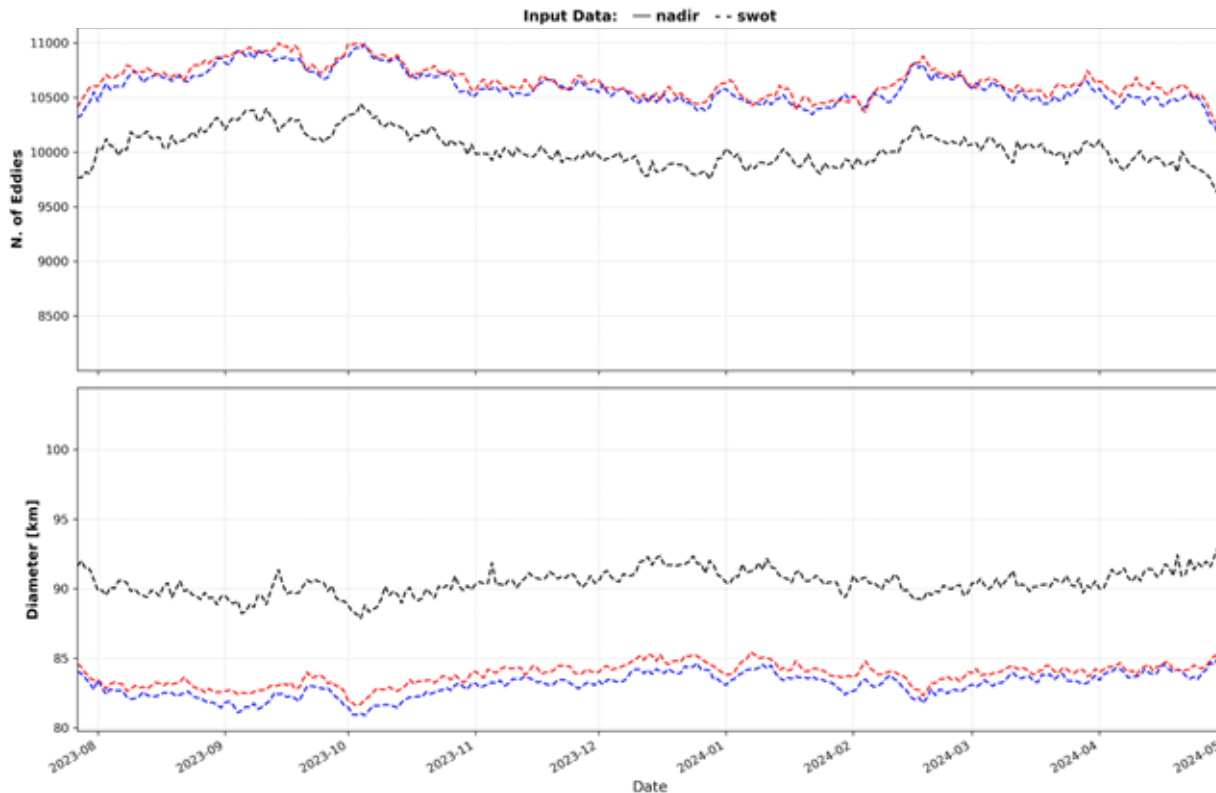
Normalized Eddy Detection Summary



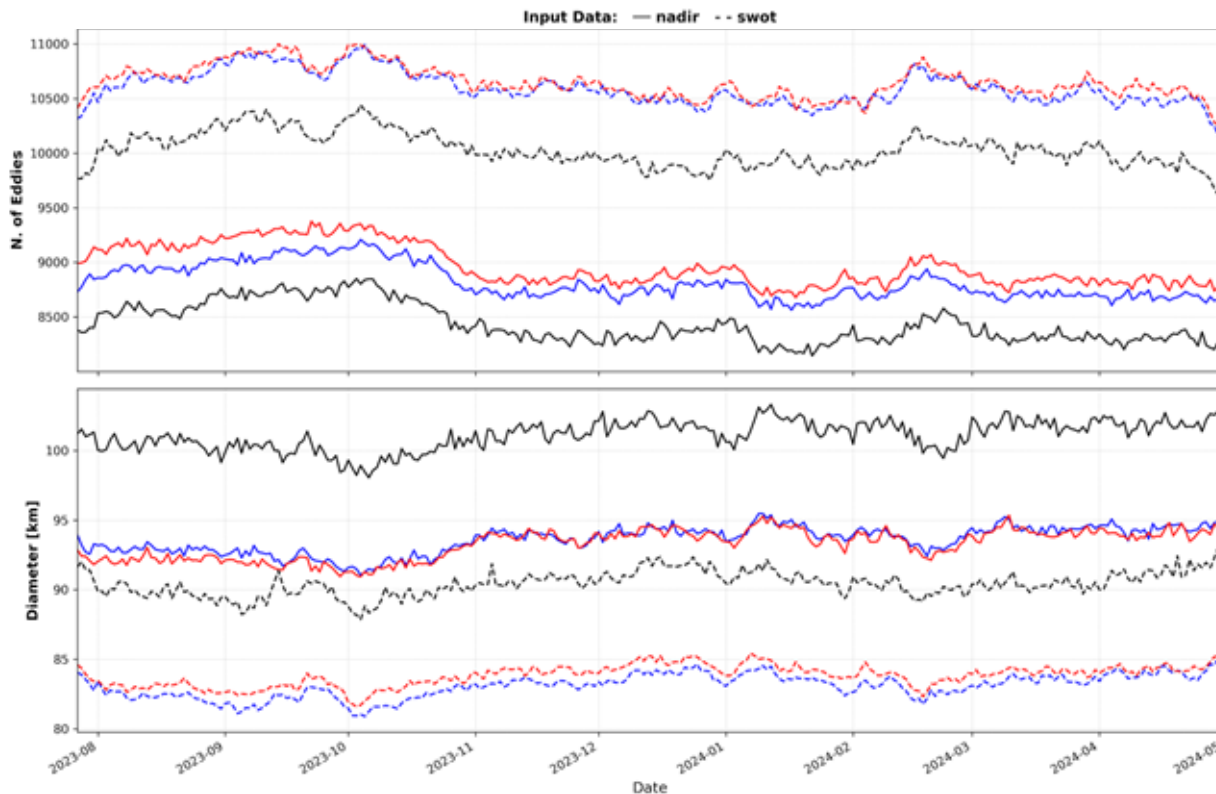
- Nadir U-Net
- SWOT U-Net
- Dynamical algorithm

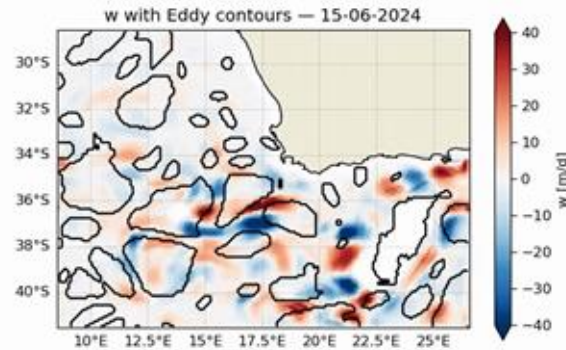
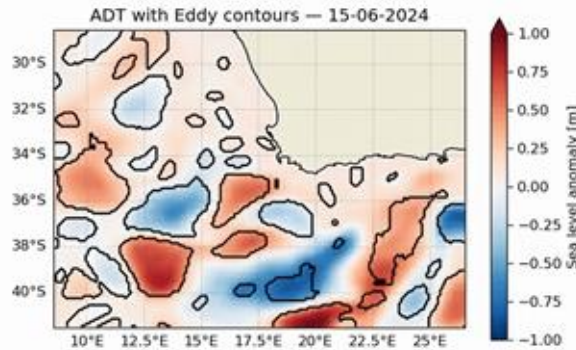
➤ larger population with smaller structures detected by U-Net

➤ little sensitivity to training data



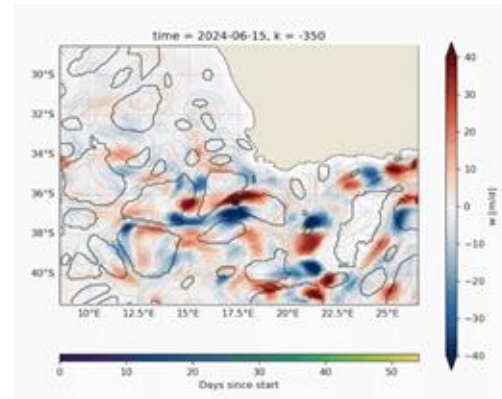
- Nadir U-Net
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 - Dynamical algorithm
- larger population with smaller structures detected by U-Net
- little sensitivity to training data
- 30% more eddies detected by **SWOT U-Net** when applied to nadir data w.r.t. dynamical algorithm





Application example Carli *et al.*, in progress

- Detection on VarDyn data
 - regional instead of global
 - never seen in training
- To be used to inform field campaign

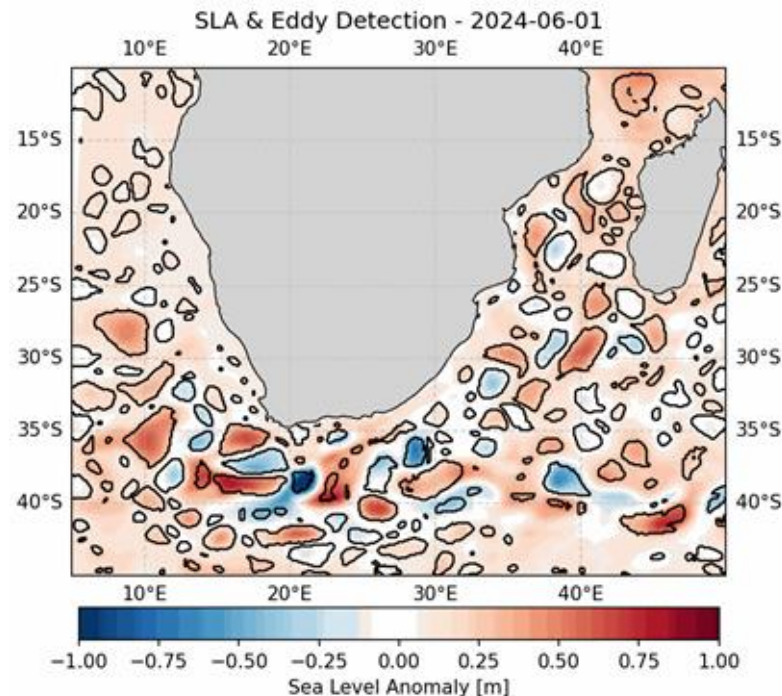


Data-driven eddy detection algorithm

- Global high-resolution
- Flexible (regional dataset)
- Good performance
 - even better than ground-truth?
- Promising result for conventional altimetry reconstruction
 - 30% more eddies compared to SWOT altimetry

Next steps

- Study the physics of the ML-detections (EKE, statistics, etc)
- Understand impact of fine-tuning
 - longer SWOT timeseries
- Reconstruct higher-resolution detection for the whole conventional altimetry timeseries (1993 - today)



WATER – Wide-swath AlTimetry for Eddy Reconstruction

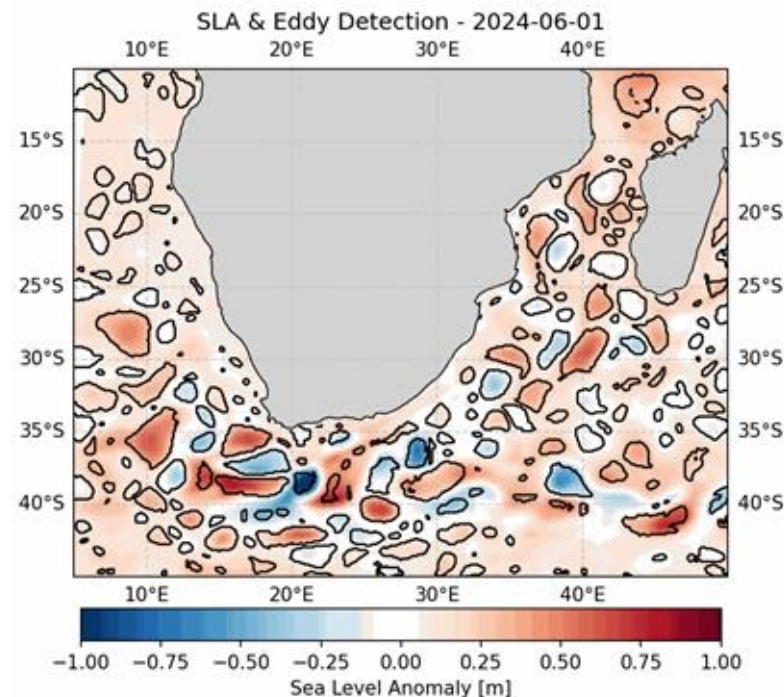


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THANK YOU!

WATER – Wide-swath AlTimetry for Eddy Reconstruction



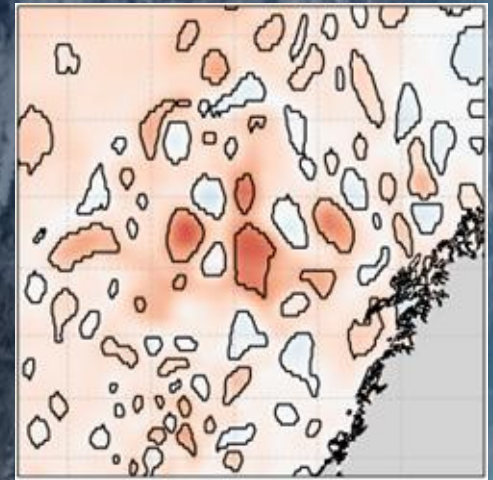
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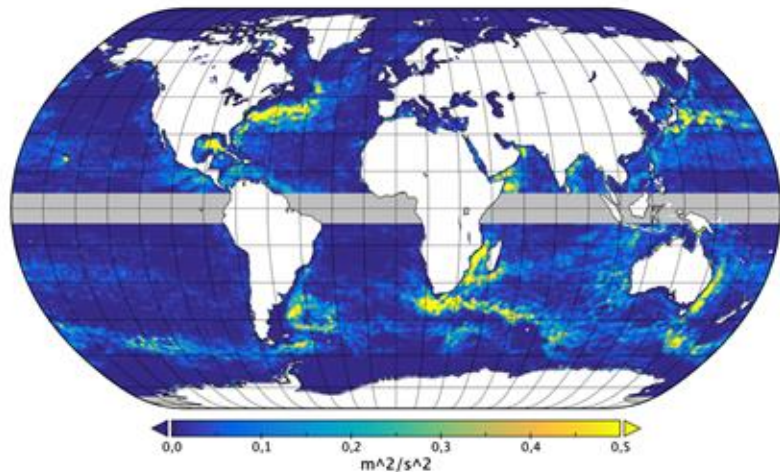


WATER – Wide-swath AlTimetry for Eddy Reconstruction, funded by the European Space Agency
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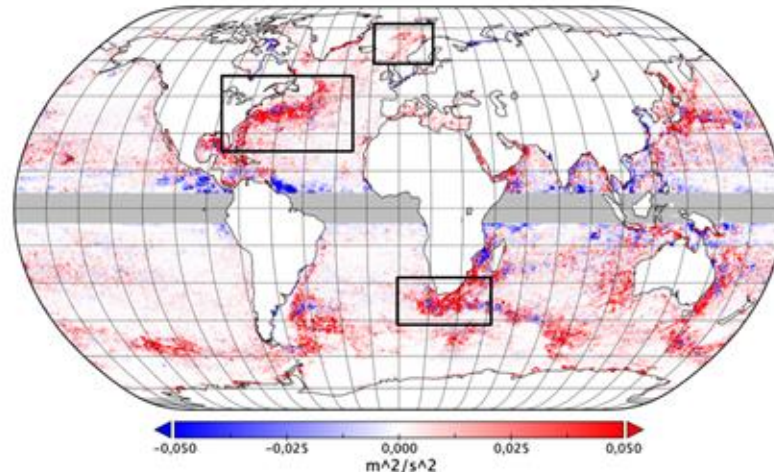
5th ECMWF-ESA Machine Learning Workshop, Bologna 13-17 April 2026



Bonaduce *et al.*, in preparation (2026)



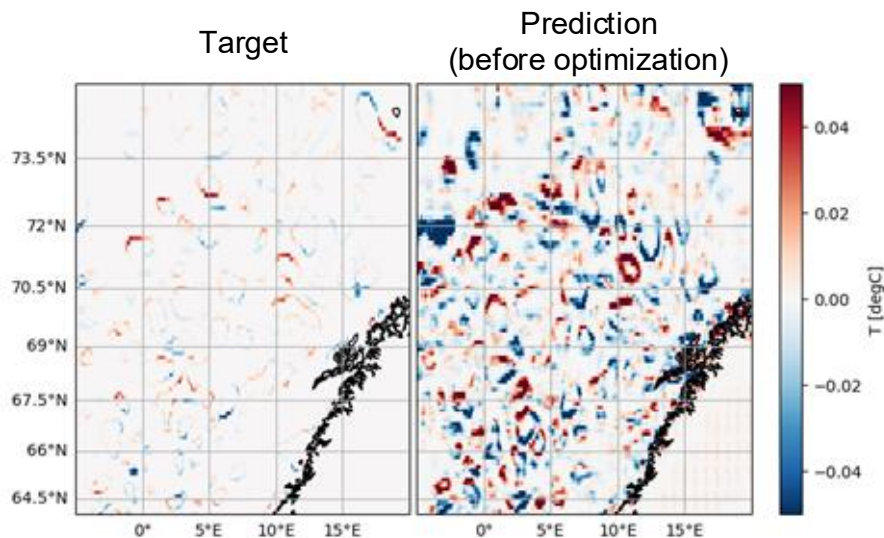
- Eddy kinetic energy induced by eddy with lifetime larger than 7 days detected in SWOT-enriched satellite altimetry maps



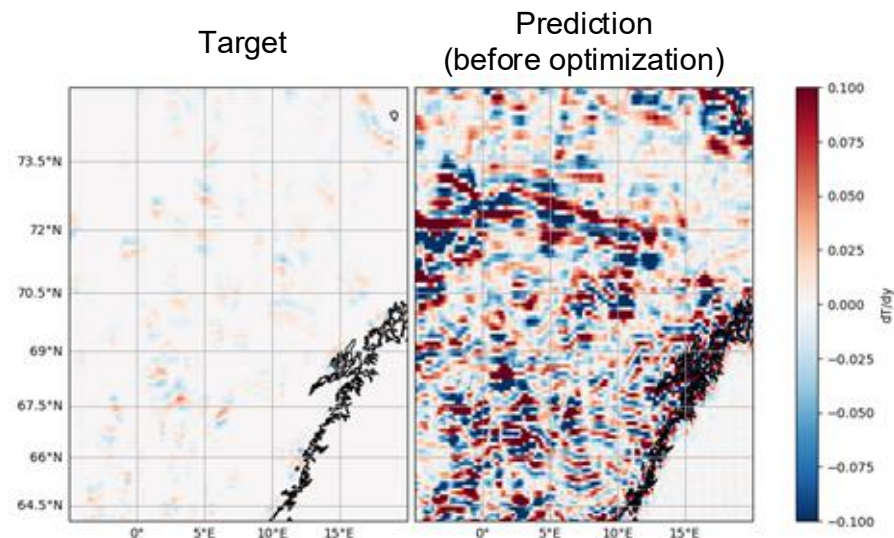
- Differences in eddy kinetic energy per eddy obtained from SWOT-enriched and conventional satellite altimetry maps from eddy with lifetime larger than 7 days

	Conventional altimetry	SWOT-enriched altimetry	Sea Surface Temperature
Processing level	L4	L4	L4
Spatial domain	global ocean	global ocean	global ocean
Spatial resolution	0.25°	0.10°	0.05°
Temporal resolution	daily	daily	daily
Mapping method	Optimal Interpolation	Multiscale Inversion of Ocean Surface Topography (MIOST)	Analysis
Distributed by	Copernicus Marine Service	AVISO	ESA CCI

Border term: spatial SST anomaly at the eddy border



Gradient term: gradients of spatial SST anomaly



Evaluation metrics

TP = True Positive (hit)

Negative (miss)

FP = False Positive (false alarm)

TN = True Negative

FN = False

$$\text{Precision} = \frac{TP}{TP + FP}$$

$$\text{Recall} = \frac{TP}{TP + FN} = \frac{TP}{P}$$

$$F_1 = 2 \times \frac{\text{precision} \times \text{recall}}{\text{precision} + \text{recall}}$$

Range: [0 - 1]



- measures how many correct predictions out of all positive predictions
- ignores how many actual positives are missed (FN)

Range: [0 - 1]



- measures how many positive samples are correctly classified out of all positive samples
- ignores how many false alarms are issued (FP)

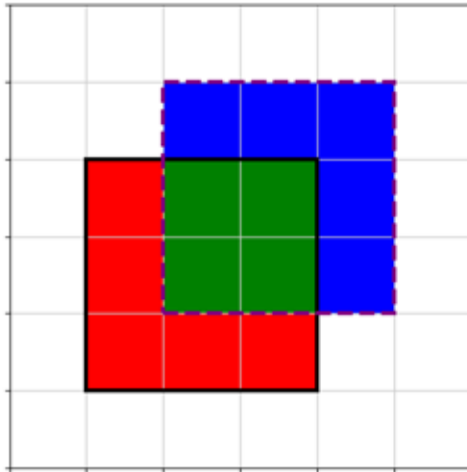
Range: [0 - 1]



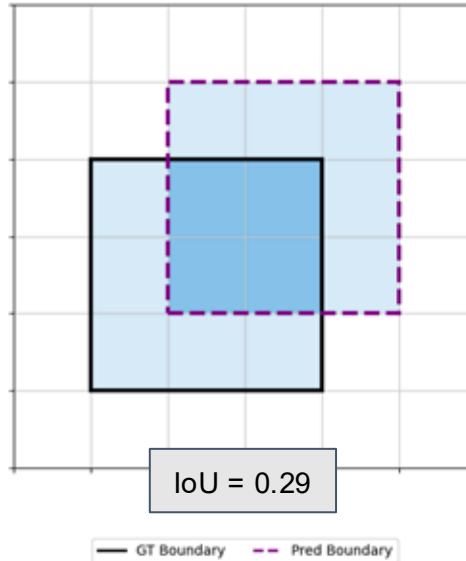
- high F1 iff both precision and recall are high
- single overall score to assess the performance of the classifier

Evaluation metrics: pixel-wise and structure-wise

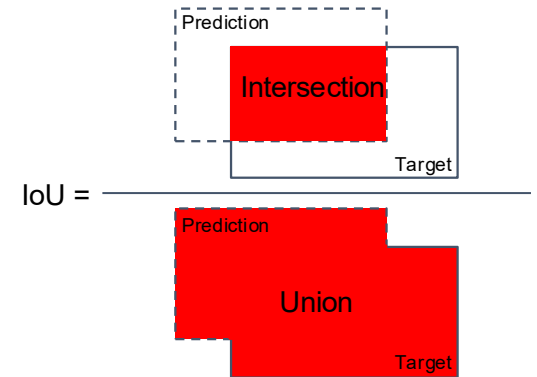
Pixel-wise Validation



Structure-wise Validation

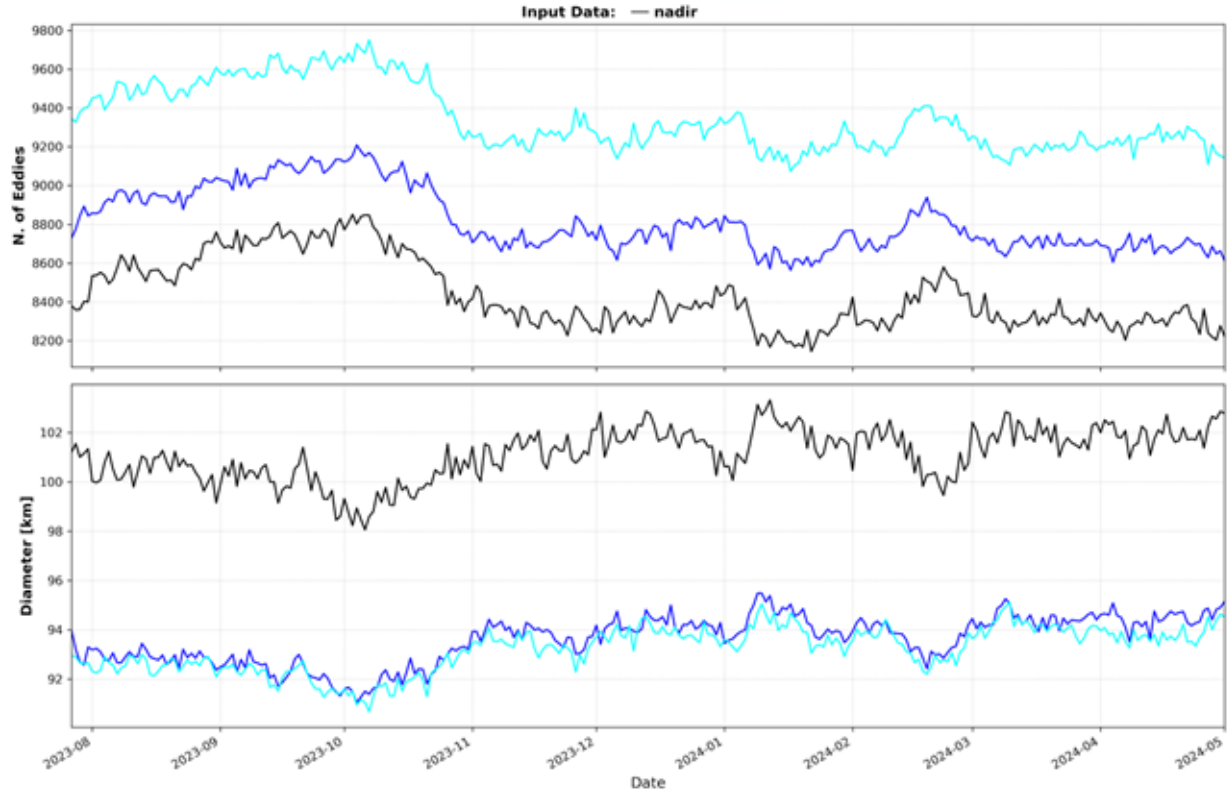


Intersection over Union (IoU)



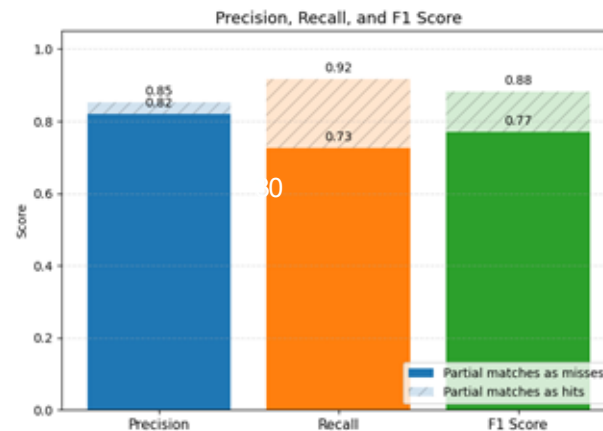
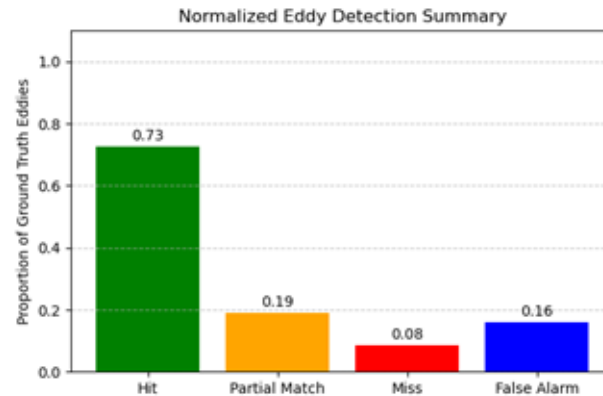
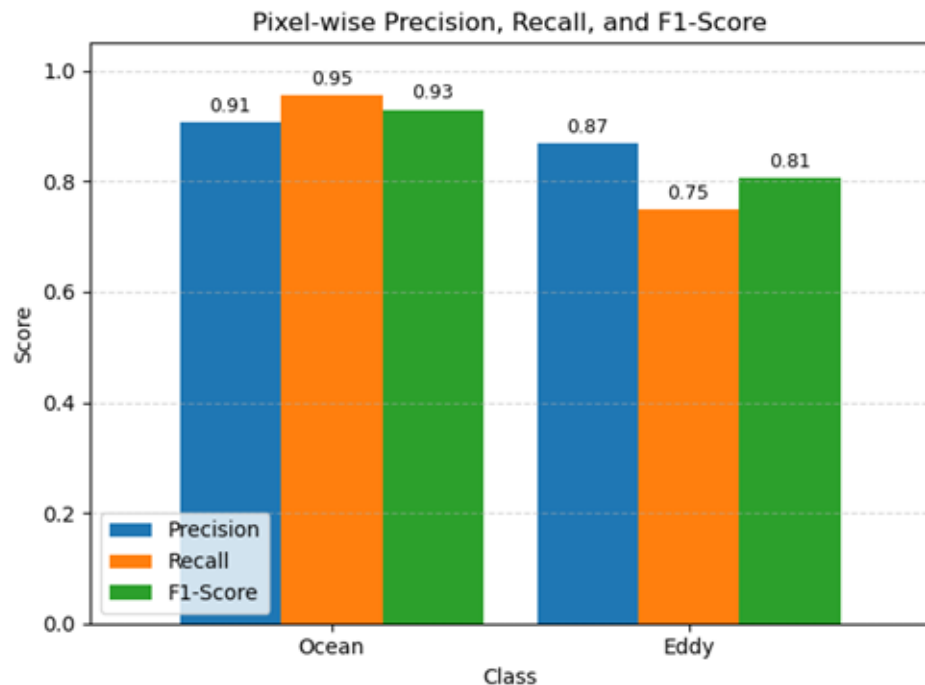
- $IoU \geq 0.5$ → Hit
- $0 < IoU < 0.5$ → Partial match
- $IoU = 0$ → Miss or false alarm

- Nadir U-Net with no SST
 - Nadir U-Net
 - Dynamical algorithm
- SST filters out spurious detections
- larger population with smaller structures detected by U-Net

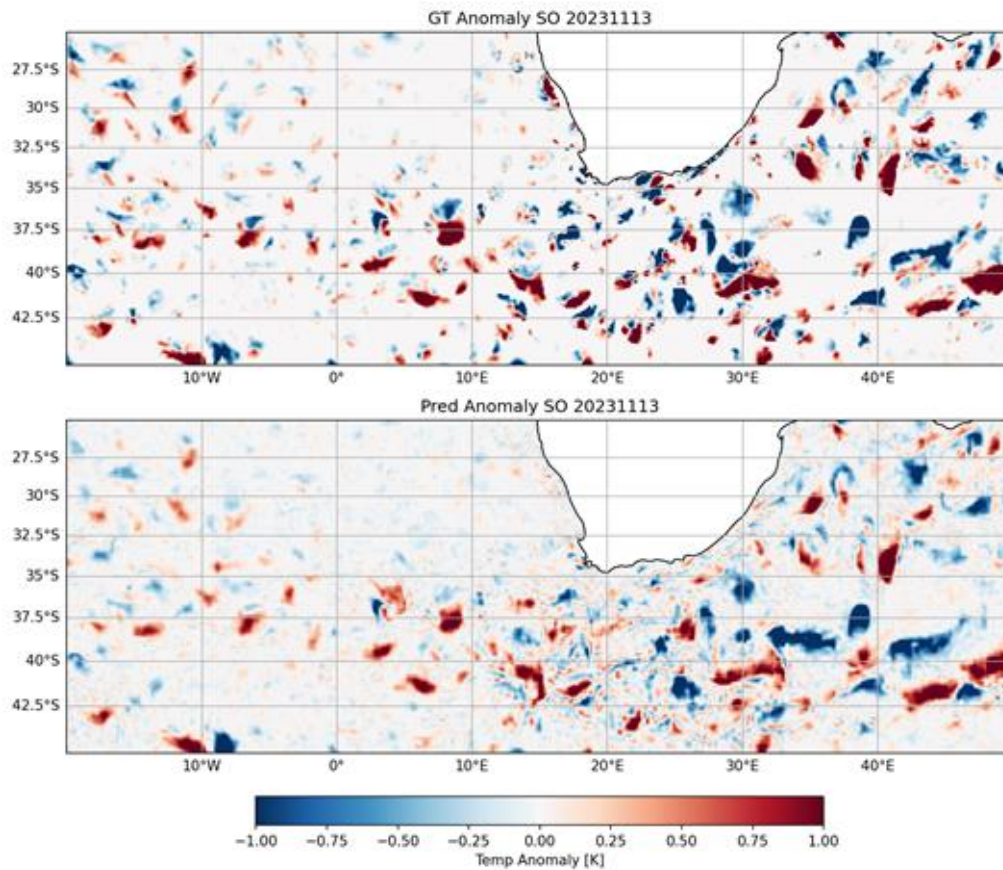
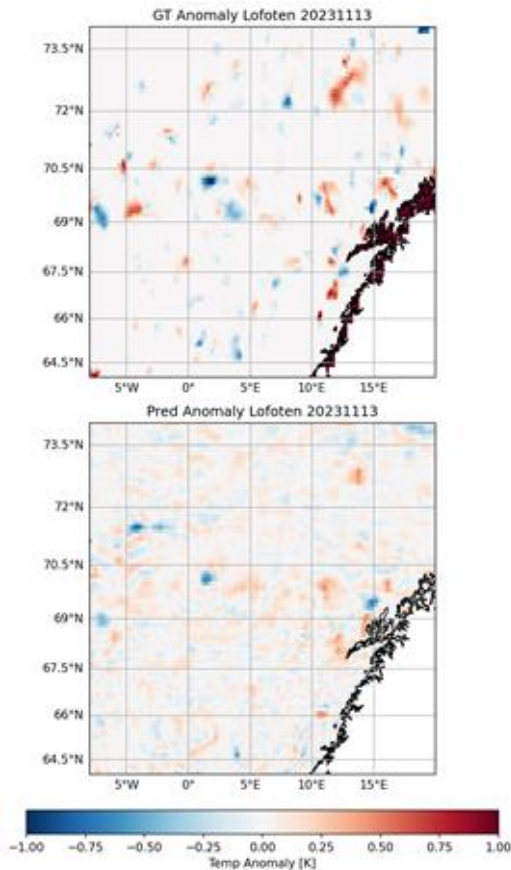


Back-up: Nadir U-Net Detection

Results on conventional altimetry maps



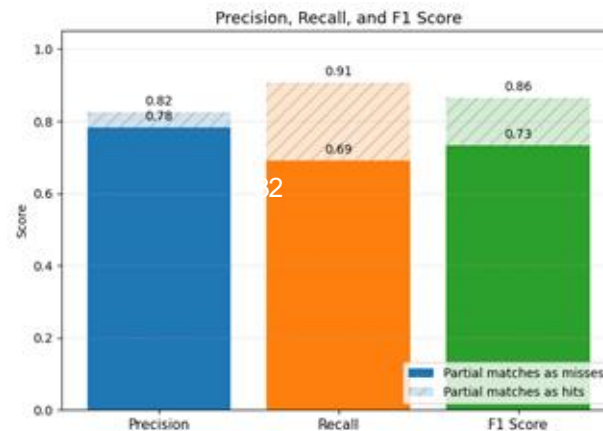
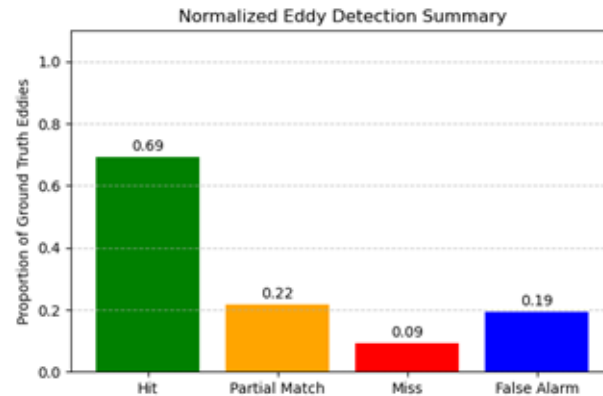
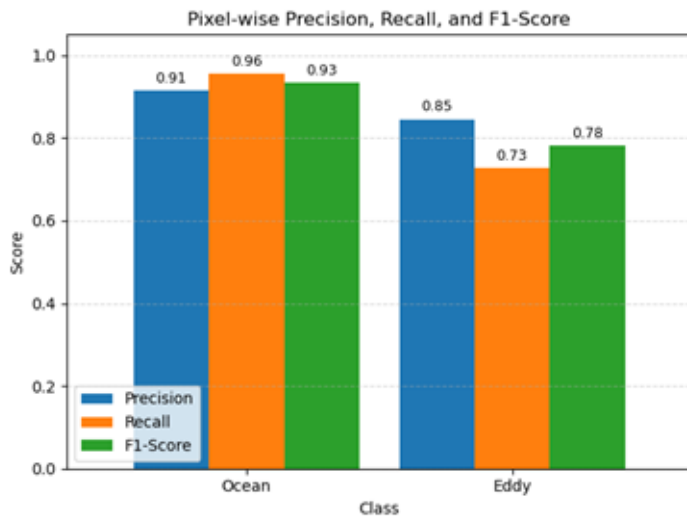
Back-up: Nadir U-Net Spatial SST Anomaly



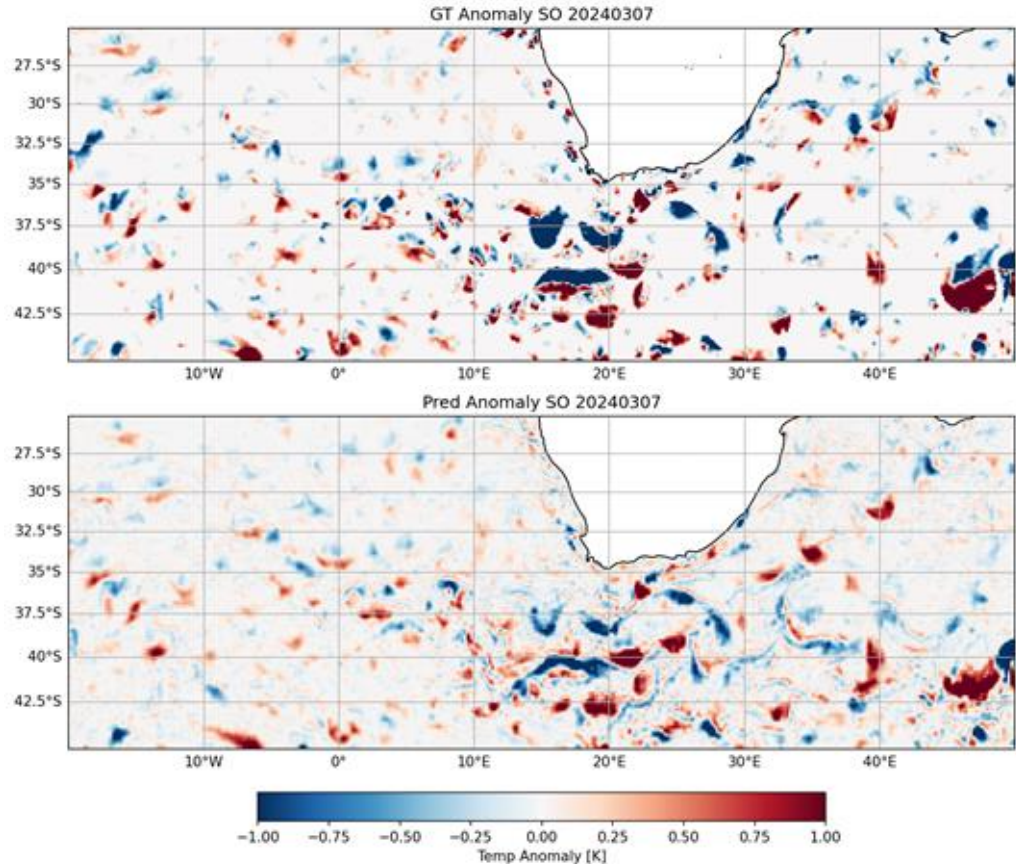
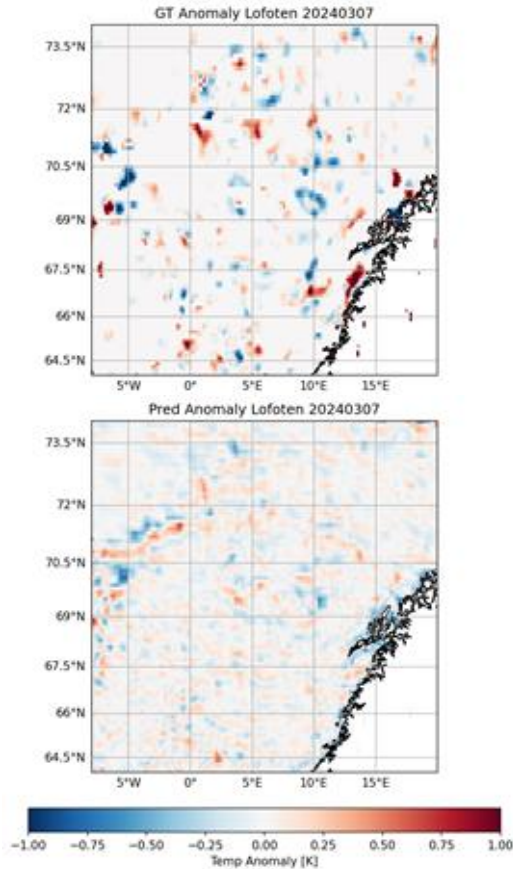
Back-up: SWOT U-Net Detection

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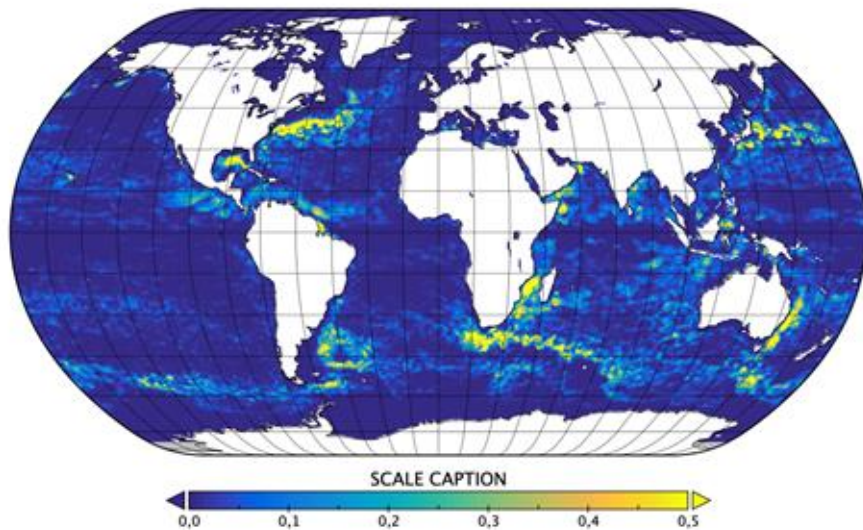


Back-up: SWOT U-Net Spatial SST Anomaly

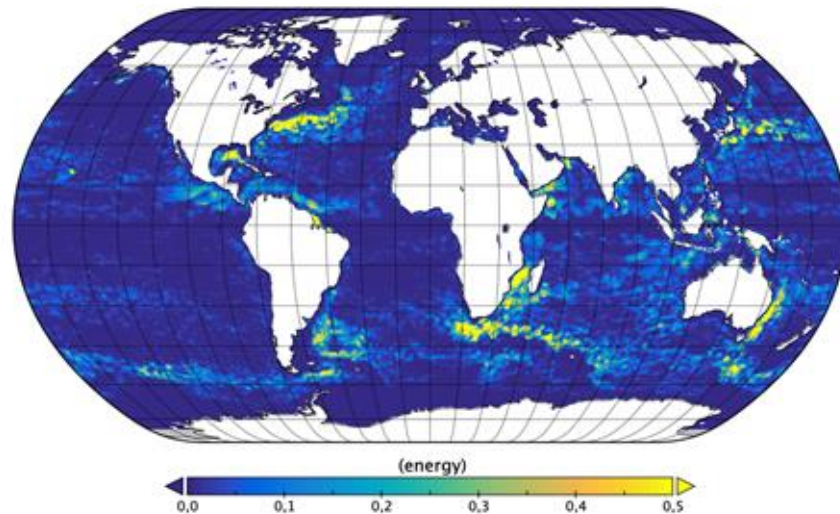


- Eddy-induced Kinetic Energy (Nov. `23 - May `24), eddy lifetime > 14 days; SST anomaly larger than +/- 0.1 degC

Dynamical algorithm

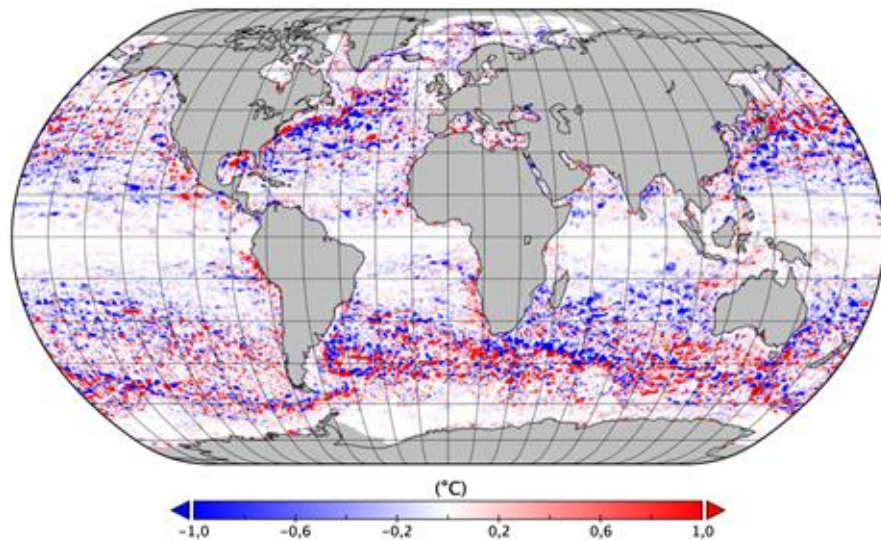


Nadir U-Net



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Dynamical algorithm



Nadir U-Net

