WORLD OCEAN CIRCULATION

FINAL REPORT

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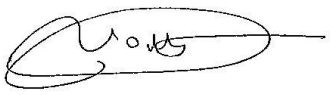
1.5	1	03/11/2023	Version 1	Accepted by ESA on January 29th 2024 

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1 Introduction

1.1 Purpose of the document

This document is the Final Report of the World Ocean circulation project. This document contains a synthesis of the main achievements and lessons learned during the project and a scientific roadmap providing ideas for existing products evolution and way of new investigation.

1.3 Applicable & Reference documents

- [RD-1] ESA WOC2019: http://woc2019.esa.int/index.php
- [RD-2] Synthesis of the WOC2019 User Consultation Meeting recommendations http://woc2019.esa.int/files/WOC2019_summary_synthesis.pdf
- WOC User Requirements Document (URD), 6 December 2019.

1.4 Terminology

ACCUA	Analisi della dinamica della Corrente CircUmpolare Antartica
AQUA	Aqua Earth Observing Satellite Mission
AMSR2	Advanced Microwave Scanning Radiometer 2
ADT	Absolute Dynamic Topography
AI	Artificial Intelligence
AIL	Action Items List
AIS	Automatic Identification System
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced SCATterometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
CCD	Contract Closure Document
CCI	Climate Change Initiative
CCMP	Cross-Calibrated Multi-Platform

CFOSAT	Chinese-French Oceanography Satellite
CIESM	Mediterranean Science Commission
CMEMS	Copernicus Marine Environment Monitoring Service
CNES	Centre National d'Etudes Spatiales
CNR	Consiglio Nazionale delle Ricerche
CTD	Conductivity, Temperature and Depth
DP	Data Pool
DTU	Danmarks Tekniske Universitet
DUACS	Data Unification and Altimeter Combination System
EBUS	Eastern Boundary Upwelling System
ECCO	Estimating the Circulation & Climate of the Ocean
ECMWF	European Centre for Medium-Range Weather Forecasts
EFARO	European Fisheries and Aquaculture Research Organisations
EMB	European Marine Board
ENVISAT	Environmental Satellite
EO	Earth Observation
EPB	European Polar Board
EOEP-5	5th Earth Observation Envelope Programme (2017-2021)
ERA	ECMWF Reanalysis
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESF	European Science Foundation
EU	European Union
EuroGOOS	European Global Ocean Observing System
FAO	Food and Agriculture Organization of the United Nations
FR	Final Report
FSLE	Finite Size Lyapunov Exponent
GCM	Global Circulation Model
GCOM-W	Global Change Observation Mission - Water
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System
GMI	Global precipitation monitoring Microwave Imager
GMM	Gaussian Mixture Models
GPM - Core	Global Precipitation Monitoring Mission Core Observatory
HYCOM	Hybrid Coordinate Ocean Model
IAR	Impact Assessment Report
ICCAT	International Commission for the Conservation of Atlantic Tunas

ICSU	International Council for Science
IGPB	International Geosphere-Biosphere Programme
IUGG	International Union of Geodesy and Geophysics
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
IOC	Intergovernmental Oceanographic Commission
ITCZ	InterTropical Convergence Zone
mEOF-r	Multivariate Empirical Orthogonal Functions reconstruction
METEOSAT	Meteorological Satellite (geostationary)
MoM	Minutes of Meeting
NATL3D	North Atlantic 3D Ocean Currents
NEMO	Nucleus for European Modelling of the Ocean
NOAA	National Oceanic and Atmospheric Administration
NCC	Norwegian Coastal Current
NwAFC	Norwegian Atlantic Front Current
NwASC	Norwegian Atlantic Slope Current
OLCI	Ocean and Land Color Imager
OSSE	Observing System Simulation Experiment
OC	Ocean color
OSCAT	Oceansat-2 SCATterometer
PD	Product Delivery
PM	Project Manager
PMP	Project Management Plan
PUB	Publication
PUM	Product User Manual
QUID	Quality Information Document
RB	Requirement Baseline
REMSS	Remote Sensing Systems
ROMS	Regional Oceanic Modeling System
RTOFS	Real-Time Ocean Forecast System
S3	Sentinel 3
SAR	Synthetic Aperture Radar
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SCOR	Scientific Committee on Oceanic Research
SIED	Single Image Edge Detection
SKIM	Sea surface KInematics Multiscale monitoring
SLSTR	Sea & Land Surface Temperature Radiometer
SOCIB	Sistema d'observació i predicció costaner de les Illes Balears
SODA	Simple Ocean Data Assimilation Ocean/sea ice reanalysis

SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SoW	Statement of Work
Suomi-NPP	Suomi National Polar Orbiting
TN	Technical Note
TOPAZ	Tracers of Phytoplankton with Allometric Zooplankton
TUOC	Total Upper Ocean Currents
UCL	Use Case LibraryUCM User Consultation Meeting
UCPC	Upper-layer ocean Circulation Processes e-Catalogue
UI	Upwelling Index
UN	United Nations
URD	User Requirement Document
VR	Validation Report
VT	Visualization Tool
WBS	Work Breakdown Structure
WOC	World Ocean Circulation

2 Summary report of UCM

The WOC User consultation meeting took place at ESA ESRIN between the 10 to 12th october 2022. A workshop summary is available here and will be accessible through the WOC UCM portal. (https://woc2022.esa.int/).

3 Scientific roadmap

3.1 Main achievement and lessons learned

3.1.1 Theme 1 : Sea-state interactions for Safe Navigation

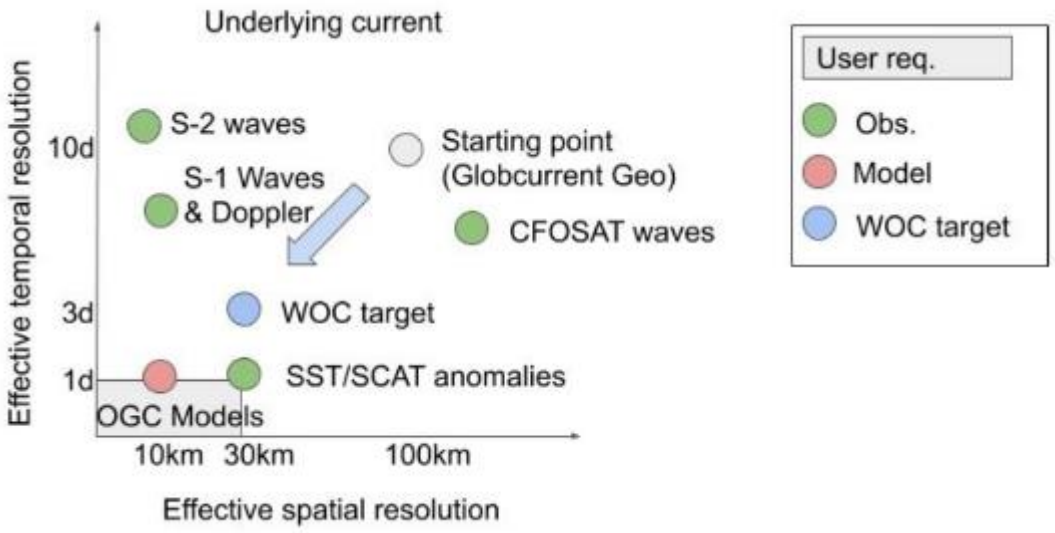

Figure 1: Effective resolution targeted for Theme 1

Realized activities

- Dangerous seas/cross seas index
- Development of a Level 4 wind & stress product (ERA5*)
- Altimeter sea state surface current interactions
- Sentinel1 wave Doppler
- validation diagnostics
- Improved geostrophy

Main outcomes

- Improved geostrophy reached WOC target
- Sentinel1 Doppler was used to provide validation surface current snapshots
- Validation diagnostics based on SST fronts was used for surface current ranking by intermediate user
- Little involvement of ends users

Main recommendations

- Involve more intermediate users

3.1.2 Theme 2: 3D currents and vertical motion for sustainable fisheries

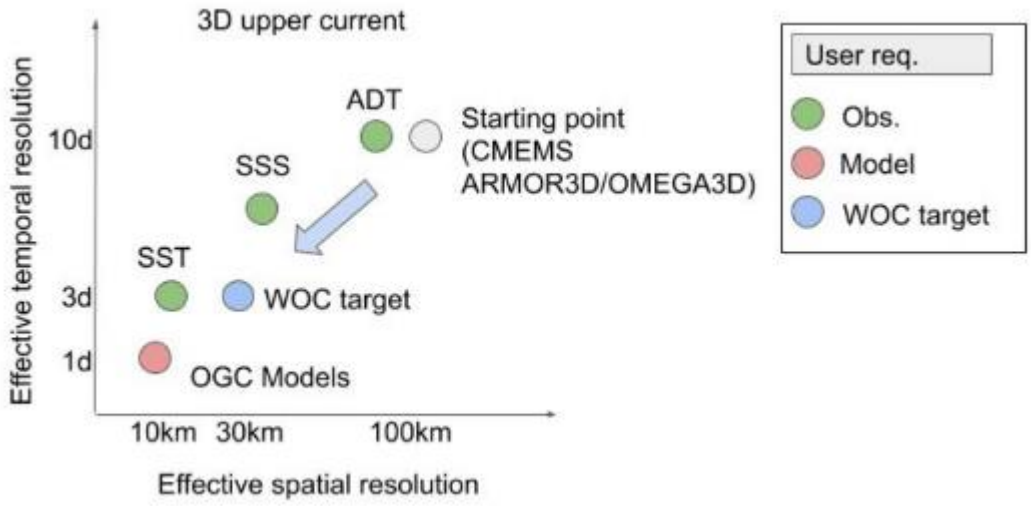

Figure 2: Effective resolution targeted for Theme 2

Realized activities

- Improved resolution of 2D ADT maps through altimetry/SST synergy and generation of an additional synergistic 2D surface currents product in the WOC Catalog
- New 2D-to-3D salinity/temperature reconstruction technique based on AI (Long-Short Term Memory network)
- Improvement of spatial resolution for 3D upper ocean circulation with respect to Copernicus product
- Improvement of Q vector diabatic term (mixing parameterization) with respect to Copernicus product

- Upwelling indexes
- Chla/sst correlations, detection and tracking of ocean dynamical features using expert assisted by Artificial Intelligence
- Validation diagnostics development

Main outcomes

- New data-driven reconstruction of mesoscale-resolving 3D upper ocean circulation in the North Atlantic
- Successful Involvement of intermediate (expert) users

Main recommendations

- Investigate new techniques to further exploit high resolution SST and ocean color information for dynamical reconstructions
- Interactions with SST/OC data providers
- Investigate new approaches to make Omega computation more efficient

3.1.3 Theme 3: Surface lagrangian drift for a Clean Ocean

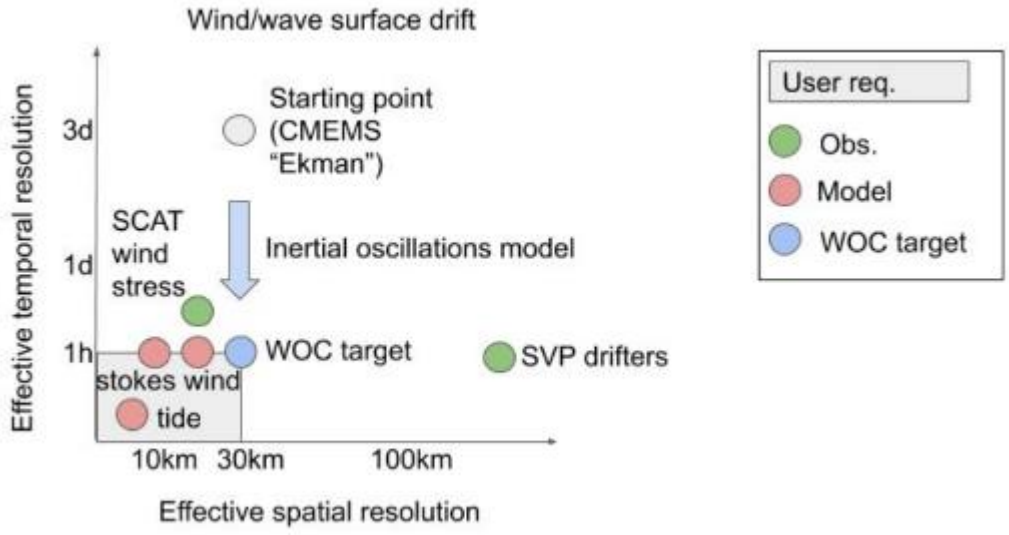

Figure 3: Effective resolution targeted for Theme 3

Realized activities

- Lagrangian advection and validation of surface drift
- Combination of drifters, high-frequency winds and altimetry to reconstruct high-frequency surface current

Main outcomes

- High frequency NIO current better resolved in time (intensity still not fully captured)
- limited user cases suitable for WOC surface current components (tidal/coastal …)

Main recommendations

- collect more ground truth in a suitable area to validate the proposed approaches.

3.1.4 Theme 4 : High Resolution wave and current model assessment for a Productive Ocean

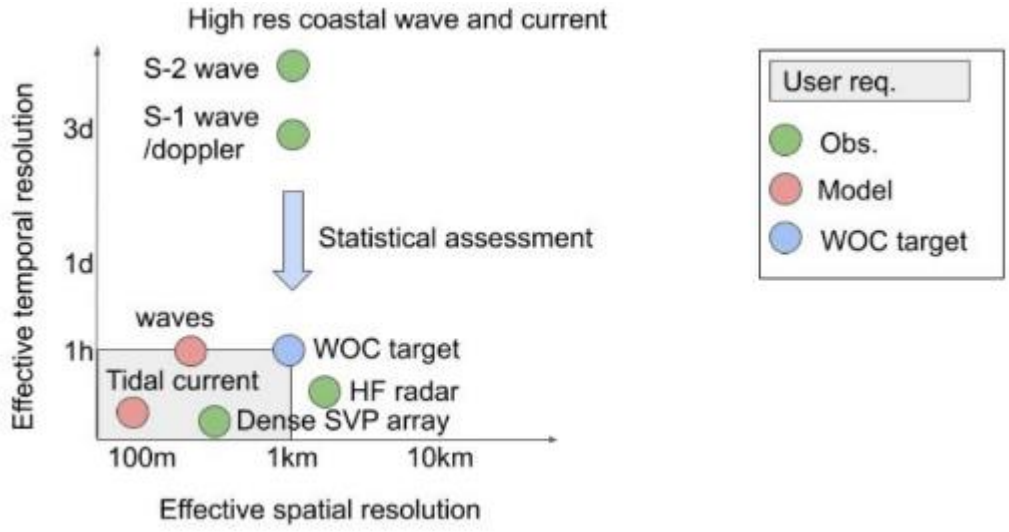

Figure 4: Effective resolution targeted for Theme 4

Realized activities

- Coastal High-Resolution Data-Driven Physics-Constrained Model HR-DDPCM attempt
- Sentinel1 Doppler in coastal zone
- Sentinel1/2 estimates of waves transformations by surface currents (coastal strong tidal current revealed on S1 SSR to be deployed anywhere with sufficient S1 coverage when no other measurements available)

Main outcomes

- HR-DDPCM is a promising technique but too few sat observations for learning systematic wave transformation (current, bathymetry) to implement it : the conditional analysis shall be

pursued to include combined S1, S3. S2 to be used for validation.
- Coastal Sentinel1 Doppler
- Wave/tidal current interaction by accumulation of SSR vs tidal phase

Main recommendations
- organize a collection of all possible third party observations across space agencies to increase learning dataset size.

3.2 Priority activities to further develop

Based on the WOC activities analysis and main outcome, we propose some general recommendations and 3 groups of activities that should be developed and are likely to have a significant impact on the WOC community in the near future.

The general recommendations are the following :
- Organize the legacy of successful activities in the form of a WOC repository of open code and methods for users to apply the techniques and metrics on their own area and period of interest. WOC products and relevant case studies shall also be made available on a longer timeframe after the project ends. This should be linked to the ESA ocean cluster website.
- Promote the use of developed metrics to be applied by modelers as a target in their assimilation experiments.
- Organize communication and transition to Copernicus Marine Service (this is already the case for ERA5* and improved omega forcing terms computation, i.e. adaptation of WOC-NATL3D algorithm to Copernicus OMEGA3D product). This should cover direct reach out to intermediate users of developed successful WOC products.

3.2.1 Follow-on activities for the exiting 4 theme for three different time horizons

- **Consolidation (1 year timeframe)**

safe navigation	• Produce more systematic cross seas and dangerous seas

	index, building relationships with front detections and with ship motions. ● Develop synoptics maps of detected fronts and eddies ● Wave Doppler by using cross spectra applied to Sentinel-1 IW mode, benefiting from SARWAVE project IW cross-spectra.
productive ocean	● Initialize validation and analysis of new 2D/3D NATL products ● Test methodologies to exploit altimetry/SST synergy for dynamical reconstructions based on convolutional neural networks (super-resolution)
clean ocean	● Produce more systematic predicted drift vs observed drift from in-situ natural drifters detected on Sentinel1/2. ● NIO estimation in a more global coverage. Investigate impact of using ERA5*.
sustainable ocean	● Generalize the SAR based SSR/Doppler accumulation in all strong tidal current areas important for Marine Renewable Energy development.

- **Further development (2 to 3 years timeframe)**

safe navigation	● Develop validation front metrics based on ocean color and extend to eddies ● Improved temporal resolution of geostrophy using microwave SST/SSS with dynamical SSH interpolation. Comparison and learning with SWOT SSH mapping capabilities. ● Develop automated processing capabilities for wave ray tracing in TOPS mode. ● Integrate ocean surface current in global swell tracking and detect local anomalies between detected and propagated swell.
productive ocean	● Test methodologies to exploit altimetry/SST synergy for dynamical reconstructions based on physically-informed approaches/test new

	architectures (e.g. U-nets, transformers, etc.). Priority for target areas dominated by large mesoscale motions and with availability of several WOC/operational products for intercomparison ● Improve the efficiency of the Omega equation diabatic forcing parameterization (e.g. by testing neural network approaches)
clean ocean	● Investigation of NIO under extreme tropical and extratropical cyclones forcing, using MAXSS blend winds and upcoming ERA6. ● Decomposition of drifter trajectories into surface current components. may require specific low cost drifter deployment ● Investigate machine learning approach for both the operational implementation and the historical data record development of ERA5*
sustainable ocean	● Combined analysis of inter-agency SAR derived integrated wave parameters (Sentinel-1, Radarsat2, RCM, Cosmo-Skymed, Terrasar, Alos2, HY3a, …), in possible combination with altimeter FF-SAR and LRM estimates, with in situ buoy networks

- **Future perspectives (4 to 10 years timeframe)**

safe navigation	● Retrieval of surface current gradients from swell rays observations ● Learning and Prediction of expected wave related ship motions caused by wave current interactions ● Diffusivity estimates from SST gradients
productive ocean	● Develop neural network solver for Omega Equation (PDE-NN solver) ● Impact studies on synergistic surface currents reconstructions from future satellite Missions (e.g. ESA-CIMR, 2029)
clean ocean	● Improve quality and resolution of ERA5* using physically-informed neural network approaches and/or Deep Learning architectures
sustainable ocean	develop an open source SAR multisensor retrieval scheme for ocean wave parameters to build a multisensor database of coastal wave parameters as function of offshore wind and wave conditions.

3.2.2 Potential new groups of activities

The three identified promising group of activities to further develop are the following :

1. **Upper ocean high resolution circulation for targeted applications**

- Analysis of frontal structures and eddies for surface current field evaluation and benchmark,
  - further develop surface current evaluation metrics using temperature and ocean color fronts. Investigate direction difference statistics vs scales. velocity vs. fronts gradients and curvature.
  - metrics for comparison of lagrangian LR advections with HR snapshots (both data driven and CMEMS model)

- Improved temporal resolution of geostrophy using microwave SST/SSS with dynamical SSH interpolation -> target 1 to 5 days.
  - Link the back and forth nudging with lagrangian advection.
  - Segmentation of regions with deep or shallow mixed layer.
  - Link anomalous Lagrangian diagnostics with Eulerian observations (frontal localization, eSQG deviations, …)
  - prepare CIMR SST simulation based OSSE

- Pursue the analysis of waves transformations by surface current and related vorticity (from Sentinel-1 TOPS, SCAT, Alti, glitter using S2 L1b). Develop automated processing capabilities for wave ray tracing in Sentinel1 TOPS mode.

- Further improve snapshot validation dataset based on
  - SAR Doppler by using cross spectra for wave Doppler and applying it to Sentinel-1 IW mode, benefiting from IW cross-spectra developed in SARWAVE project.
  - Sentinel 2 L1-b processing to provide reference data sets for quantitative validation.
- Continue interaction with shipping but targeting intermediate users, instead of end users.
  - provide routing applications support, synthetic synergetic view, short term forecast based on previous observed situation
  - provide assessment of surface current models based on remote sensing data and validated with drifters and ship based observations.

- Further support analysis of Sargassum drift based on combined Sentinel-1 and Sentinel-2 HR observations

- Tidal-conditional Sentinel-1 IW mode analysis, and also altimeter products, over coastal

dedicated regions

- Improve surface dynamical reconstructions based on physically-informed neural network approaches/test new architectures
- Exploit results from other ESA project focused on the reconstruction of 4D fields (4DMED Sea) to improve 4D dynamical reconstruction (i.e. include Omega quasi-geostrophic u,v,w diagnostics)
- Exploit present-day/incoming thermal infrared missions (< 100 m, e.g. ECOSTRESS, LSTM, TRISHNA) for dynamical applications in coastal areas
- Exploit ERA5* improvements for both open ocean and coastal current applications

2. Mixed layer depth estimation/4D tracers' reconstruction

There are many applications of having a Mixed Layer Depth (MLD) information for predicting both dynamical and biological properties of the upper ocean. Today this information is coming mostly from ARGO profilers distributed in the global ocean, providing an accurate MLD information at very low spatial and temporal

- As for the dynamical properties, a simplified description of the inertia of the surface ocean inertia subjected to atmospheric forcing is needed, enabling then to predict how the surface current will respond to atmospheric forcing. The Mixed Layer Depth (MLD) information with good spatial and temporal resolution is the main parameter to control this dynamics, and we should aim to estimate it by combining ARGO fist guess at low resolution with several other sources of information:

  - Drifter observations associated with forcing observations (Scatterometers and radiometers). Exploiting an improved upper layer model with higher temporal resolution of the transfer function would enable to improve the unsteady Ekman estimations in WOC.
  - Correlation between surface properties (from satellite SST, SSS, and ocean color CDOM) and SSH.
  - Internal waves properties such as wavelength and phase speed that are linked to the mixed layer depth. This can be estimated by exploiting multisensor synergy from different space optical and radar sensors or constellations during tandem phases.
  - Information on scales below which there is reduced signal on the surface of subsurface circulation due to filtering in the MLD. This can be estimated on infrared and ocean color sensors such as on Sentinel-3.

Target effective resolution should be 25km and 1 day

If successful this could become an important part of the satellite observation based Digital Twin components.

- decomposition of drifter trajectories into surface current components. This activity can start with the existing drifter network but may require specific low cost drifter deployment.

- Continue and improve NIO and Stokes-Ekman for surface drift.
    - improved forcing and assess the role of interior ocean properties (MLD, surface and internal waves…).
    - Better exploit argo float surface drift to estimate the G transfer function
    - Use of satellite together with in-situ (drifter/sat obs snapshots collocation).
    - drifter trajectory analysis (decomposition/classification/short term forecasting)
    - interaction of inertial motion and geostrophy
    - MAXSS storm atlas and very intense upper ocean currents associated to high wind conditions

- Provide higher resolution upwelling index based on improved scatterometry, Doppler and SAR winds, also using HR SST. Link to MAXSS improved wind temporal resolution.

- Consider analogue diagnostics and recurrence analysis to be more systematically implemented, to further help creating AI-ready datasets for model training and validation.

- Exploit results from other ESA project focused on the reconstruction of 4D fields (4DMED Sea)/test new methodologies for target areas

3. Ocean heat content, and eddy fluxes

- Better assess variability of western boundary current instabilities influencing the separation when leaving the shelf and subsequent eddies. interannual variability of eddy fluxes using SST/SSS satellite observations and data-driven 4D reconstructions

- Analysis of impact on Arctic ocean heating

- To actively perform synthesis and curation of reference data (including in situ, satellite, and numerical simulations)

- Develop regional focus on climate relevant processes
  - Circulation in Arctic and high latitude
  - tropical ocean, tropical instability waves
  - closed basin dedicated area