Sub-mesoscale and coastal ocean dynamics in the North Indian Ocean using SWOT and EOS-06/OCM-3 observations

Aditya Chaudhary*, Neeraj Agarwal, and Rashmi Sharma

Earth & Planetary Sciences and Applications Area (EPSA), Space Applications Centre, ISRO, Ahmedabad, Gujarat-380015, India

Email: *aditya.osd@sac.isro.gov.in

Abstract

In this study, we make use of sea level anomaly and sea surface current observations from wide swath altimeter onboard surface water and ocean topography (SWOT) mission and high-resolution ocean color observations from EOS-06 to observe the sub-mesoscale variability in the North Indian Ocean. The study involves two components, firstly the SWOT sea levels observations over the Indian region are compared with coastal tide gauge data. Validation results shows an error of 3-10 cm based on multiple tide gauge observations. The coastal observations for the SWOT is also shown to have more valid observations in the 0-30 km coastal band as compared to along-track nadir observations. SWOT show 17% more variability with respect to the standard seal level gridded products. The RMSD between the SWOT and standard seal level gridded products is nearly 3.3 cm; however, there are considerable differences near the coast, where SWOT sea levels depict significantly higher difference (~5cm RMSD). Secondly, we analyze the covariability of the chlorophyll form EOS-06/OCM3 and the circulation features derived from the SWOT. A scheme to correct the SWOT circulation for the cyclostrophic features has also been proposed.

Motivation

High resolution SWOT sea level products in the Indian Ocean are capable of improving our understanding of understanding of sea levels especially in sub-mesoscale O(0-100 km) and coastal dynamics. This study focuses on validation and evaluation of SWOT different products in the North Indian Ocean. Circulation features form SWOT have been compared to the EOS-06 observations and a scheme to correct the currents is also shown.

Data Used and Methodology

Data :

1. **SWOT:** For validation, dynamics : L3 Version 0.3, 2.0, 2.0.1
   For assessment : L2 PIC2, L2 PID0
2. **L3 sea level data :** Sentinel-6a, 3a, 3b, Cryosat-2, AltiKa, SWOT-Nadir
3. **Tide Gauge :** MOES (35), ISRO (1)

Study Area : North Indian Ocean

1. SWOT SSHA KaRIn validation with Tide gauges:

TG SSHA = SSH(TG) - Ocean Tide - $\overline{\text{SSH(TG)}}$

SWOT SSHA = ssha_unfiltered + DAC - $\overline{\text{ssha\_unfiltered}}$

2. SWOT KaRIn Coastal Data Assessment

Coastal data availability within the 30 km from the coasts in Indian mainland & Sri Lanka coast was assessed, using numbers and density plots scatter plots

3. Sub-mesoscale corrections & Intercomparison with EOS-06 Chlorophyll

Geostrophic Assumptions	Corrected Geostrophic (proposed in Agarwal et al. 2025)
$u_g = -\frac{g}{f}\frac{\partial h}{\partial y}, v_g = \frac{g}{f}\frac{\partial h}{\partial x}$	$u_x = \frac{-\frac{g\partial h}{f\partial y}}{\left(1+\frac{\lvert V\rvert}{fR}\right)}, v_y = \frac{\frac{g\partial h}{f\partial x}}{\left(1+\frac{\lvert V\rvert}{fR}\right)}$

$|V| = \sqrt{u_i^2 + v_i^2}$ & R is the radius of curvature (Dhruv et. al. 2021)

4. Assessment of different SWOT L2 versions & Feedback

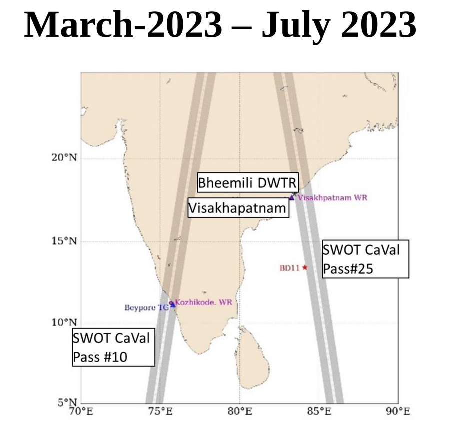
SWOT L2 SSHA : ssha_karin + height_cor_xover

SWOT L3 SSHA : ssha_unfiltered

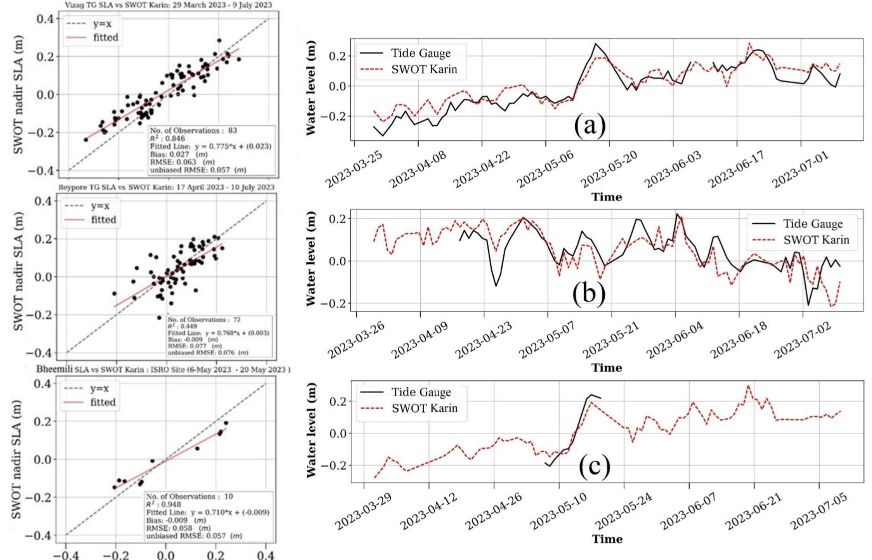
Results

1. SWOT Cal-Val Phase Validation North Indian Ocean

SWOT L3 V-0.3
Cal-Val Phase
March-2023 – July 2023



Scatter plots for comparison of SSHA (m) from SWOT-KaRIn with Tide gauge stations at a) Visakhapatnam, (b) Beypore and, (c) Bheemili



Scatter plots and Line plots Tide gauge SSHA (black) and collocated SWOT-KaRIn SSHA for the sites for (a) Visakhapatnam, (b) Beypore, (c) Bheemili

Root mean square error (RMSE) of 6.3 cm, 7.7 cm, and 5.8 cm were observed for the three tide gauges

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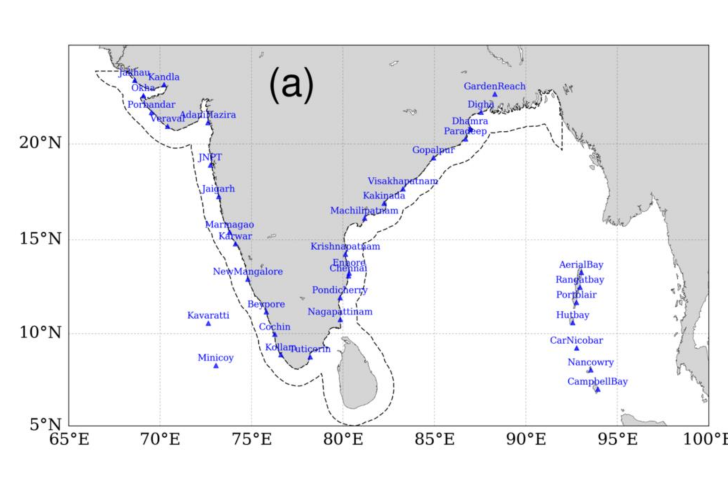
Chaudhary et . Al. 2025, JISRS

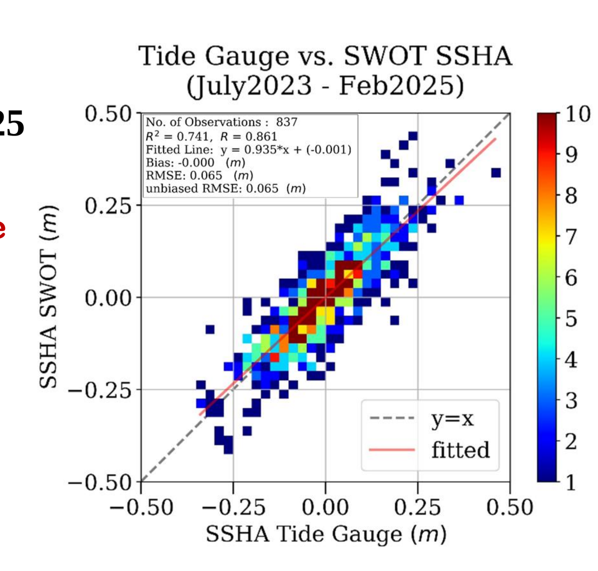
SWOT Science Phase Validation North Indian Ocean



Tide Gauge locations

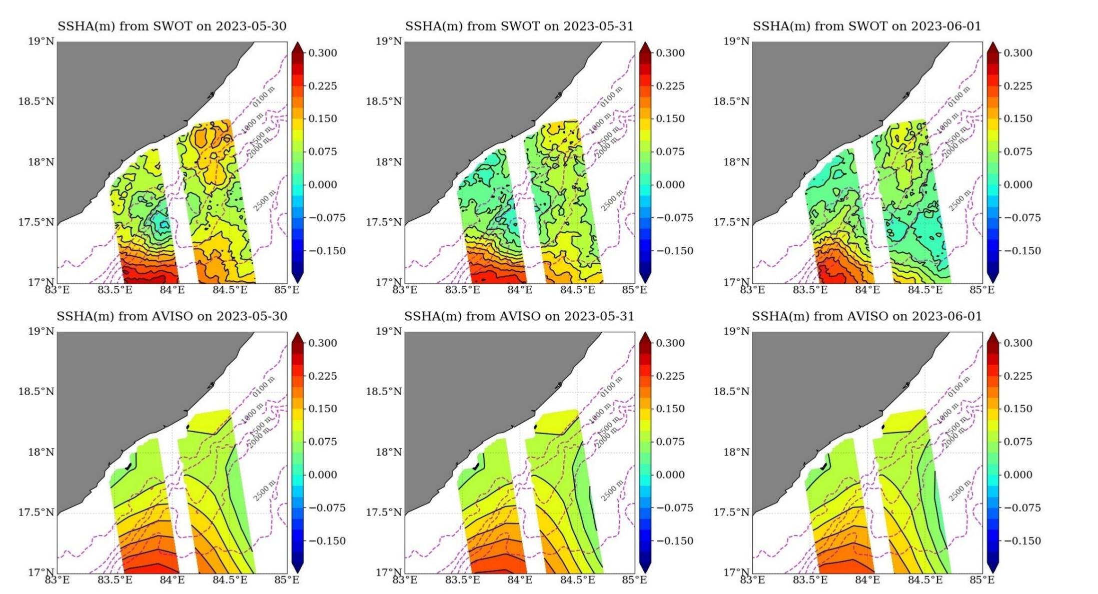
SWOT L3 V-2.0
Science Phase
Jul-2023 – Feb 2025

- With selected tide gauges $R^2 \geq 0.6$
- RMSE of SWOT sea levels for these selected tide gauges are 6.5 cm !!



3. SWOT Coastal Data Assessment

Small scale variability seen in SWOT as compared to the standard gridded product

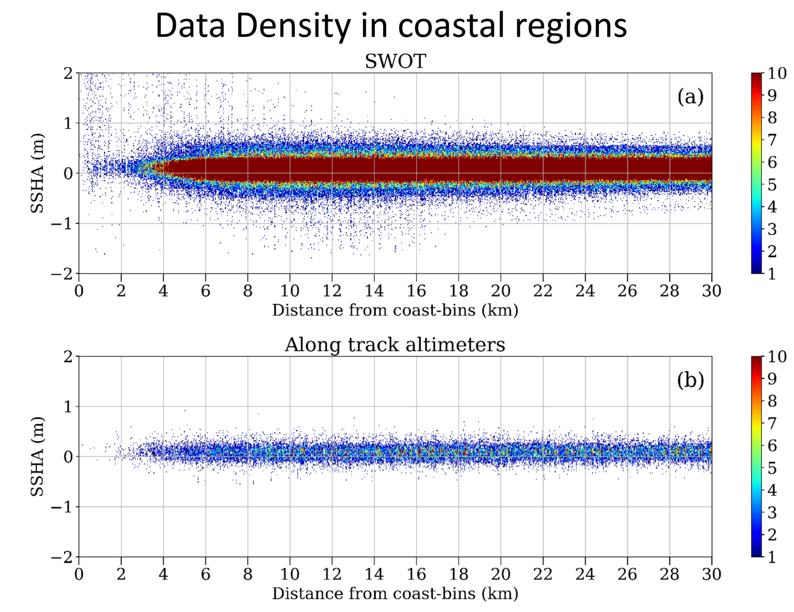


SWOT Sea levels Pass 25 during Cal-Val Phase

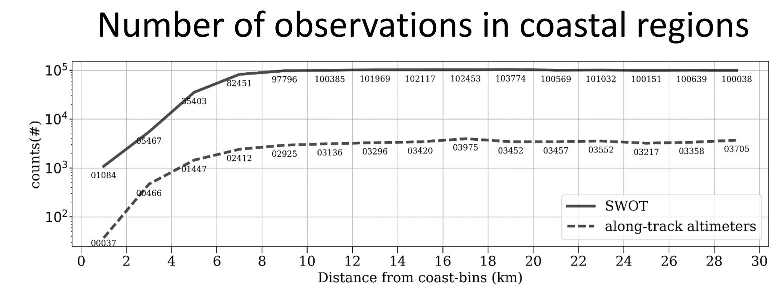
25-30 times more observations from SWOT as compared to along-track observations in the coastal regions

SWOT L3 V-2.0 Science Phase KarIn Compared with L3 SSHA from nadir altimeters July-2023 – November 2024

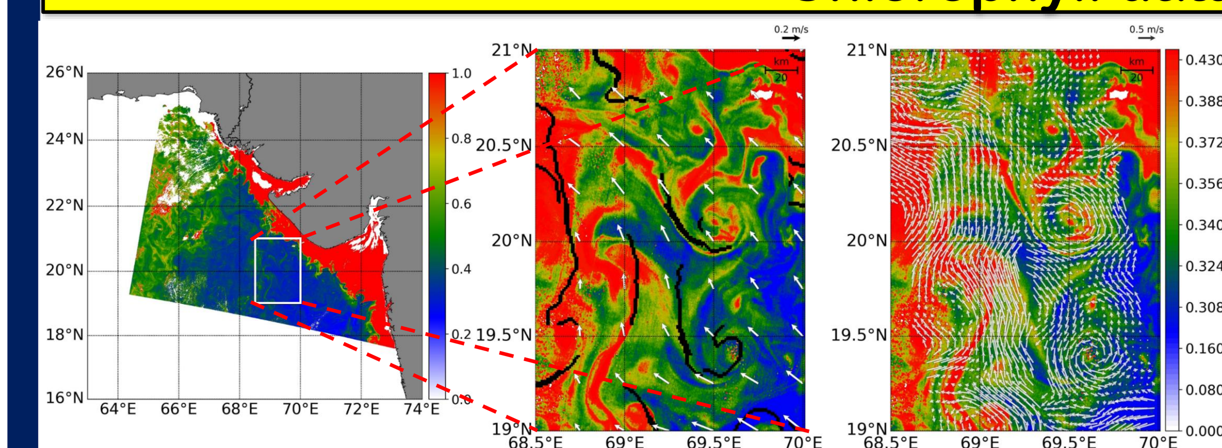
Data Density in coastal regions



Number of observations in coastal regions



4. Sub-mesoscale circulation corrections & synergy with EOS-06 Chlorophyll data



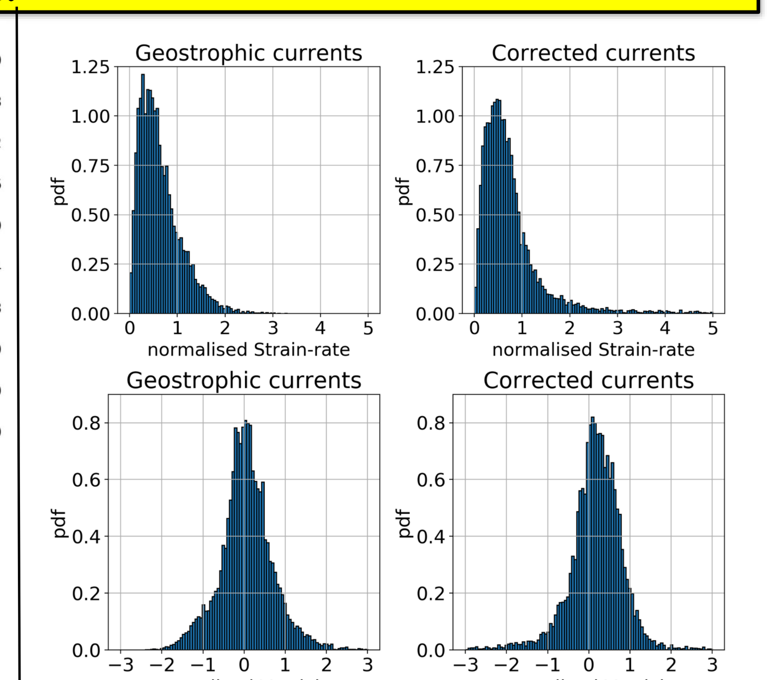
EOS06 Chl0-Data 02-Feb-2024

Low resolution Surface currents from merged gridded product + SST gradients Over EOS06 Chl

Surface currents from SWOT Over EOS06-Chl

- OCM -3 reveals very high resolution fine scale features in the chlorophyll field in the Northern Arabian Sea
- These features are in form of filaments and sub-mesoscale eddies (~20-30 km size) and are associated with thermal gradients at a few locations, especially at the periphery of the small scale eddies.
- Satellite derived currents at 25km resolution reveal a mean flow towards north west show no eddy like structure
- Geostrophic currents from SWOT are able resolve the fine scale eddies.

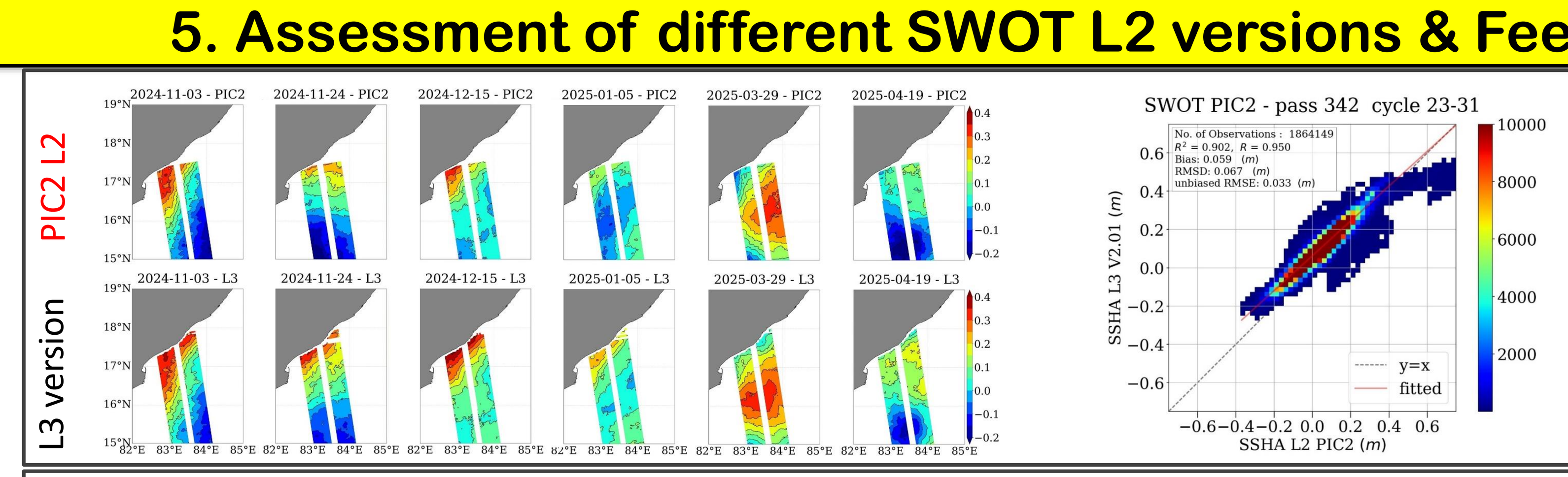
Under review:
Agarwal et . Al. 2025, IEEE-JSTARS

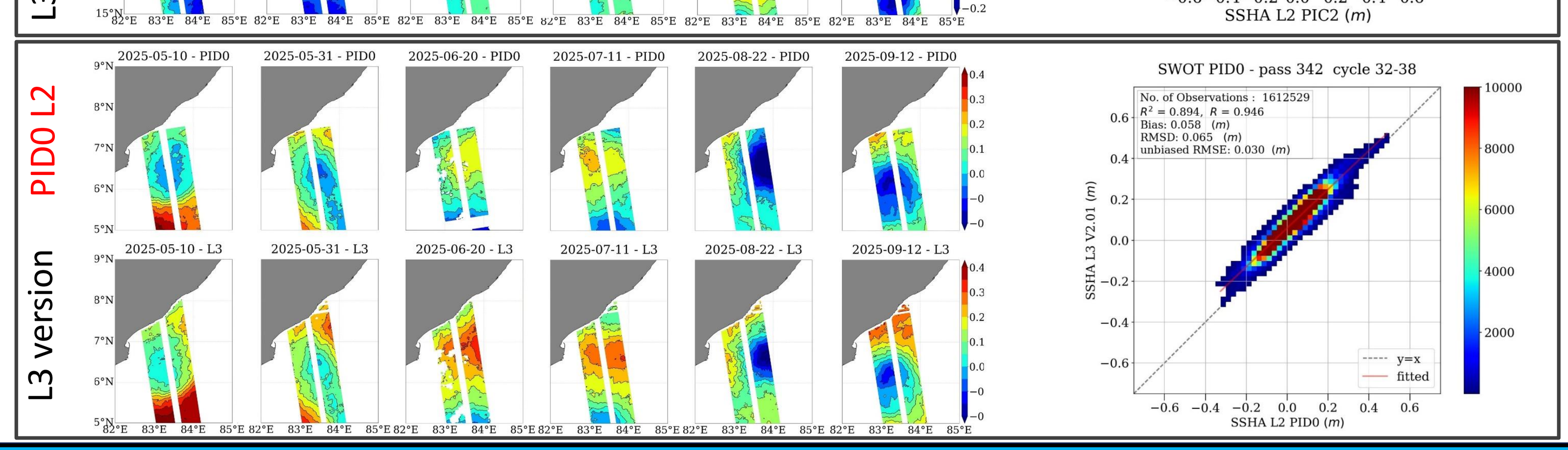


Probability distribution functions for normalised (by f) strain rates and vorticity computed using velocity from the geostrophic assumption (a and b) and our approach (c and d).

Correction to the geostrophic velocity field results in an asymmetry to the relative vorticity histogram which becomes skewed to the right, indicating the presence of more positive vortices as compared to the negative vortices. These results are also consistent with Torres et. al. (2024)

5. Assessment of different SWOT L2 versions & Feedback





Comparison with L3 shows PIC2 has more difference than L3 versions as compared to PID0

Although significant difference in both the L2 versions as compared to L3 version

Summary

1) SWOT Cal-Val Phase SSHA (L3-V0.3) was validated with the tide gauges in the NIO with RMSE ranging 5.8-7.7 cm
2) SWOT Science Phase SSHA (L3-V2.0) was validated with the tide gauges in the Indian Ocean with RMSE of 6.5 cm
3) In Indian coastal region 25-30 times more observations from SWOT as compared to along-track observations in the coastal regions.
4) SWOT is able to resolve fine scale dynamics consistent with ocean color observations.
4) Corrections in geostrophic velocities in SWOT proposed, which qualitatively improved the expected statistics of dynamical parameters.
5) Comparison with L3 shows PIC2 has more difference than L3 versions as compared to PID0. Although significant difference in both the L2 version as compared to L3 version.

Acknowledgements

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