Physics-Informed Scale Separation for High Resolution Sea Surface Height Inpainting

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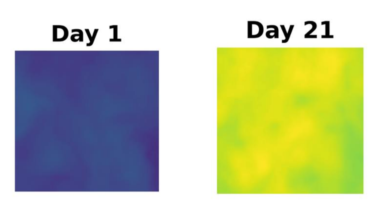
Introduction

Image credit: Canadian Space Agency [1]

- The SWOT satellite passes over every piece of the ocean once every **21 days**
- The satellite has unprecedented **high-resolution** sea surface height (SSH) data [2]
- Our motivation is to **spatio-temporally inpaint** submesoscale dynamics between these SWOT measurements

- The problem will use 2 input images spaced 21 days apart and output the SSH data of intermediate days
- This model will be developed using **LLC4320 simulation** data for testing before being adapted to real-world SWOT data [3]



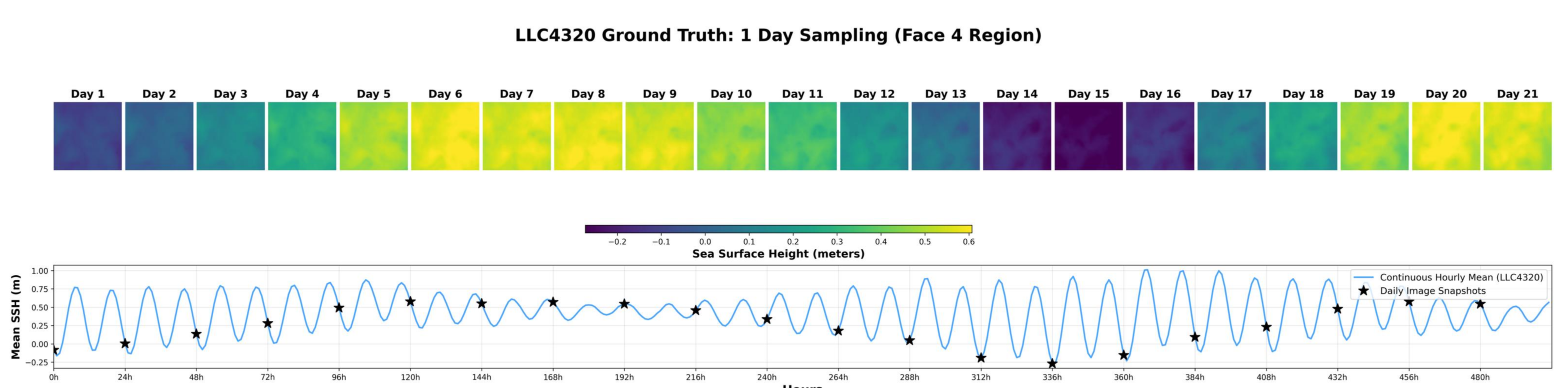


Figure 1: The mean varies significantly over the course of 21 days sinusoidally

Data Investigation

- Means of SSH data clearly vary sinusoidally over time, with peaks not exactly **every 24 hours**
- We found that this oscillatory behavior is dependent on **tides**, with the **M2 Lunar Tide** having a significant impact on SSH means in face 1 (South Atlantic)

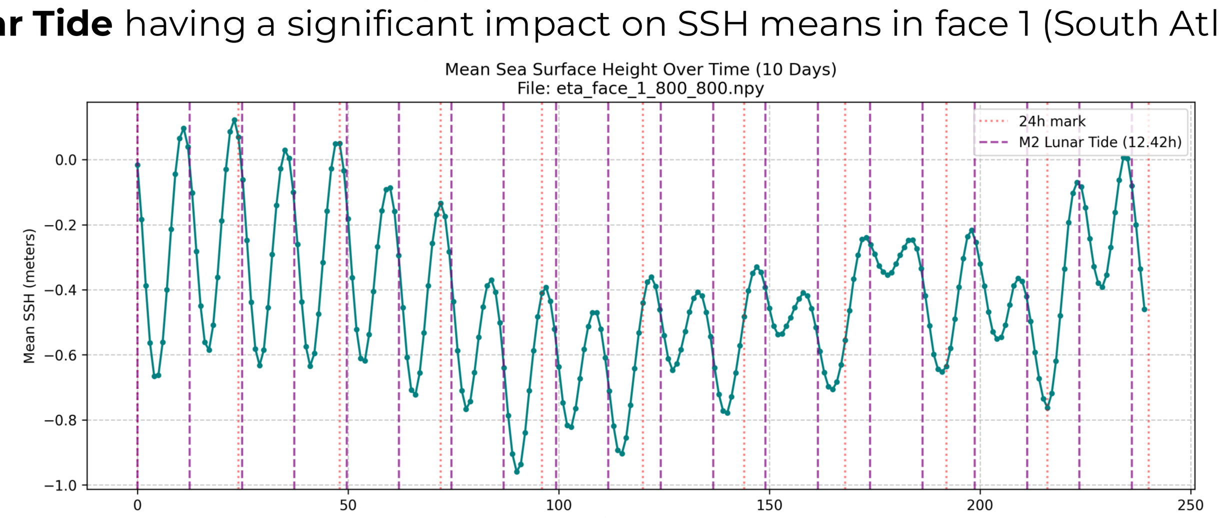


Figure 2: The mean SSH varies **sinusoidally**, and in this region in the South Atlantic the period of these waves is **in sync** with the **M2 Lunar Tide**

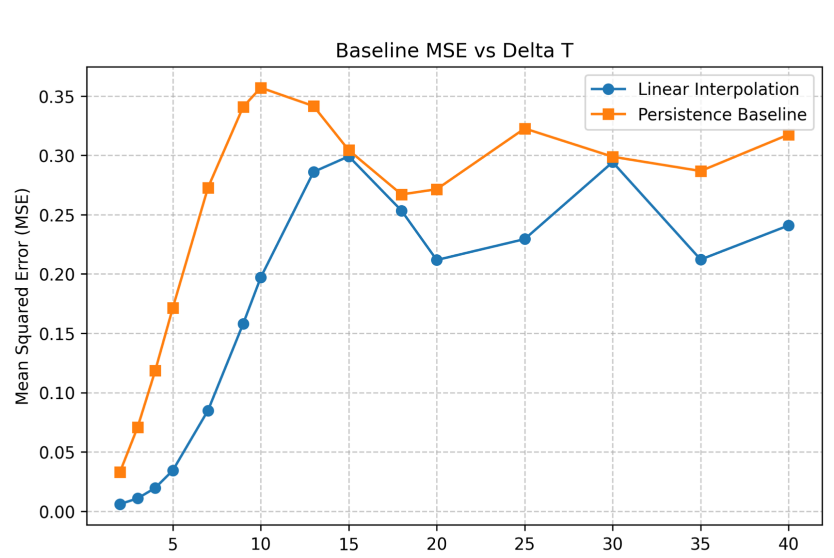


Figure 3: This displays the error obtained from **linearly interpolating** between the inputs and outputs in sync with the M2 Lunar Tide. Delta T is the gap between the input and output images and MSE is calculated by comparing linearly interpolated values to LLC values.

Methodology

- We address this **variation in the mean** by fitting the means using a Fourier series

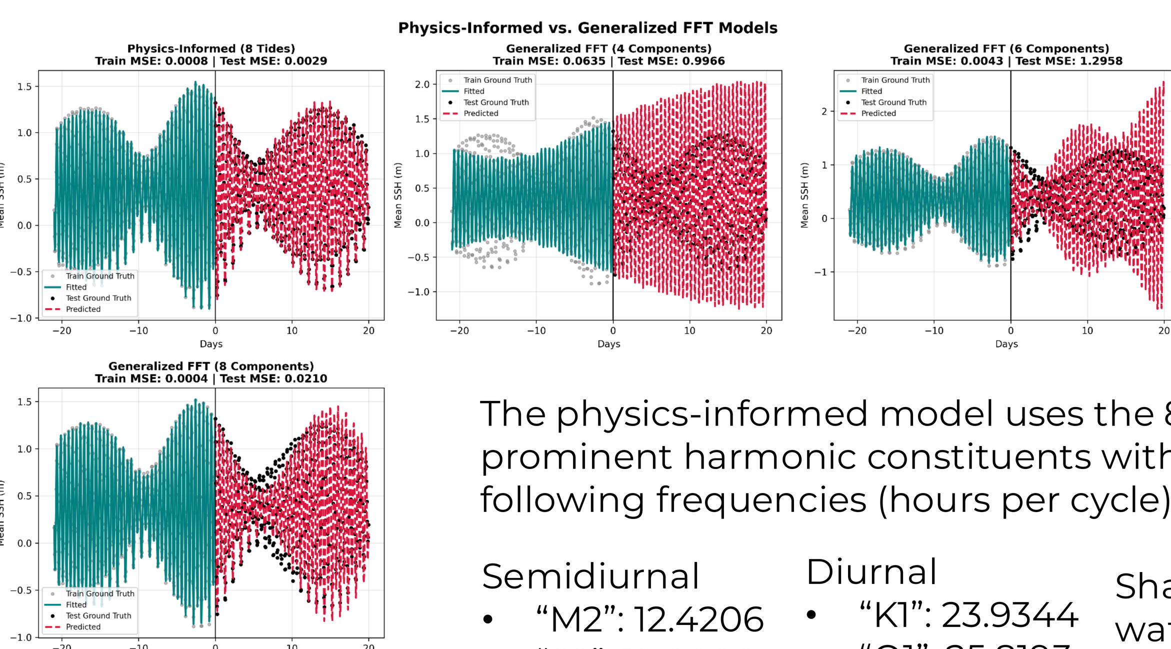


Figure 4: The physics-informed model with known **tidal harmonic constituents** fitted only for magnitude and phase, generalizes to test data significantly better than generalized FFT models that fit for frequency, magnitude, and phase.

The physics-informed model uses the 8 most prominent harmonic constituents with the following frequencies (hours per cycle):

Semidiurnal
- "M2": 12.4206
- "S2": 12.0000
- "N2": 12.6583

Diurnal
- "K1": 23.9344
- "O1": 25.8193
- "P1": 24.0659
- "Q1": 26.8684

Shallow water
- "M4": 6.2103

- Using **physics-informed** frequencies prevents **overfitting** to the training data by grounding the model in real-world frequencies

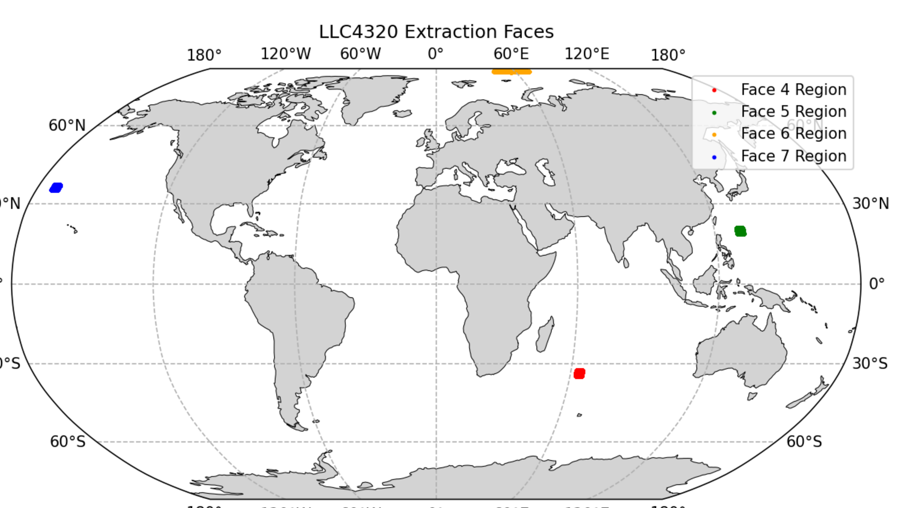


Figure 6: The locations of the **4** unique regions we used to determine the optimal choice of **parameters** fitting this mean variation on the general ocean

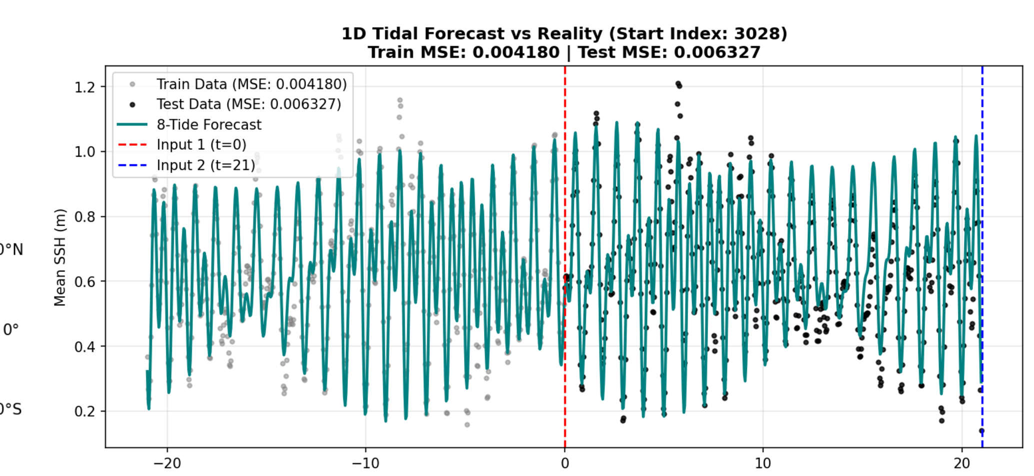


Figure 5: The physics-informed model is highly accurate with an **abundance** of training data (21 days of continuous data before the region it needs to inpaint)

Results

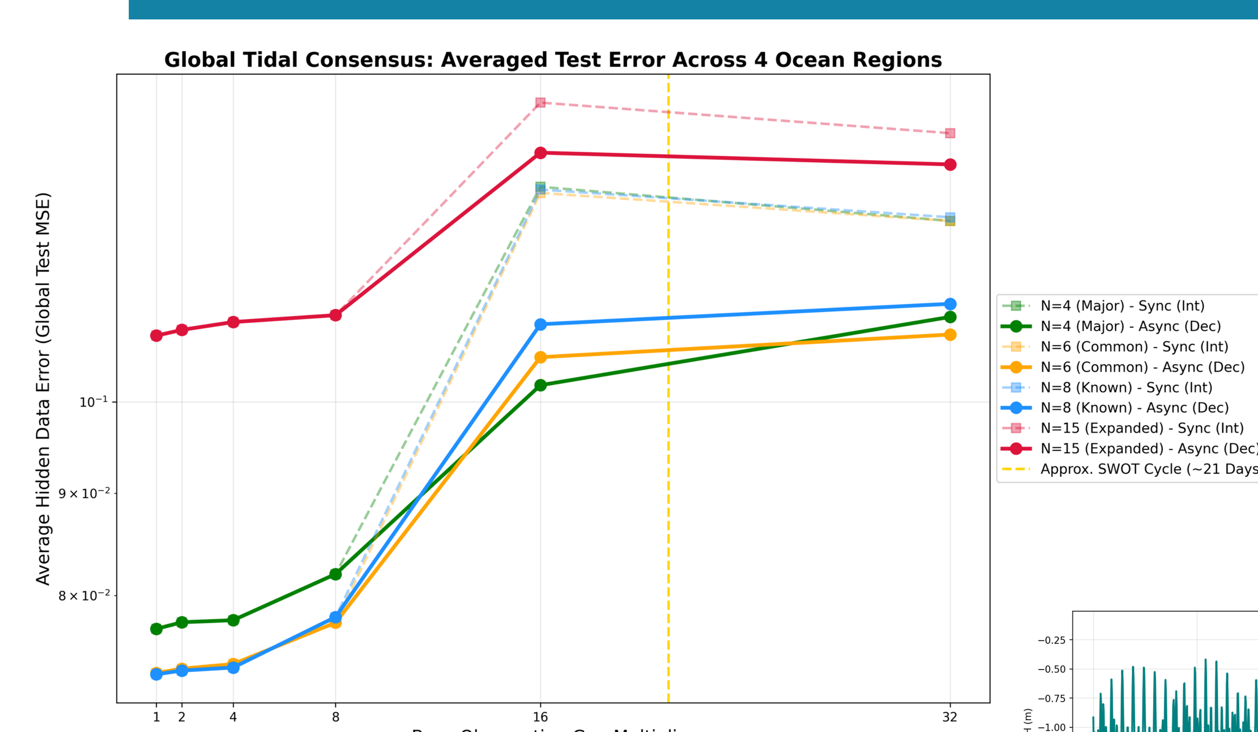


Figure 7: The performance of models with different numbers of tidal constituents on 400 days of data sampled at different observation gaps. A higher number of tides seems to **overfit** the training dataset with this limited number of samples.

Based on these results (Figs 4 and 7) we chose to use a **6-tide physics-informed model** to predict the mean variation, isolating the anomalies of the image. The following results depict a good example (Fig 8) and bad example (Fig 9) of the model using **linear interpolation** to predict the change in **anomalies**.

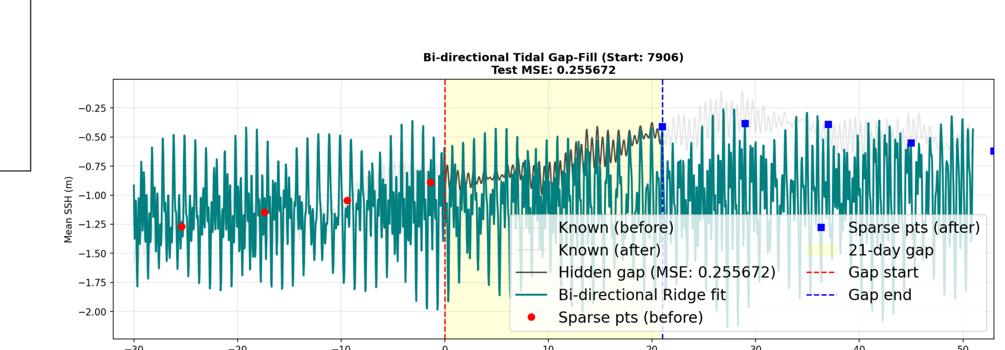


Figure 8: The performance of the model on fitting the means in figure 9

Results (cont.)

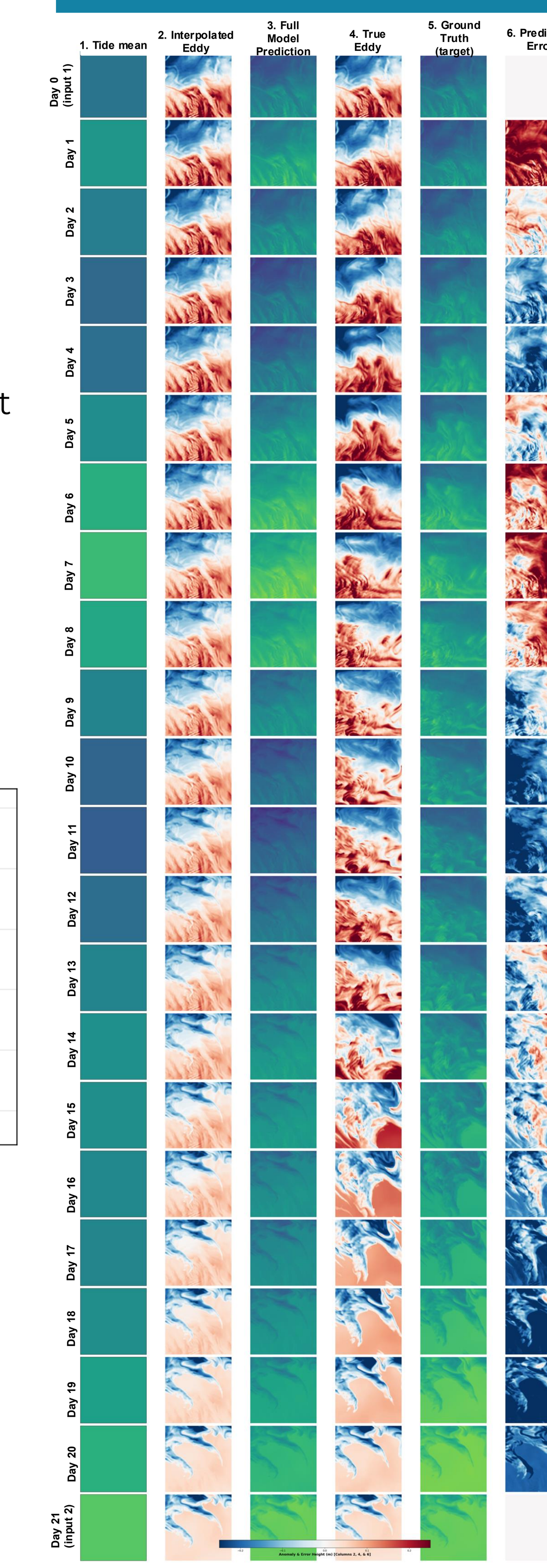


Figure 9 (left): 21-day example on face 6 where our model of mean fitting with linear interpolation **fails** to accurately predict SSH data

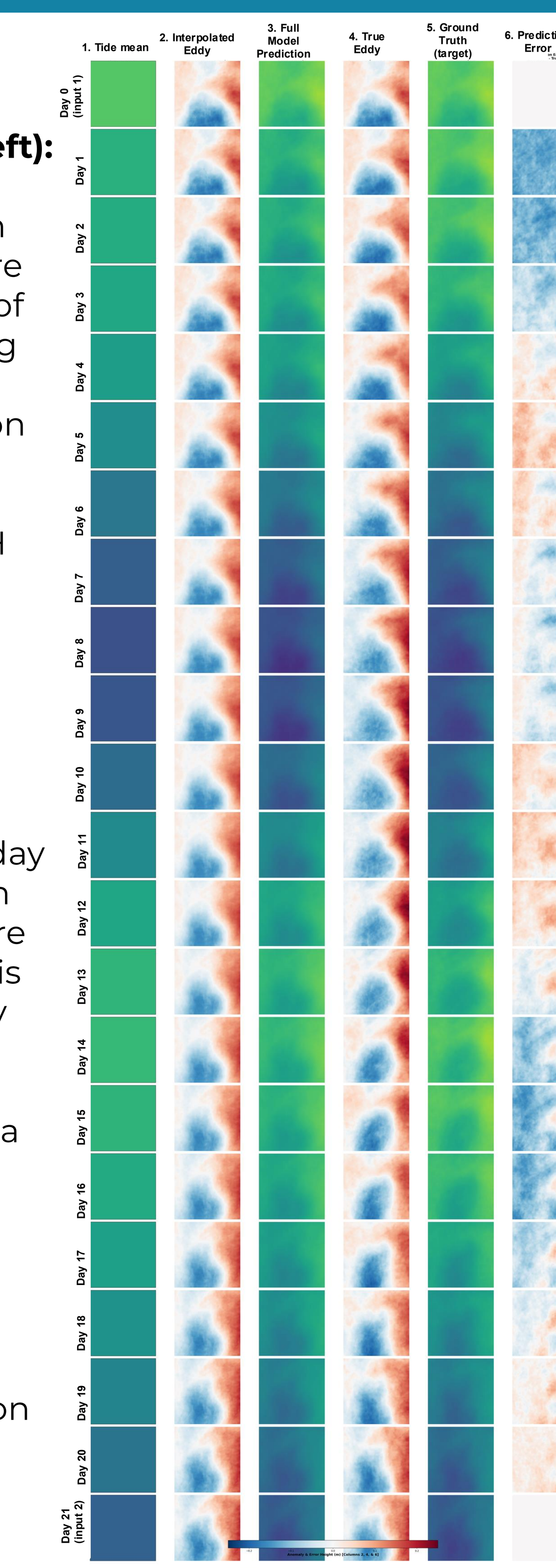


Figure 10 (right): 21-day example on face 7 where our model is able to very **accurately** inpaint sea surface data using only our 6-tide physics-informed model and linear interpolation

Summary

- We see this model clearly is very successful in many cases, and can **reduce** the problem to an easier problem of inpainting the anomalies
- This model with linear interpolation gives accurate inpainting results in areas **dominated** by tides
- We look to improve this model by **combining** spatial data to generate more accurate predictions based on neighboring regions

References

[1] Canadian Space Agency, "Surface Water and Ocean Topography (SWOT), "n.d. [Online]. Available: https://www.asc-csa.gc.ca/eng/satellites/swot/. [Accessed: Apr. 21,2026].

[2] R. Morrow et al., "Ocean eddies and mesoscale variability from SWOT," *Fronteirs in Marine Science*, vol. 6,p. 232,2019.

[3] D. Menemenlis et al., "ECCO2: High resolution global ocean and sea ice data synthesis," *Mercator Ocean Quarterly Newsletter*, vol. 31, pp. 13-21, 2008.