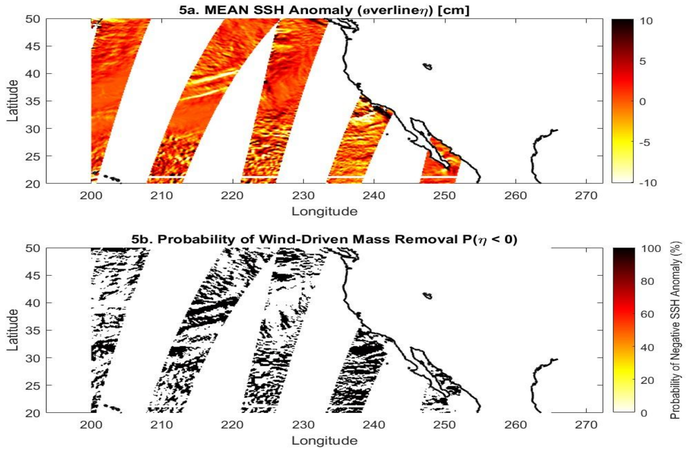
Using Wind Stress Divergence and a Monte Carlo framework as a constraint for SSHA Validation

Rachel Spratt, in collaboration with Restoration Science, LLC, and UCSB Marine Science Institute, rachelspratt@ucsb.edu

Rationale--Enhance mission continuity by connecting linking measurements

Abstract: The advancement of Earth Observation mission continuity requires establishing robust, physics-based links between diverse sensor measurements. Starting with global ASCAT Level 3 wind stress data over the California Current System (CCS); the uncertainty in surface density is used to generate an ensemble of Ekman Upwelling Velocity and corresponding SSHA fields. The rationale of this project is to create a probabilistic framework for Sentinel-1 to Sentinal-6 data comparison. Note on data/framework: The scope of the poster has been modified from the original abstract due to some data acquisition logistical issues. The probability framework and sensitivity tests outlined below will assist the project once the data comparison is available.

Mean Ekman Transport in this framework represents the average of horizontal mass transport across all 1,000 Monte Carlo realizations, (of the surface density variation). This value is given a mean of 1025 kg/m^3 and a standard deviation of 2 kg/m^3. Its divergence is a direct physical cause of vertical upwelling velocity and resulting **Mean Wind-Driven SSHA** in this framework. The mean density for the lower layer of the 2-layer ocean framework in the SSHA estimate is given as 1026.5 kg/m^3 with a standard deviation of 1.5 kg/m^3. The probability of wind driven mass removal above is a discrete calculation of percentage of SSHA in the Monte Carlo ensemble >0.



$$W_E = \frac{1}{\rho_0 f}(\nabla \times \tau) \qquad \eta \approx -\frac{f W_E}{g'}$$

- When the wind blows across the surface, it drags the top layer of water away from the coast.
- When that top layer moves away, the *interface* between the two layers gets tilted upward near the coast. This upward tilt brings cold, deep water (the bottom layer) closer to the surface. **This is upwelling.**
- **Vertical Velocity:** The velocity of water crossing the base of the Ekman layer (the interface between the two layers). Positive W_E is upwelling.
- **Reference Density:** The mean density of the upper layer (a core uncertainty parameter in the Monte Carlo run).
- **Coriolis Parameter:** The effect of Earth's rotation, which determines the direction of transport (constant for a given latitude band).
- **Wind Stress Curl:** The rate of rotation of the wind stress field, which measures how wind-driven transport diverges or converges.

Future Work:

The probabilistic Monte Carlo framework of this project provides a method for quantifying confidence in wind-driven circulation, demonstrating that **confidence maps** (**P(W_E > 0)** and **P(η < 0)**) may serve as diagnostics for **Metop ASCAT wind forcing. This is a first-order driver of SSH variability** in this 2-layer model when uncertainty is introduced into the physical parameters (ρ and Δρ).

. The hypothesis for future work in the CCS boundary current is that this finding will remain stable, even when uncertainty is introduced into the physical parameters.

This study establishes large-scale forcing field required for high-resolution analysis:

1. **Validation:** Compare modeled confidence maps directly against high-resolution, observed SSH data from **Sentinel-6 data as well as SWOT (KaRIN)**.
2. **Probabilistic Wind Stress (τ) Input:** Transition from the scatterometer-derived τ(ASCAT) to a high-resolution, **probabilistic τ field** derived directly from t **Sentinel-1 SAR** data using the **OceanSAR-1 Foundation Model**. Choose a standard, published formula that relates C_D to U_{10} (e.g., a recent wave-dependent model) given associated modeled uncertainty with the drag coefficient and 10 m wind speed, calculate $\tau = \rho_{air} \cdot C_D \cdot U^2_{10}$
3. **Integration:** Use the established Ekman forcing foundation to better interpret the complex, small-scale surface wave dynamics observed by **Sentinel-1 SAR (OceanSAR-1 model products)**, exploring how wind uncertainty propagates into observed wave energy.

Wind stress divergence

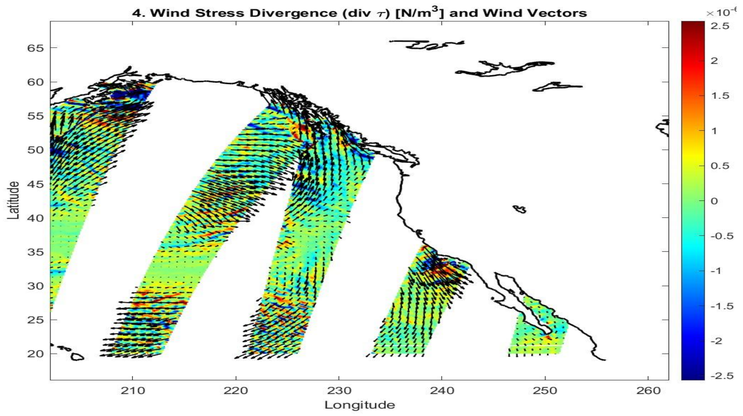


Figure 4 illustrates the Wind Stress Divergence ($\nabla \cdot \tau$) derived directly from the deterministic ASCAT Level 3 dataset. The quiver arrows are: (τ_x, τ_y) All associated probabilistic plots (e.g., Figures 1,2 and 5) are generated using a mean of 1000 Monte Carlo simulations where seawater density (ρ) and stratification (Δρ) were varied to quantify the resulting uncertainty in W_E and SSH.

The study area for the project is the California Current System (CCS) and the larger Pacific Ocean; because of its high-resolution, I will use Sentinel-1 Wave mode data preprocessed by the oceanSAR-1 model to generate wind vectors. The primary goal of this project is to create a probabilistic framework for wind-driven upwelling, which is presented here on this poster. We compare a probabilistic estimate of the Ekman Upwelling Velocity (W_E) to a similarly derived probabilistic estimate of the Sea Surface Height (SSH) anomaly (η) that results from mass removal at the surface.

References and acknowledgements:

Kerdreux, T., Tuel, A., Febvre, Q., Mouche, A., & Chapron, B. (2025). Efficient Self-Supervised Learning for Earth Observation via Dynamic Dataset Curation. *arXiv preprint arXiv:2504.06962*.

MEaSUREs/OSWV. 2025. MetOp-B ASCAT Scatterometer Inter-Calibrated ESDR Level 3 Ocean Surface Equivalent Neutral Wind Vectors and Wind Stress Version 1.0. Ver. 1.0. PO.DAAC, CA, USA. Dataset accessed [2025-11-07] at https://doi.org/10.5067/ESASB-L3W10

Google Gemini, "Refining the land mask generation heuristic, refinements, graphing assistance, and text generation" (personal communications, November 10-14, 2025).

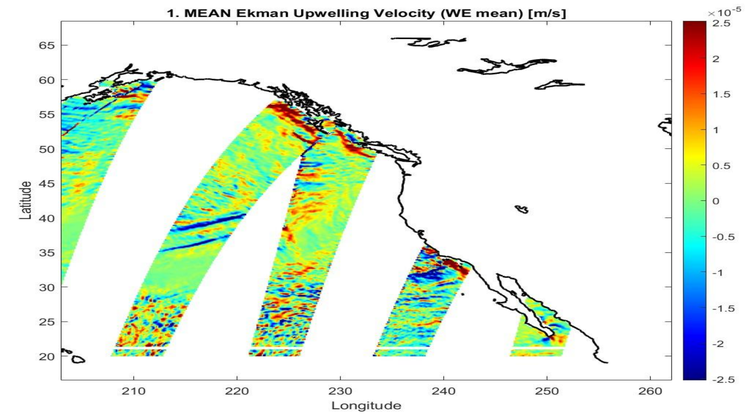
Jorge Vazquez and Fred Bingham, "Developing an altimetry and wind stress comparison framework" (personal communication, November 10, 2025).

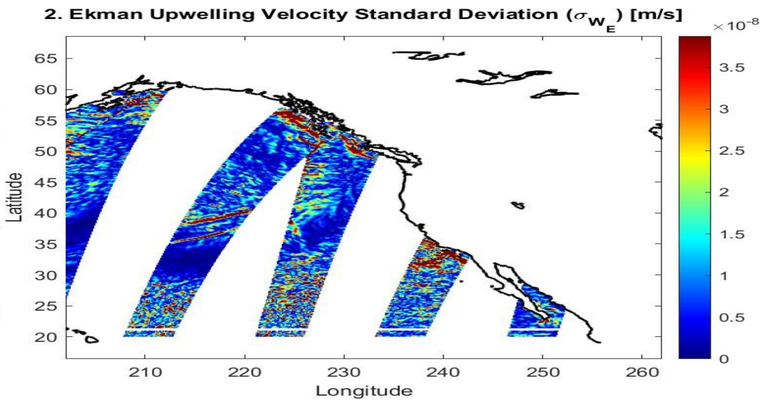
Workflow for Sentinel data comparison:
Input: Sentinel-1 Ground Range Detected (GRD) SAR (~10 m resolution)

Processing: OceanSAR-1 Foundation Model (CNN/Transformer)
Output: High-Resolution Wind Vectors

Why divergence? --Helps to understand mass conservation and coastal upwelling/downwelling

Mean Upwelling Velocity





Calculating Mean Upwelling Velocity (W_E)

This method uses the satellite wind stress data (τ) in a two-step process to calculate vertical velocity (W_E) for each run of the Monte Carlo simulation.

1. **Ekman Transport (M):** The wind stress (τ) causes surface water movement. This transport is calculated using:
   M = (τ x k) / (ρ_{mc} · f)
   *(where **M** is the Ekman Transport vector, **τ** is the wind stress vector, **k** is the unit vector pointing upward, ρ_{mc} is the sampled seawater density, and **f** is the Coriolis parameter).*
2. **Vertical Velocity (W_E):** Upwelling is determined by the **divergence of the Ekman Transport** (Div(M)). If transport diverges (pulls away from an area), water must rise from below to replace the mass. We calculate the W_E for each of the 1,000 runs.
   $W_E = \nabla \cdot M$

The **Mean Upwelling Velocity (W_E)** is then the average of all 1,000 vertical velocity maps, giving the most likely vertical flow speed with a known uncertainty (σ_{WE}).