

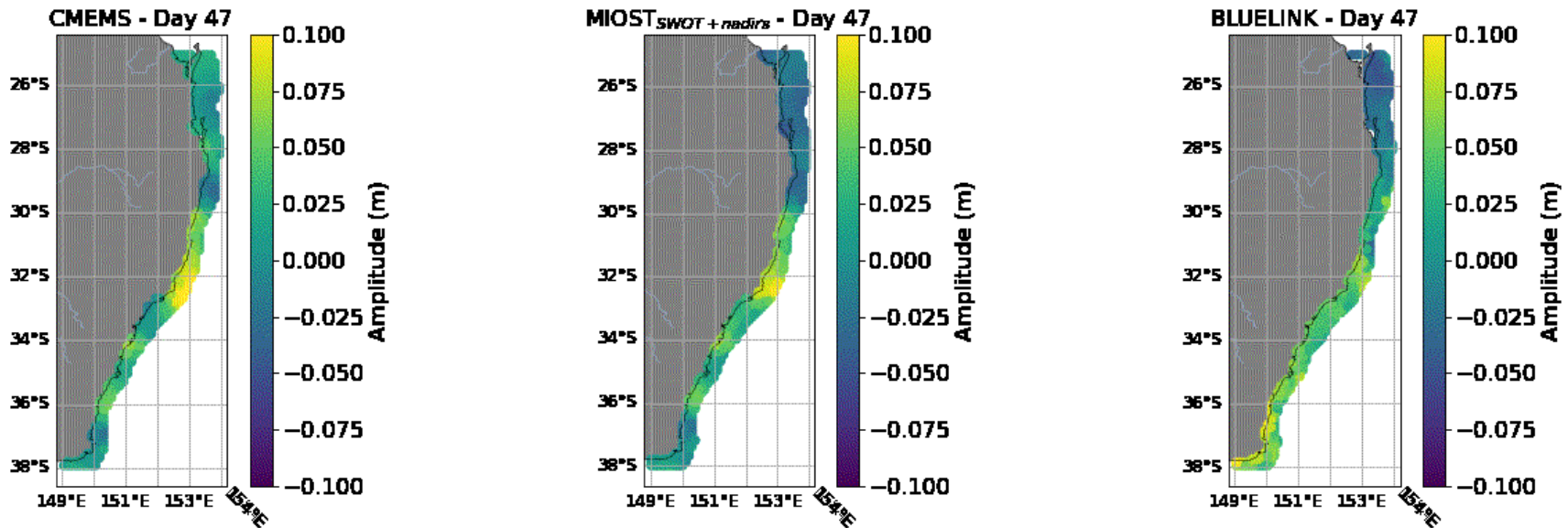
# Can satellite altimetry observe coastally trapped waves on sub-monthly timescales?

Marcello Passaro<sup>1</sup>

<sup>1</sup> Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)

SWOT Science Team Meeting  
Arcachon, 16.10.2025

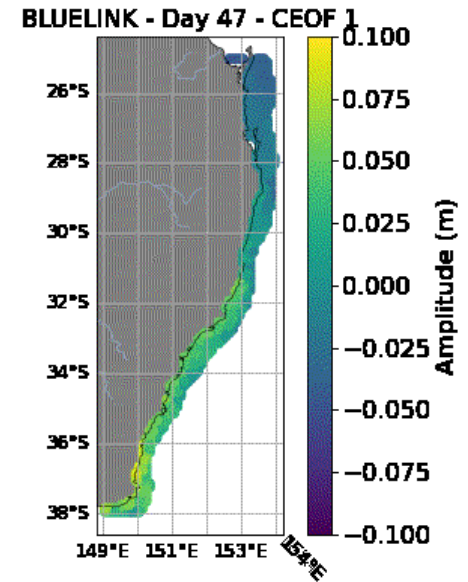
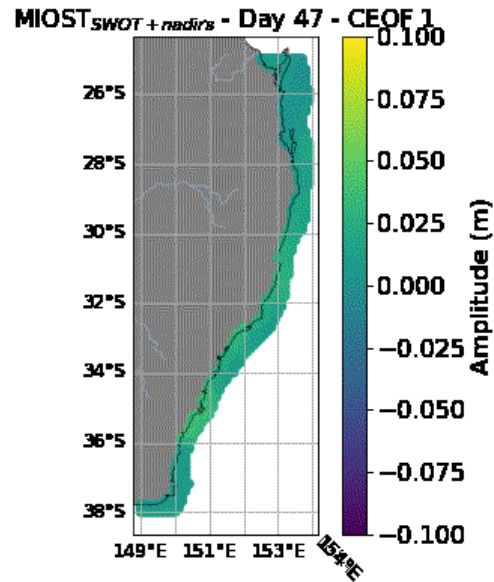
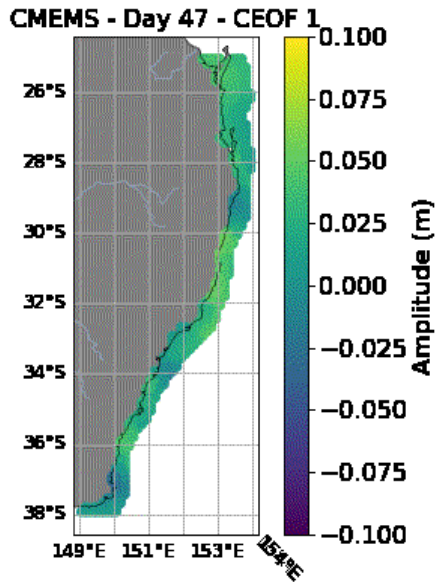
# Can satellite altimetry observe coastally trapped waves on sub-monthly timescales? Yes, but...



90 days of data with a daily sampling are considered for the following sources:

- 1) High-Frequency **Tide Gauges**
- 2) Nadir-altimetry using MIOST (called **CMEMS** from now on)
- 3) Experimental use of MIOST with nadir-altimetry AND swath altimetry (called **MIOST<sub>SWOT+nadirs</sub>**) from AVISO
- 4) A ocean general circulation model with assimilated ocean data (called **BLUELINK** reanalysis)

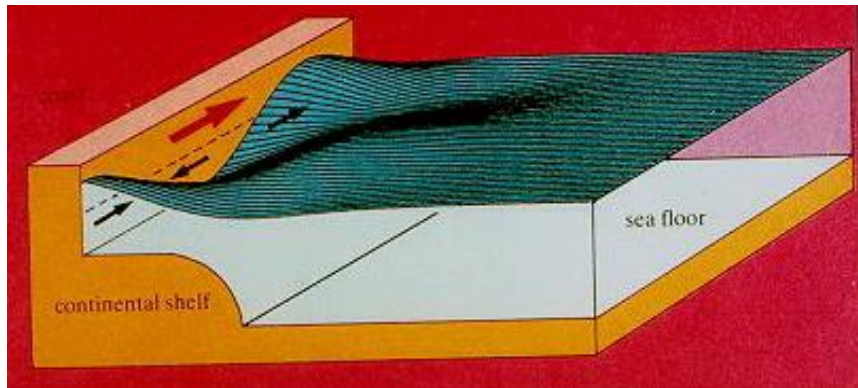
# Can satellite altimetry observe coastally trapped waves on sub-monthly timescales? Yes, but...



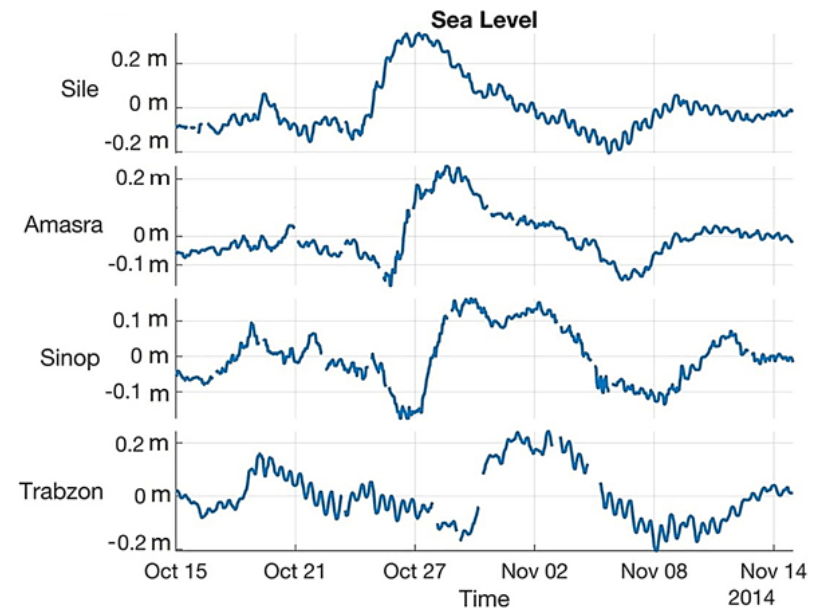
Reconstructed with Complex Principal Component Analysis!

# What are coastally trapped waves?

- Major mechanism to distribute energy from the atmosphere in the ocean
- Generated by the effect of wind stress on the coastal ocean
- Play a significant role in large-scale sea-level and current variability in continental shelf and slope areas



Source: <https://www.physocean.icm.csic.es/ShelfCoast/chapter08-en.html>

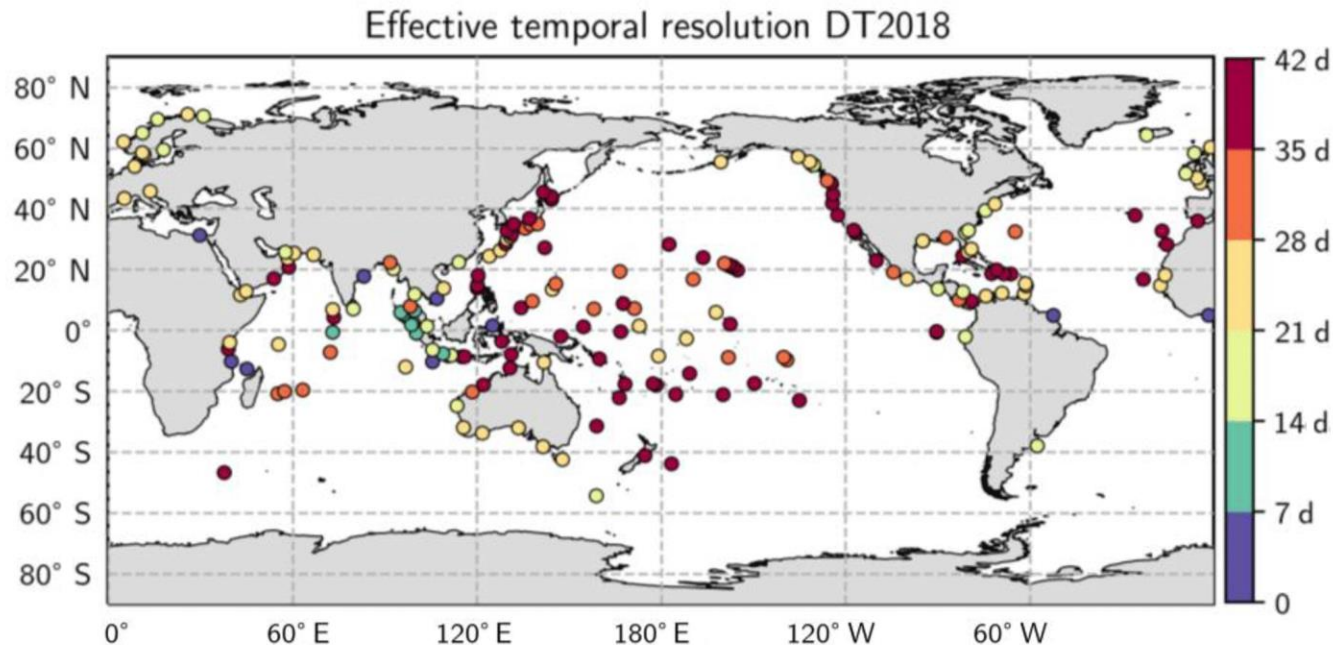


Aydın, M. and Beşiktepe, Ş. T.: Mechanism of generation and propagation characteristics of coastal trapped waves in the Black Sea, *Ocean Sci.*, 18, 1081–1091, <https://doi.org/10.5194/os-18-1081-2022>, 2022.

# Why monitoring coastally trapped waves?

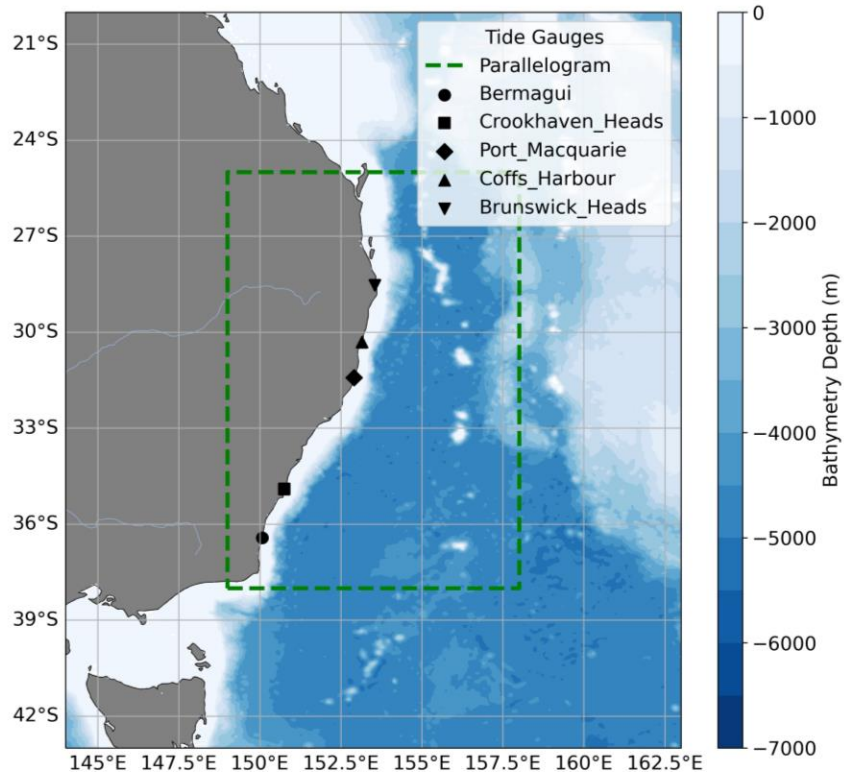
- "signature" of important oceanic processes, with wind perturbations as common driver
- They can amplify coastal sea level extremes (storm surges)
- Driving factor of coastal upwelling and downwelling events
- Major source of sea level variability on time scales from days to months

Often modelled, but hardly observed by satellite altimetry, why?  
 'Cause the **effective** resolution one average was ~1 month



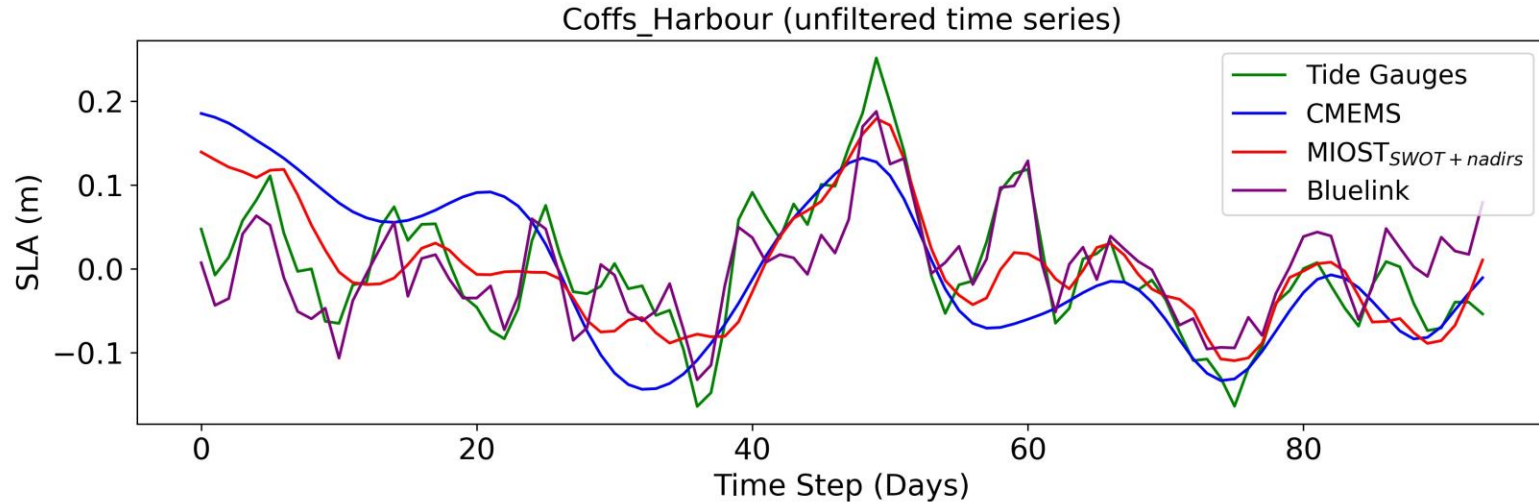
Ballarotta et al., Ocean Science, 2019

# Eastern Australia as testbed



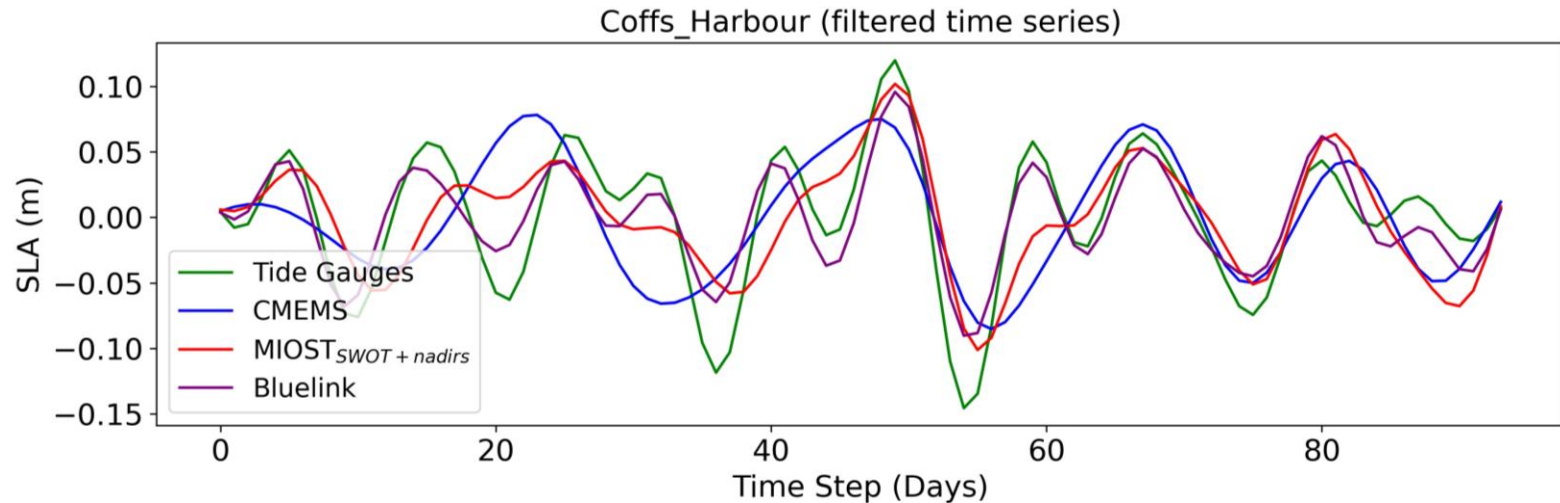
- Frequent Wind Forcing Events generate regularly CTWs
- Shelf geometry supports the trapping and guiding of wave energy along the coast.
- Dense network of tide gauges with high-frequency data (update from GESLA service)
- Regional high-resolution model (BLUELINK) already validated to observe CTWs

# First look at the time series (closest point to TG)



- BLUELINK and tide gauges very similar to each other
- Altimetry-based time series are smoother
- MIOST<sub>SWOT+nadirs</sub> has a better agreement than CMEMS

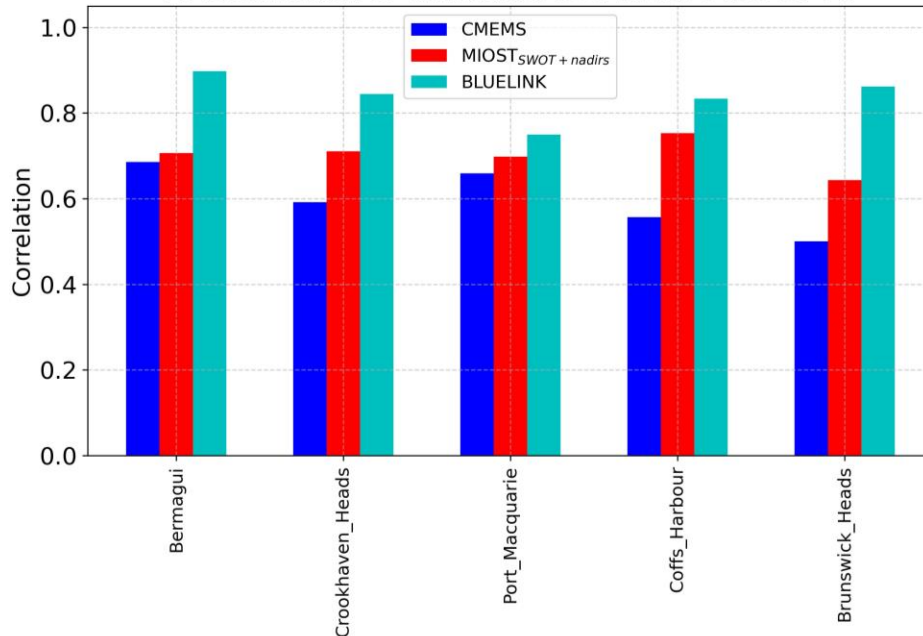
# First look at the time series (closest point to TG)



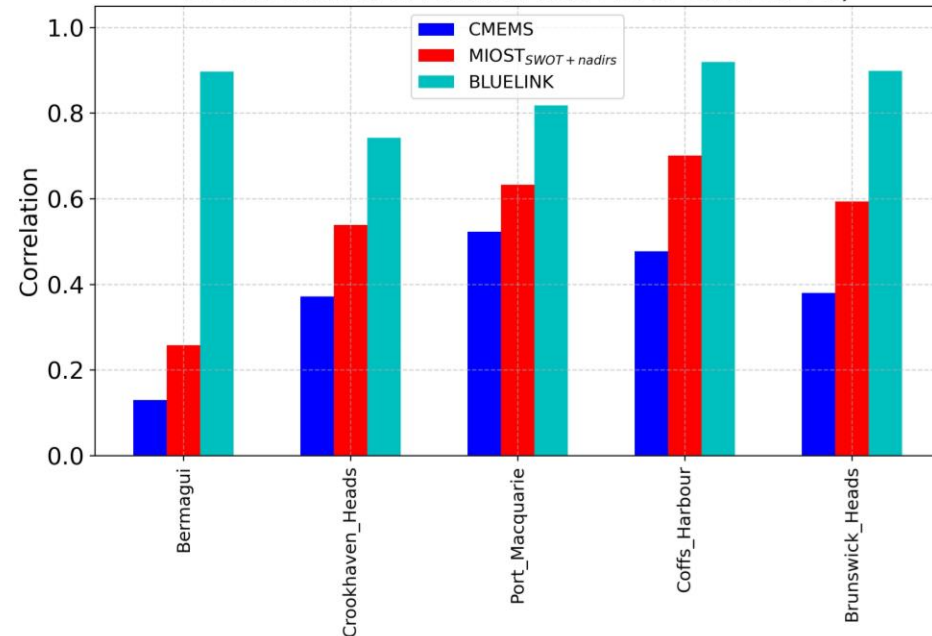
- Filtering reveals wave-like patterns
- Altimetry-based time series "miss" some of the events
- CMEMS appears more "out of phase" than MIOST<sub>SWOT+nadirs</sub>

# Correlation analysis

A: Correlation of Unfiltered Sea Level Data vs TG



B: Correlation of Filtered Sea Level Data vs TG

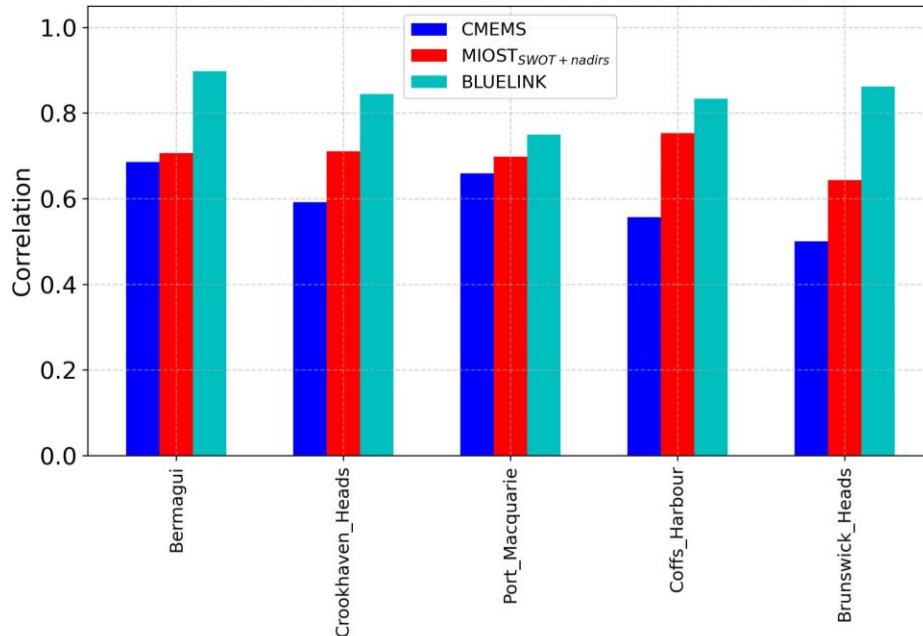


As expected, the correlation at the closest point strongly decreases for CMEMS when sub-monthly signals are considered.

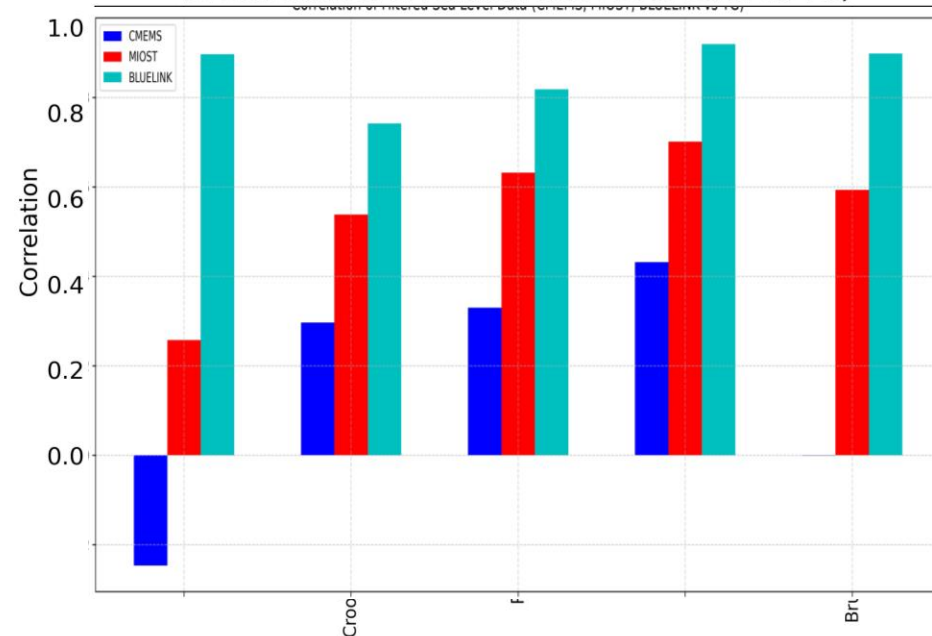
The addition of SWOT shows systematic improvements

# From DT2021 to DT2024 (effect of MIOST)

A: Correlation of Unfiltered Sea Level Data vs TG

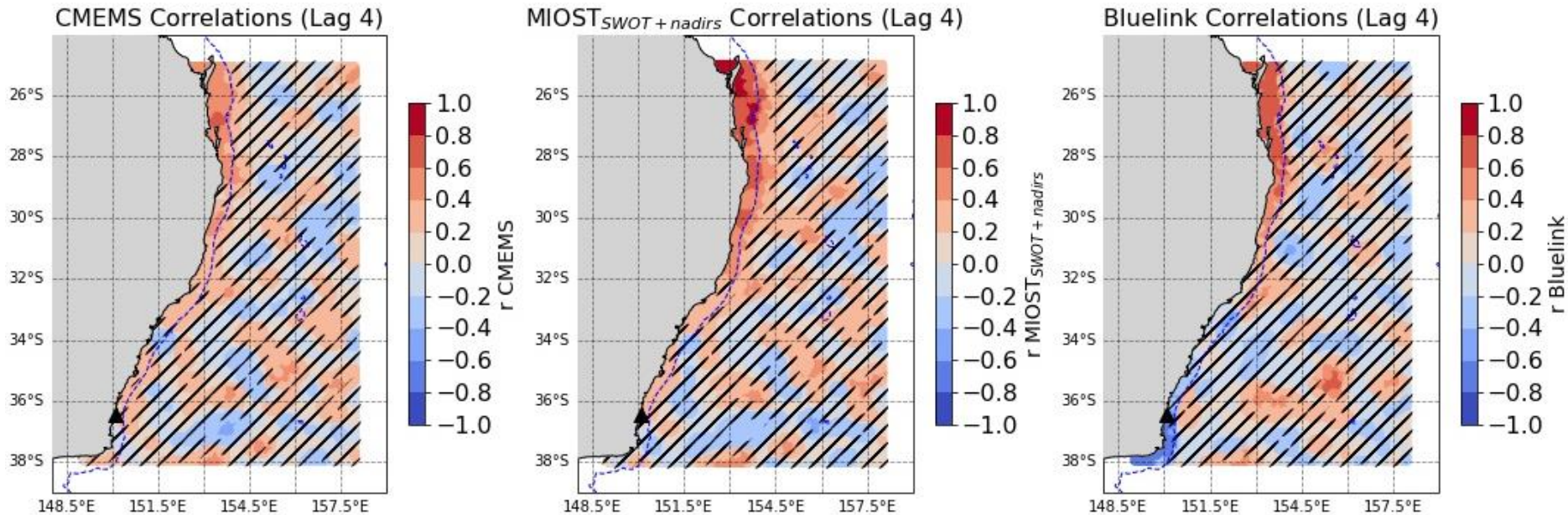


B: Correlation of Filtered Sea Level Data vs TG



**IMPORTANT:** already the introduction of MIOST in CMEMS has improved the quality of the data

# 2D lag-correlation patterns



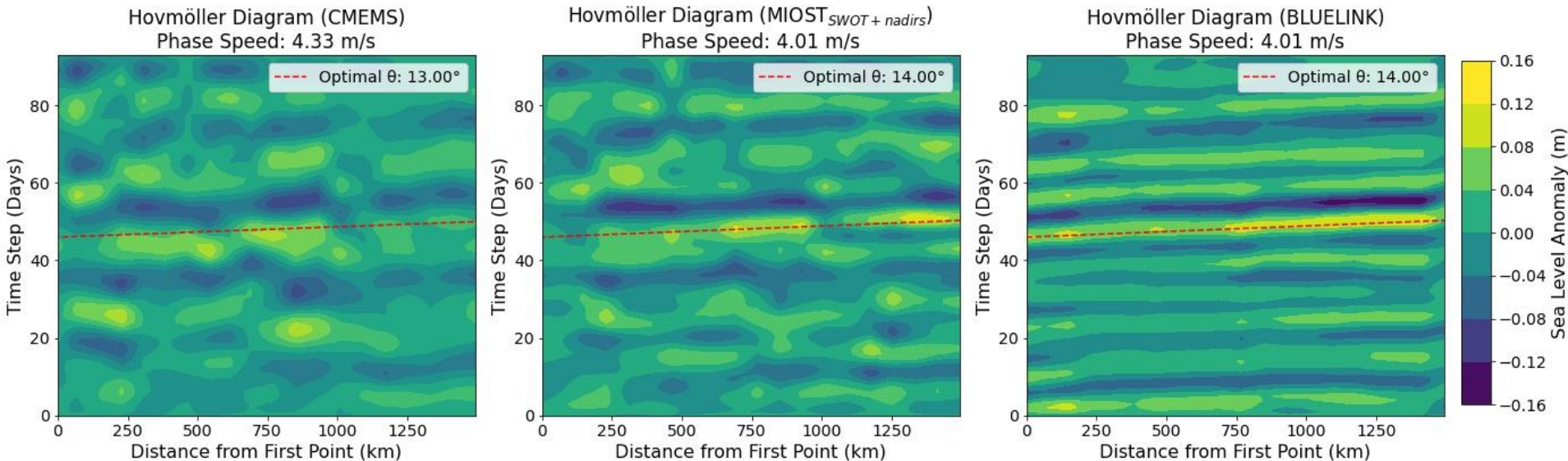
By correlating the tide gauge time series with "delayed versions" at the grid points, we can observe the moving trapped wave pattern.

Stripes show correlations values that are not statistically significant.

Keep in mind: correlation is not causality, background knowledge is needed to interpret it

# Hovmöller diagrams

Time–space plot used to visualize how a variable changes over time along a fixed spatial dimension. -> pattern identification and evaluation over time

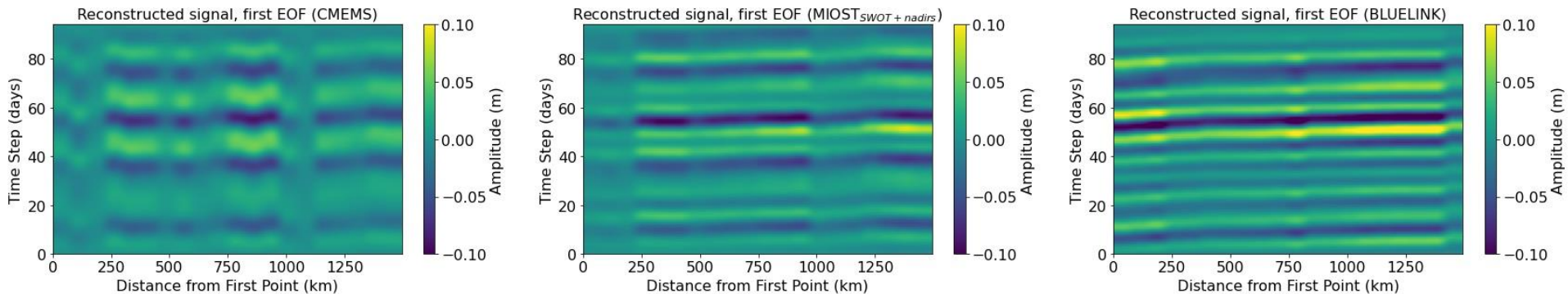


Propagation pattern from altimetry noisier than BLUELINK, but evident particularly in MIOST<sub>SWOT+nadirs</sub>

Phase speed of about 4 m/s -> takes 4-5 days to travel this distance

# 1st CEOF: phase analysis and signal reconstruction

- Thanks to the description in the complex domain, spatial and temporal phase associated with the mode are obtained
- Clear linear phase progression along the coastline, characteristic of traveling waves, noisier pattern in CMEMS



- The temporal phase of the leading mode increases linearly across all three datasets, indicating a sinusoidal oscillation with a dominant period
- The average period of the first mode is approximately 10 days for BLUELINK, 14 days for MIOST<sub>SWOT+nadirs</sub>, and 18 days for CMEMS

# Can satellite altimetry observe coastally trapped waves on sub-monthly timescales?

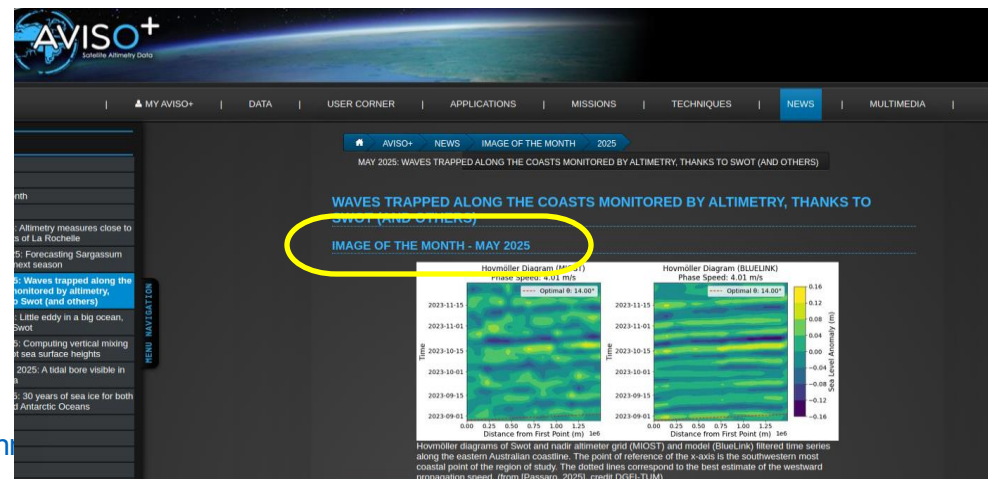
"Yes, but..."

- The addition of swath altimetry is needed to provide a realistic pattern of CTWs in terms of wavelengths and periods (a better signal-to-noise ration)
- A systematic monitoring of high-frequency CTWs looks possible in view of future S3-NGT missions
- Knowledge acquired during the SWOT years can be used to interpret results obtained in the previous years (...when a comparable number of altimeters is used)
- Using a set of grid points as "virtual stations" to monitor CTWs would complement and strengthen studies currently based on sparse in-situ stations (when available) and numerical simulations.

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- Using a set of grid points as "virtual stations" to monitor CTWs would complement and strengthen studies currently based on sparse in-situ stations (when available) and numerical simulations.
- ...and the plots are nicer than retracked waveforms!





**ACCEPTED in Ocean Science!**

## **Can satellite altimetry observe coastally trapped waves on sub-monthly timescales?**

Marcello Passaro<sup>1</sup>

<sup>1</sup>Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, Arcisstraße 21, 80333 Munich, Germany.

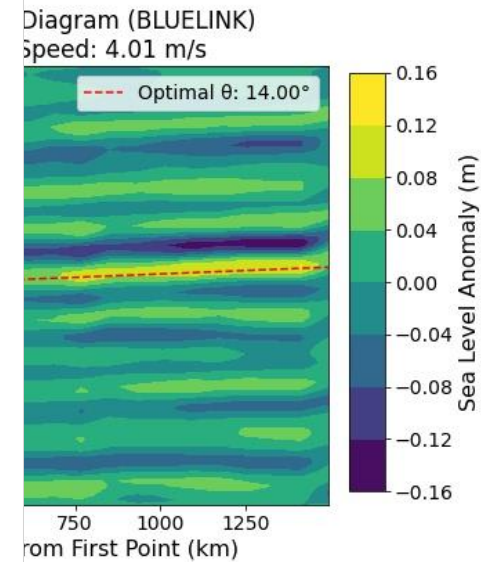
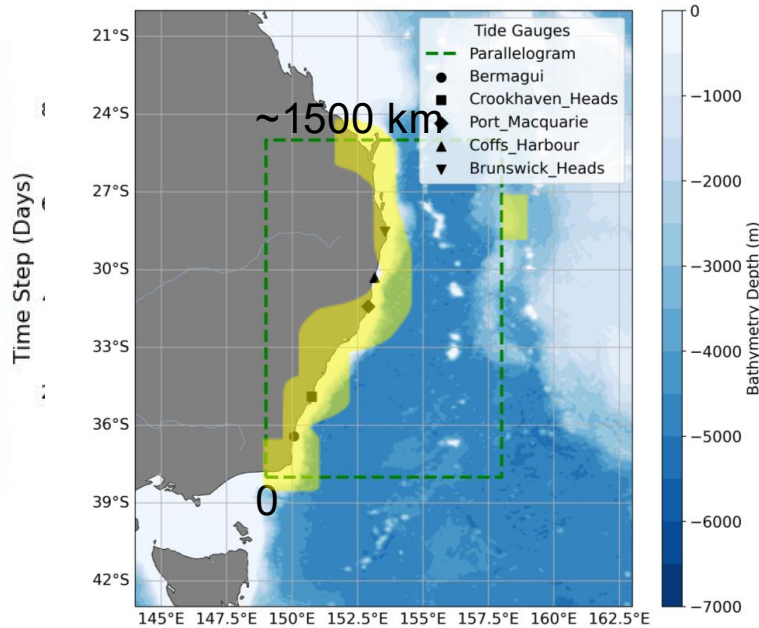
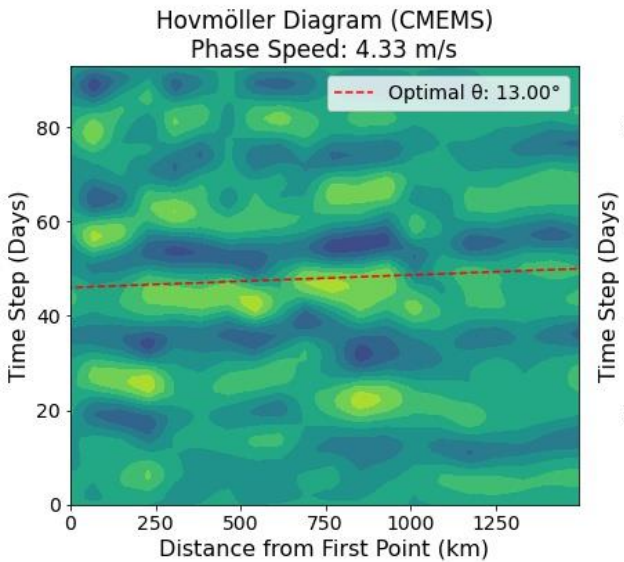
**Correspondence:** Marcello Passaro (marcello.passaro@tum.de)



**SPARE SLIDES**

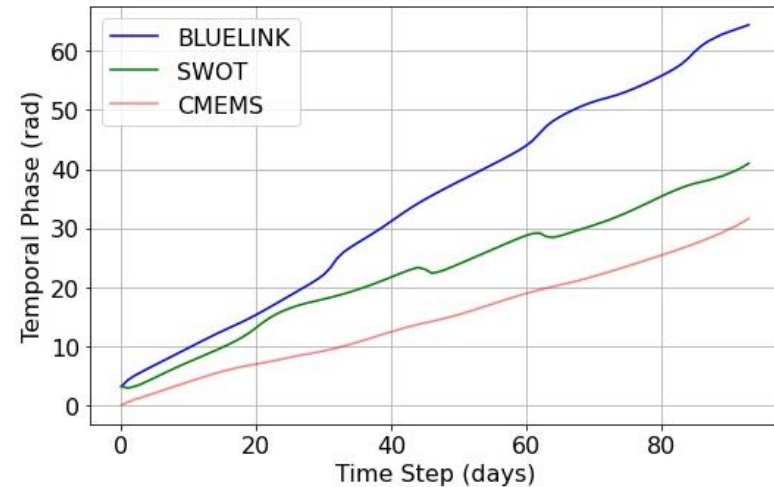
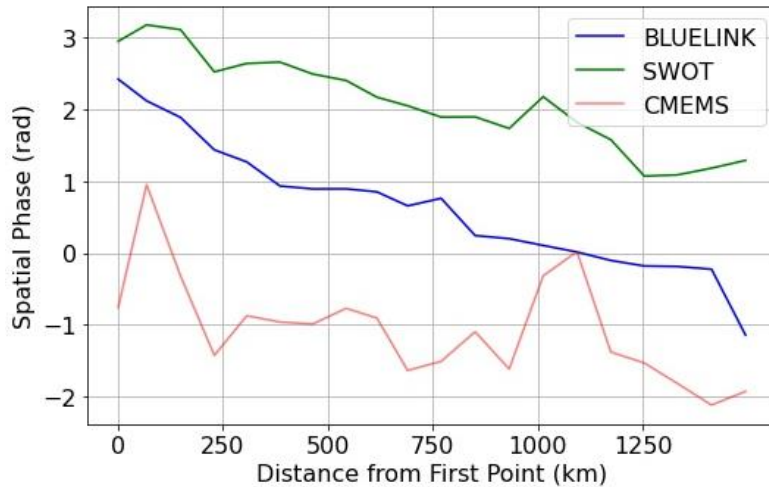
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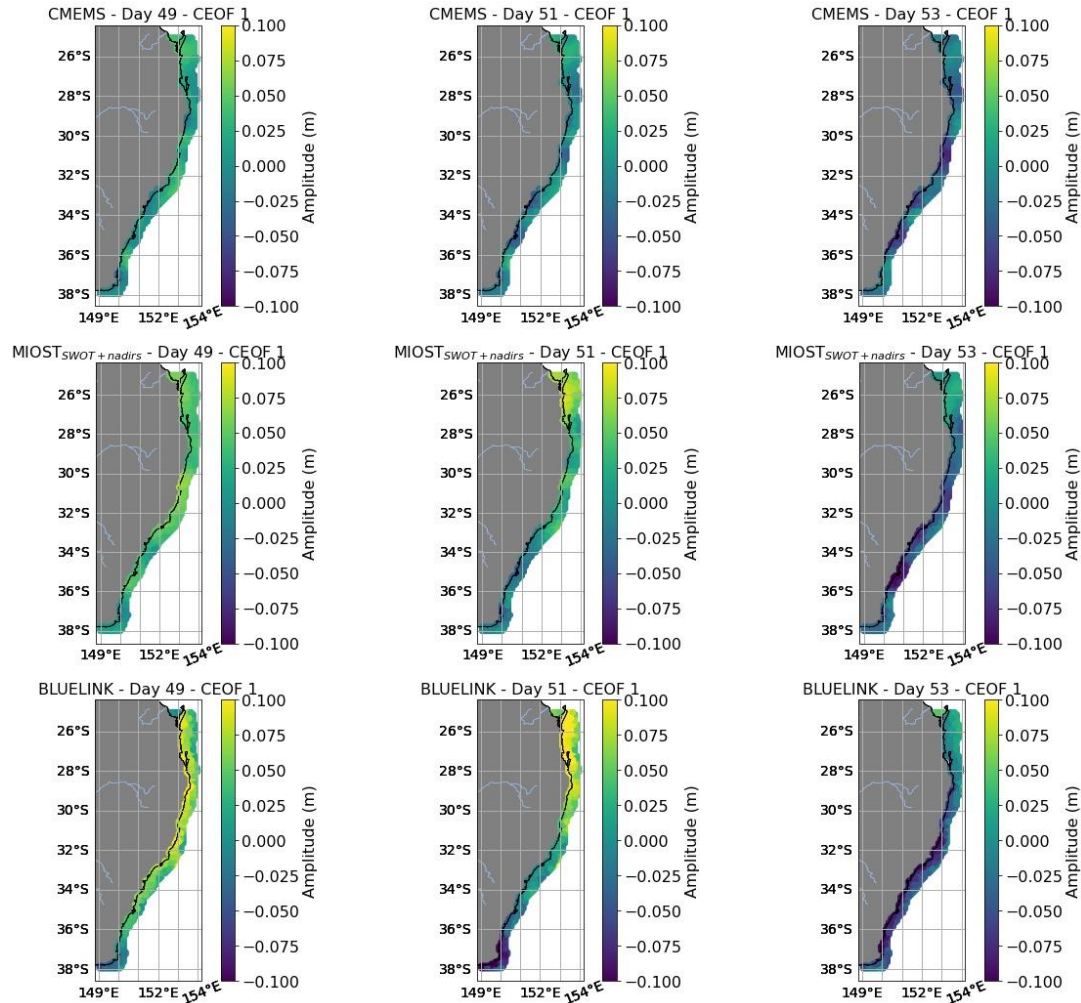


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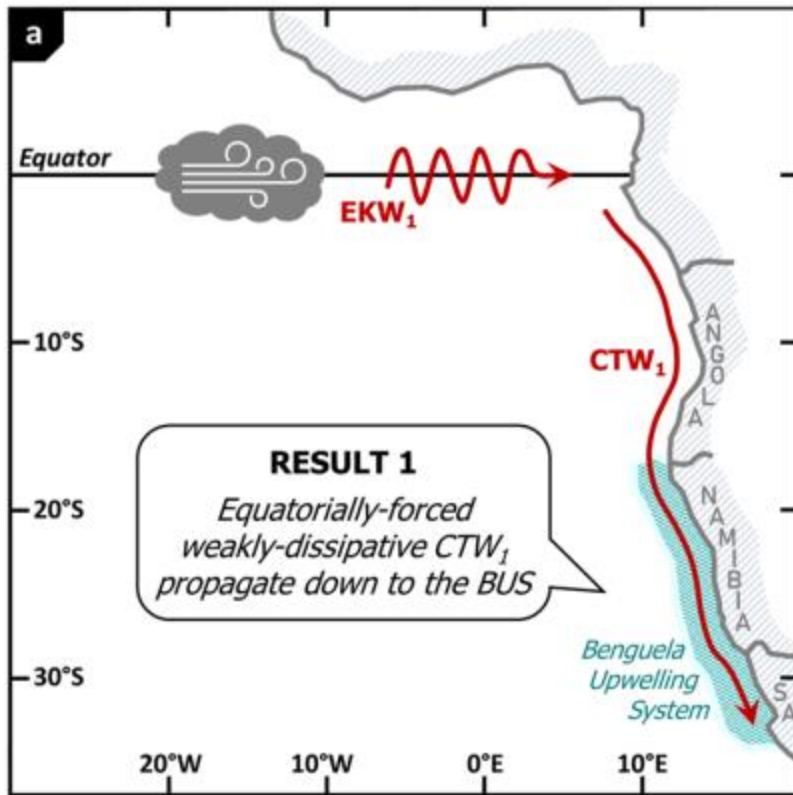
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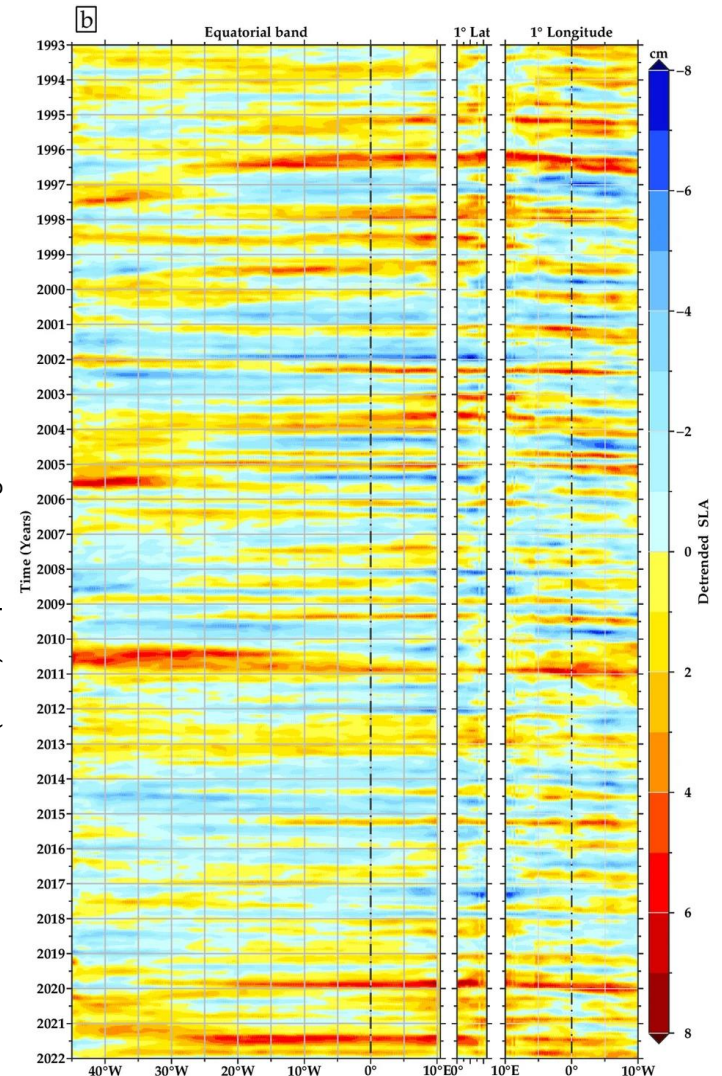


# What are coastally trapped waves?



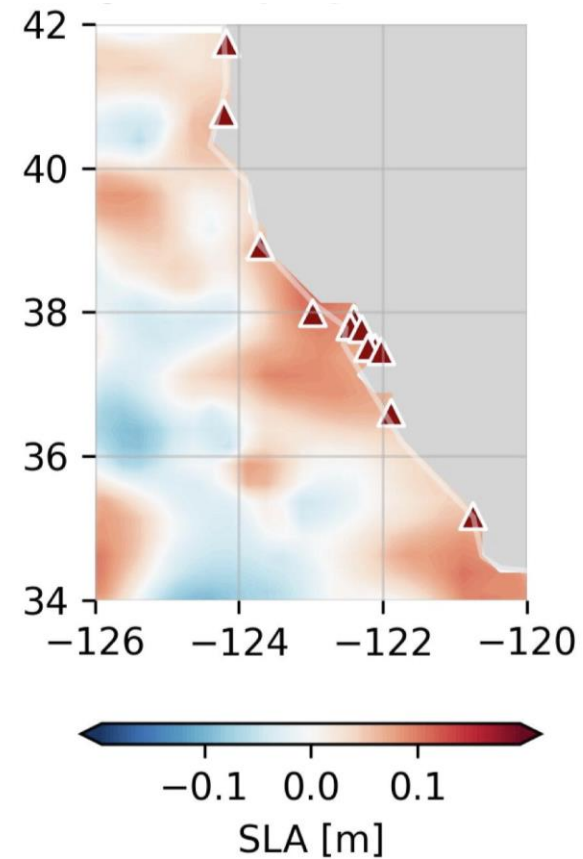
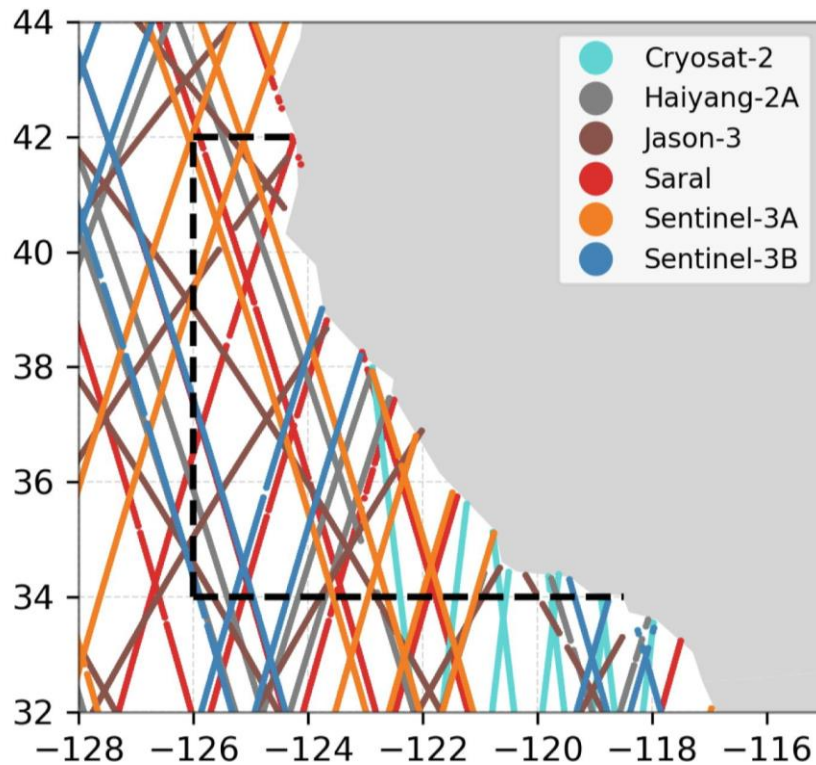
Illig, S., & Bachèlery, M. L. (2019). Propagation of subseasonal equatorially-forced coastal trapped waves down to the Benguela upwelling system. *Scientific Reports*, 9(1), 5306.

Kemgang Ghomsi, F.E., Raj, R.P., Bonaduce, A. et al. Sea level variability in Gulf of Guinea from satellite altimetry. *Sci Rep* 14, 4759 (2024), <https://doi.org/10.1038/s41598-024-55170-x>



# How daily is a daily grid?

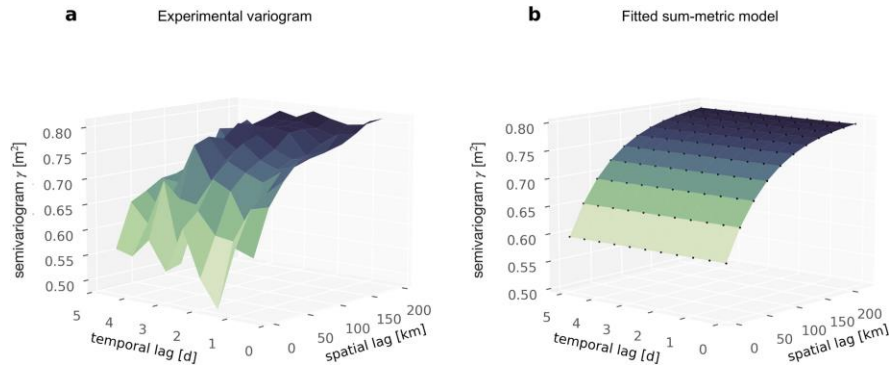
From 10 days of track, through interpolation, to a daily product, an example



Juhl M.-C., Passaro M., Dettmering D.: Regional daily sea level maps from Multi-mission Altimetry using Space-time Window Kriging. *Advances in Space Research*, 10.1016/j.asr.2025.04.014, 2025

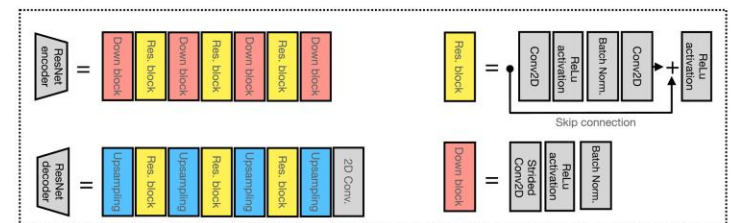
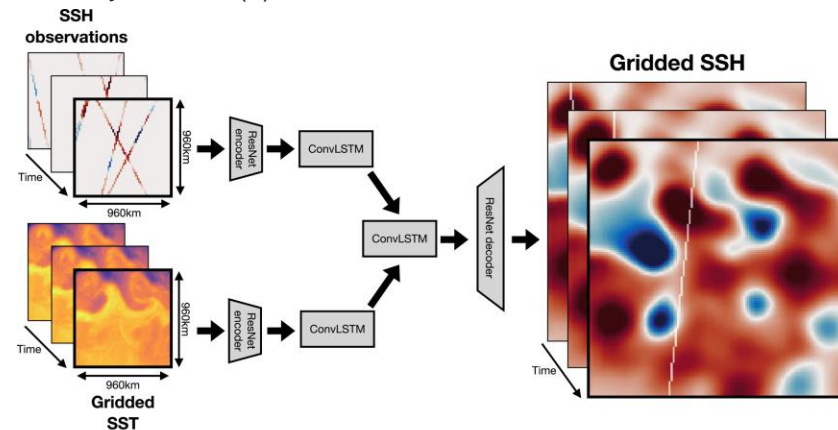
# New methods applied to the gridding problem

Several new algorithms proposed in the last years, transitioning away from the classic optimal interpolation, from Kriging to Deep Learning



Juhl M.-C., Passaro M., Dettmering D.: **Regional daily sea level maps from Multi-mission Altimetry using Space-time Window Kriging**. *Advances in Space Research*, [10.1016/j.asr.2025.04.014](https://doi.org/10.1016/j.asr.2025.04.014), 2025

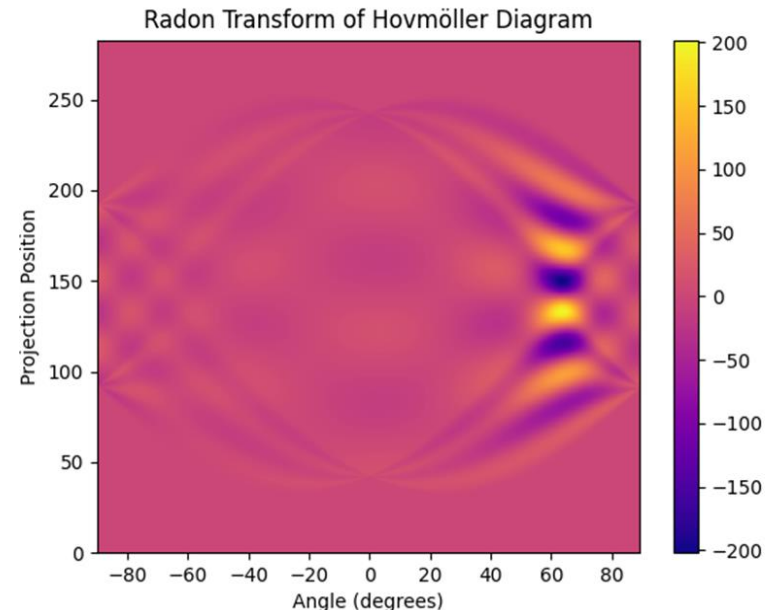
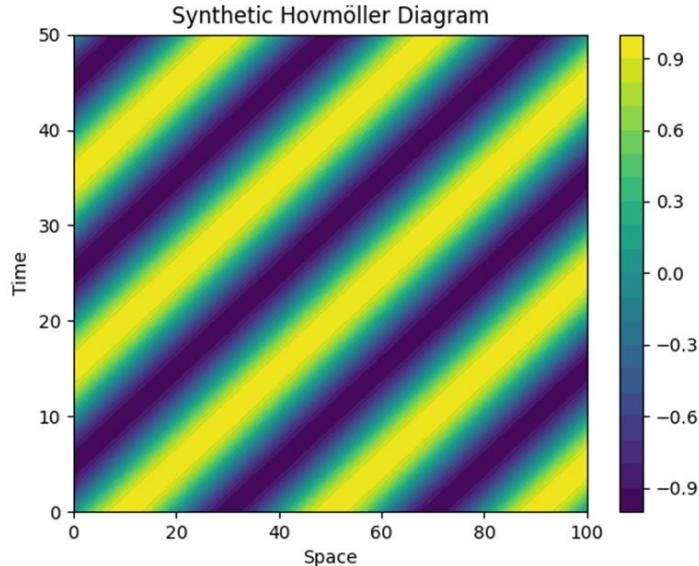
Martin, S. A., Manucharyan, G. E., & Klein, P. (2023). Synthesizing sea surface temperature and satellite altimetry observations using deep learning improves the accuracy and resolution of gridded sea surface height anomalies. *Journal of Advances in Modeling Earth Systems*, 15(5), e2022MS003589.



The providers of the altimetry data to the CMEMS service developed and adopted the "Multiscale Inversion of Ocean Surface Topography (MIOST)" (see next slide)

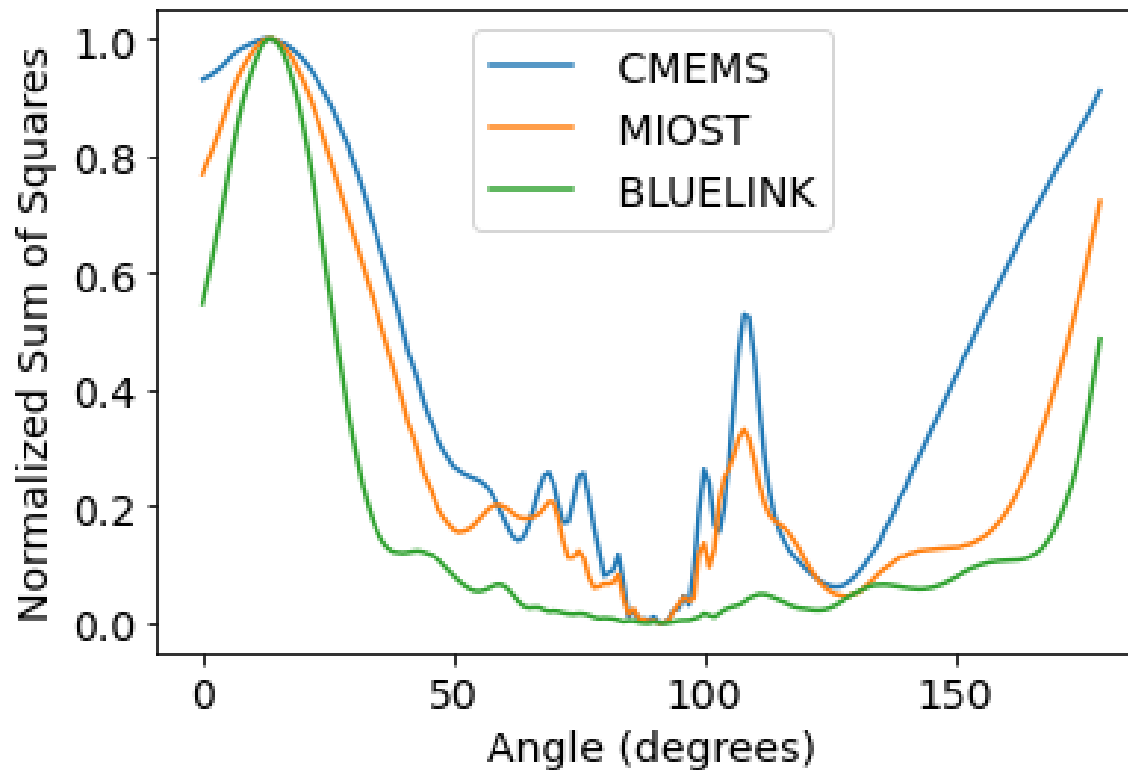
# The Radon Transform

- The Radon transform projects a 2D function  $f(x, t)$  onto a set of lines at various angles  $\theta$ .
- Mathematically:  $R(\rho, \theta) = \iint f(x, t) \delta(\rho - x \cos\theta - t \sin\theta) dx dt$
- Useful for detecting linear features (e.g., wavefronts) in space-time data.
- In a Hovmöller diagram, a propagating wave appears as a diagonal feature.
- The Radon transform identifies the dominant angle of this feature, which corresponds to the wave's velocity.
- Velocity  $v = \Delta x / \Delta t = \cot(\theta)$



# Direction of propagation from the Radon Transform

The better the signal-to-noise ratio, the more accurate is the definition of the most likely direction of propagation.



# Complex Empirical Orthogonal Functions (CEOF)

CEOFs are an extension of EOFs used to analyze oscillatory and propagating phenomena in spatial-temporal datasets.

Steps:

1. Start with a real-valued time series  $x(t)$  at each spatial location.
2. Apply the Hilbert transform to obtain the complex signal  $z(t) = x(t) + i \cdot H[x(t)]$ .
3. Construct a complex data matrix from all spatial locations.
4. Perform eigen-decomposition to extract CEOFs and complex PCs.
5. Analyze amplitude and phase to study propagation patterns.

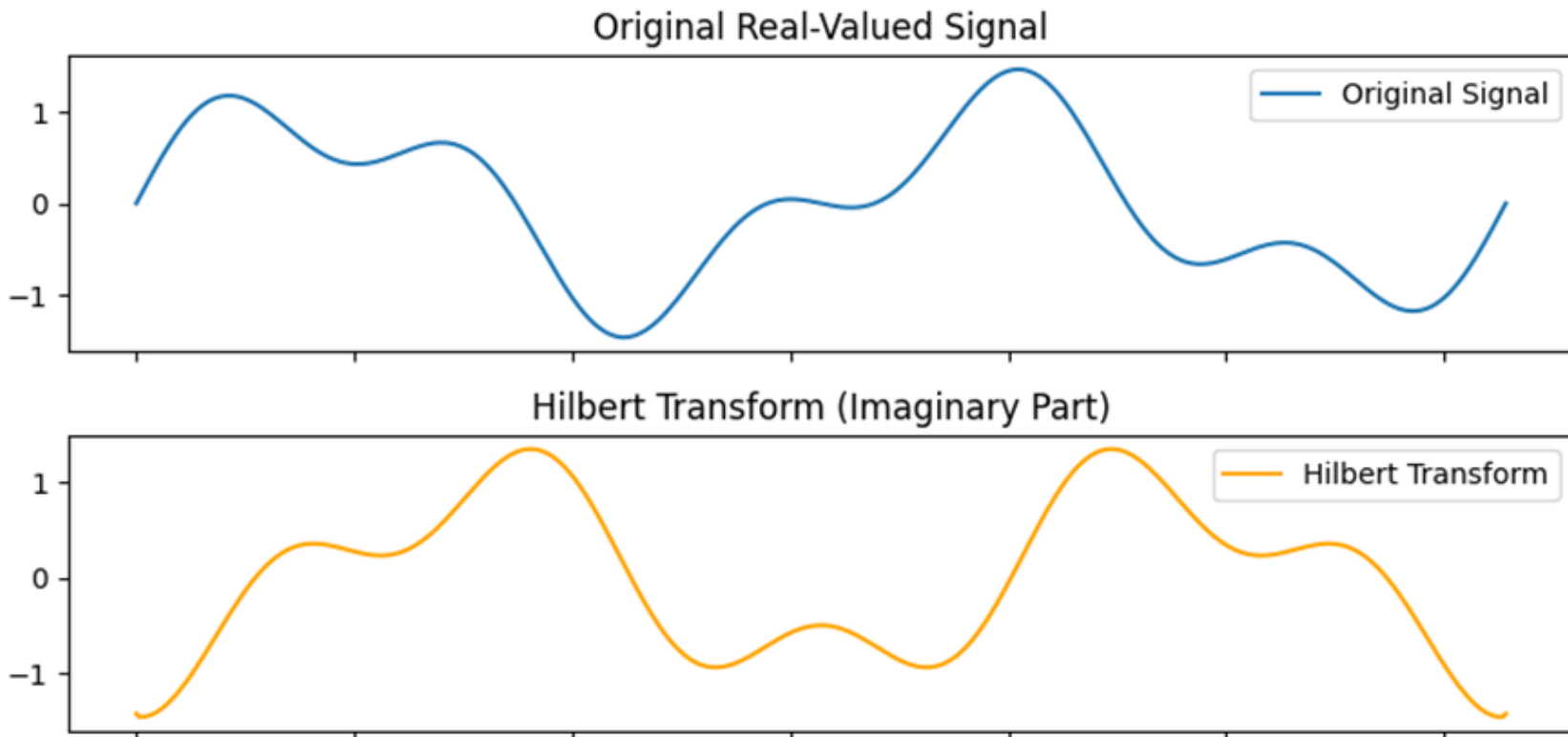
$$\mathbf{Cz} = \lambda \mathbf{z}$$

Where:

- $\mathbf{C}$  is the complex covariance matrix of the analytic signal
- $\mathbf{z}$  is the complex eigenvector (the CEOF mode)
- $\lambda$  is the eigenvalue representing the variance explained by the mode

# The Hilbert transform

- The Hilbert transform is a linear, time-invariant operation.
- It complements the real signal with a 90° phase-shifted version.
- The result is a complex-valued analytic signal:  $z(t) = x(t) + i \cdot H[x(t)]$ .
- The analytic signal reveals instantaneous amplitude and phase.

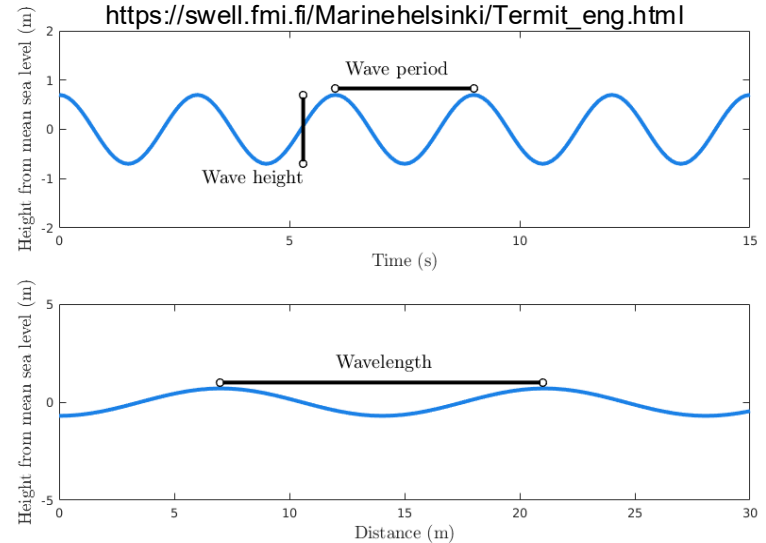


# What are coastally trapped waves?

If these are "waves", why do we see them in sea level anomalies, rather than in significant wave height? Because the spatial and temporal scales are very different!

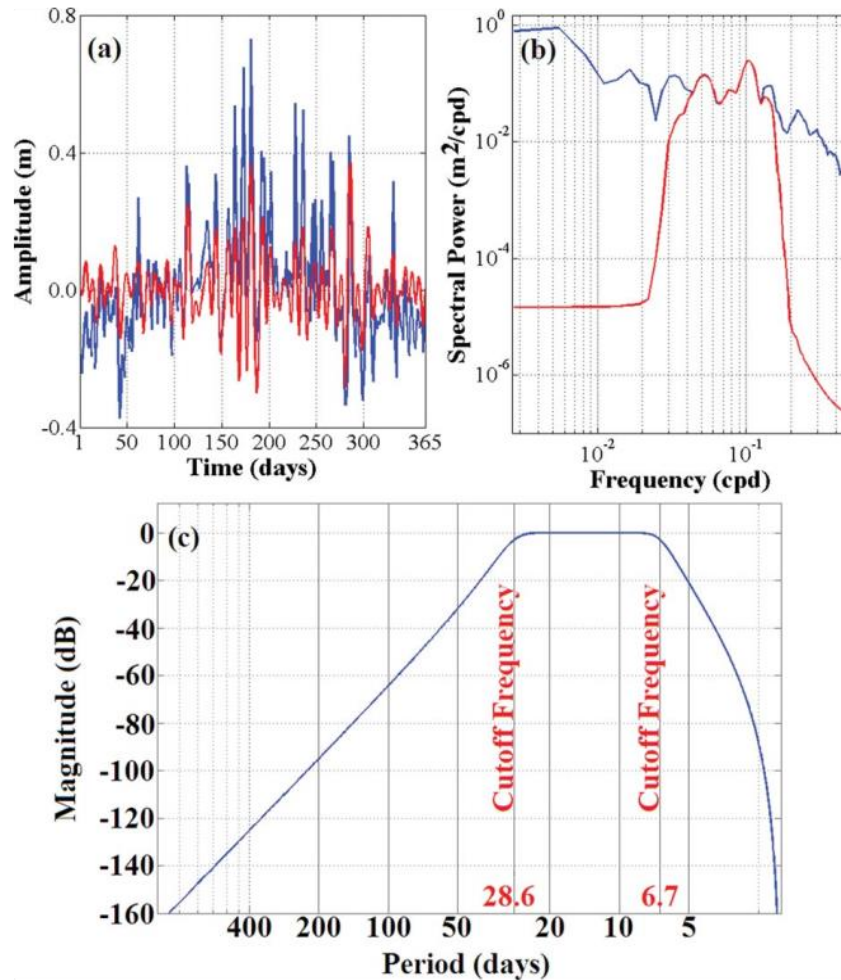
Source:

[https://swell.fmi.fi/Marinehelsinki/Termit\\_eng.html](https://swell.fmi.fi/Marinehelsinki/Termit_eng.html)



Wave Type	Wavelength	Period	Generated By
Wind-Wave	~1–100 m	~1–10 s	Local wind
Swell	~100–500+ m	~10–30 s	Distant storms
Coastally Trapped	~10–1000+ km	~hours–days	Coastal atmospheric forcing

# Analysing filtered signals



**Figure 2.** Bluelink SSH at Thevenard (blue) before and (red) after filtering in the (a) time and (b) frequency domains, and (c) the frequency response of the Butterworth filter used.

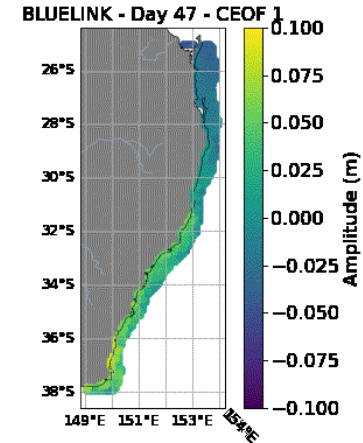
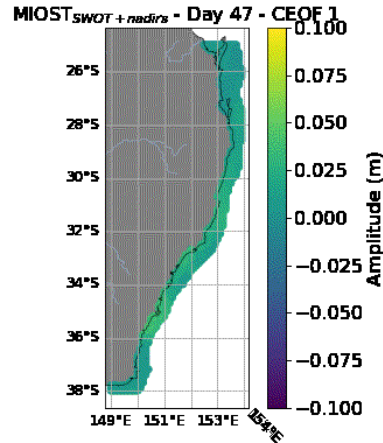
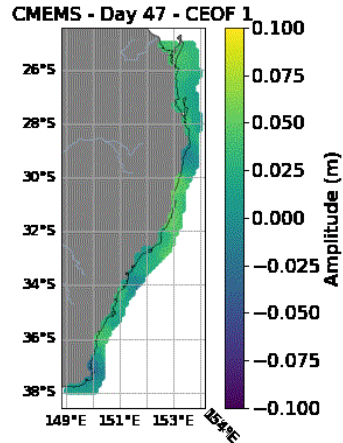
JOURNAL OF GEOPHYSICAL RESEARCH: OCEANS, VOL. 118, 4461–4473, doi:10.1002/jgrc.20317, 2013

**Propagation characteristics of coastally trapped waves on the Australian Continental Shelf**

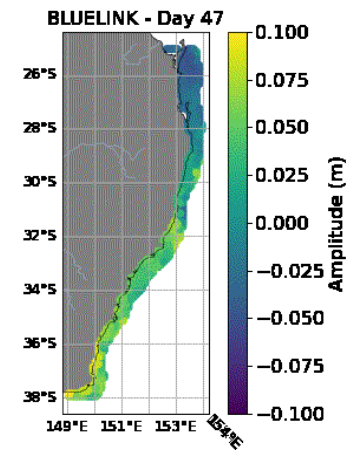
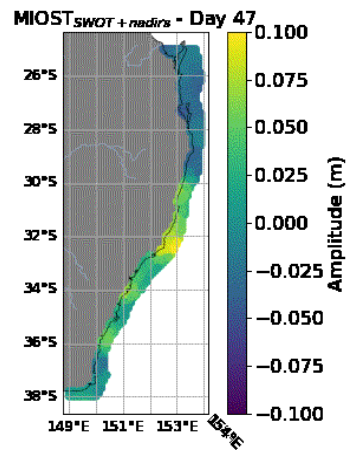
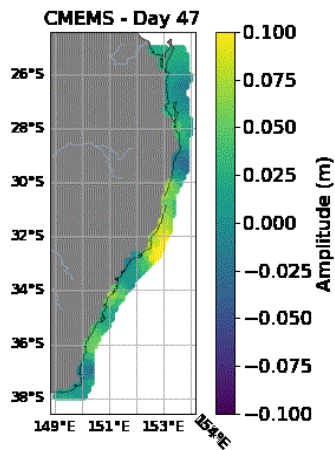
Robert Woodham,<sup>1</sup> Gary B. Brassington,<sup>2</sup> Robin Robertson,<sup>1</sup> and Oscar Alves<sup>2</sup>

Following the methodology of Woodham et al., (2013), at each grid point of the domain I compute a filtered time series. The same procedure is used for CMEMS, MIOST (with SWOT), BLUELINK and tide gauges.

# The largest CTW event reconstructed

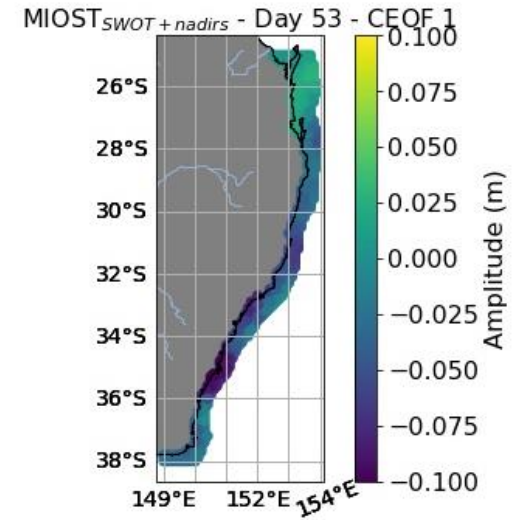
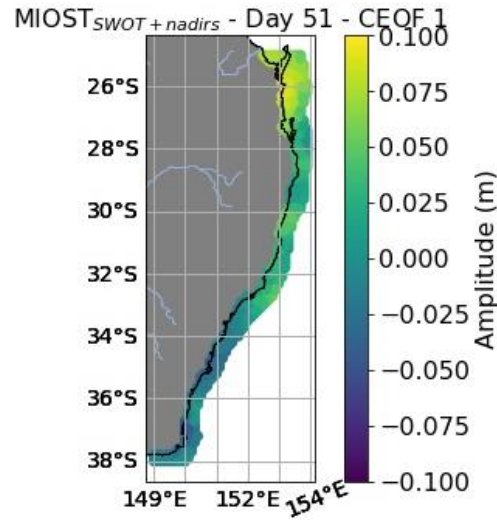
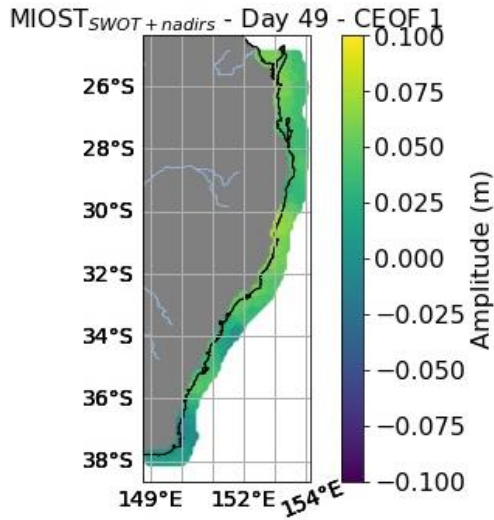


Original (filtered)

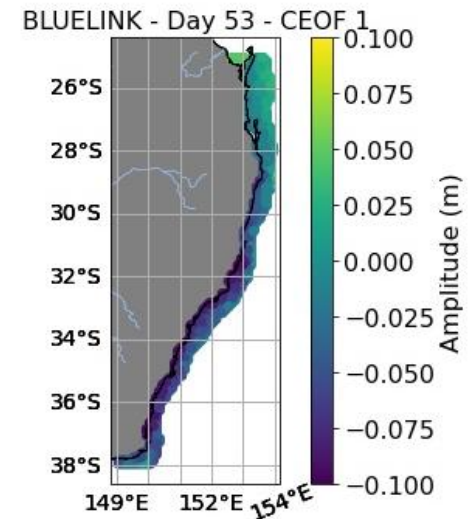
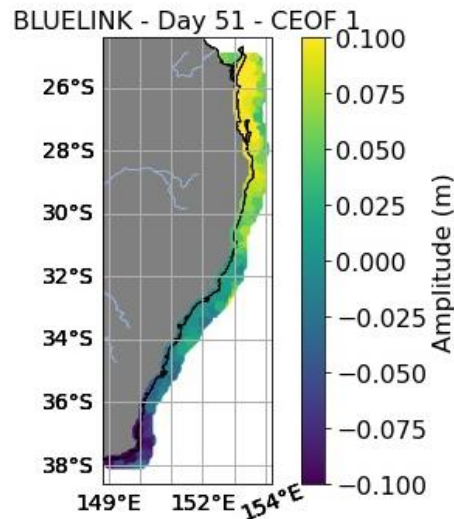
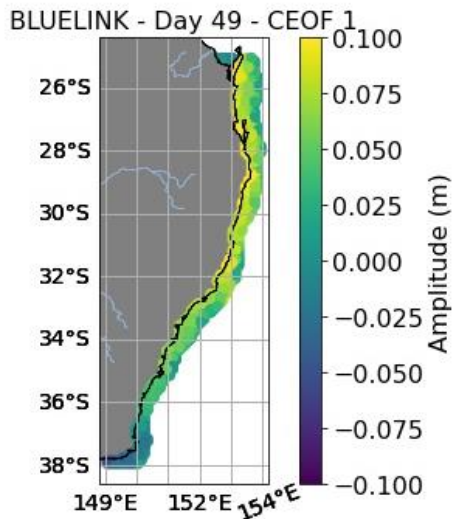


Reconstructed

# The largest CTW event reconstructed



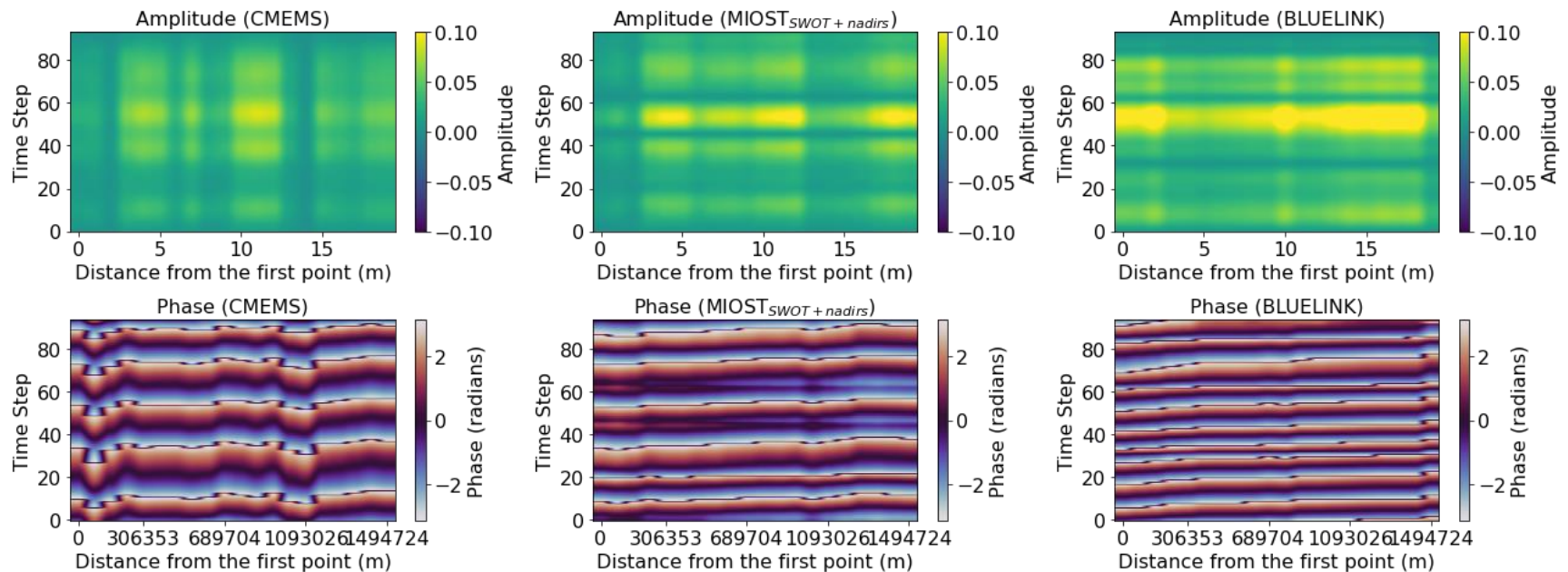
Original (filtered)



Reconstructed

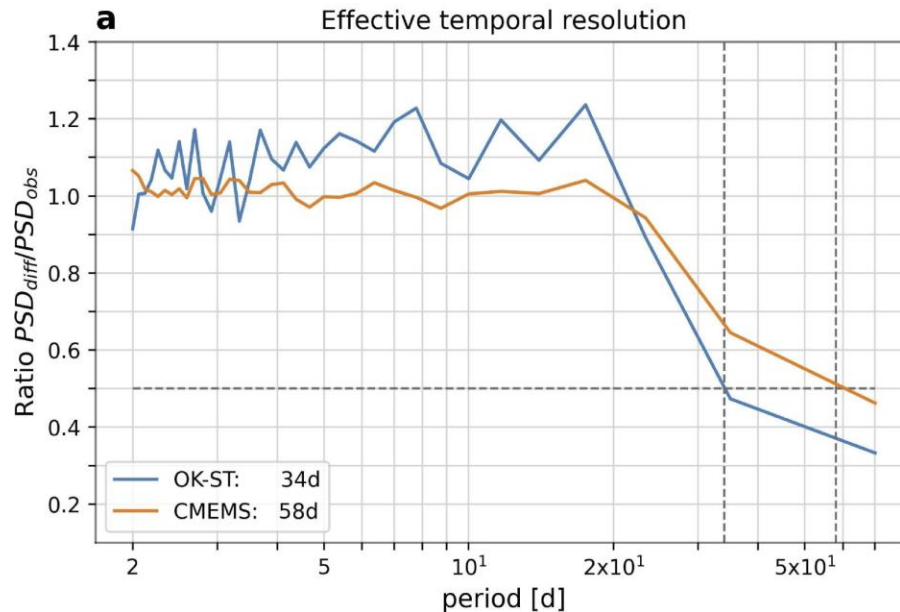
# 1st CEOF visualised in an "Hovmöller fashion"

- True CEOF analysis, amplitude and phase of each mode are obtained
- Dominant 1st mode: 75% of the BLUELINK variance (52-55% for the altimetry dataset)



# How daily is a daily grid?

Which temporal scales can altimetry measure?



Juhl M.-C., Passaro M., Dettmering D.: Regional daily sea level maps from Multi-mission Altimetry using Space-time Window Kriging. *Advances in Space Research*, 10.1016/j.asr.2025.04.014, 2025

Does this mean that "daily" altimetry cannot observe anything below 30 days?

Yes and no: it rather means that at high-frequency the signal is strongly "mixed" with noise

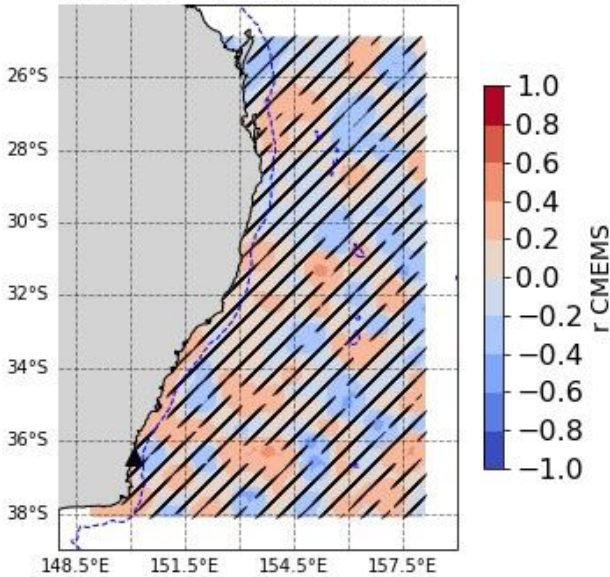
# Reminder: data used and names

90 days of data with a daily sampling are considered for the following sources:

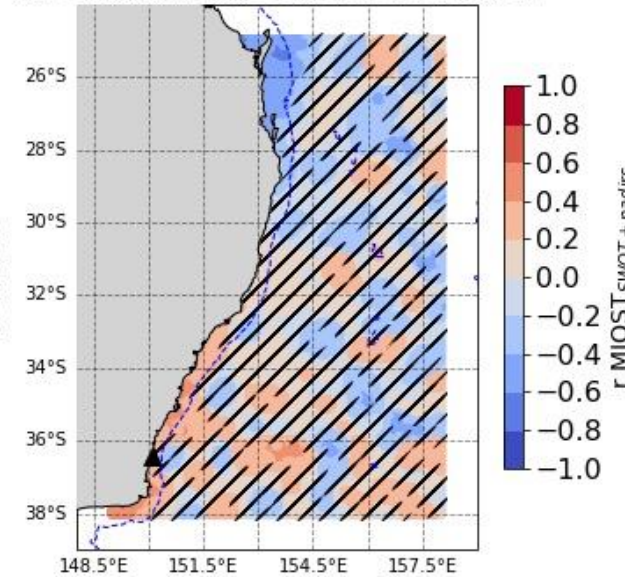
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- 4) A ocean general circulation model with assimilated ocean data (called **BLUELINK** reanalysis)

# 2D lag-correlation patterns

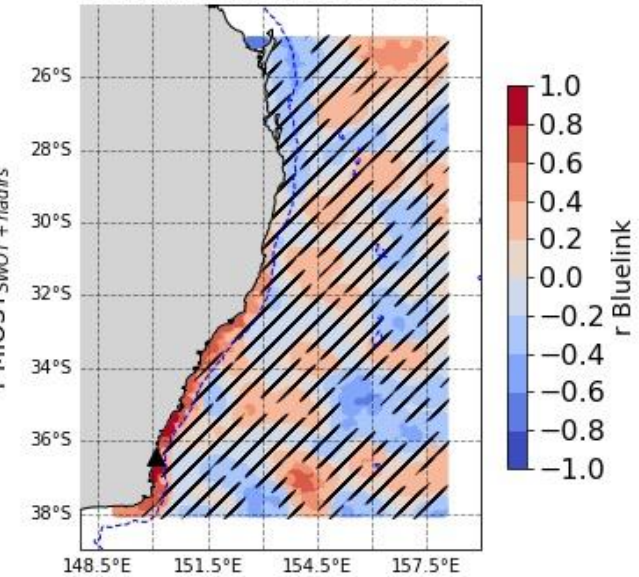
CMEMS Correlations (Lag 0)



MIOST<sub>SWOT+nadirs</sub> Correlations (Lag 0)



Bluelink Correlations (Lag 0)



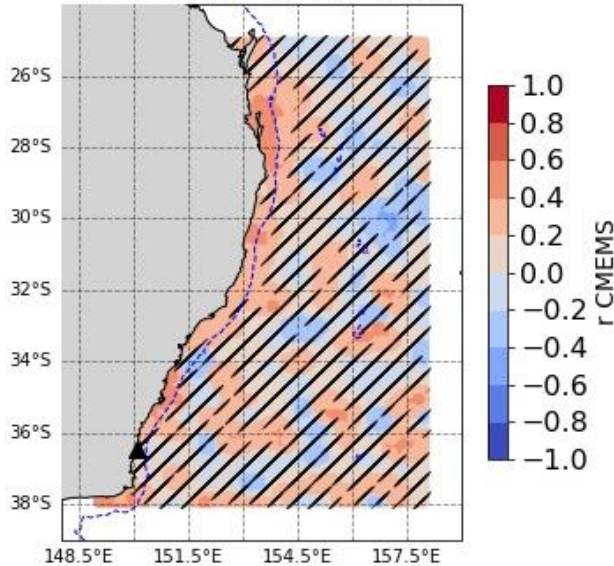
By correlating the tide gauge time series with "delayed versions" at the grid points, we can observe the moving trapped wave pattern.

Stripes show correlations values that are not statistically significant.

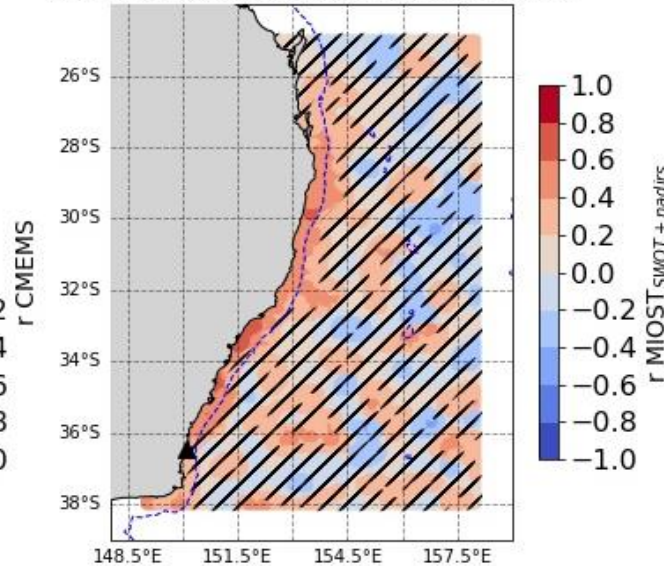
Keep in mind: correlation is not causality, background knowledge is needed to interpret it

# 2D lag-correlation patterns

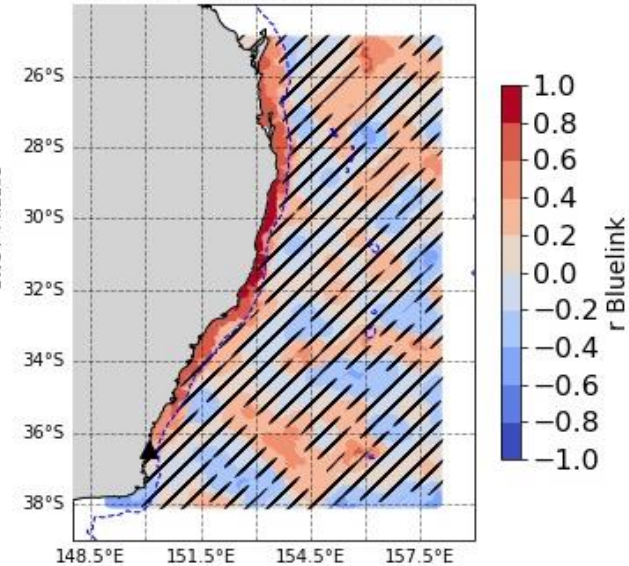
CMEMS Correlations (Lag 2)



MIOST<sub>SWOT+nadirs</sub> Correlations (Lag 2)



Bluelink Correlations (Lag 2)

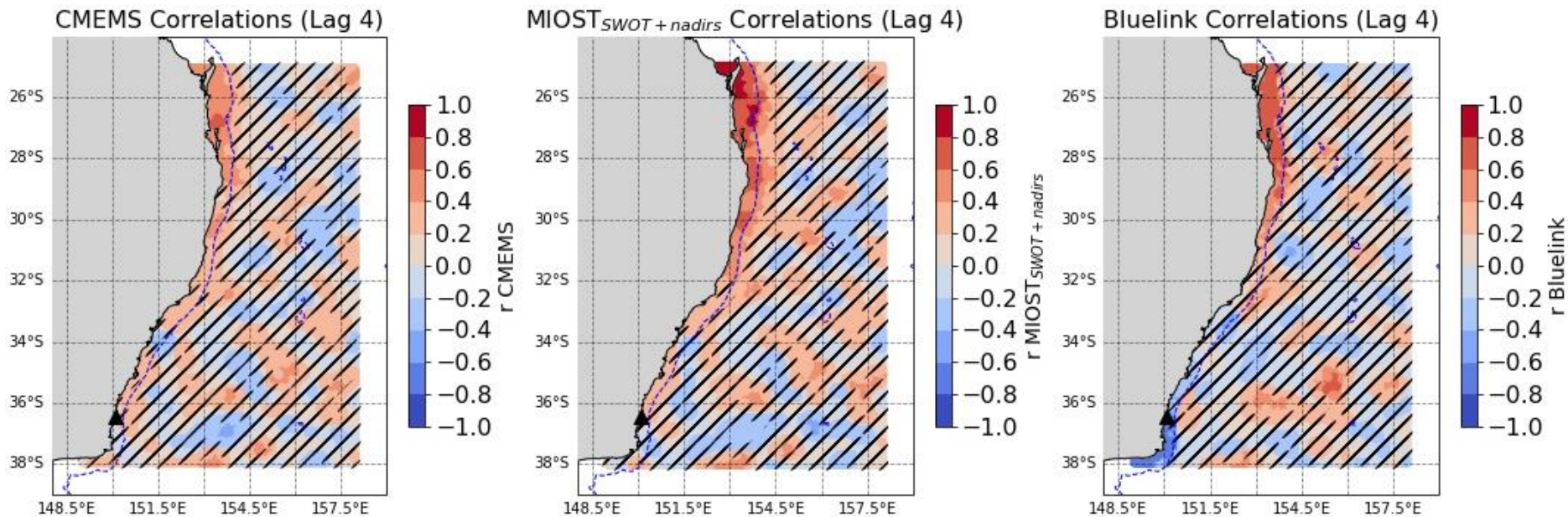


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# 2D lag-correlation patterns



By correlating the tide gauge time series with "delayed versions" at the grid points, we can observe the moving trapped wave pattern.

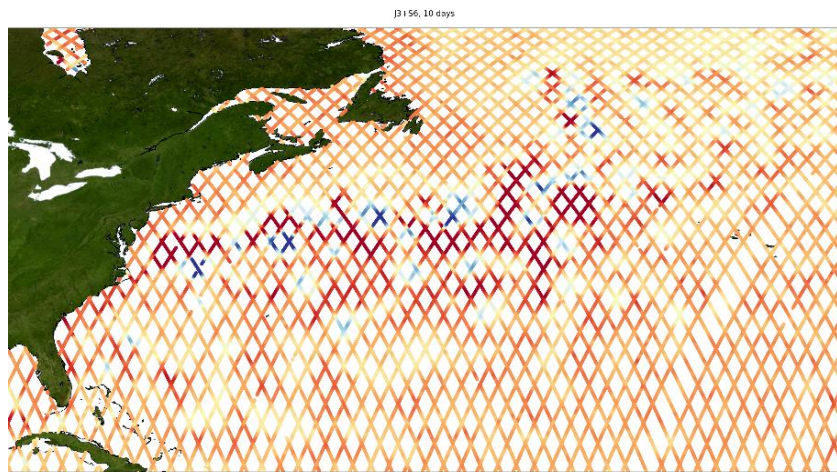
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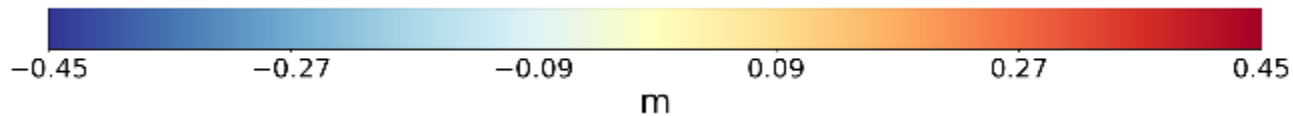
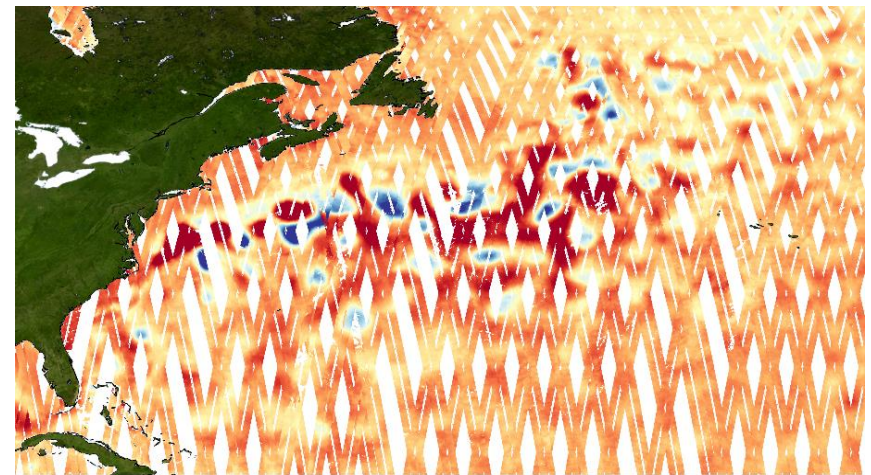
# The elephant in the room: SWOT

MIOST is used in an experimental gridded product in which both classical nadir altimetry and swath altimetry are combined

Classical Nadir Altimetry (2 satellites, 10 days)



Swath Altimetry (10 days, i.e. ~half-cycle)

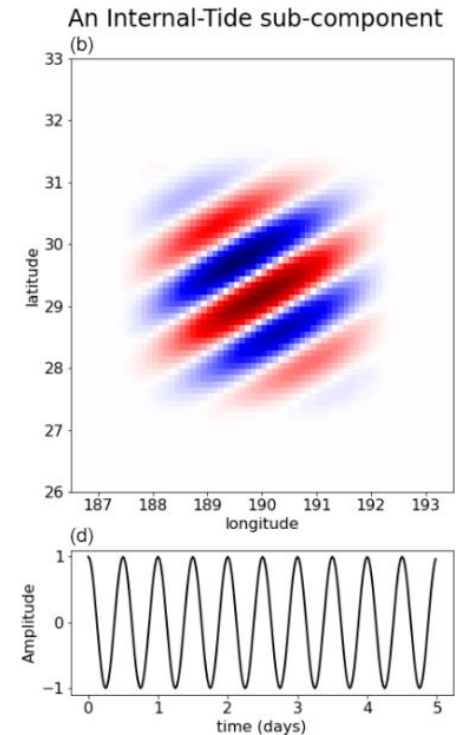
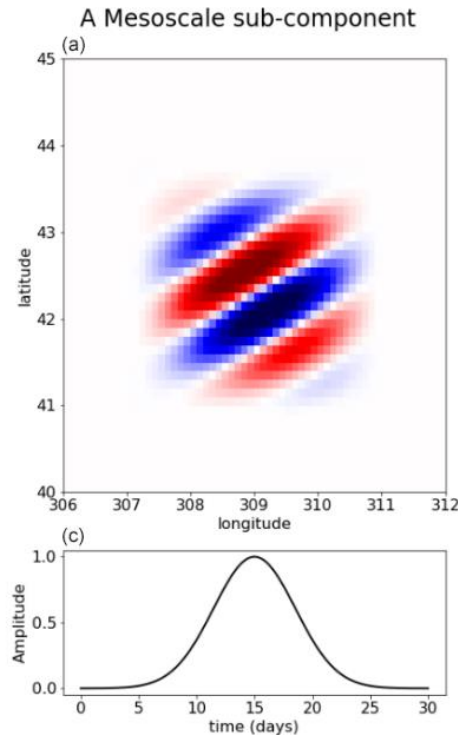


Standard grids are nowadays made with about 10 nadir altimeters...is the addition of SWOT making any difference?

Remember: SWOT has very high spatial resolution, very high quality of coastal data, but rather "standard" temporal sampling

# MIOST

- Dynamic Constraints: Ensures interpolated fields follow ocean dynamics
- Wavelet Transform Role:
  - Decomposes SLA into spatial scales ("inversion in a reduced space", similarly to EOF)
  - Enables scale-dependent interpolation
  - Reduces noise and improves reconstruction



Ubelmann, C., Carrere, L., Durand, C., Dibarboure, G., Faugère, Y., Ballarotta, M., Briol, F. and Lyard, F., 2022. Simultaneous estimation of ocean mesoscale and coherent internal tide sea surface height signatures from the global altimetry record. *Ocean Science*, 18(2), pp.469-481.