Nonlinear interactions of internal solitary waves off the Portuguese coast: SAR observations

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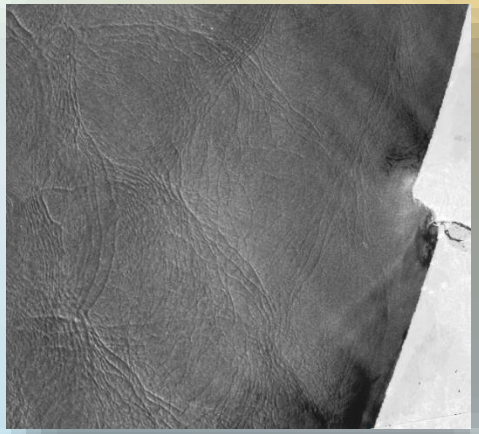
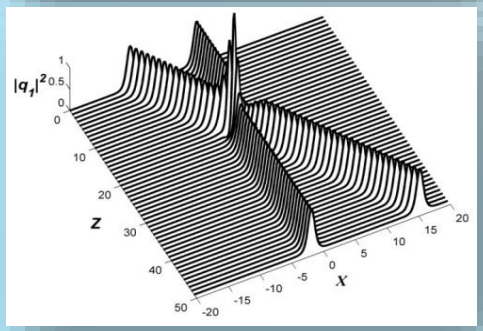
Overview





- Satellite Remote Sensing is showing that Internal Wave (IW) interactions are a frequent phenomenon off coastal regions.
- In situ measurements are consistent with this picture.
- Internal wave–wave interactions yield increased amplitudes up to four times the waves' initial values, which may help explain coastal dynamics in other fields of ocean sciences.

But before that...

What are Internal Waves, how can we see them and why should we care?

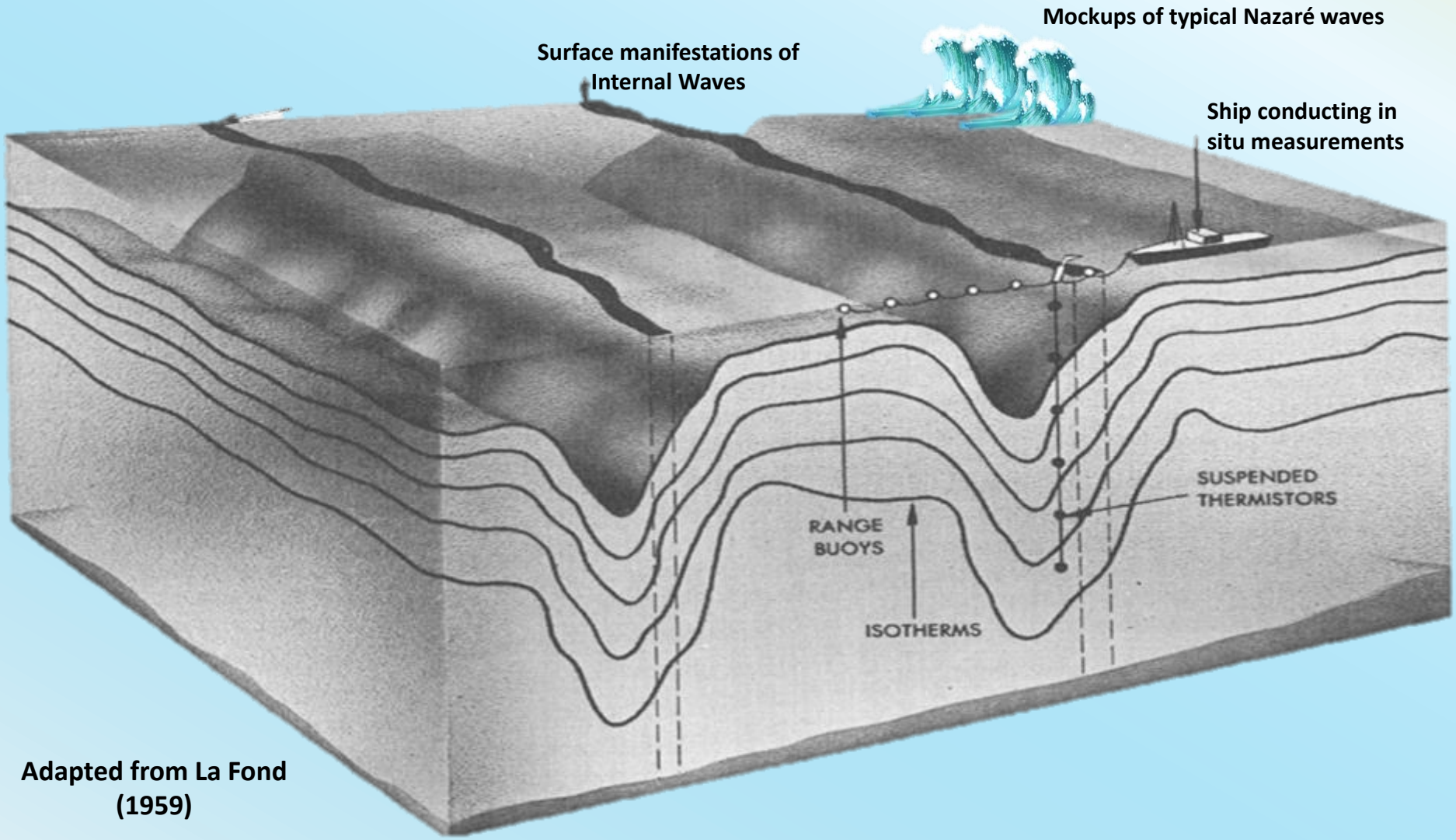
What are internal waves?

Academic subject vs. real world features
(note the surface wave breaking)

Internal Waves seen from a height in Rosario Strait (Washington)
Source: TAF Lab at University of California

Internal waves: defying physical intuition

Internal Waves can be seen as the analog of surface waves propagating in the ocean's interior. A schematic representation of Internal waves is seen here as they travel along the ocean's pycnocline. Note that a typical Nazaré *Big Wave* has been added (to scale) for reference.

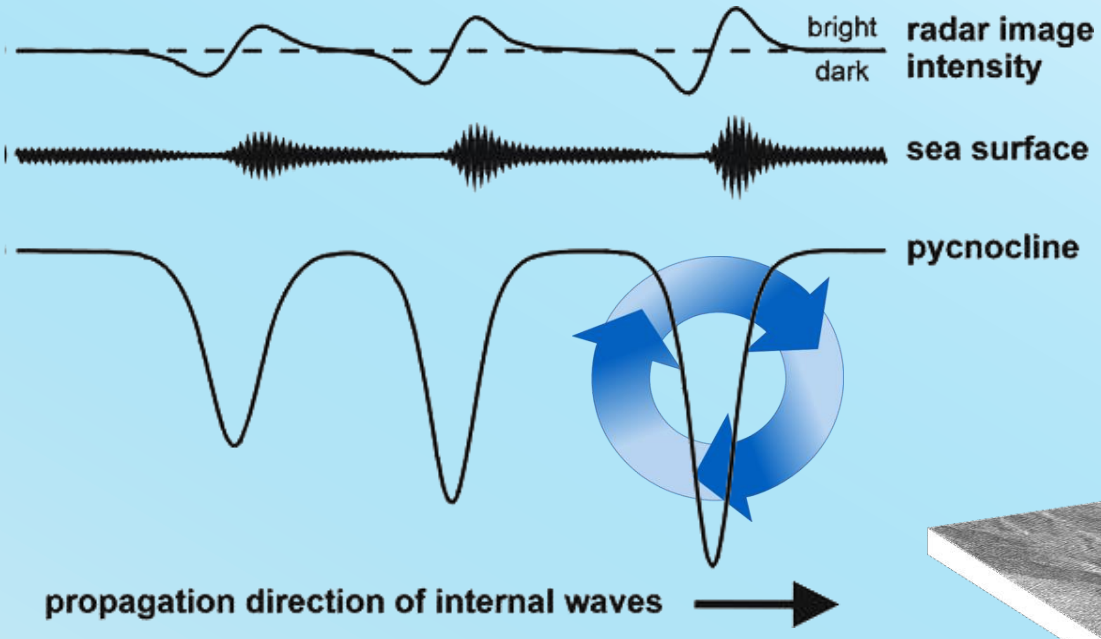


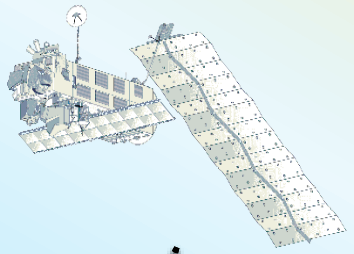
Adapted from La Fond (1959)

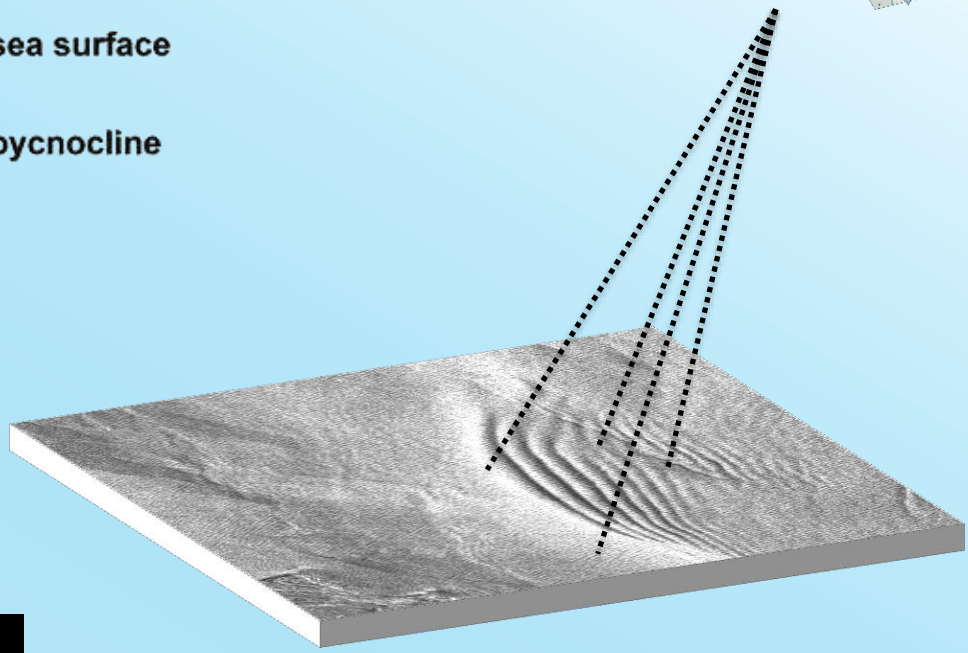
Why are internal waves seen from space?

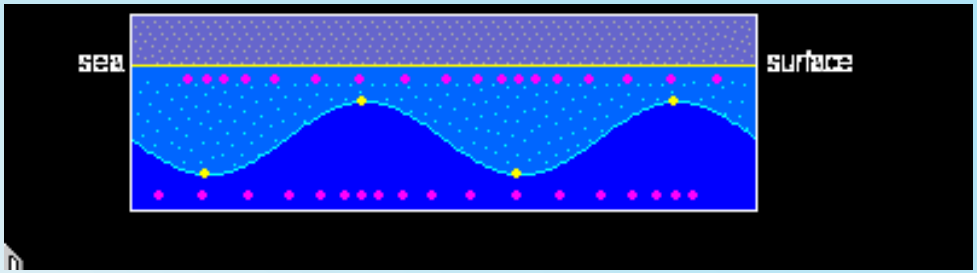
Internal waves are NOT seen from space, but their surface signatures are

Schematics of satellite Synthetic Aperture Radar (SAR) imaging of IWs



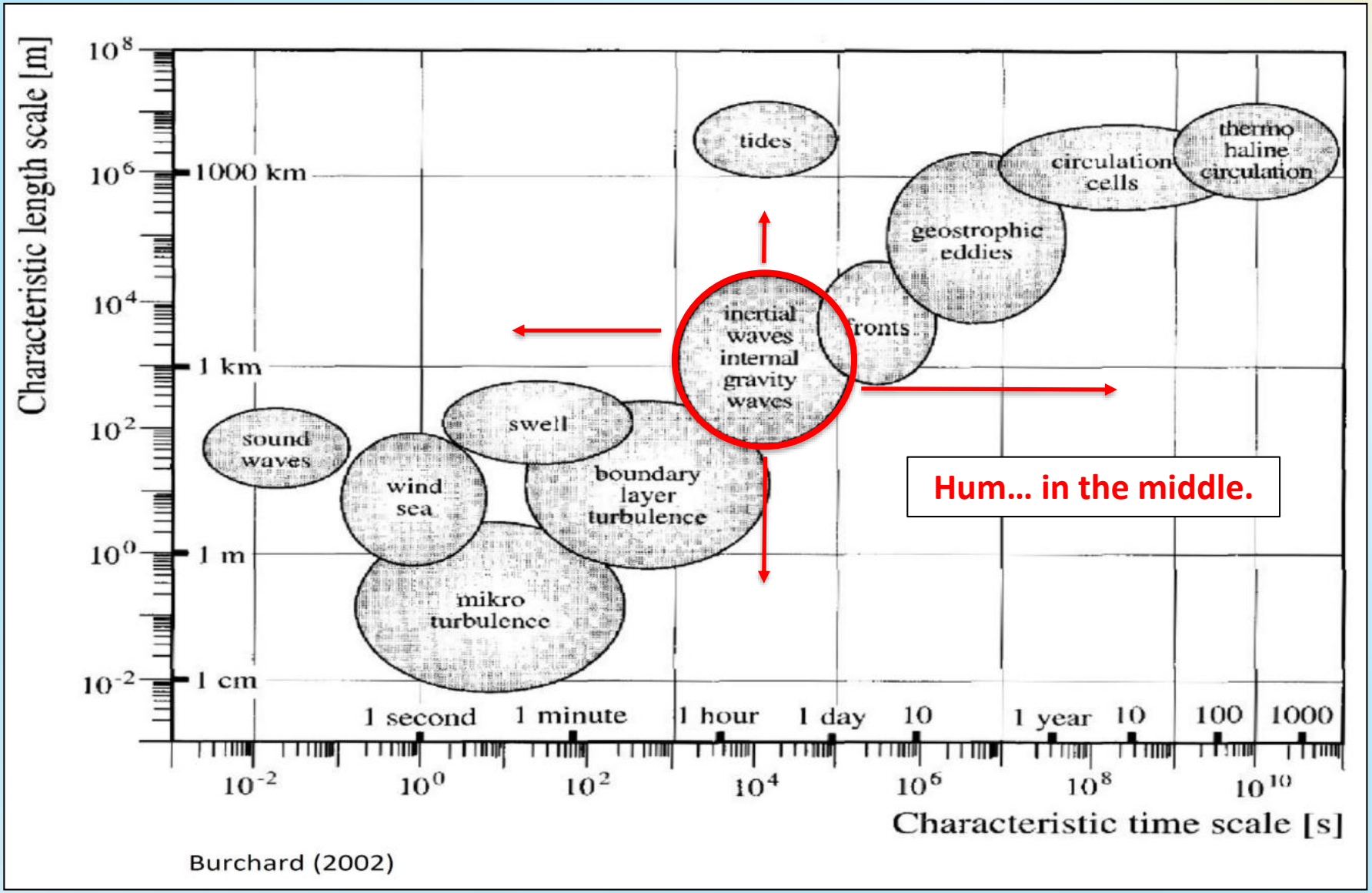






Example of ISWs signatures seen in SAR

The Big Picture in the ocean



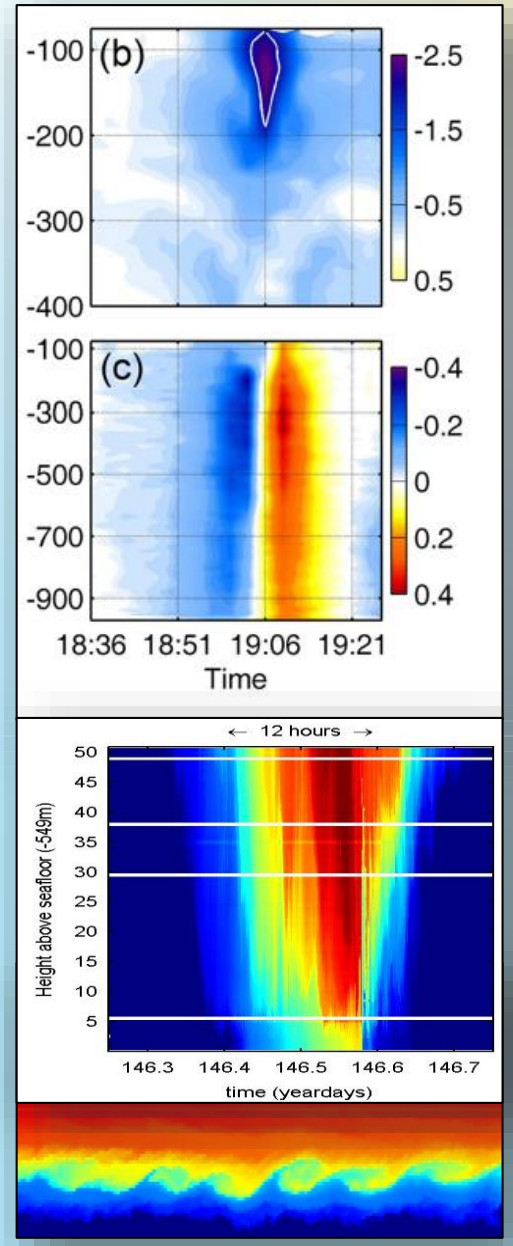
But now we know there is more …

The Big Picture in the ocean

Now we know that:

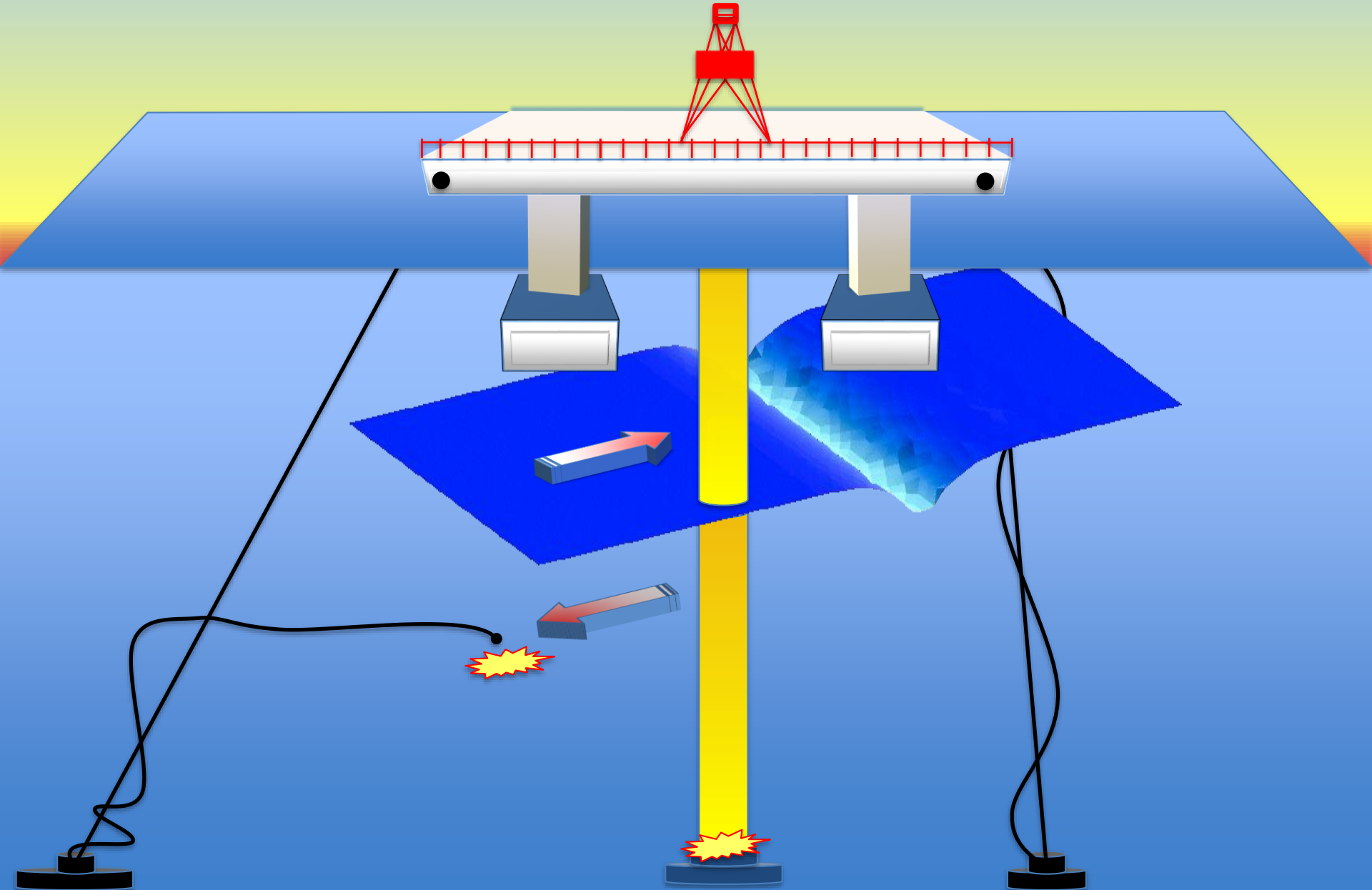
- IWs have the largest vertical velocities in the in the ocean (of the order of 0.5 m/s).
- Interestingly, the maxima of these vertical velocities is close to the pycnocline… so directly related to diapycnal mixing.
- They break and interact with surface waves, causing surface breaking.
- They are nearly everywhere, nearly all the time.
- Horizontal scales from a few meters to a few hundred kilometres.
- Propagation paths ranging up to O(1000) km.
- At the generation sites, turbulence levels are 10,000 times that in the open ocean.
- Remote sensing suggests quasi-perpetual generation in some locations.

Huang et al. (2016). (b) horizontal velocities, (c) vertical velocities (m/s)



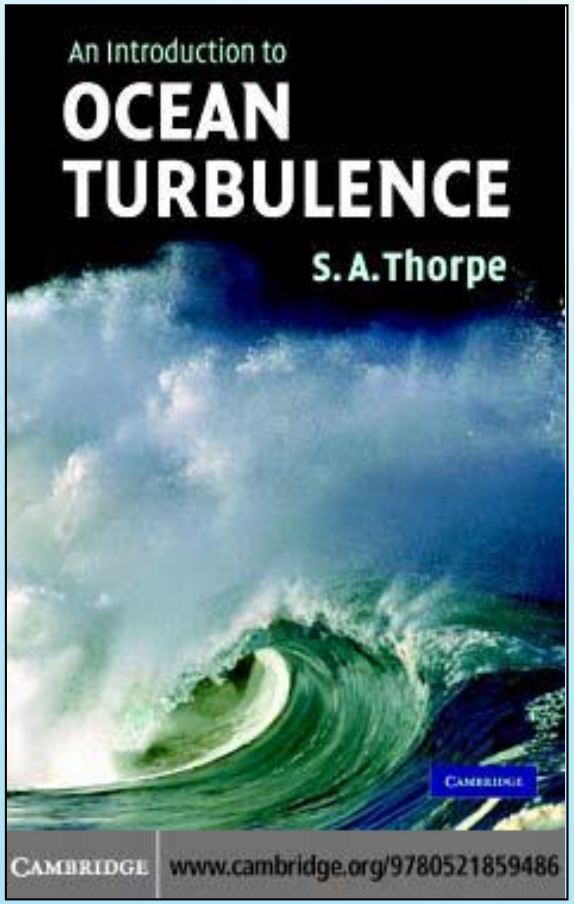
KH instabilities in an Internal Wave, kindly provided by Dr. Van Haren (Royal Netherlands Institute for Sea Research)

Real world applications. ISWs tilting oil rigs – schematics



IWs can be very turbulent in nature

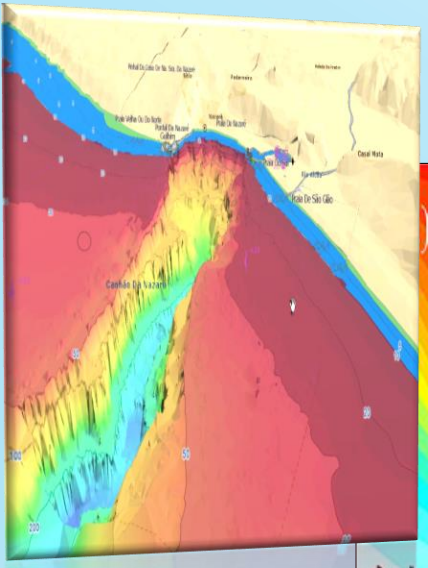
More at https://www.youtube.com/watch?v=i9uVMmmiVFE



Some way or another (at least some of) these waves will eventually have to break.

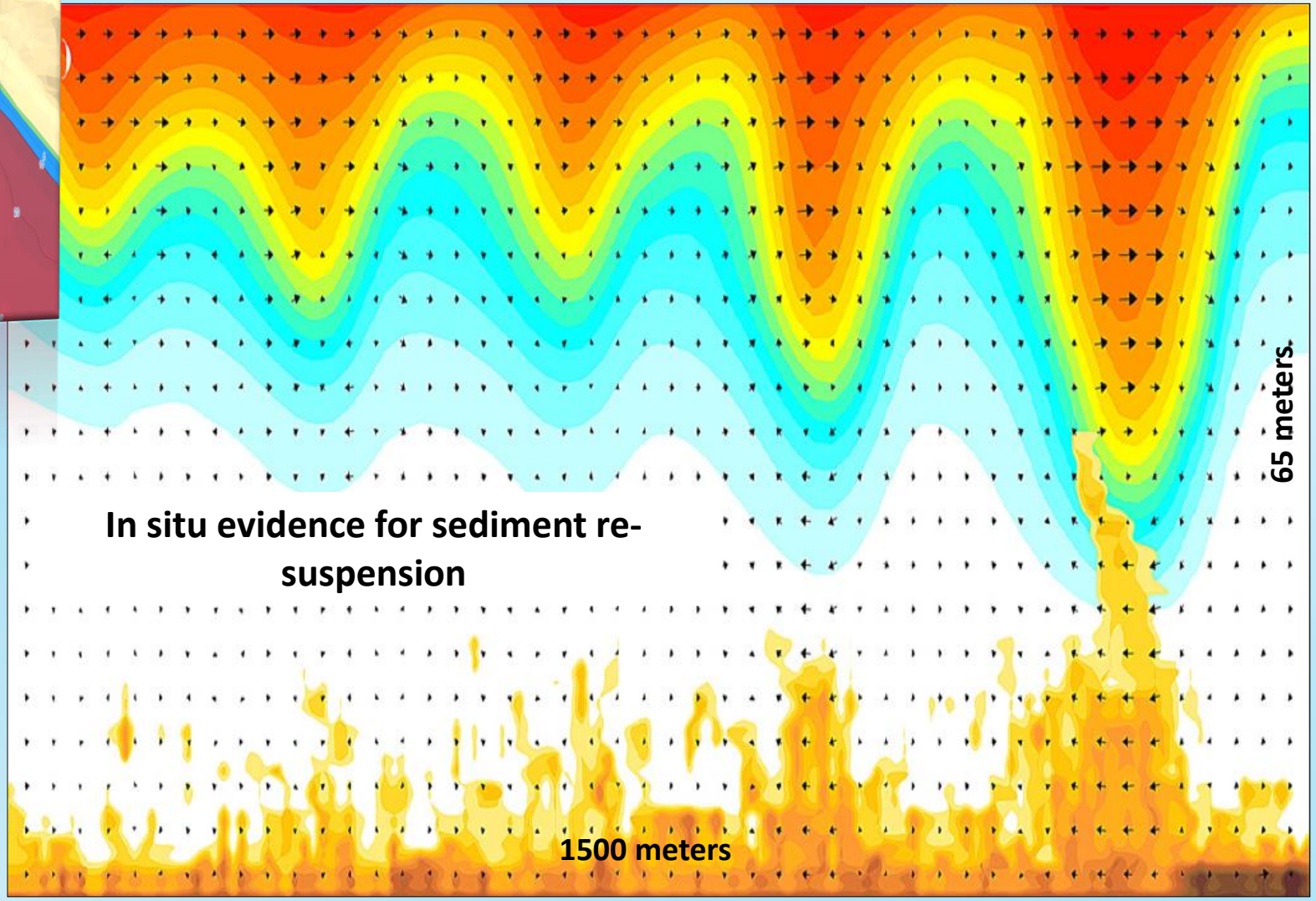
“It disperses dissolved matter in an irreversible way”

(In An Introduction to Ocean Turbulence, by Steve Thorpe, 2007)



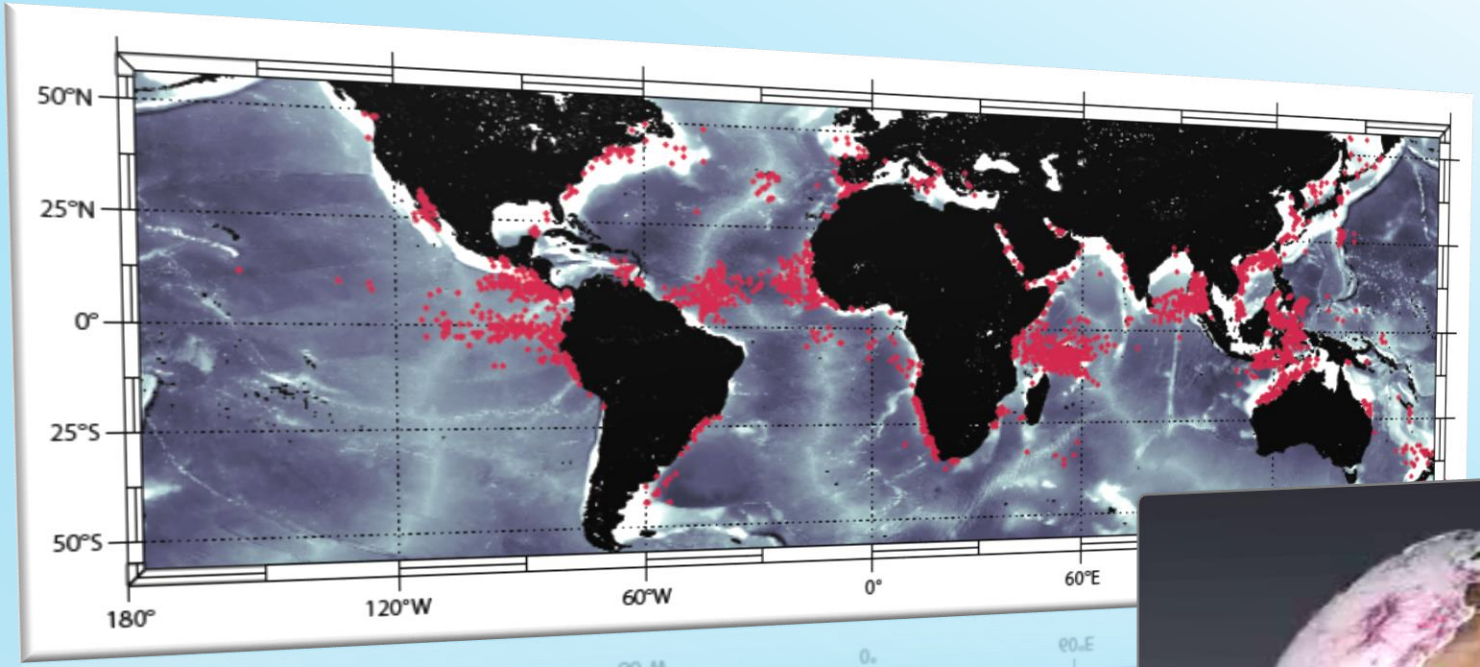
Nazaré Canyon
Portugal

Thermistors chains & 300 kHz ADCP echo intensity, adapted from Quaresma et al. (2007)



Why study internal waves?

They are ubiquitous phenomena

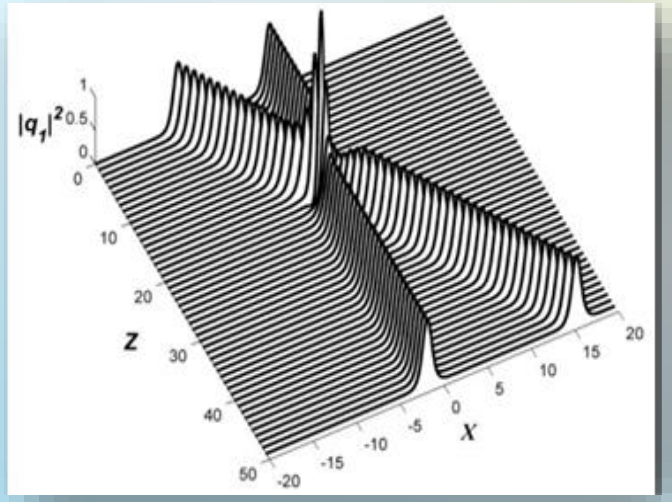


ISWs observed in MODIS imagery (Jackson et al., 2012)

Max-Planck Institute Ocean Model with real time tidal forcing, showing internal tides around 10-60 meters large (from Müller et al., 2012)

An important question then arises: If Internal waves are frequent phenomena in the ocean, what happens when they meet?

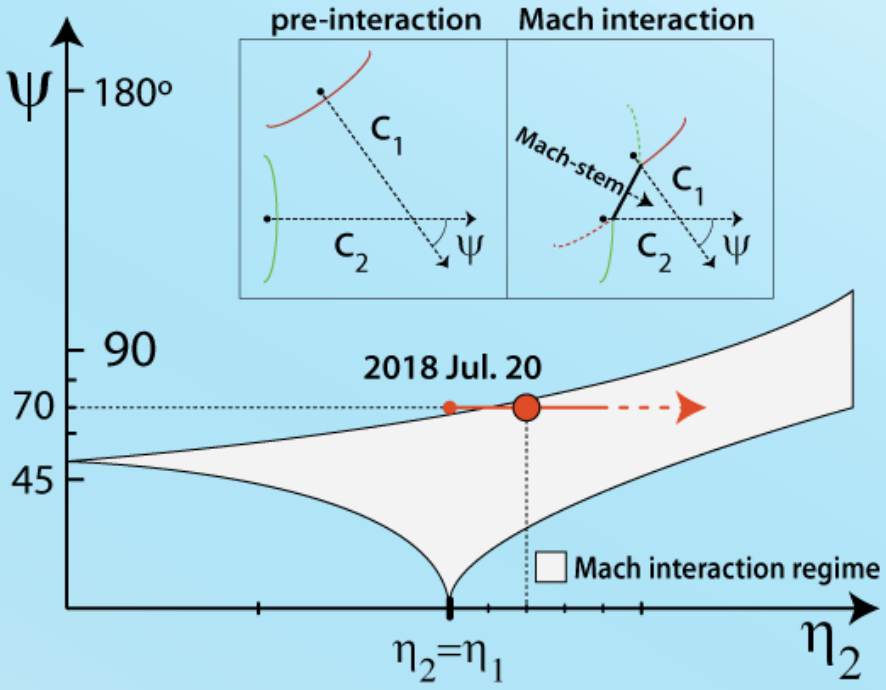
Theory (Ablowitz and Baldwin, 2012)



Analogue (Ablowitz and Baldwin, 2012)

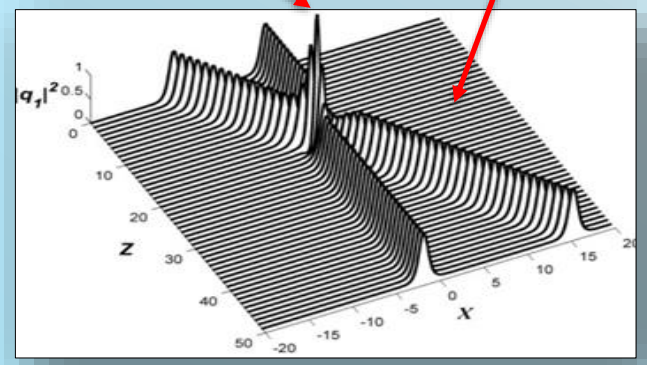
Linearly speaking not much… but IWs are highly nonlinear and there things get interesting.

A very quick summary of the underlying theory:



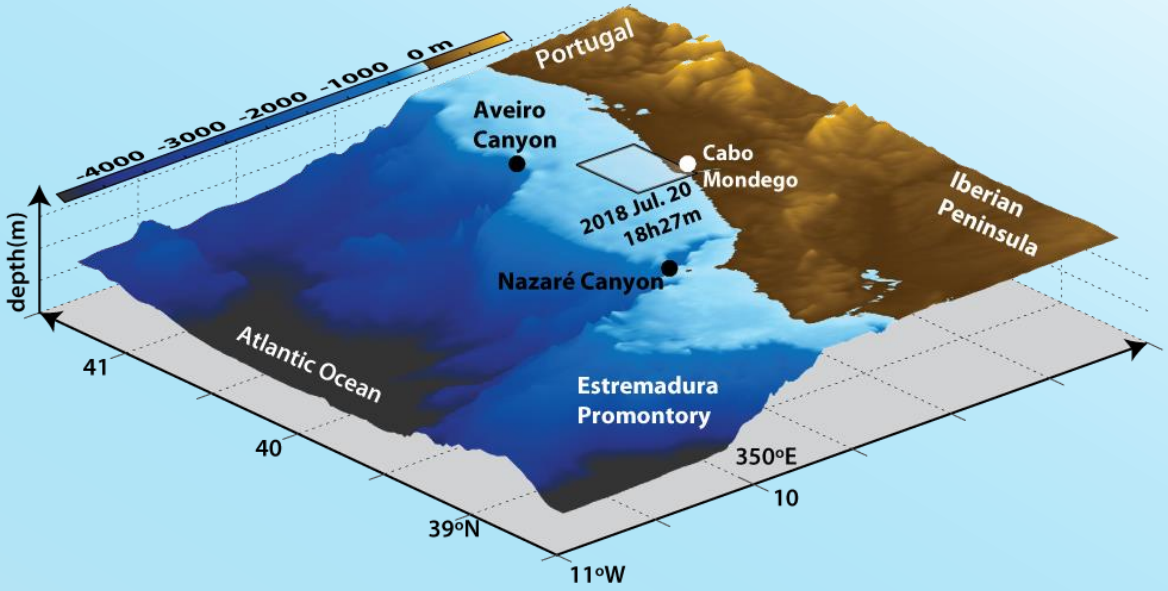
$$\varepsilon < 1$$

$$\eta_M = (1+\varepsilon)^2 \eta_i$$



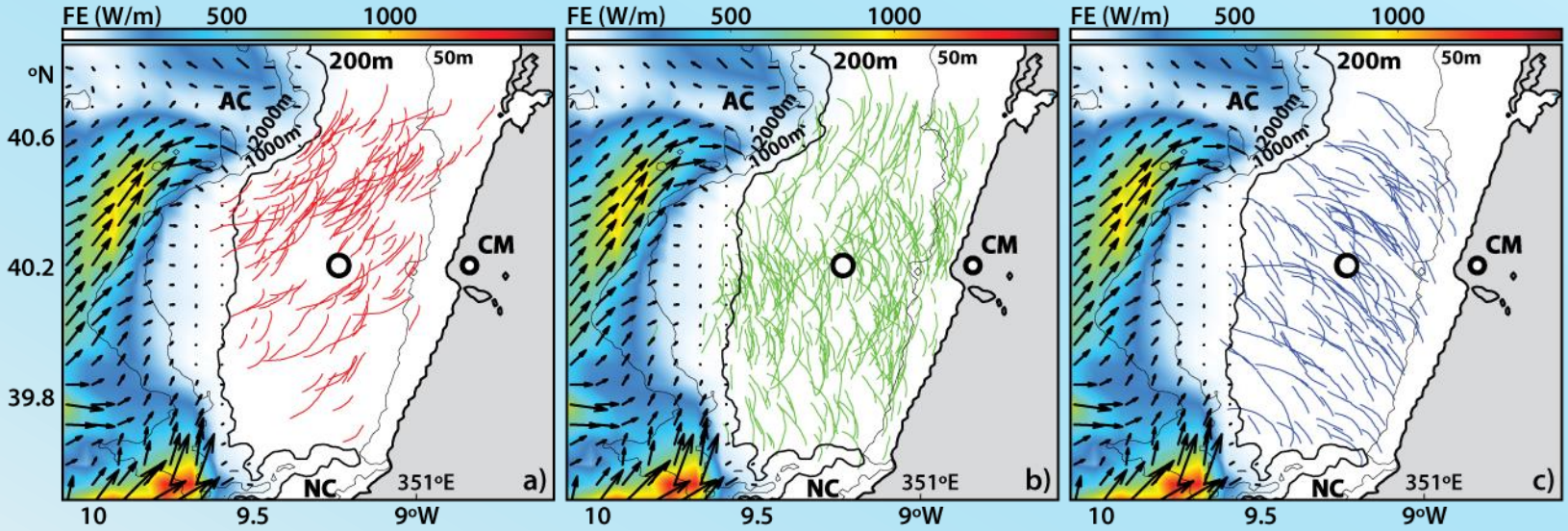
So in essence, Internal Waves can grow (up to four times) in amplitude during special cases of nonlinear interaction.

SAR evidence of IW interactions

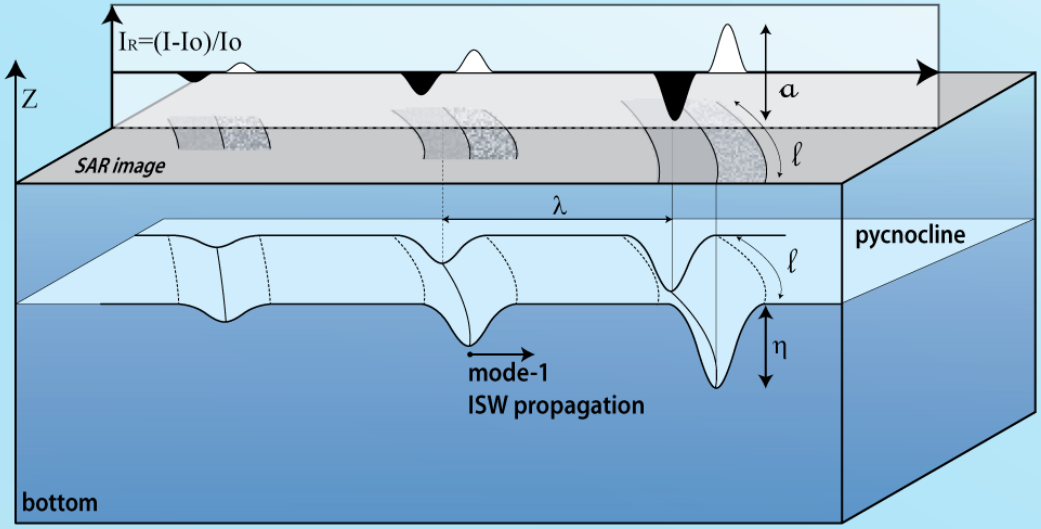


Clearly, SAR shows that IWs are a frequent feature off the Portuguese coast.

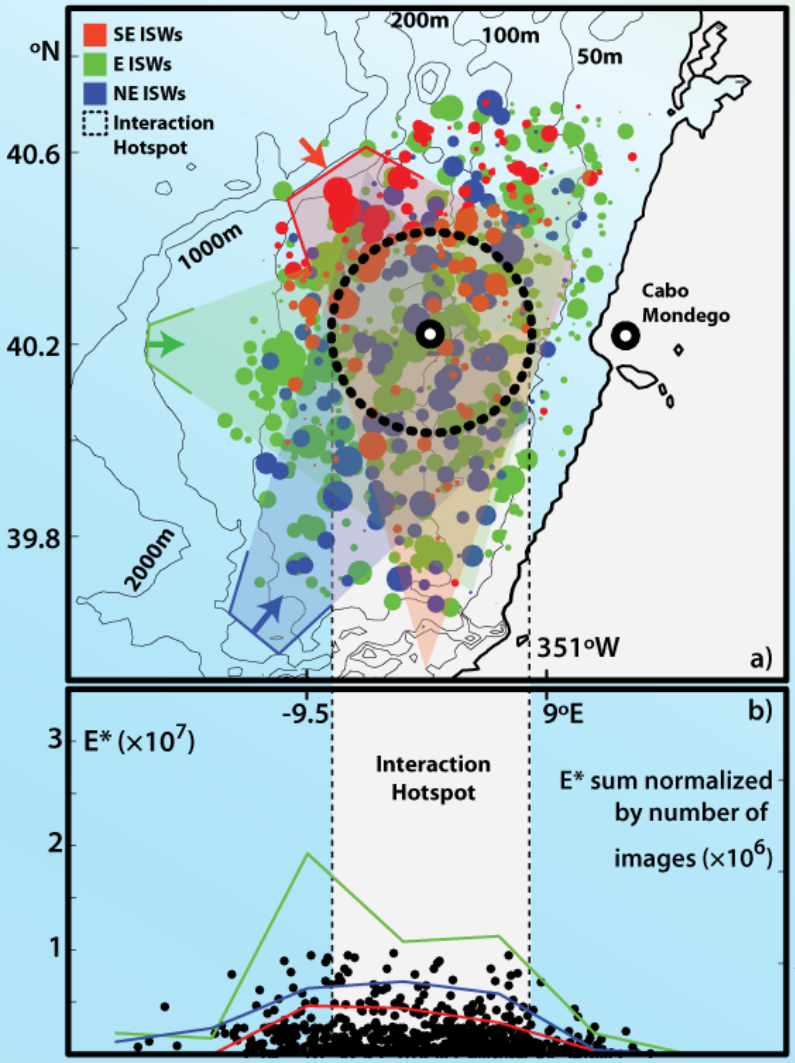
Off Cabo Mondego they propagate shoreward from three main directions, which are bound to intersect along the mid-shelf.



SAR evidence of IW interactions

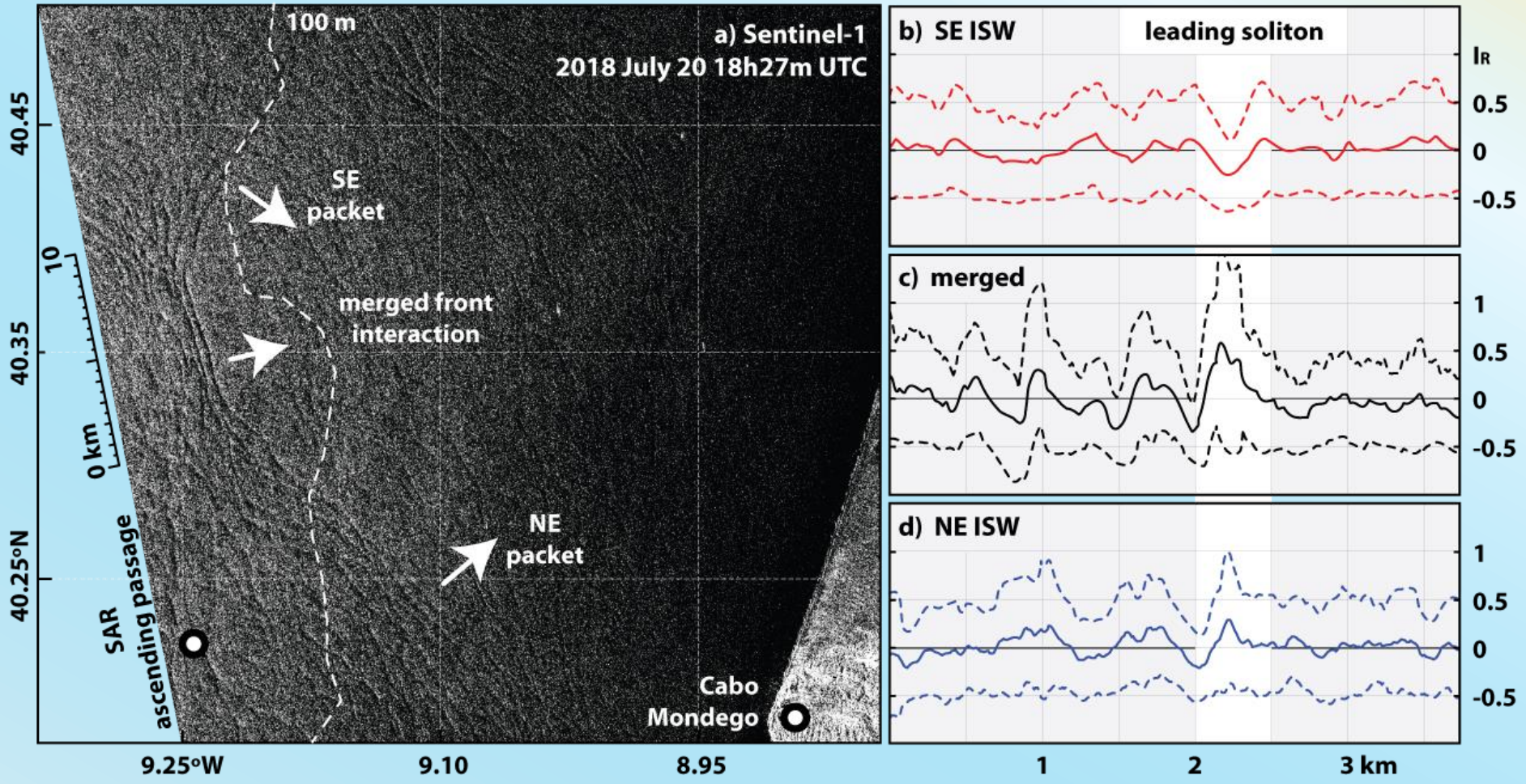


A proxy for the waves' energy can be estimated using their sea surface signatures from SAR



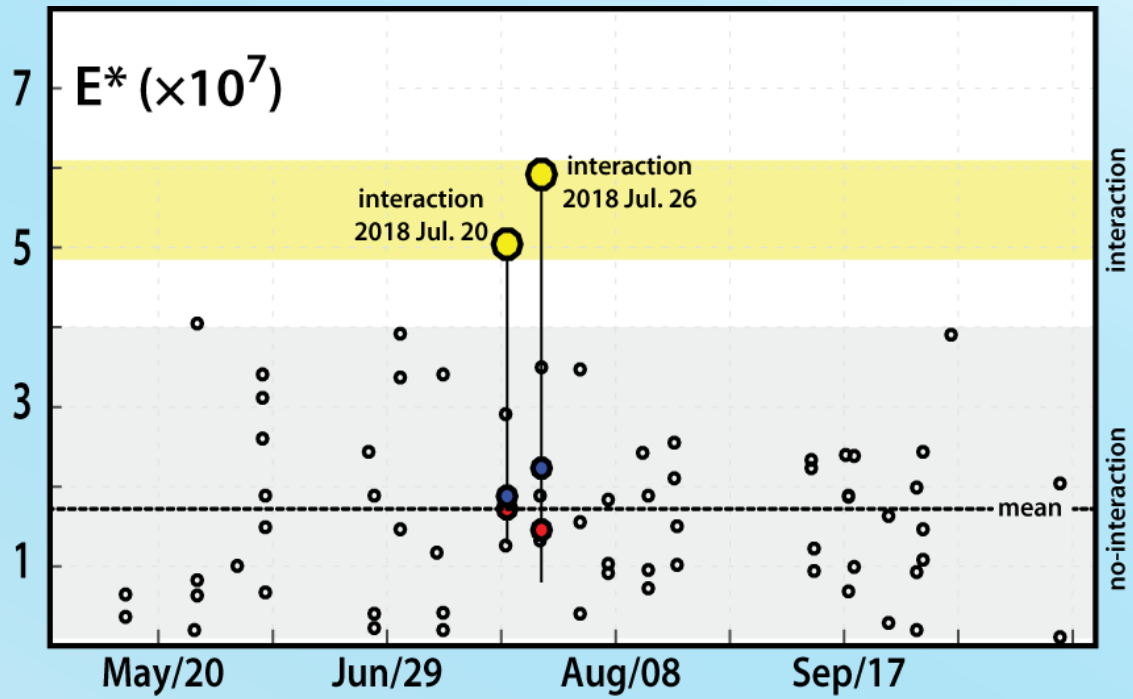
This *energy proxy* shows that for this particular region the waves' will likely intersect with fully developed waves approximately along the 100 meter isobath.

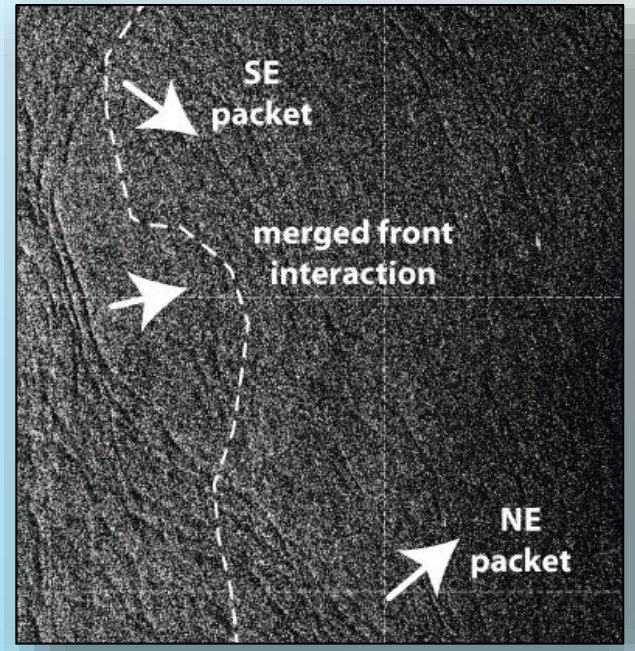
SAR evidence of IW interactions



SAR shows that these interaction do occur between waves originating from different locations. Moreover, their sea surface signatures are consistent with a large increase in amplitude within the waves' interacting sections – and their geometry resemble that of a Mach-stem.

SAR evidence of IW interactions





SAR showing a possible Mach-stem interaction

Energy proxy (E*) time series from SAR for each ISW packet (opened black circles) within the interaction hotspot for the extended summer of 2018. Note that the energy proxies estimated for images resembling Mach interactions (in yellow circles) are larger than those of their individual waves (roughly by two-fold, shown in filled circles color-coded), and also larger than a nominal background for non-interacting ISWs (gray envelope).

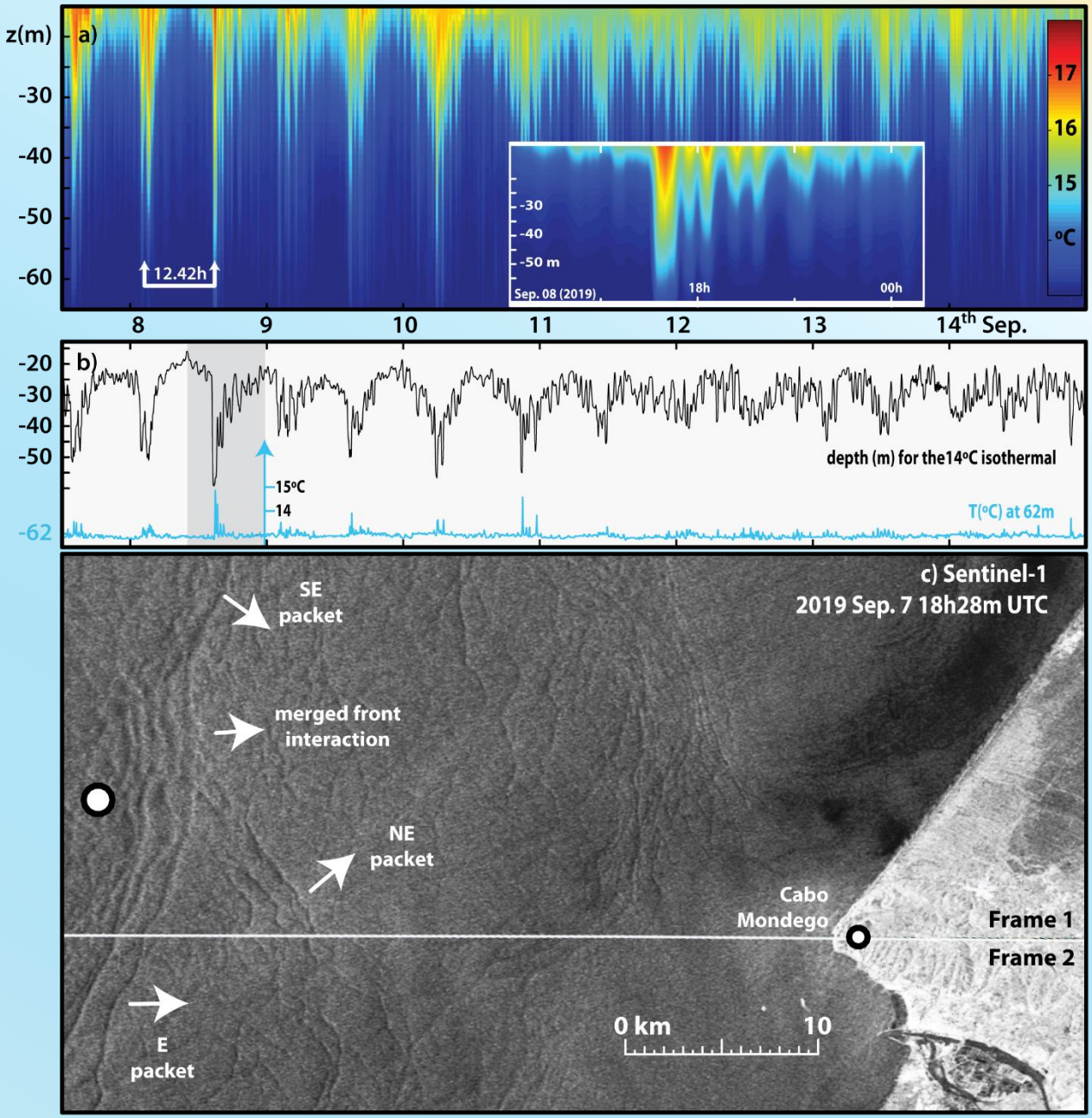
SAR and in situ evidence of IW interactions

And so we went out to sea…

A moored thermistor chain (close to the white dot in c) shows large IWs propagating approximately at 18h30m UTC during September 8th.

To highlight possible interactions the vertical displacements reaching lower depths are shown via the temperature record of the 62 m thermistor.

SAR images acquired September 7th, 2019, around 18:28 UTC, show an interaction pattern between two (possibly three) ISWs. A merged section is seen propagating approximately in the eastward direction, which is very close to a moored thermistor chain (shown as a white circle).



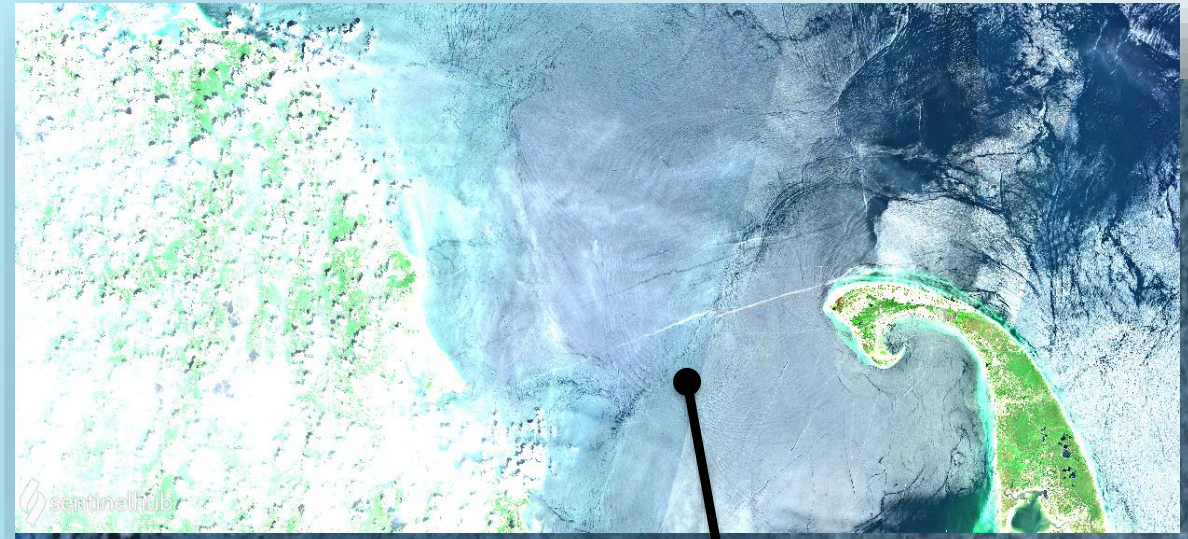
Some concluding remarks

- There is increasing evidence that IW interactions are a frequent phenomenon off coastal regions – in particular off the Portuguese coast.

- SAR can help in a first-approach to determine possible locations for enhanced wave-wave interactions.

- These locations can be used to study the wave interactions – e.g. their vertical structure – where open questions still remain (see e.g. Oliveira et al., next).

Thank you



High resolution view (10m) of a possible **Mach-stem** with evidence of surface wave breaking.