Marine Heatwaves at High Resolution in Fjord Ecosystem

ENCUENTRO DE LA OCEANOGRAFÍA FÍSICA 2026

CÉCILE PUJOL,
ALEXANDER BARTH,
IVÁN PÉREZ-SANTOS,
PATRICIO DIAZ,
GUIDO MANCILLA GUTIÉRREZ,
AIDA ALVERA-AZCÁRATE

08-10/07/2026

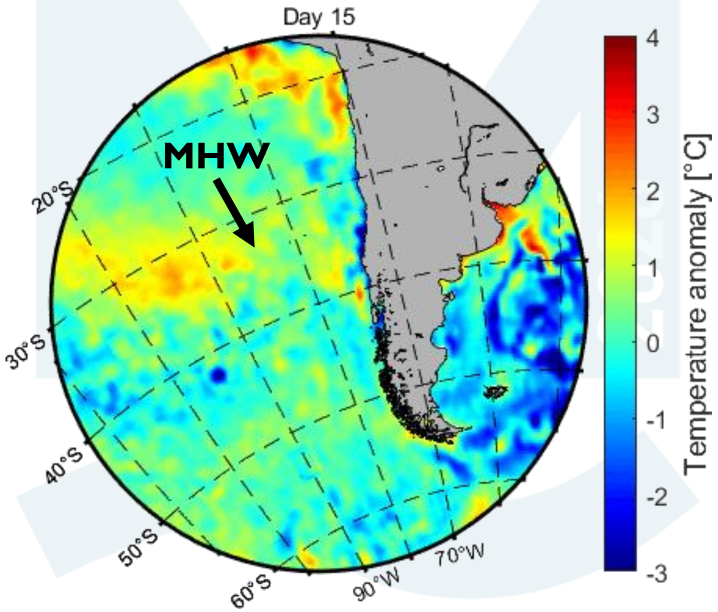
What are marine heatwaves (MHWs)?

MHWs

Anomalously warm water events

Discrete

Variable persistence: days to months



Triggered by

Atmospheric processes

Oceanic processes

Increasing frequency and intensity of MHWs(2) because of **global warming**(4)

First definition in 2016 by from Hobday et al.(1): Prolonged discrete periods of anomalously warm sea surface temperature (SST) lasting for at least 5 days

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST
- Long-term climatology
- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)
- Calculated for each pixel or averaged over a region

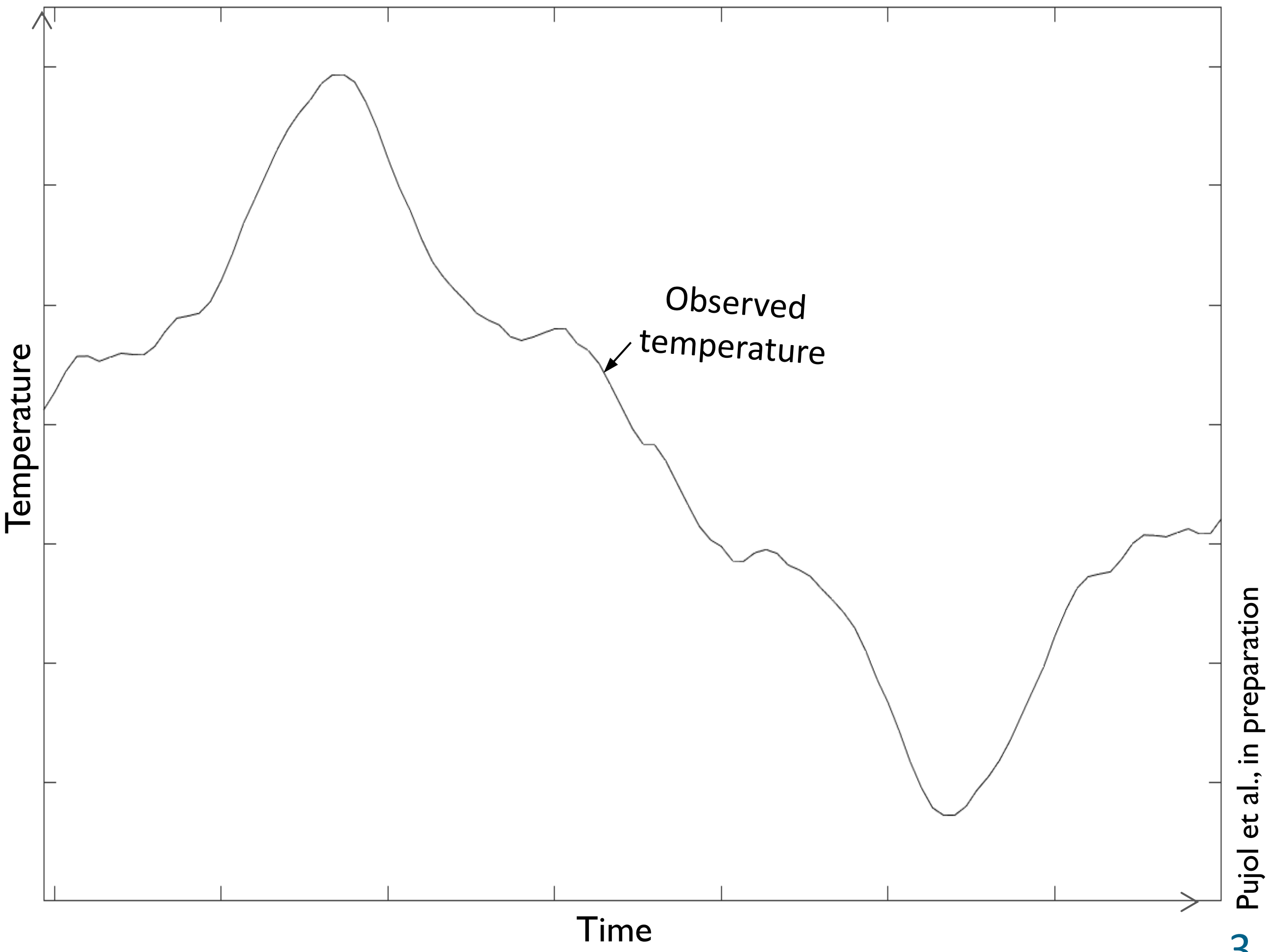


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) (1):

- Daily SST

- Long-term climatology

- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)

- Calculated for each pixel or averaged over a region

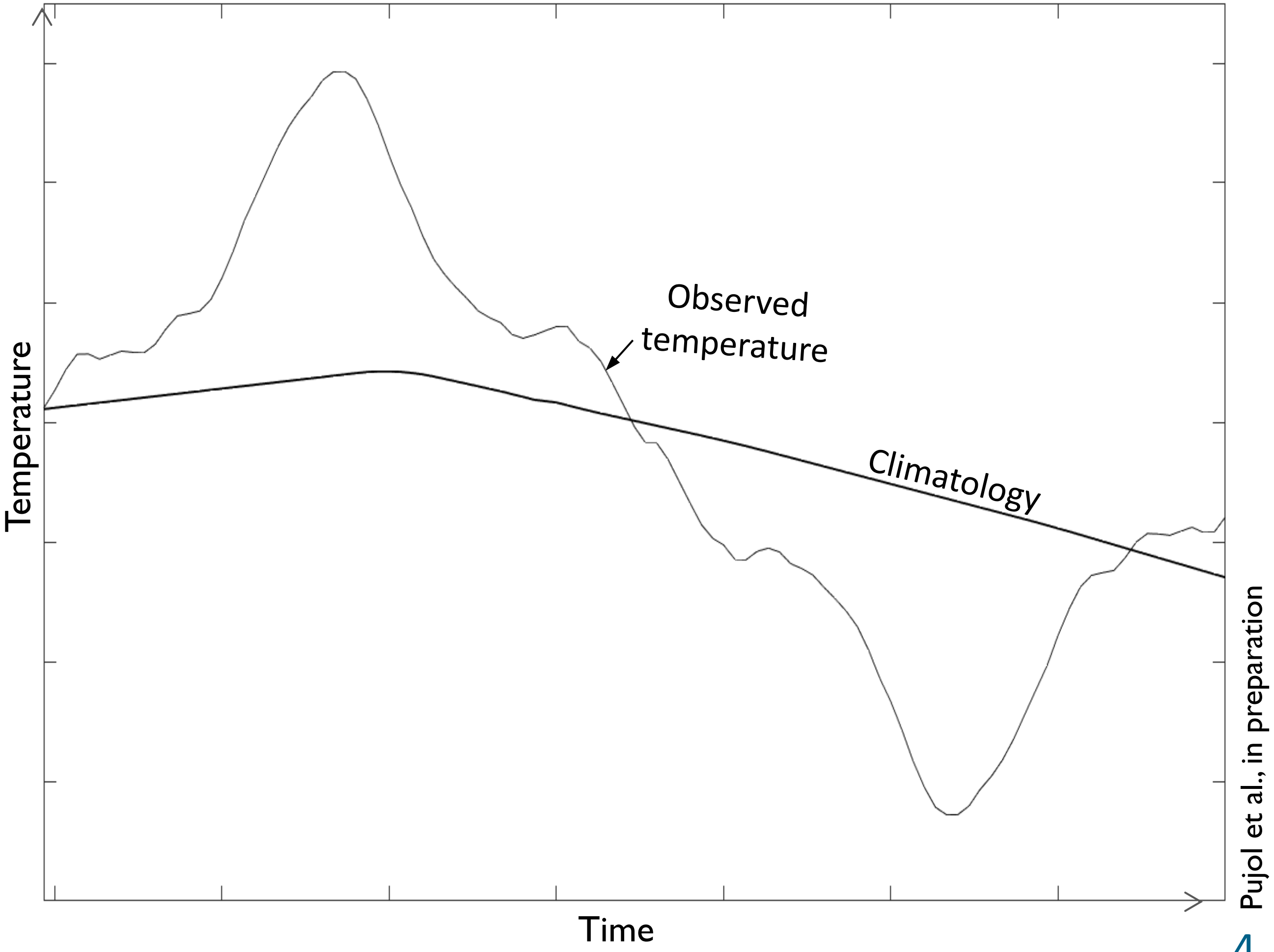


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST

- Long-term climatology

- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)

- Calculated for each pixel or averaged over a region

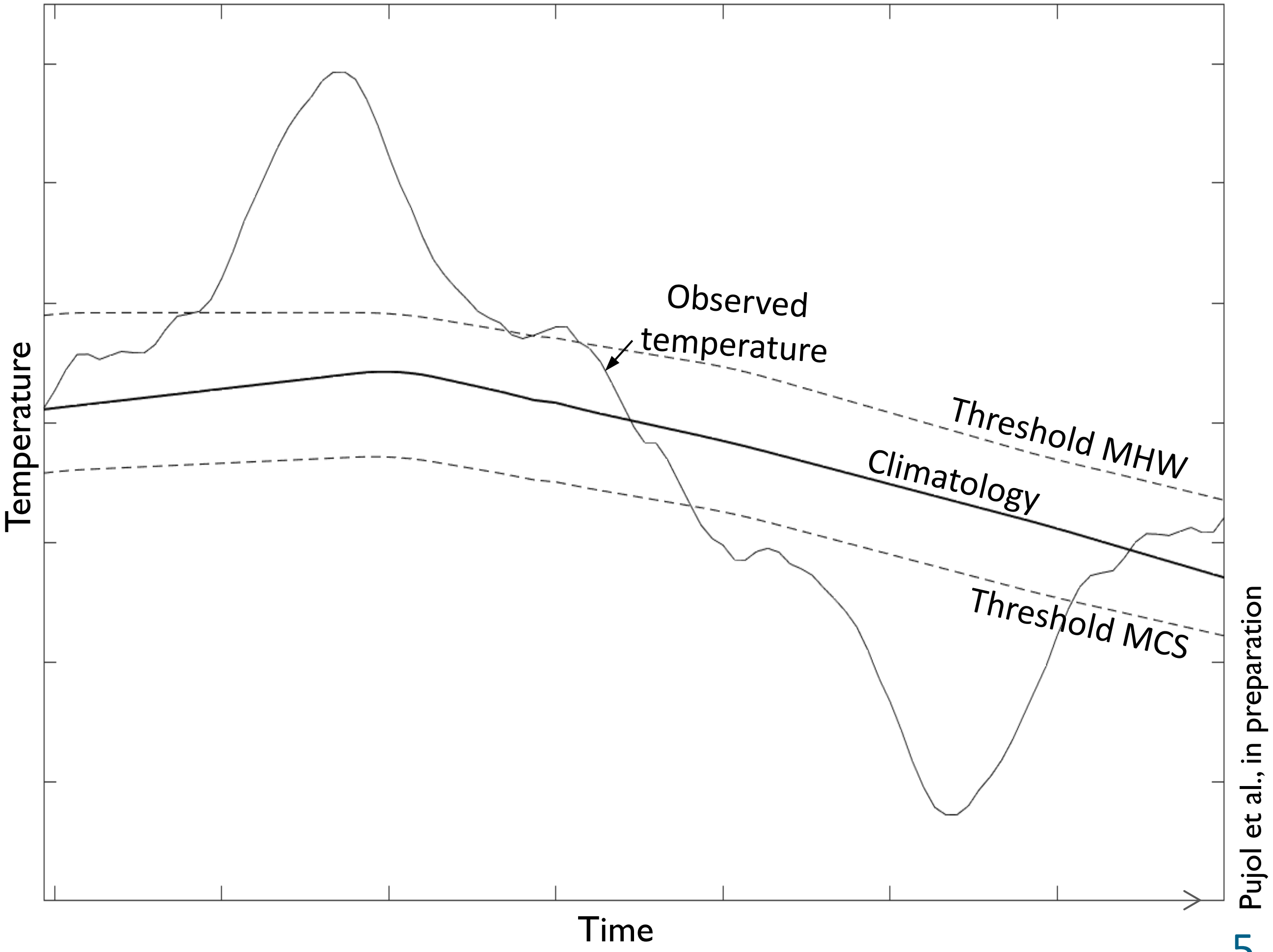


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST

- Long-term climatology

- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)

- Calculated for each pixel or averaged over a region

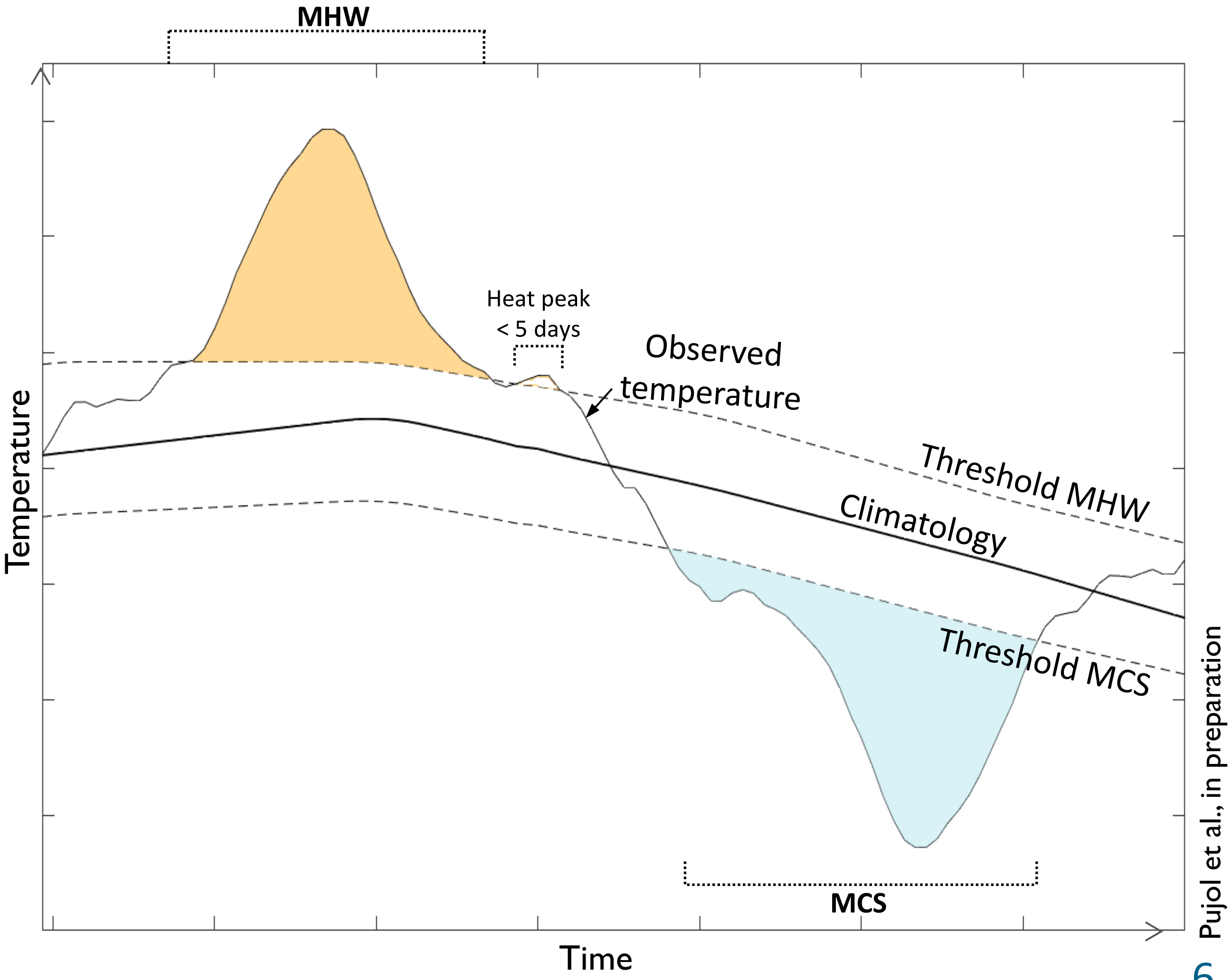


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST

- Long-term climatology

- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)

- Calculated for each pixel or averaged over a region

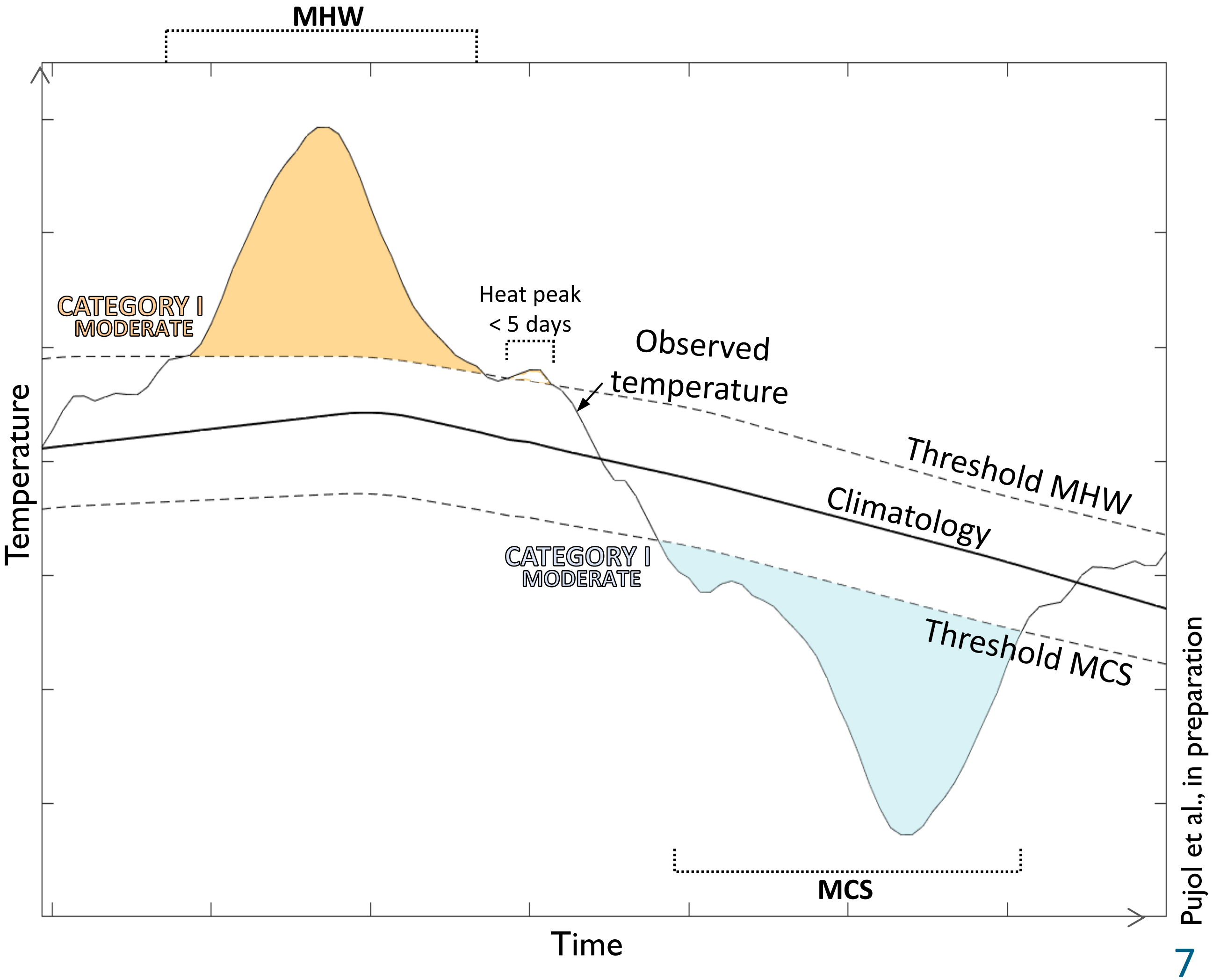


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST
- Long-term climatology
- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)
- Calculated for each pixel or averaged over a region

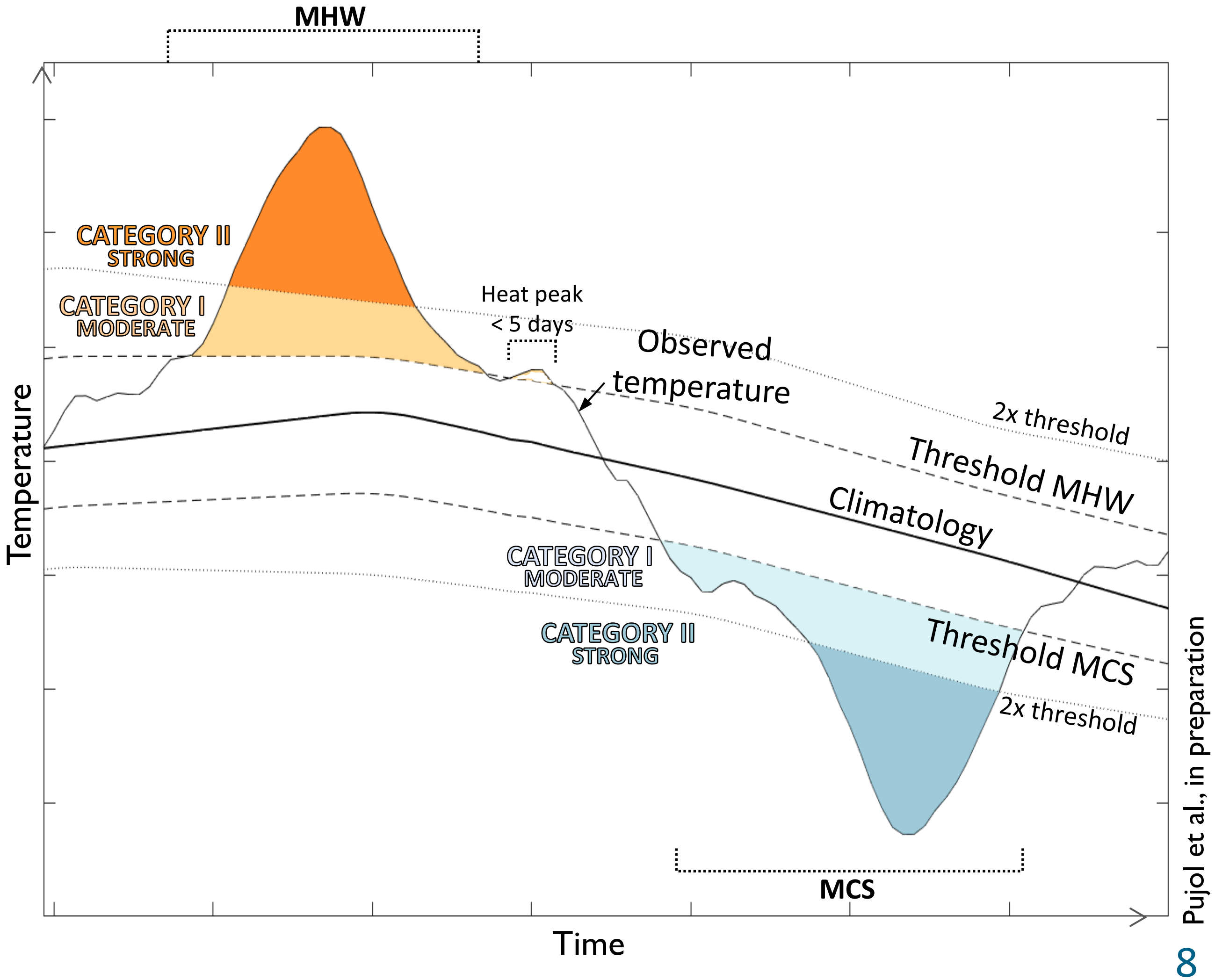


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST
- Long-term climatology
- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)
- Calculated for each pixel or averaged over a region

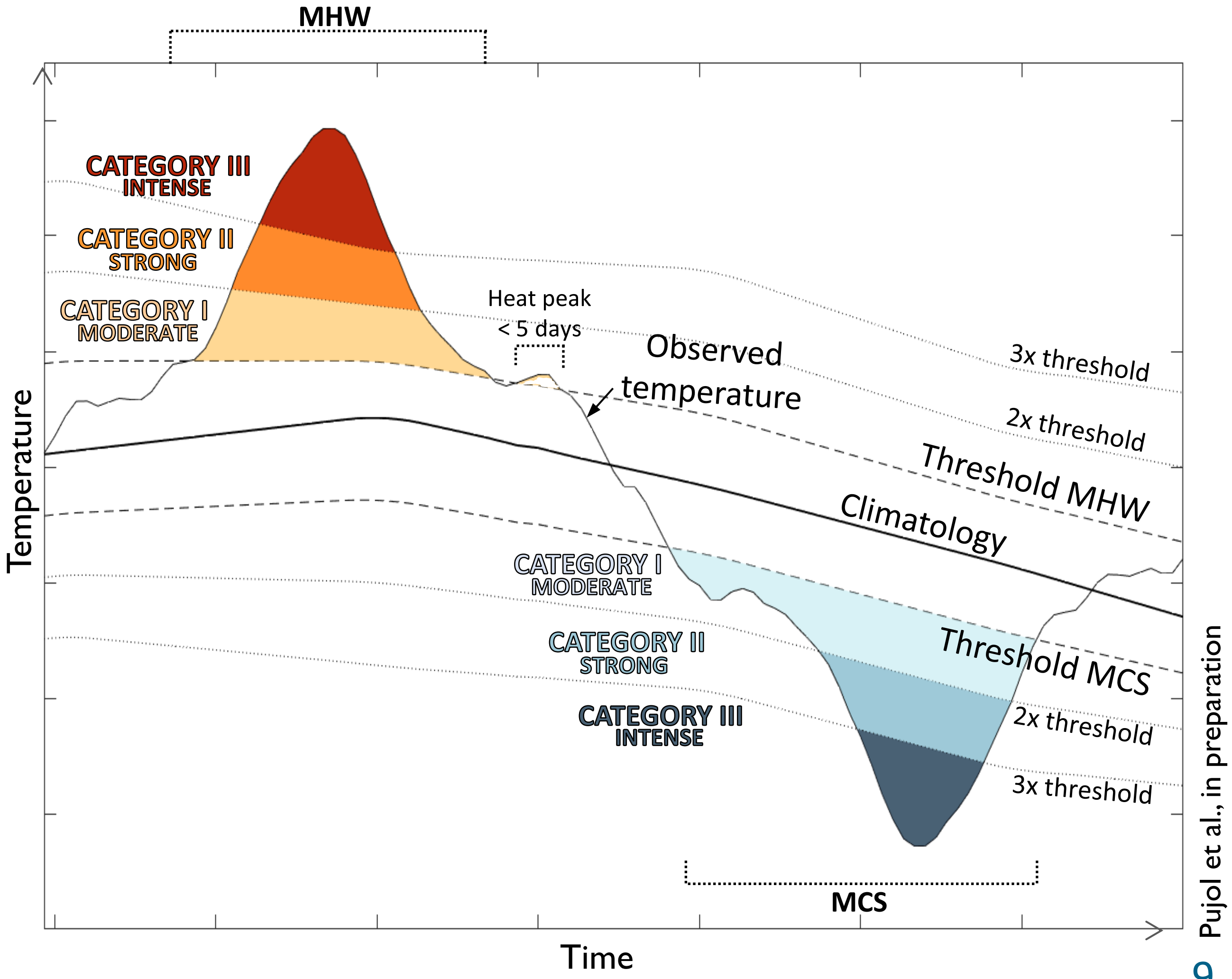


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST
- Long-term climatology
- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)
- Calculated for each pixel or averaged over a region

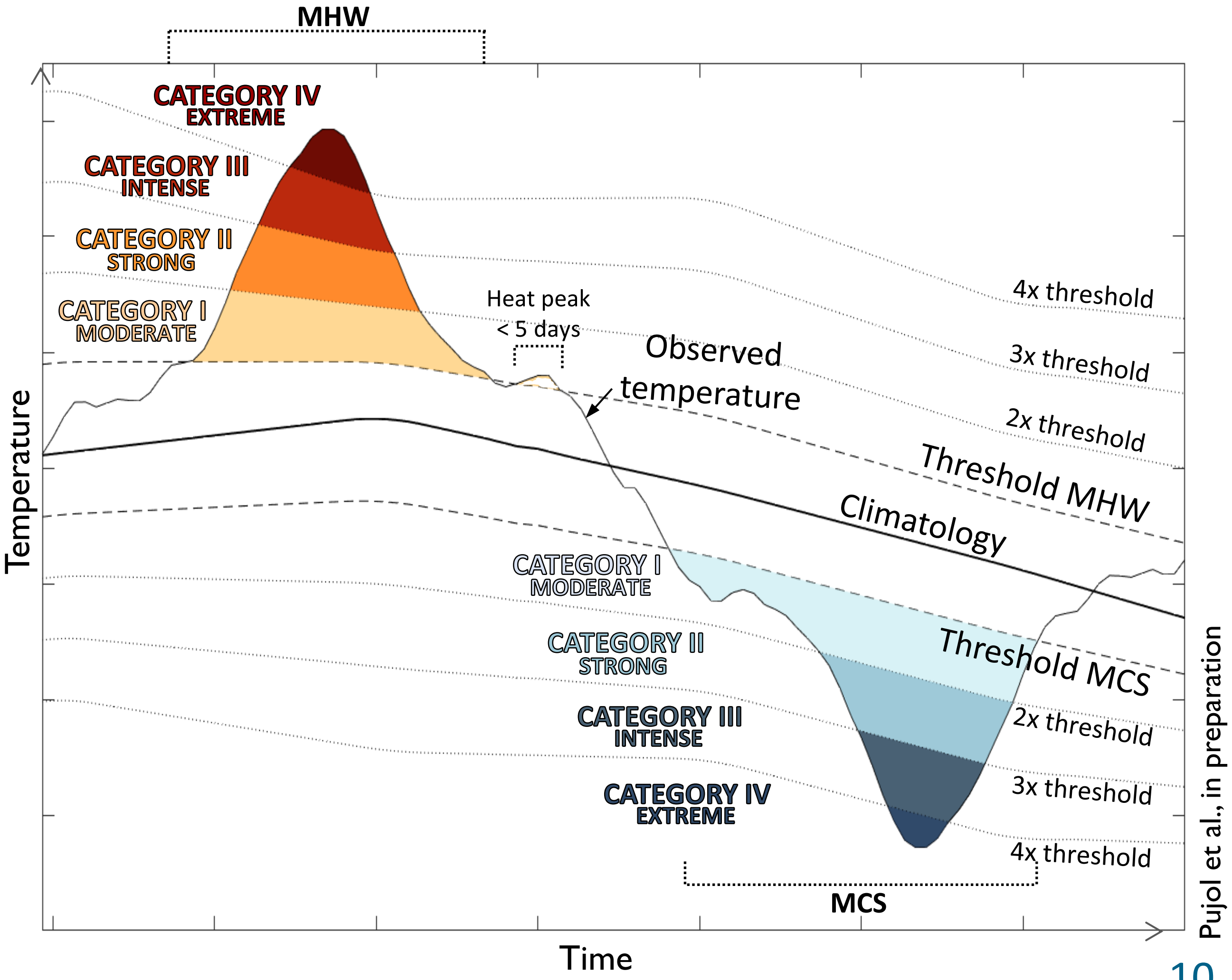


Fig. 1. Example of temporal detection of MHW and MCS.

How are they calculated ?

Hobday et al. (2016) [1]:

- Daily SST
- Long-term climatology
- Threshold (generally 90th percentile of the dataset for MHWs and 10th percentile for MCSs)
- Calculated for each pixel or averaged over a region

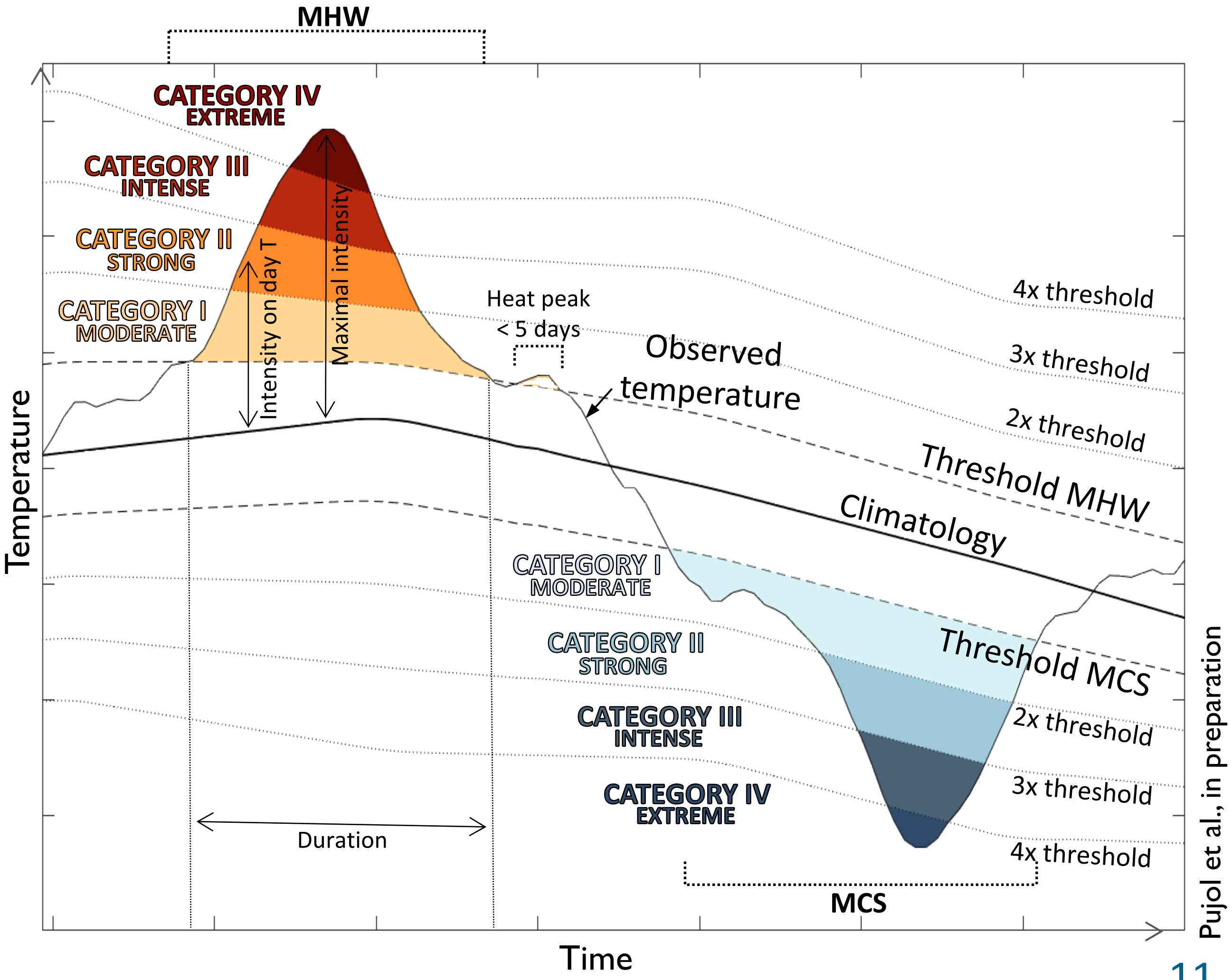
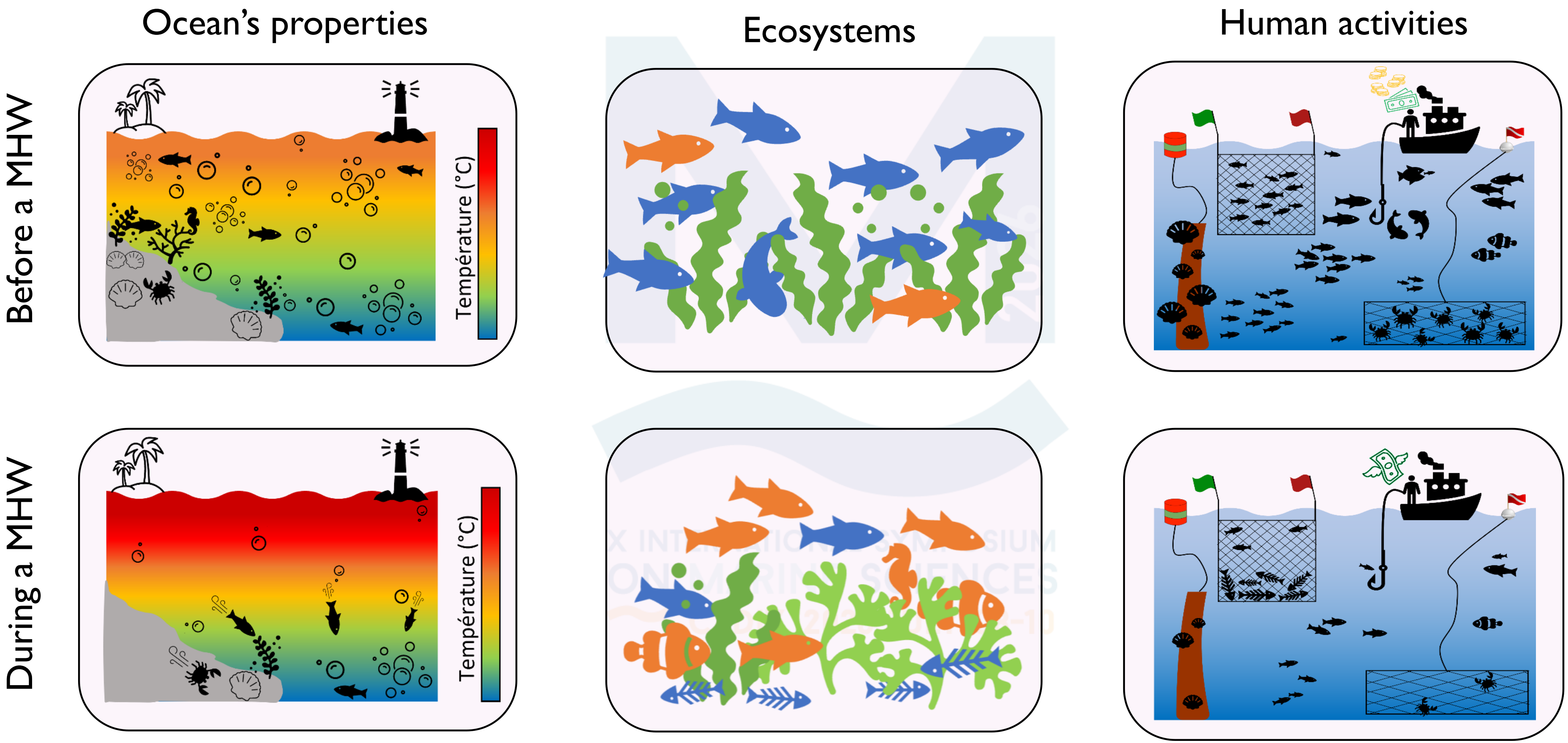


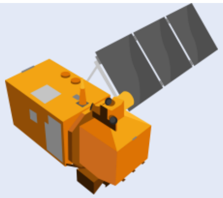
Fig. 1. Example of temporal detection of MHW and MCS.

Consequences of MHWs



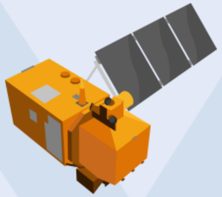
Detection of MHWs

- Daily SST



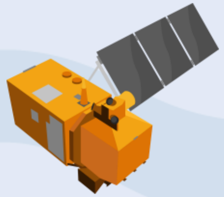
SATELLITE DATA

- Long-term Climatology



SATELLITE DATA

- Threshold



SATELLITE DATA

- Global products
- Daily temporal resolution
- Spatial resolution of several kilometres

OISST

Global product(6)
Temporal resolution: daily
Temporal coverage: 1982 - 2026
Spatial resolution: 1/4° (~25km)

Detection of MHWs

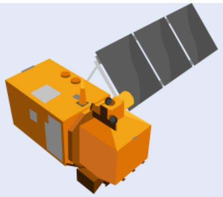
Daily SST
Threshold
Climatology

heatwaveR

Schlegel and Smit, 2018(7)

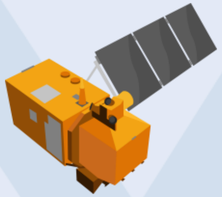
Detection of MHWs

Daily SST



SATELLITE DATA

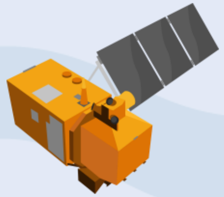
Long-term Climatology



SATELLITE DATA

- Global products
- Daily temporal resolution
- Spatial resolution of several kilometres

Threshold



SATELLITE DATA

Detection of MHWs

Daily SST

Threshold

Climatology

heatwaveR

Schlegel and Smit, 2018[7]

OISST

Global product[6]

Temporal resolution: daily

Temporal coverage:1982 - 2026

Spatial resolution: 1/4° (~25km)

What about coastal regions?

Complex coastal environment such as fjords ?

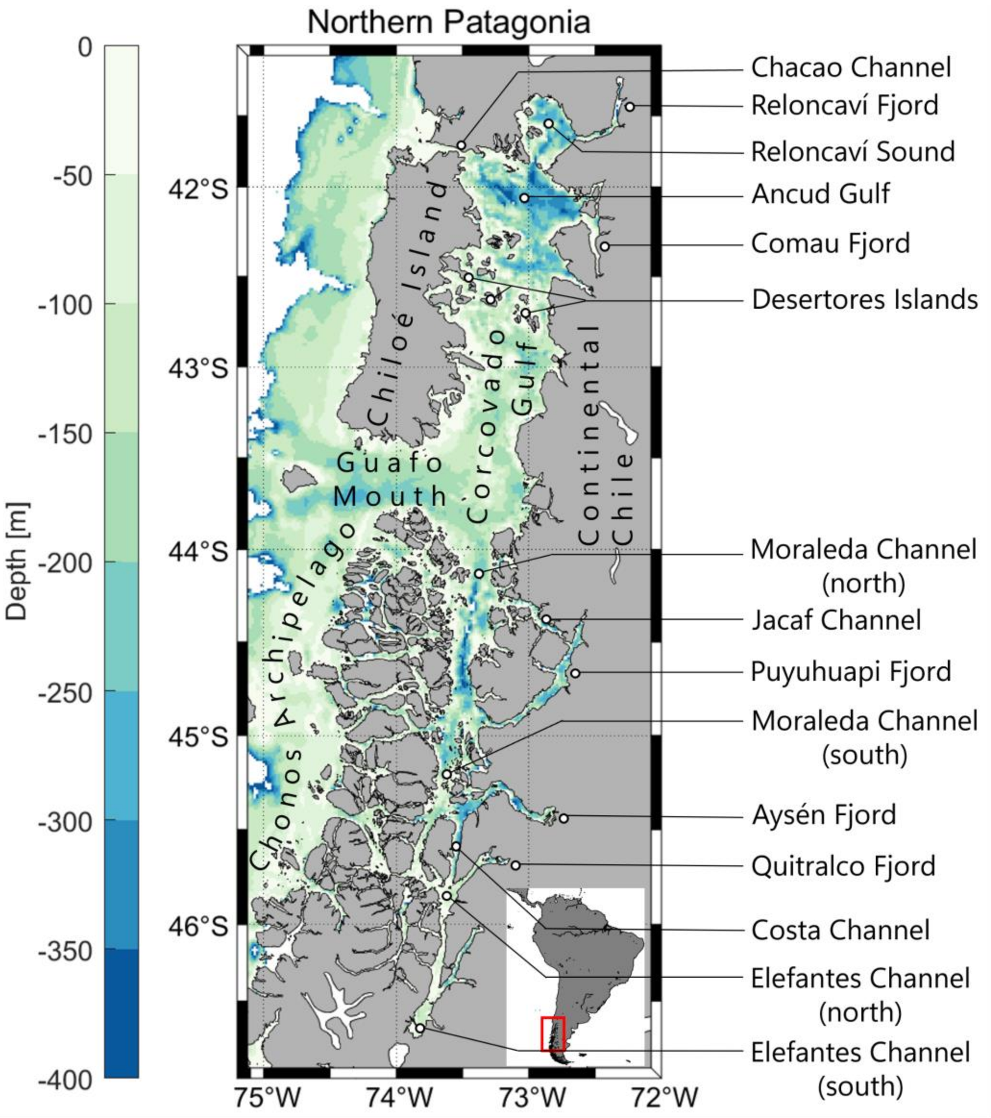


Fig. 2. Northern Patagonia. *Pujol et al., submitted 2025*

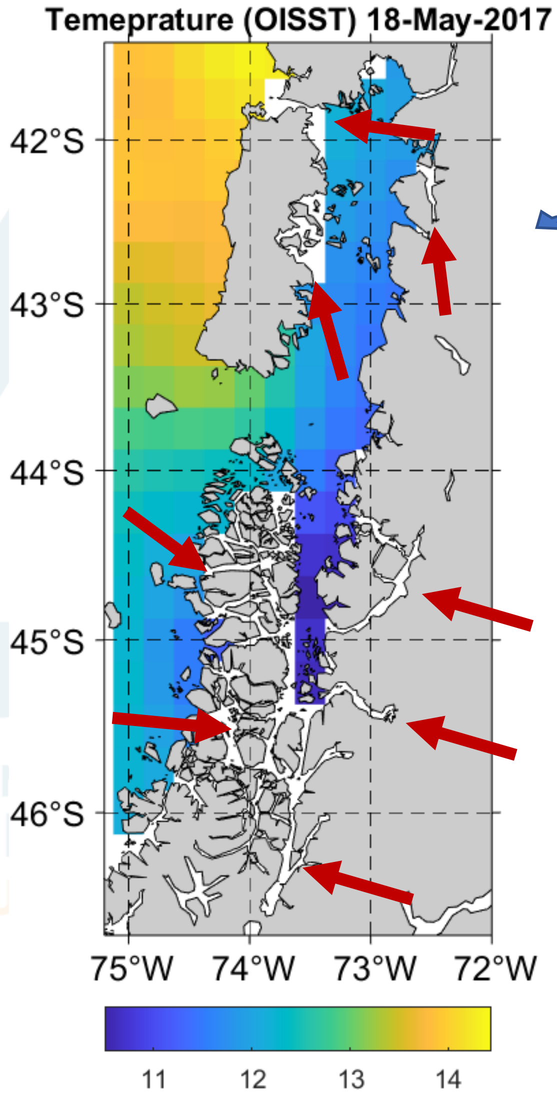


Fig. 3. Example of SST with OISST in Northern Patagonia,

OISST

Global product(6)
Temporal resolution: daily
Temporal coverage: 1982 - 2026
Spatial resolution: 1/4° (~25km)

Fjords and channels not resolved

Complex coastal environment such as fjords ?

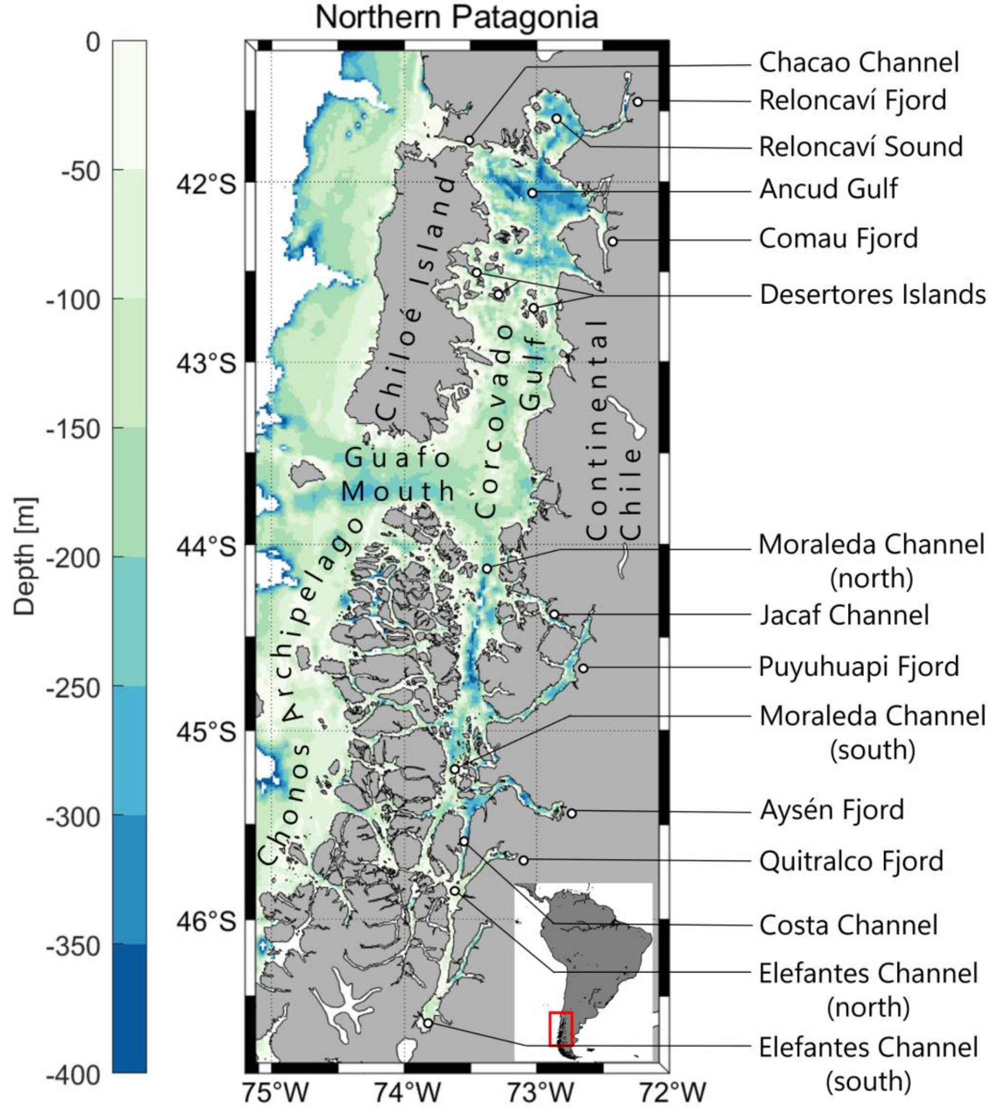


Fig. 2. Northern Patagonia. *Pujol et al., submitted 2025*

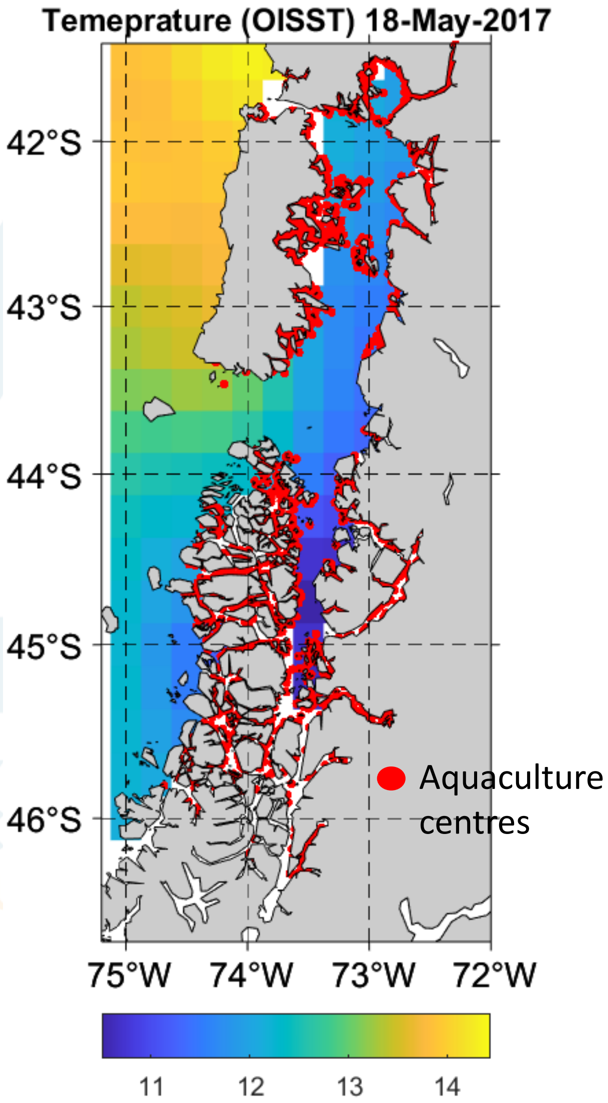


Fig. 4. Aquaculture centres and surface temperature from OISST. *Data from subpesca.cl*

Need of good coastal, channels and fjords representation for aquaculture industry

Complex coastal environment such as fjords ?

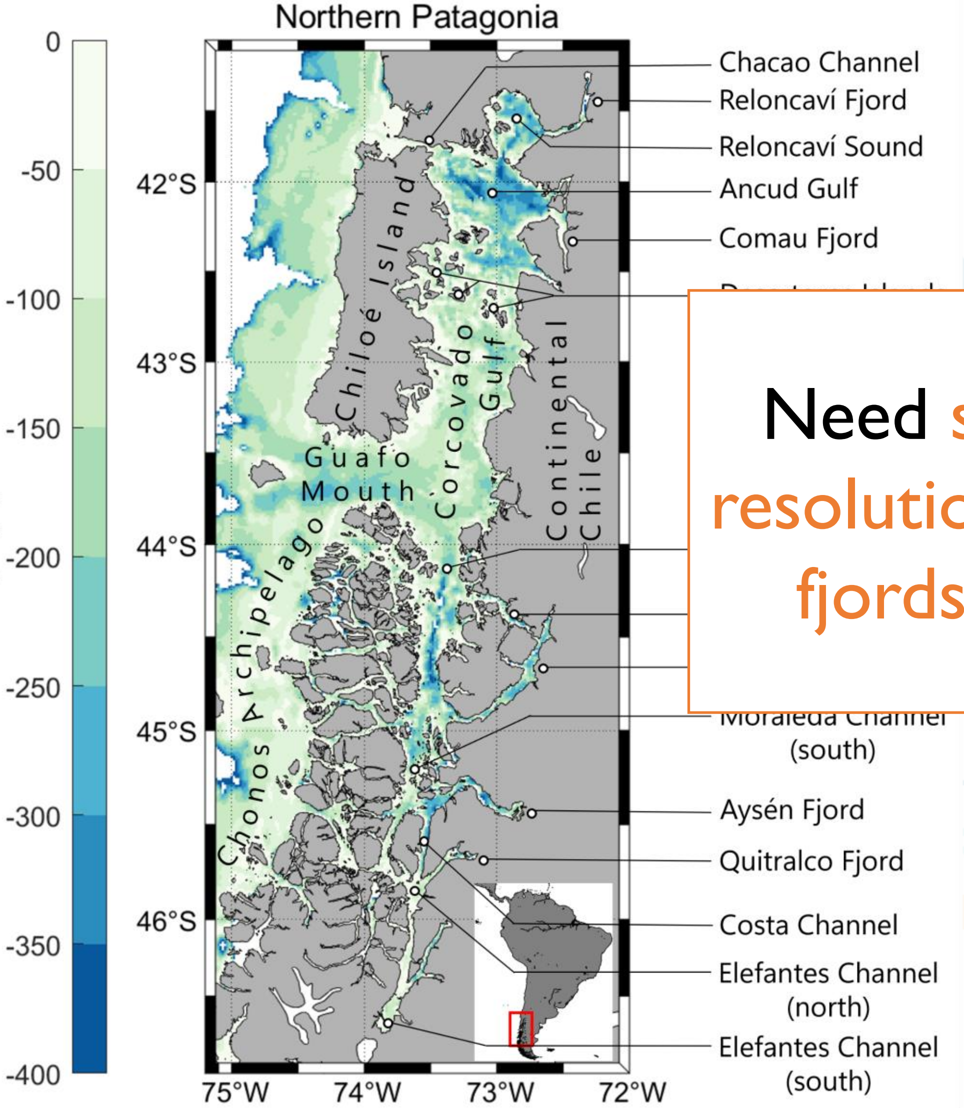


Fig. 2. Northern Patagonia. *Pujol et al., submitted 2025*

Need sufficiently high resolution to resolve the fjords and channels

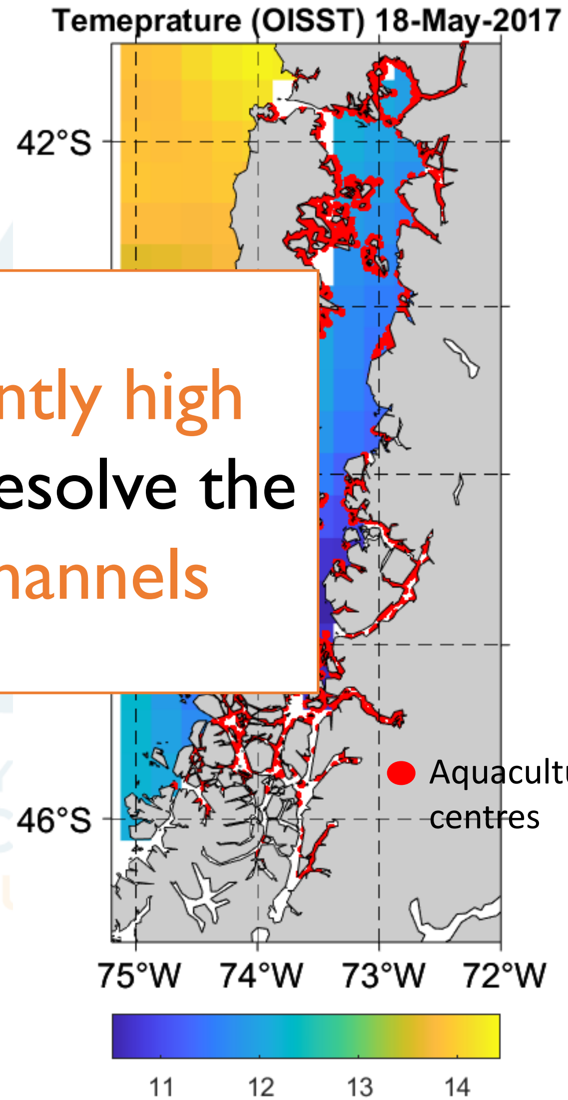


Fig. 4. Aquaculture centres and ... data from subpesca.cl

Need of good coastal, channels and fjords representation for aquaculture industry

Climatology

Needs to be based on long-term data >30 years

Should be a robust and representative baseline

What kind of data?

Threshold 90th percentile

SST for MHW detection

Needs daily temporal resolution

Needs spatial homogeneity

What kind of data?

In situ data

Advantages:
Fjords and channels highly sampled
Temporal coverage >30 years

Disadvantages:
Spatial and temporal heterogeneity

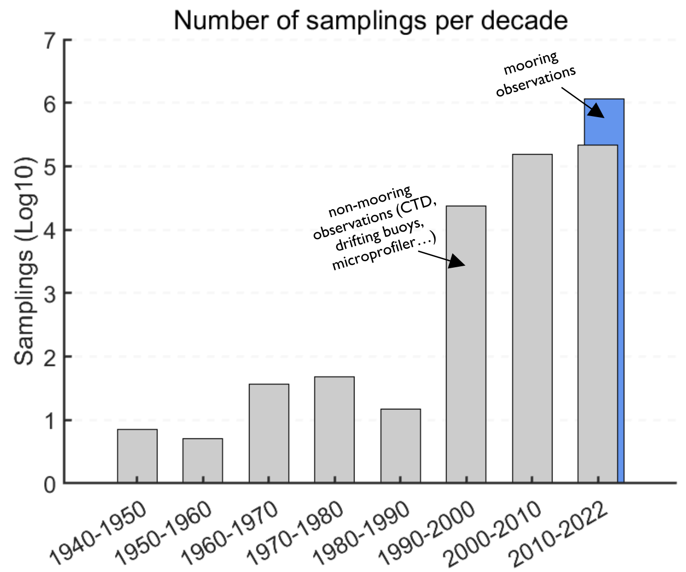


Fig. 5. In situ samplings in Northern Patagonia per decade.

Pujol et al., preprint 2025

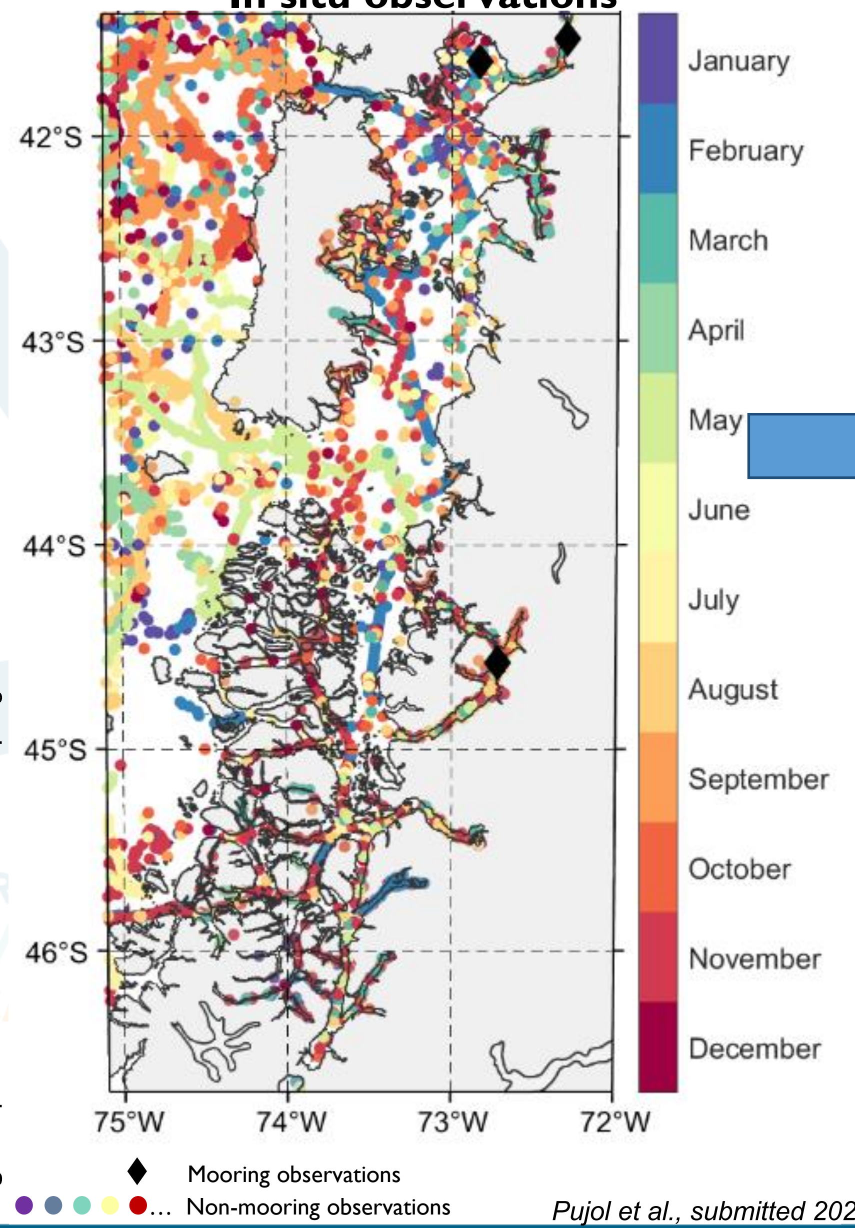


Fig. 6. Spatial distribution of in situ samplings

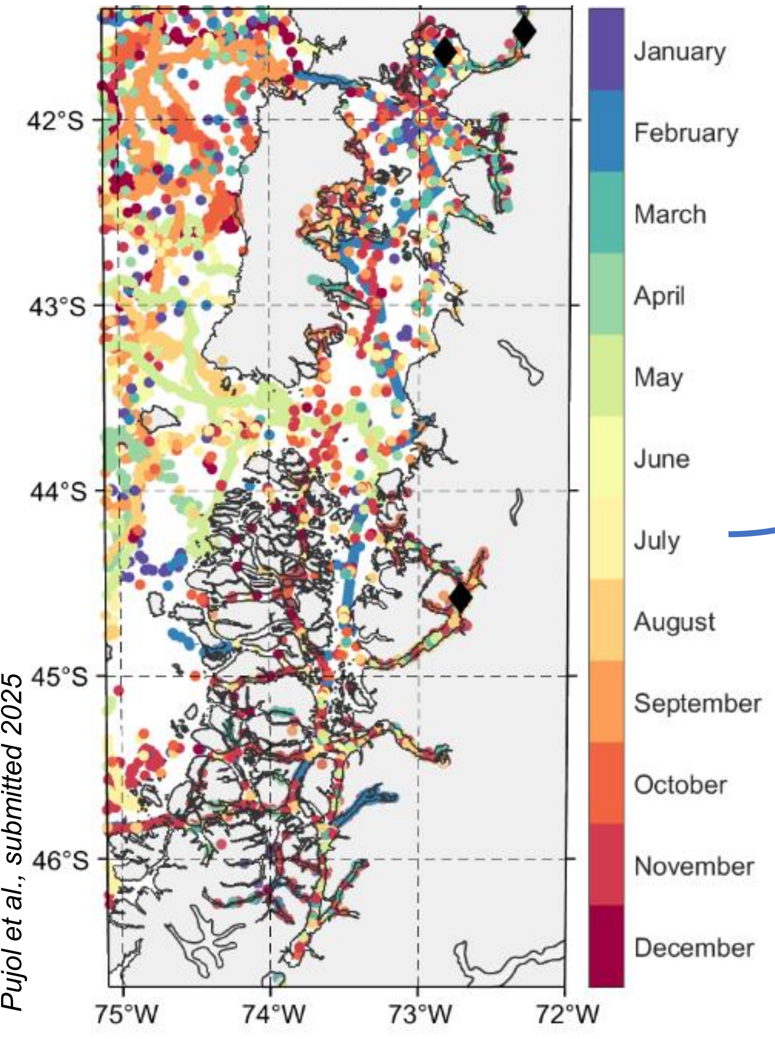
Pujol et al., submitted 2025

Build the climatology from in situ data

In situ data
Total: 3 million observations

Interpolation of the in situ data

In situ observations



Pujol et al., submitted 2025

♦ Mooring observations
● ● ● ● ●… Non-mooring observations

Fig. 7. Spatial distribution of in situ samplings

Data-Interpolating Variational Analysis

(Troupin et al., 2010[8]; Barth et al., 2014[9])

DIVA

Uses scattered in situ points to generate a continuous field

3D Monthly climatology

Horizontal correlation length: 50km
Lower weight attributed to data clusters

DIVA reconstruction

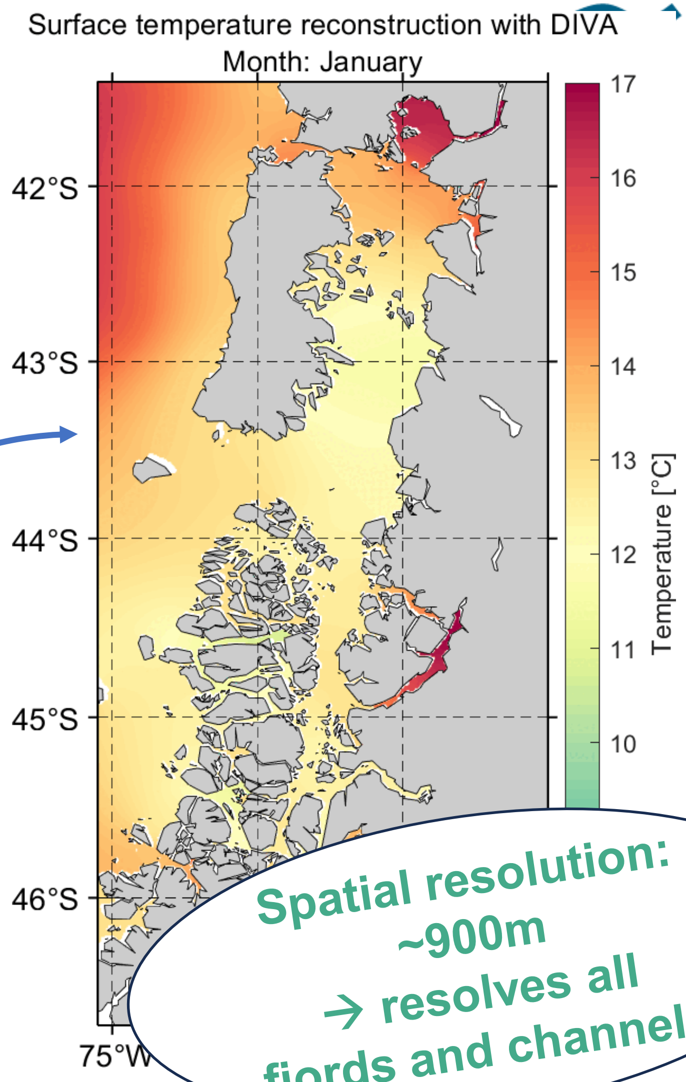


Fig. 8. Monthly cl... ...ature.

Spatial resolution: ~900m → resolves all fjords and channels

Validation of the climatology

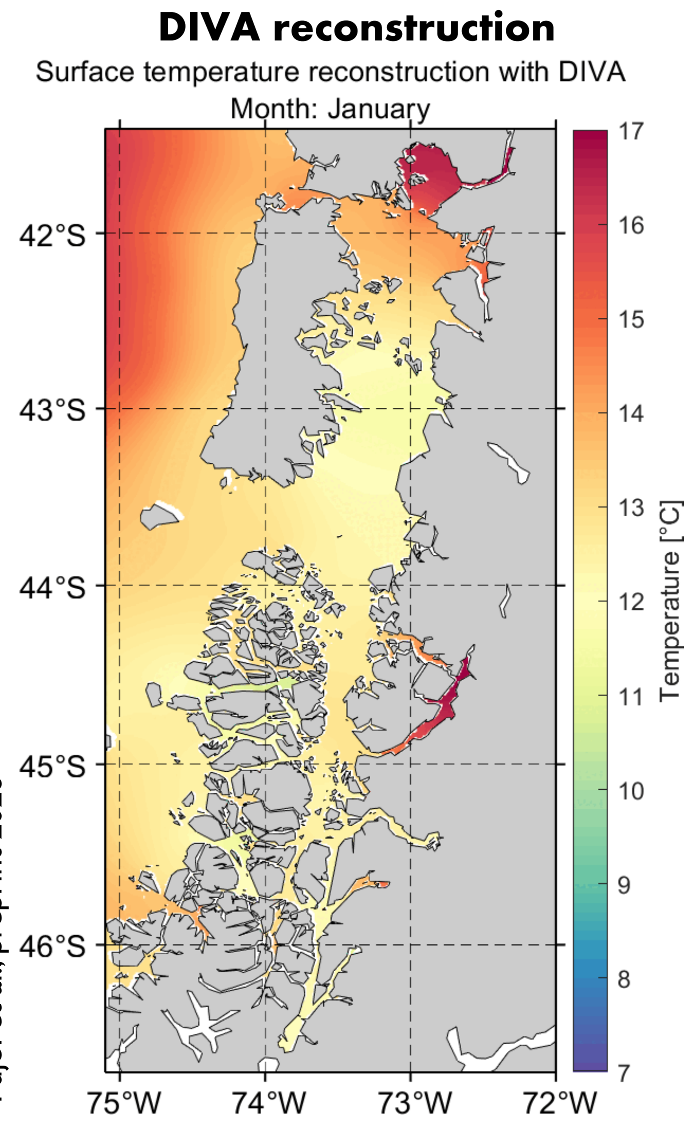


Fig. 8. Monthly climatology of surface temperature.

Pujol et al., preprint 2026

5% of the in situ data kept apart for validation

	Bias between DIVA and in situ (°C)	rmse	crmse	Standard deviation in situ data
Jan	0,21	1,85	1,83	1,97
Feb	0,04	1,43	1,43	2,05
Mar	0,11	1,14	1,14	1,68
Apr	-0,07	1,01	1,00	0,83
May	-0,08	0,78	0,78	0,77
Jun	-0,08	0,71	0,70	0,46
Jul	0,06	0,87	0,87	0,59
Aug	-0,14	0,71	0,69	0,58
Sep	0,01	0,73	0,73	0,51
Oct	0,20	0,95	0,93	0,82
Nov	0,09	1,23	1,23	1,23
Dec	0,10	1,42	1,42	2,18

Table. 1. Validation of the climatology with root mean square error (rms) and centred root mean square error (crmse).

Climatology

Needs to be based on long-term data >30 years

Should be a robust and representative baseline

Based on in situ data

Threshold 90th percentile

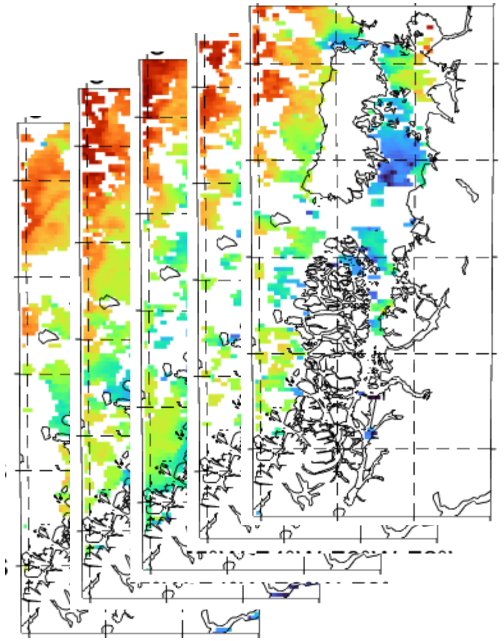
SST for MHW detection

Needs daily temporal resolution

Needs spatial homogeneity

Based on satellite dataset but contains cloud-gaps

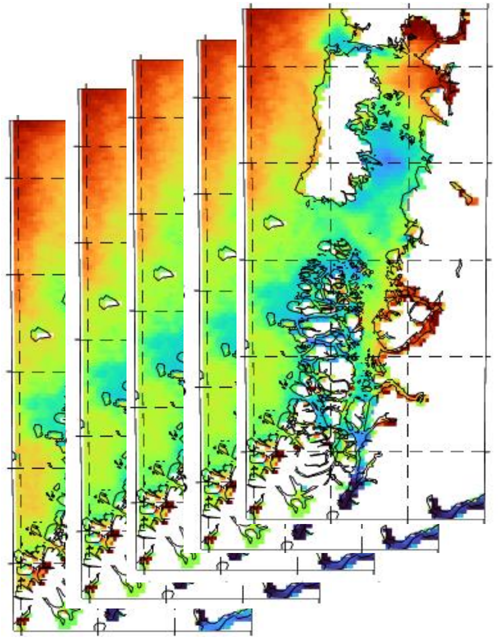
Satellite data



MODIS AQUA
L3 SST
Daily (2003-2023)
4km spatial resolution
Gaps

Data Interpolating Empirical Orthogonal Functions (DINEOF)
(Alvera-Azcárate et al., 2005[10])

EOF-based method to fill-in missing data from geophysical fields



L4 SST
Daily SST (2003-2023)
Gap-free
Resolving most fjords and channels

Climatology

Needs to be based on long-term data >30 years

Should be a robust and representative baseline

Based on in situ data

Threshold
90th percentile

SST for MHW detection

Needs daily temporal resolution

Needs spatial homogeneity

Calculated from satellite data

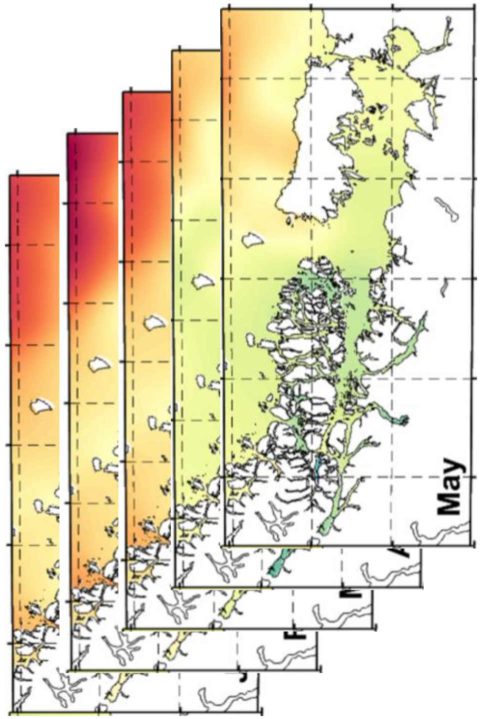
Based on satellite data

Need to combine both datasets

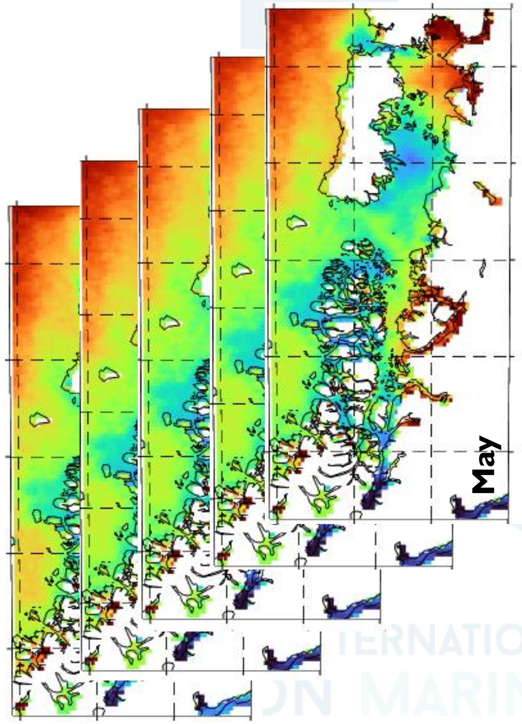
Adapting the datasets

Difference

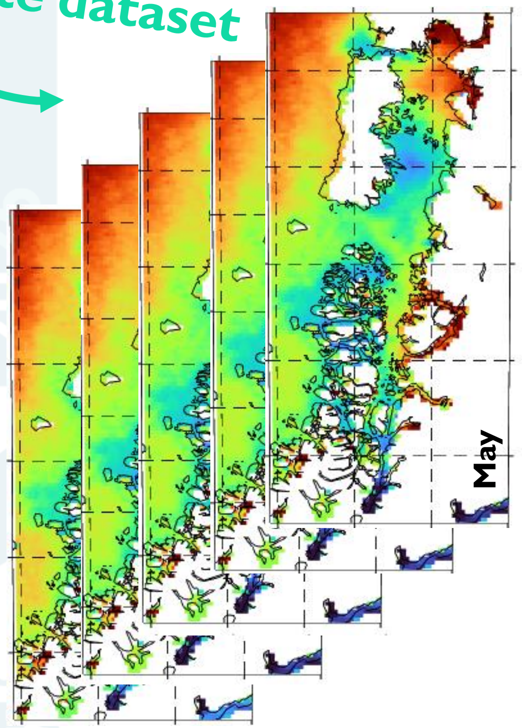
Removing the difference from the satellite dataset



In situ-based climatology



SST Satellite dataset



SST Satellite dataset

Align the satellite dataset on the in situ dataset

Climatology

Needs to be based on long-term data >30 years

Should be a robust and representative baseline

Based on in situ data

Threshold 90th percentile

SST for MHW detection

Needs daily temporal resolution

Needs spatial homogeneity

Calculated from satellite data

Based on satellite data

Need to combine both datasets

Zoom on Northern Patagonia

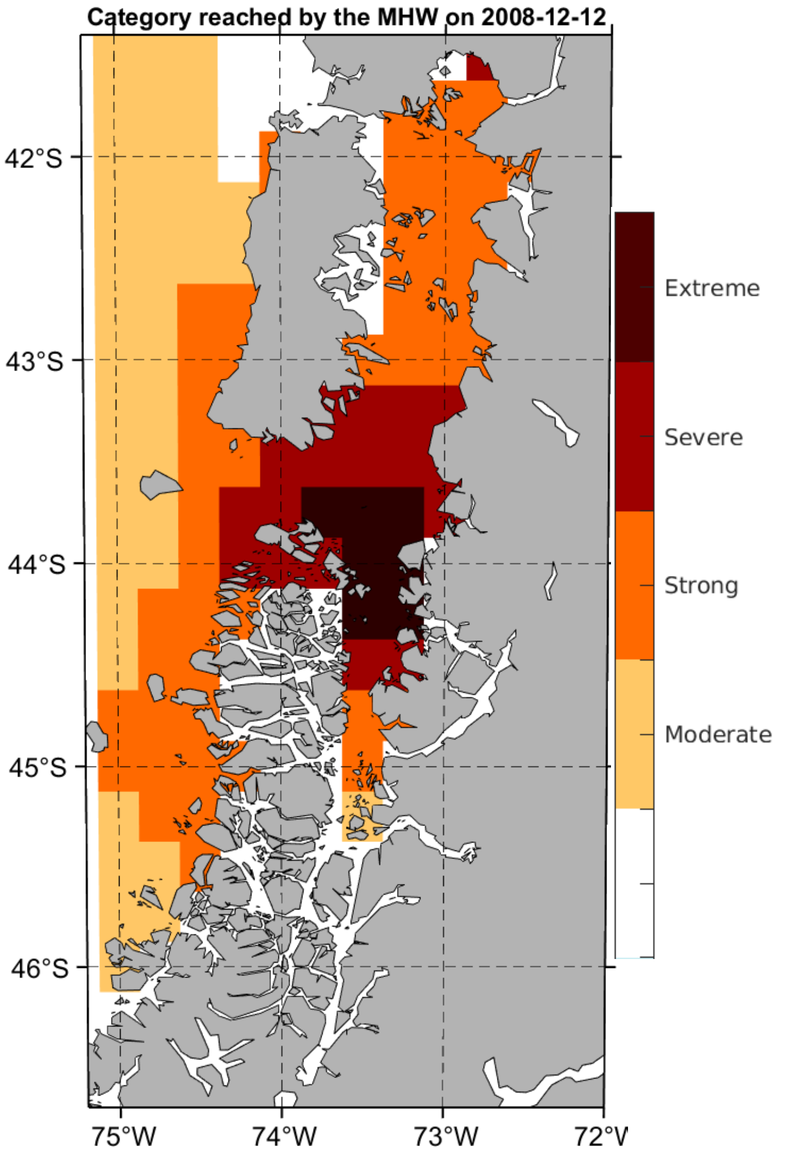


Fig. 9. MHW with OISST

MHW on 2008-12-12 with NOAA OISST product (spatial resolution 1/4°)

MHW on 2008-12-12 with our approach (spatial resolution ~900m)

Pujol et al., in preparation

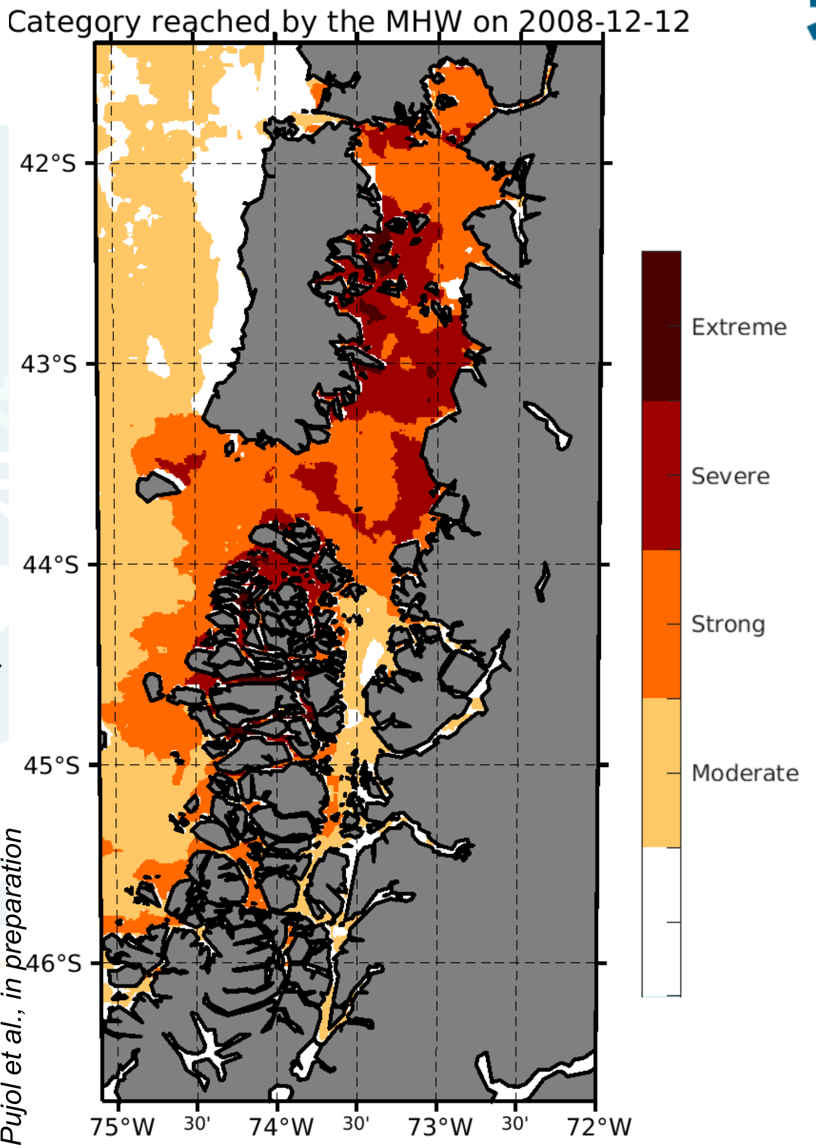


Fig. 10. MHW with our methodology

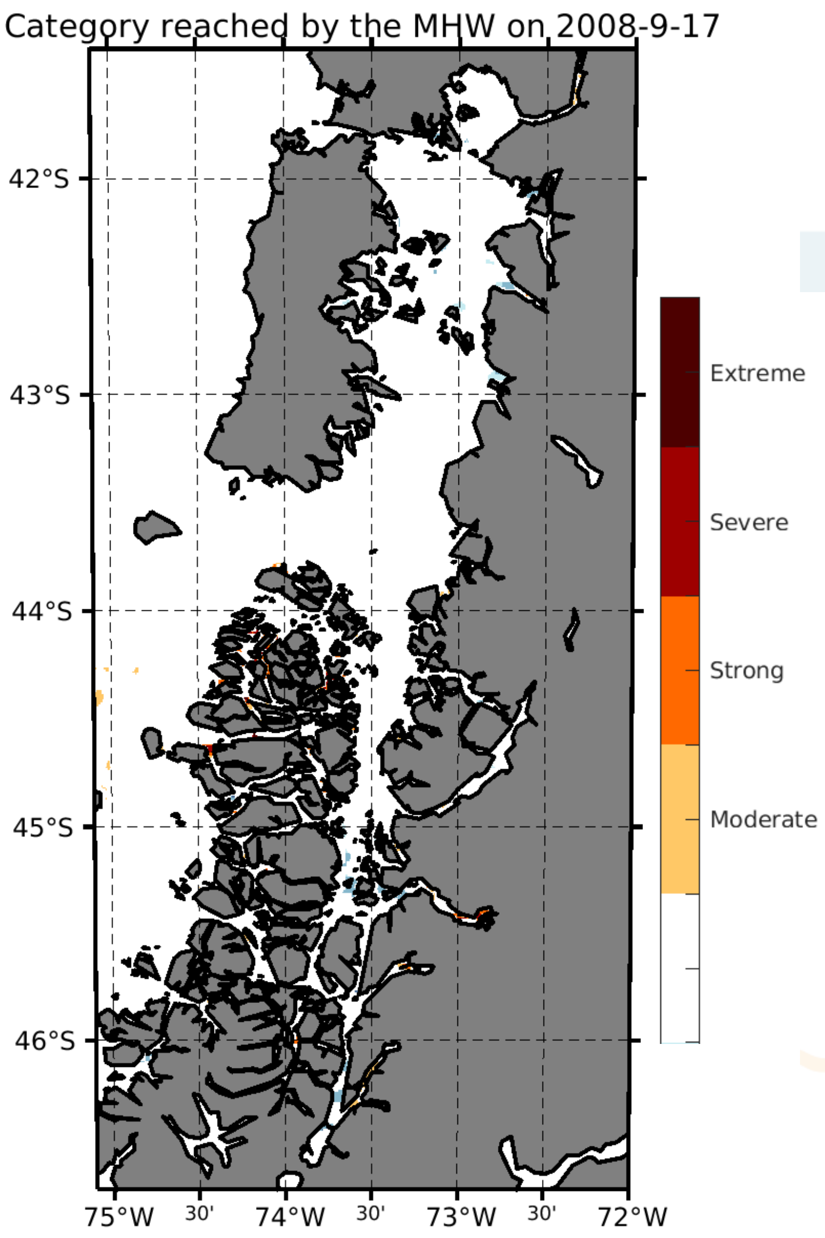
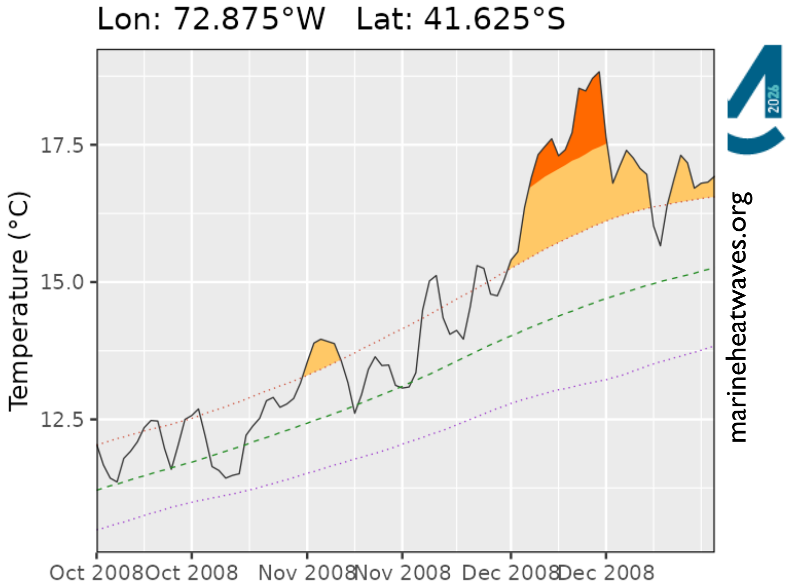


Fig. 11. MHW with our methodology

Development of the MHW with NOAA OISST product (spatial resolution 1/4°)

Development of the MHW with our approach (spatial resolution ~900m)



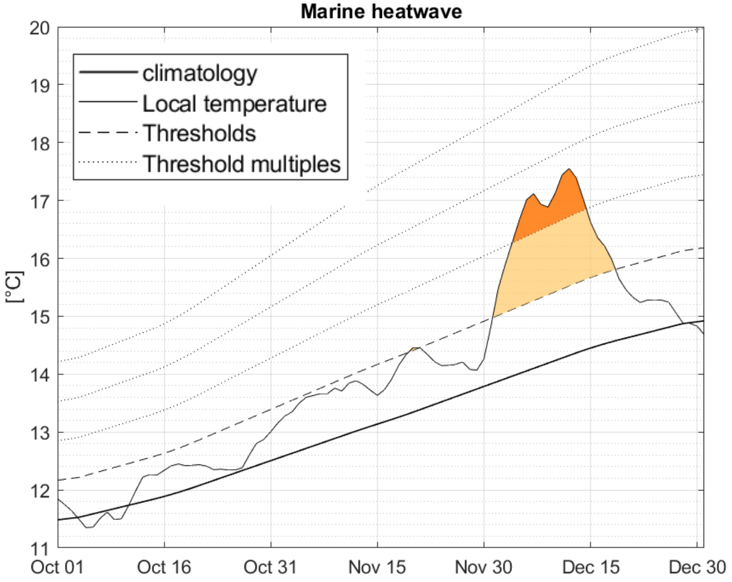


Fig. 12. Temporal evolution of the MHW with OISST (up) and our methodology (bottom)

MHWs average metrics (2003-2023)

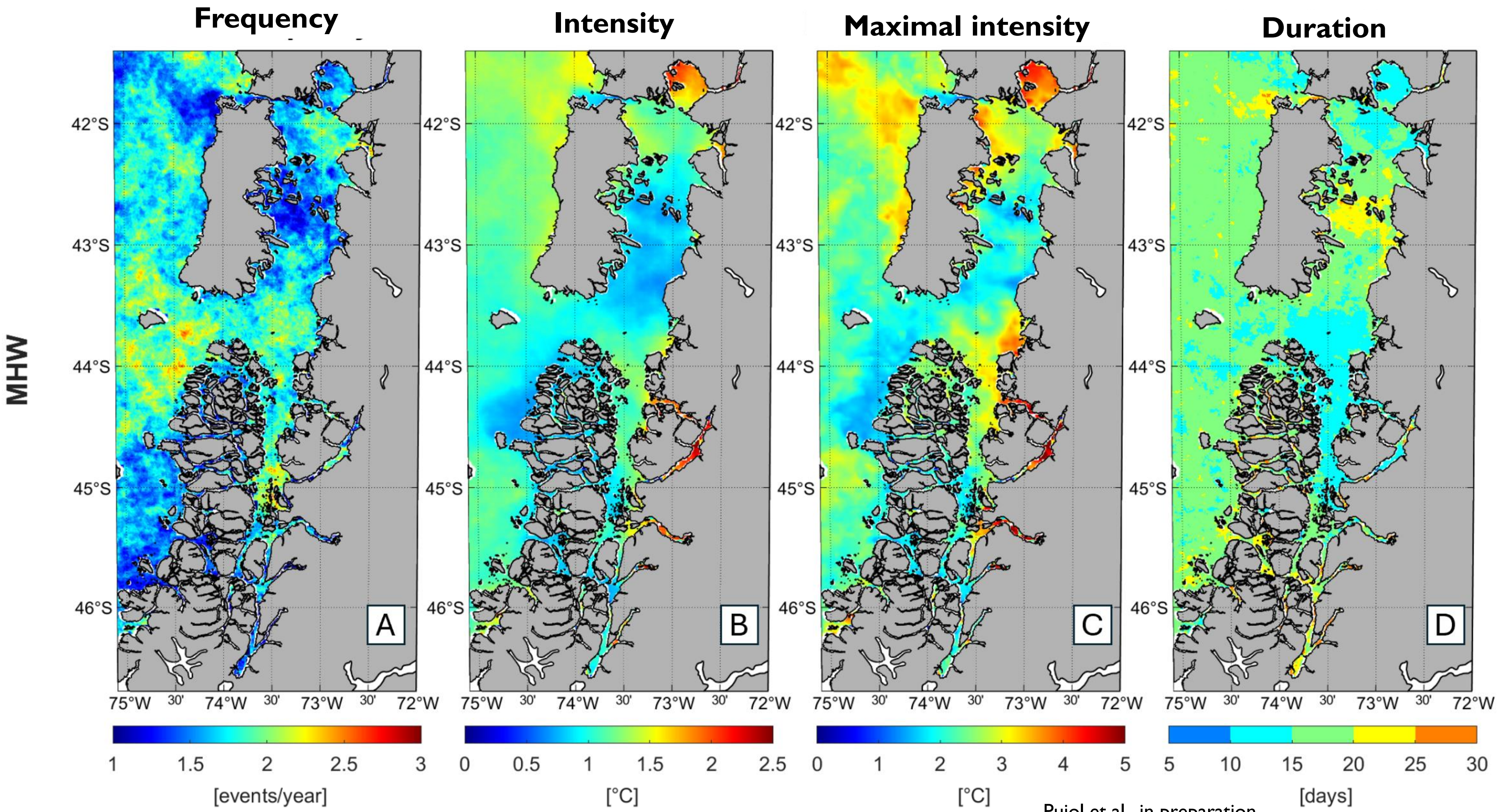


Fig. 13. MCS average metrics at the surface for the period 2003-2023 with our methodology.

Pujol et al., in preparation

High spatial variability

→ Freshwater inputs
→ Higher stratification
→ Enclosed basins
→ Local circulation

Why high resolution is important in coastal regions?

OISST product (low resolution)

Finer scale methodology

Mean frequency

Mean intensity

Mean frequency

Mean intensity

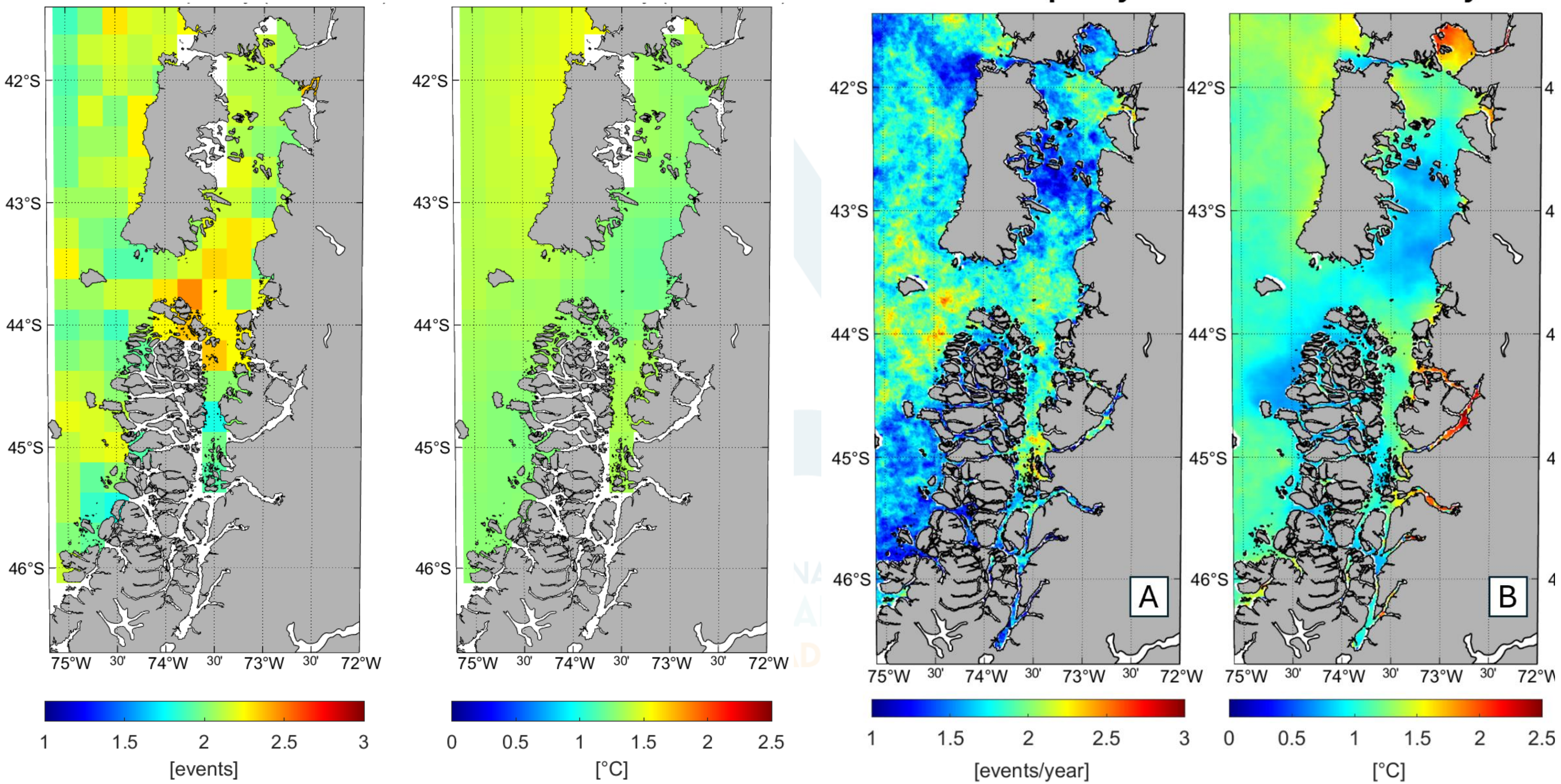
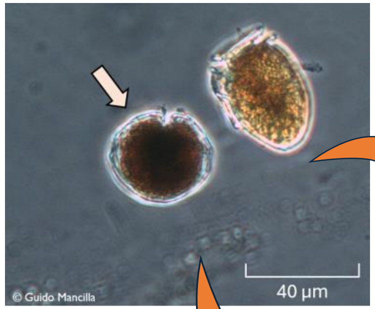


Fig. 14. MHW average metrics with OISST and with our approach.

OISST product does not take into account the small local variations of intensity

Why high resolution is important in coastal regions?



- Dinoflagellate *Alexandrium catenella*
- Generates mortality in aquatics organism and humans

January 2016

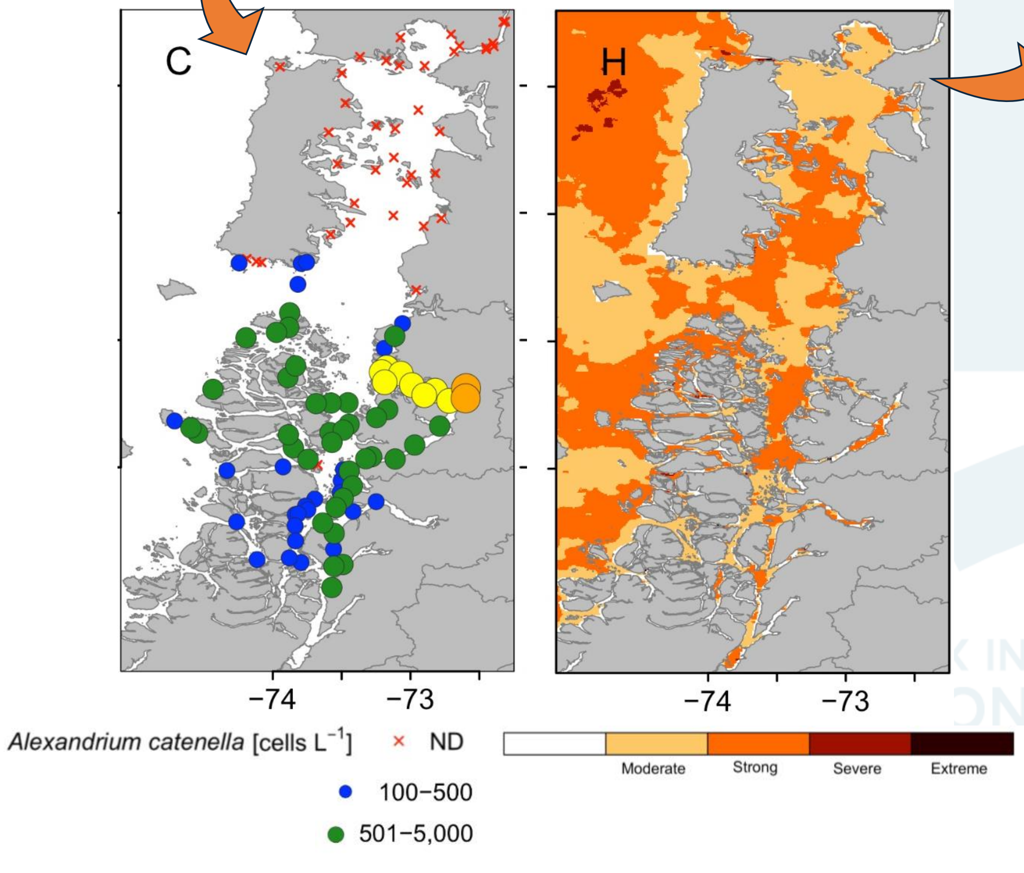


Fig. 14. *A. catenella* cell concentration (left) and MHW development (right)

Loss of 40 000 tons of salmon (800 million $)[13-15]

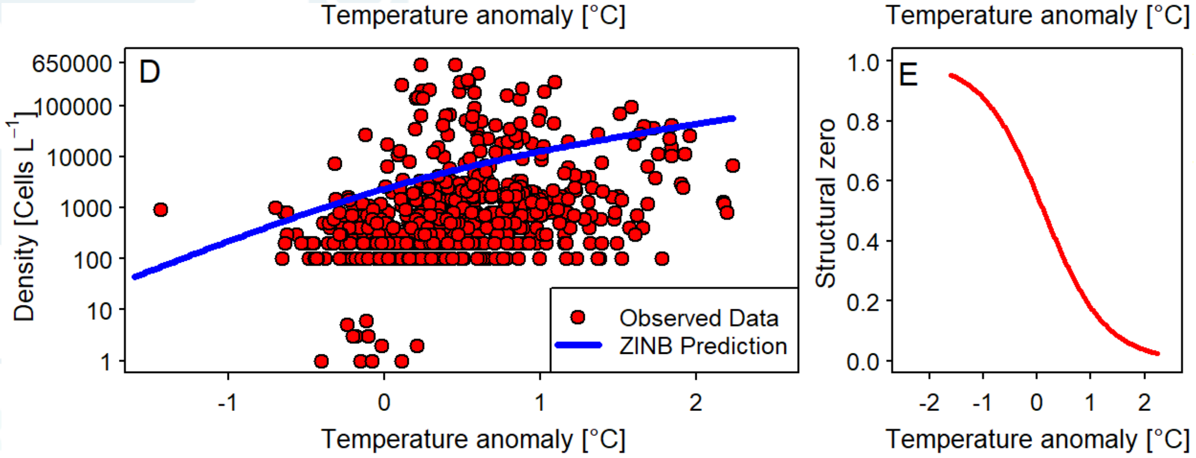


Fig. 15. ZINB model of *A. catenella* and temperature anomaly.

Conclusion: MHWs and MCSs at finer scale is necessary

Alternative for MHW detection

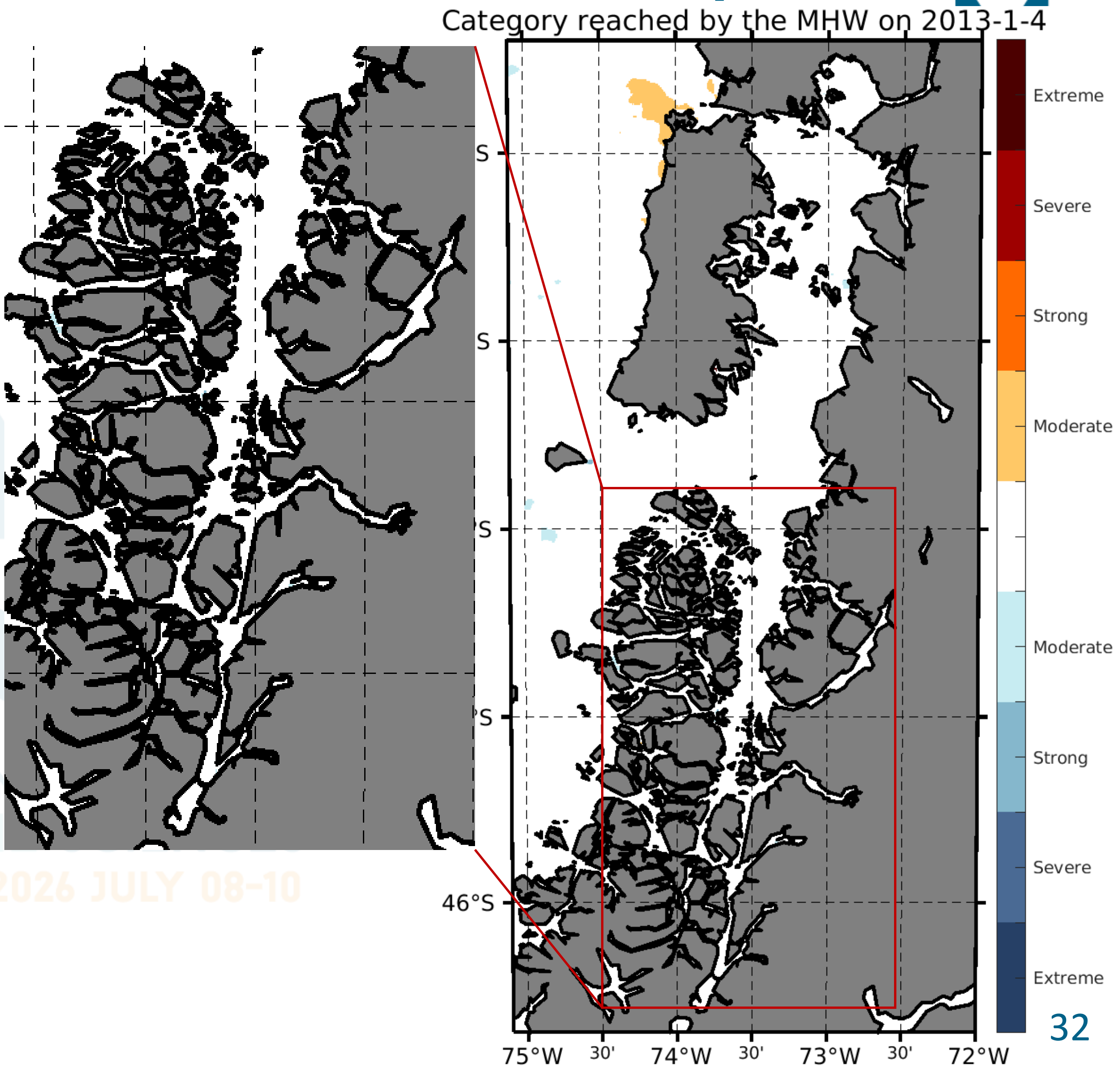
Detection of MHWs at high-resolution (~900m)

MHWs do not develop uniformly and each basin shows different characteristics

Fjords particularly sensitive to intense MHWs

Risk of harmful algal blooms

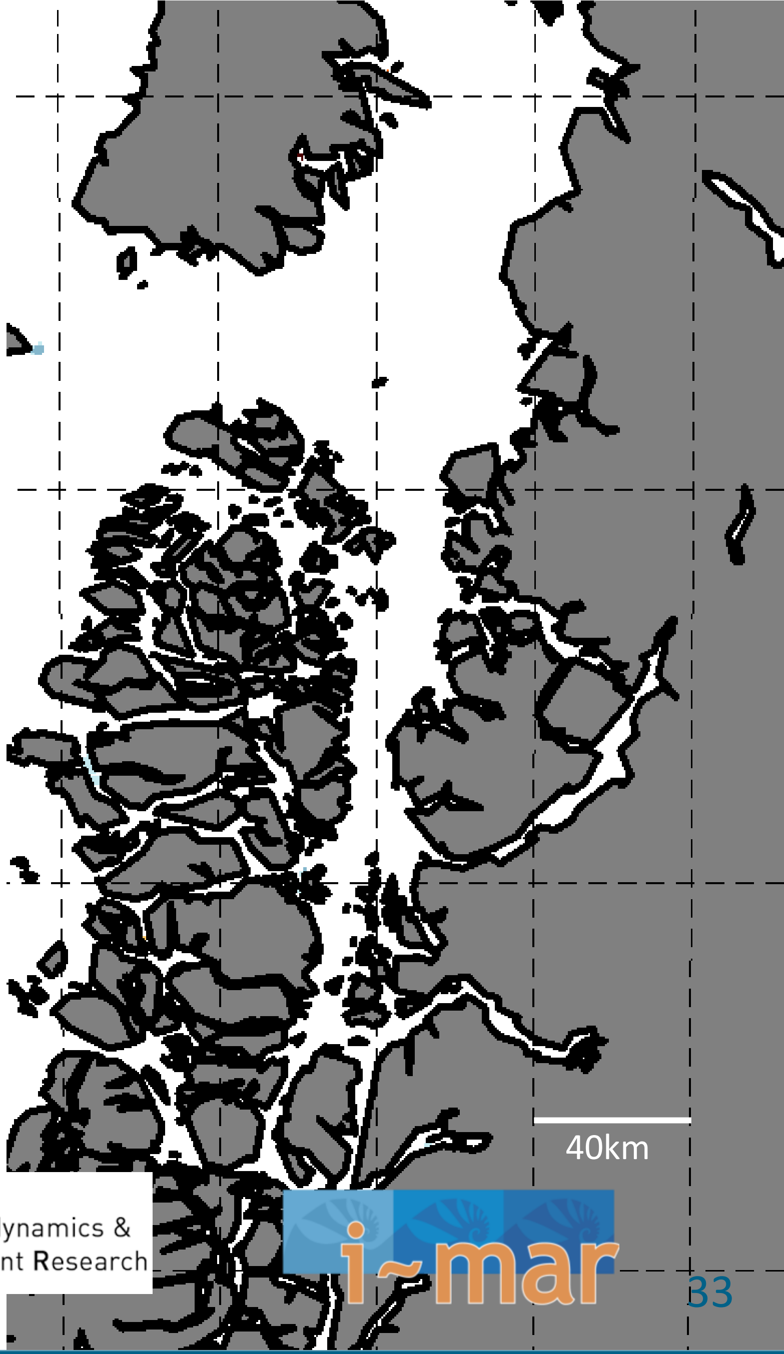
Important for aquaculture industry to monitor the different fjords and channels



Thank you !

Cécile Pujol
cecile.pujol@uliege.be

Alexander Barth, Iván Pérez-Santos, Patricio Diaz,
Guido Mancilla Gutiérrez, Aida Alvera-Azcárate



fnrs LA LIBERTÉ DE CHERCHER

FRIA.fnrs Fonds pour la formation à la recherche dans l'industrie et dans l'agriculture

LIÈGE université

GHER GeoHydrodynamics & Environment Research

i~mar

References

[1] A. Hobday *et al.*, « A hierarchical approach to defining marine heatwaves », *Progress in Oceanography*, vol. 141, p. 227-238, févr. 2016, doi: 10.1016/j.pocean.2015.12.014.

[2] C. Laufkötter, J. Zscheischler, et T. L. Frölicher, « High-impact marine heatwaves attributable to human-induced global warming », *Science*, vol. 369, nº 6511, p. 1621-1625, sept. 2020, doi: 10.1126/science.aba0690.

[4] E. C. J. Oliver *et al.*, « Longer and more frequent marine heatwaves over the past century », *Nat Commun*, vol. 9, nº 1, p. 1324, avr. 2018, doi: 10.1038/s41467-018-03732-9.

[6] B. Huang *et al.*, « Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1 », *Journal of Climate*, vol. 34, nº 8, p. 2923-2939, avr. 2021, doi: 10.1175/JCLI-D-20-0166.1.

[7] R. Schlegel et A. J. Smit, « heatwaveR: A central algorithm for the detection of heatwaves and cold-spells », *JOSS*, vol. 3, nº 27, p. 821, juill. 2018, doi: 10.21105/joss.00821.

[8] A. Barth, J.-M. Beckers, C. Troupin, A. Alvera-Azcárate, et L. Vandenbulcke, « divand-1.0: n-dimensional variational data analysis for ocean observations », *Geosci. Model Dev.*, vol. 7, nº 1, p. 225-241, janv. 2014, doi: 10.5194/gmd-7-225-2014.

[9] C. Troupin, F. Machín, M. Ouberdous, D. Sirjacobs, A. Barth, et J. -M. Beckers, « High-resolution climatology of the northeast Atlantic using Data-Interpolating Variational Analysis (Diva) », *J. Geophys. Res.*, vol. 115, nº C8, p. 2009JC005512, août 2010, doi: 10.1029/2009JC005512.

[10] A. Alvera-Azcárate, A. Barth, M. Rixen, et J. M. Beckers, « Reconstruction of incomplete oceanographic data sets using empirical orthogonal functions: application to the Adriatic Sea surface temperature », *Ocean Modelling*, vol. 9, nº 4, p. 325-346, janv. 2005, doi: 10.1016/j.ocemod.2004.08.001.

[13] A. Buschmann, L. Farías, F. Tapia, D. Varela, et M. Vásquez, « Scientific report on the 2016 southern Chile red tide », *Chilean Department of Economy*, p. 66, 2016.

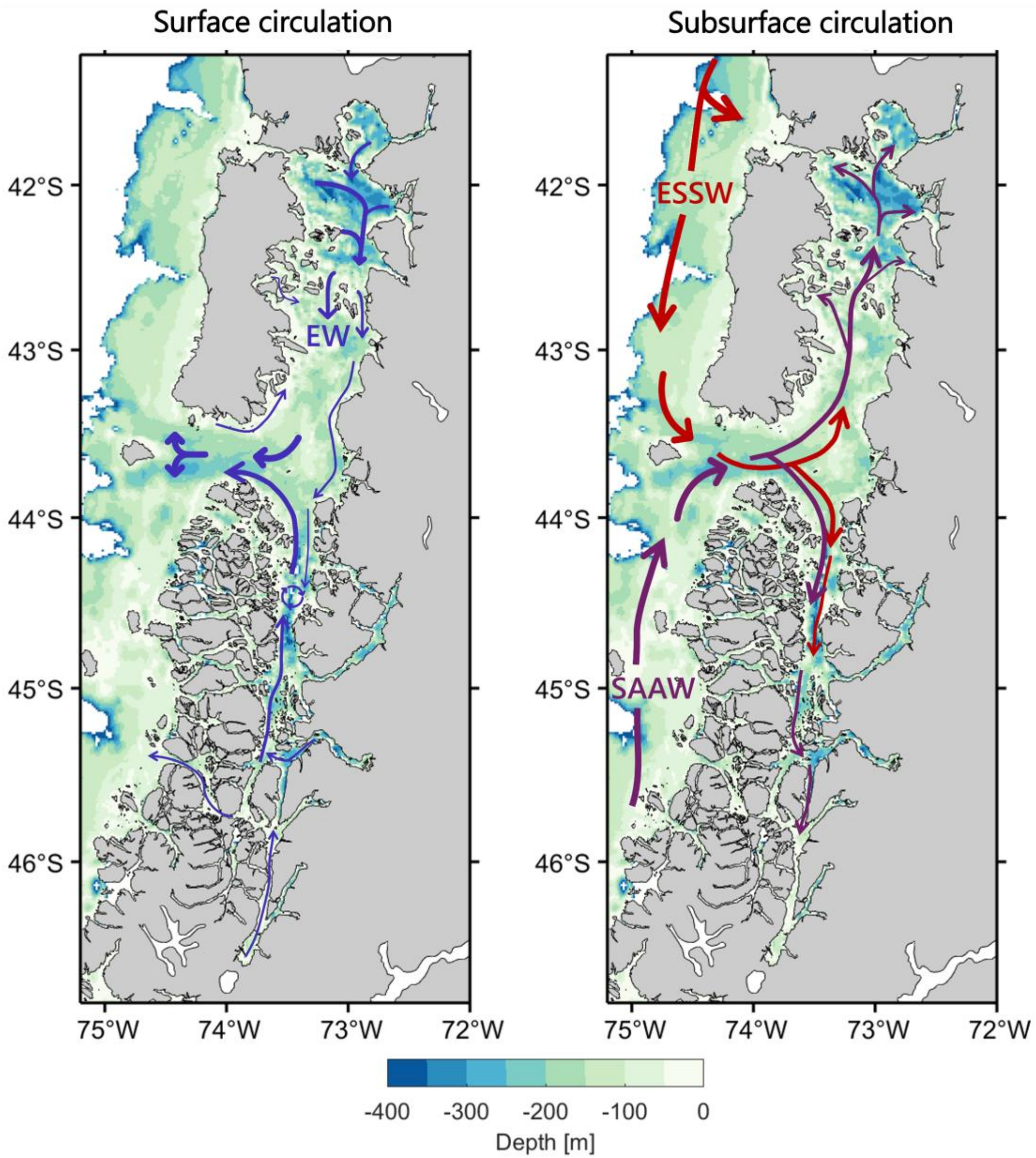
[14] J. León-Muñoz, M. A. Urbina, R. Garreaud, et J. L. Iriarte, « Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016) », *Sci Rep*, vol. 8, nº 1, p. 1330, janv. 2018, doi: 10.1038/s41598-018-19461-4.

[15] J. Mardones, « Chile: Causes, impacts and management of a “hot spot” for toxic algal blooms », in *Abstract book of the 19th International Conference on Harmful Algae*, International Society for the Study of Harmful Algal Blooms., C. J. Band-Schmidt et C. F. Rodríguez-Gómez, Éd., La Paz, B.C.S., Mexico, 2021, p. 10.

Water circulation in Northern Patagonia

3 main layers

- Surface layer: Estuarine Waters (EW)
- Intermediate layer: Subsurface Antarctic Waters
- Bottom layer: Equatorial SubSurface Waters



MHW and MCS trends

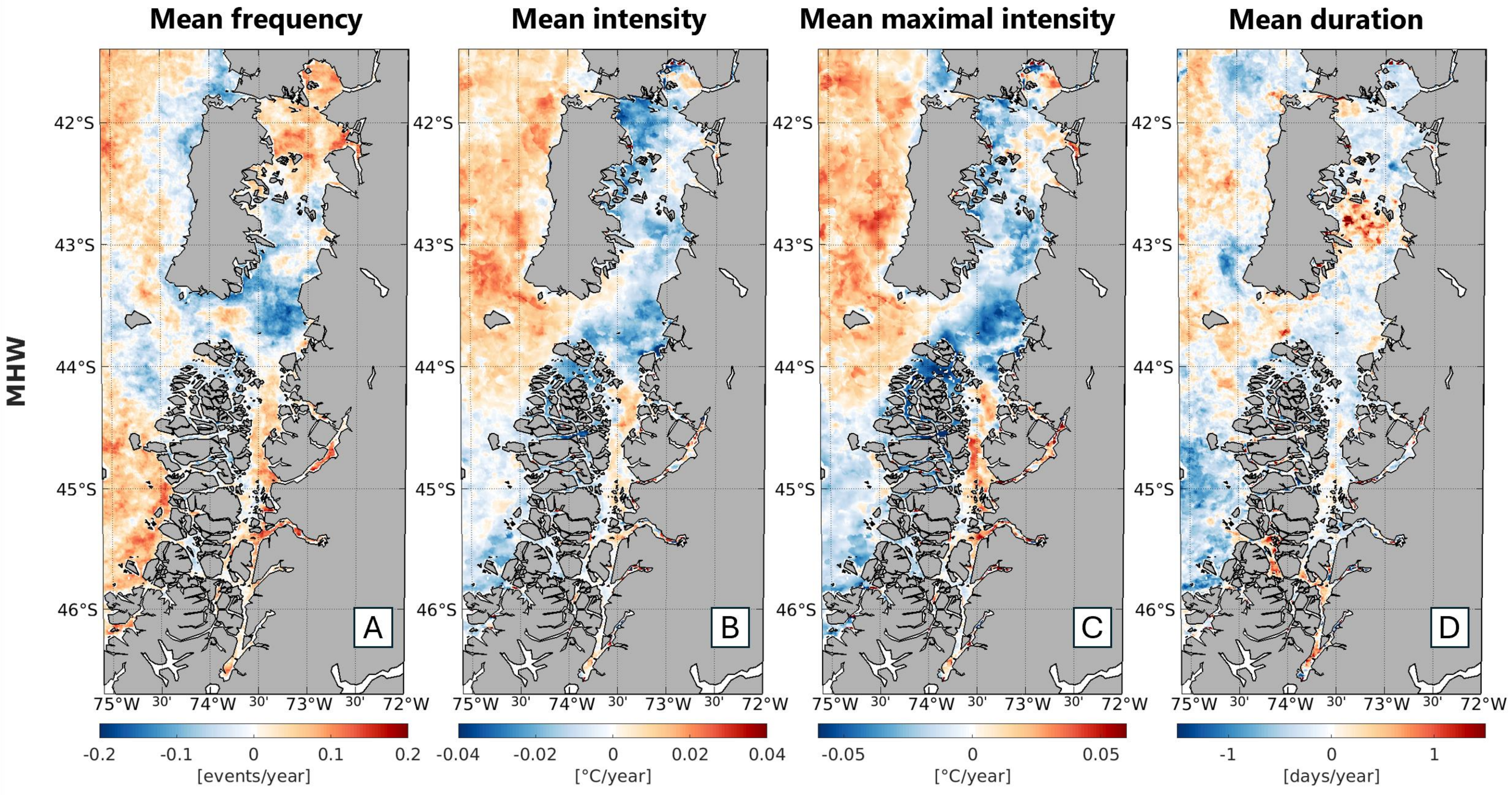
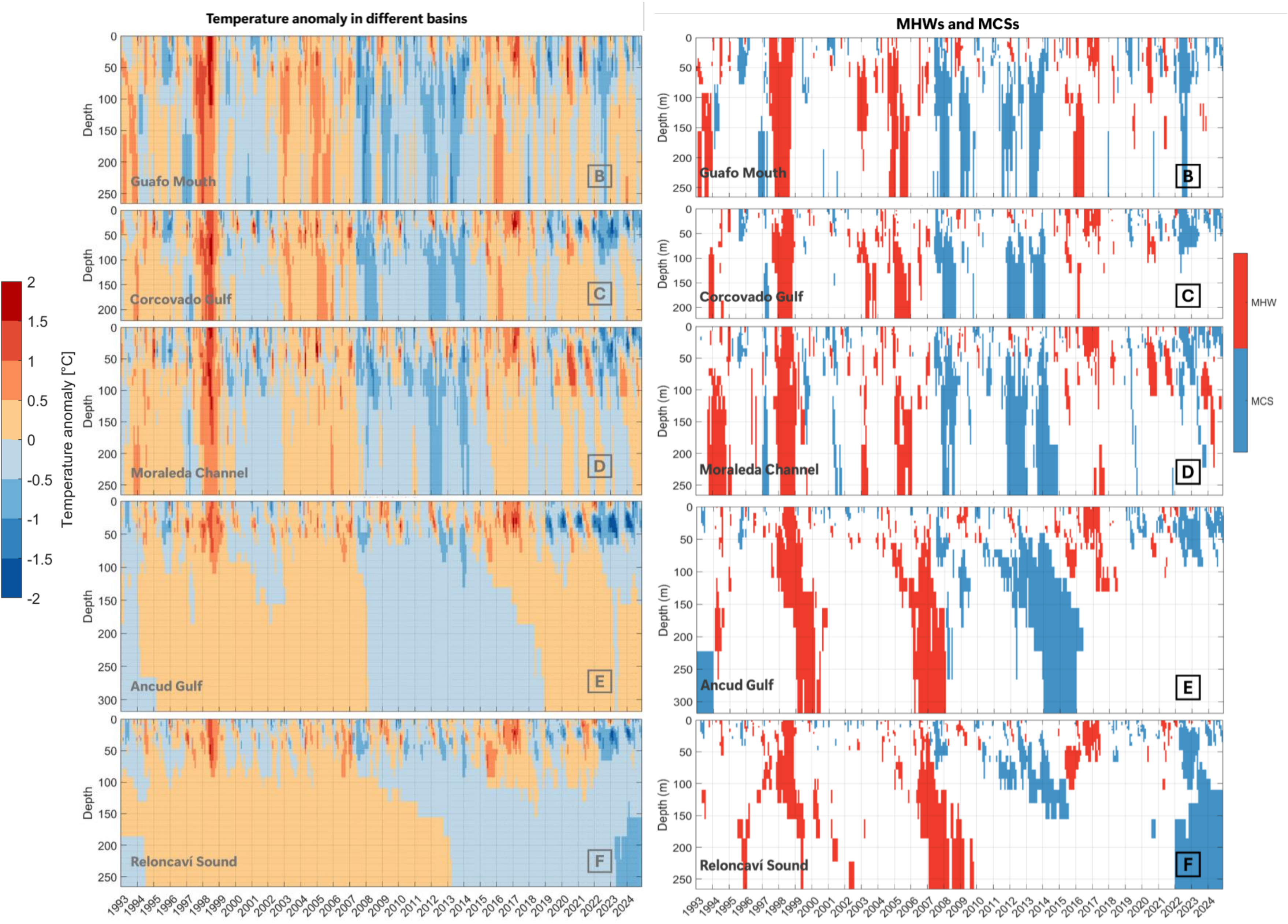
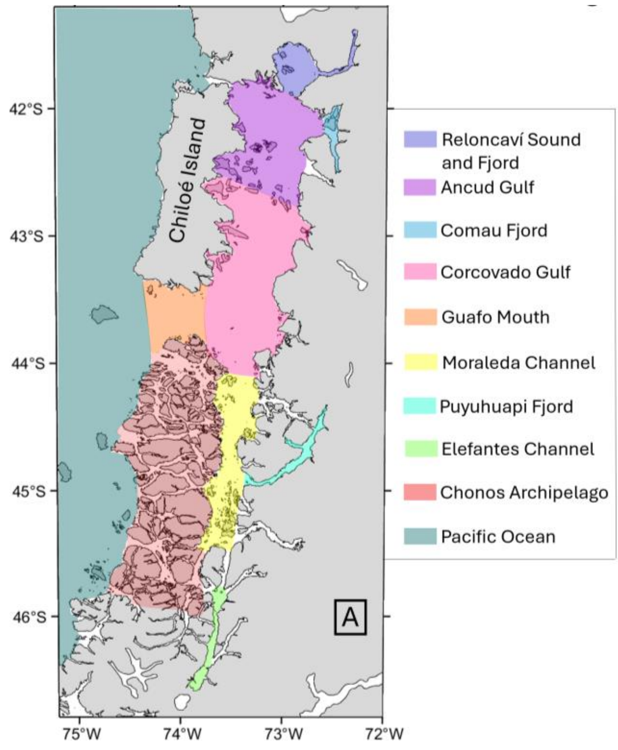


Fig. 49. MHWs trends at surface.

Pujol et al., in preparation

Subsurface MHWs and MCSs





Subsurface development: 2008

- Surface MHW that stayed confined to the upper layers
- November-December 2008
- Higher solar radiation + atmospheric heatwave

MHW category and SST anomaly at the surface

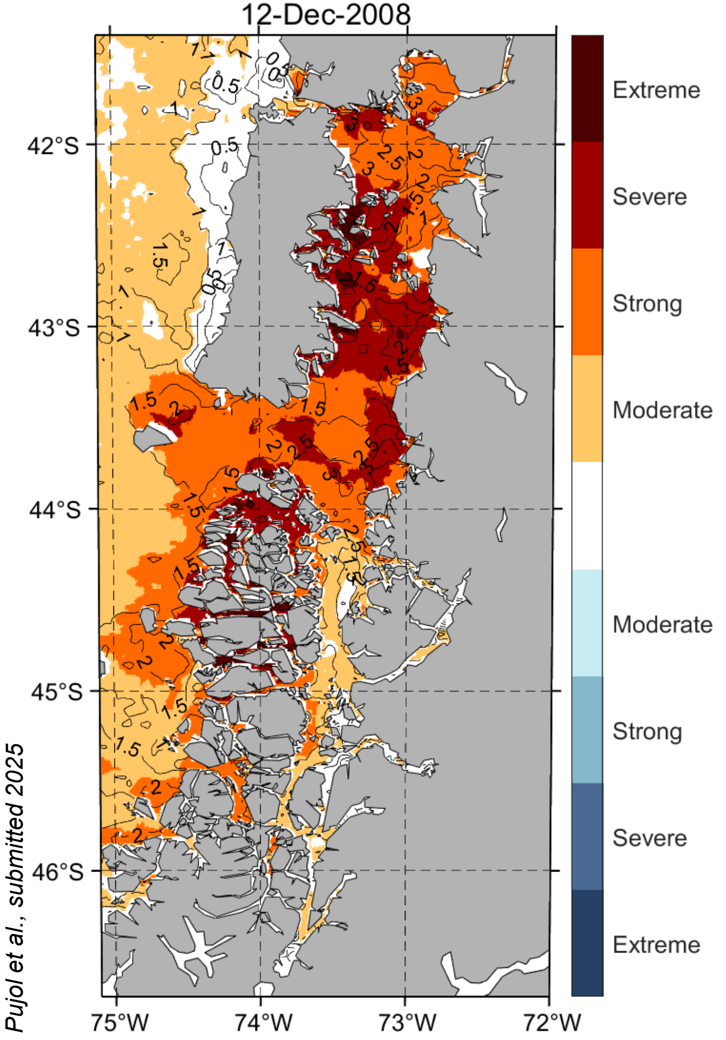
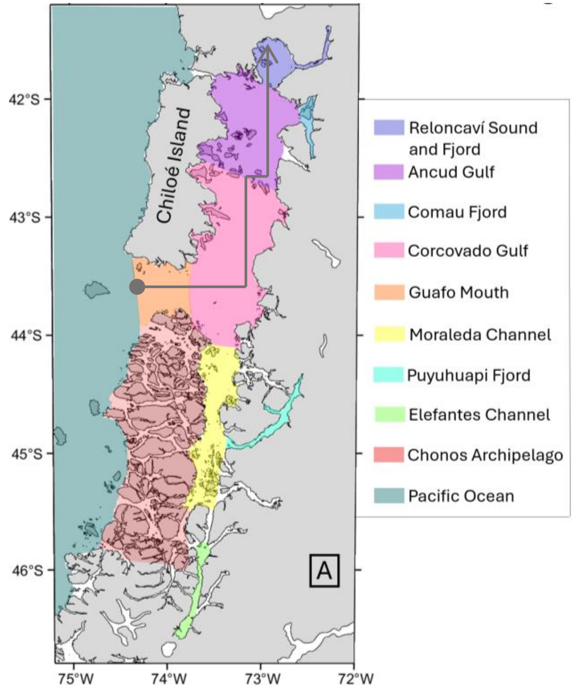


Fig. 30. MHW with our methodology in December 2008 and SST anomaly (lines).



Fig,32. Reminder of the study area.

Temperature anomaly over water column

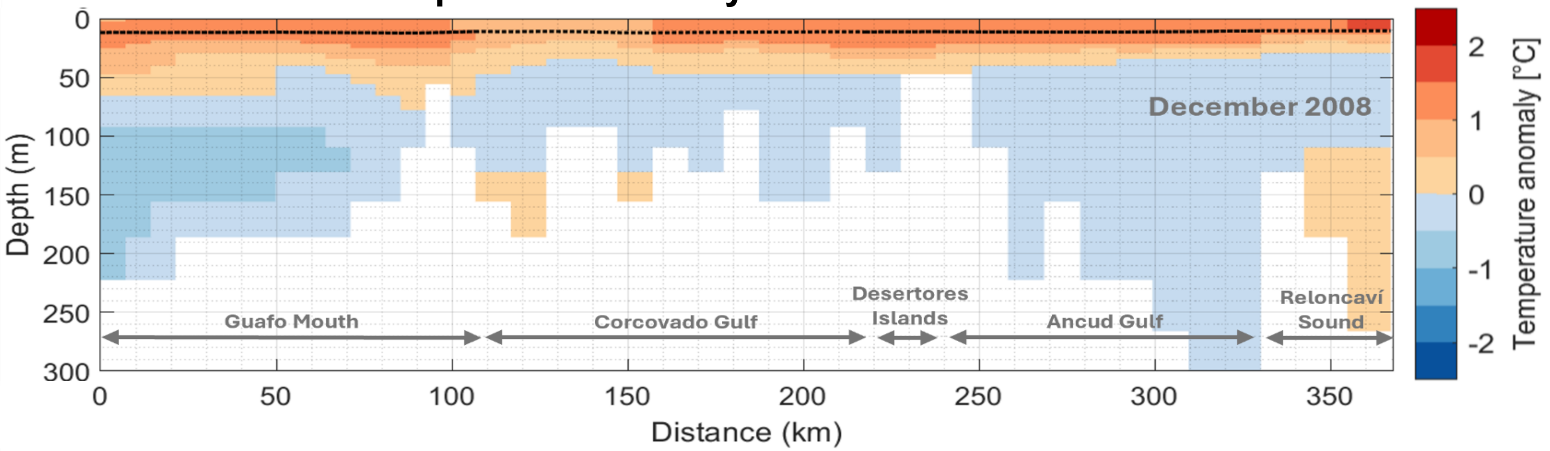


Fig. 31. Subsurface temperature in December 2008. Dotted line: mixed layer depth. Climatology: 1993-2024.

Subsurface development: 1998

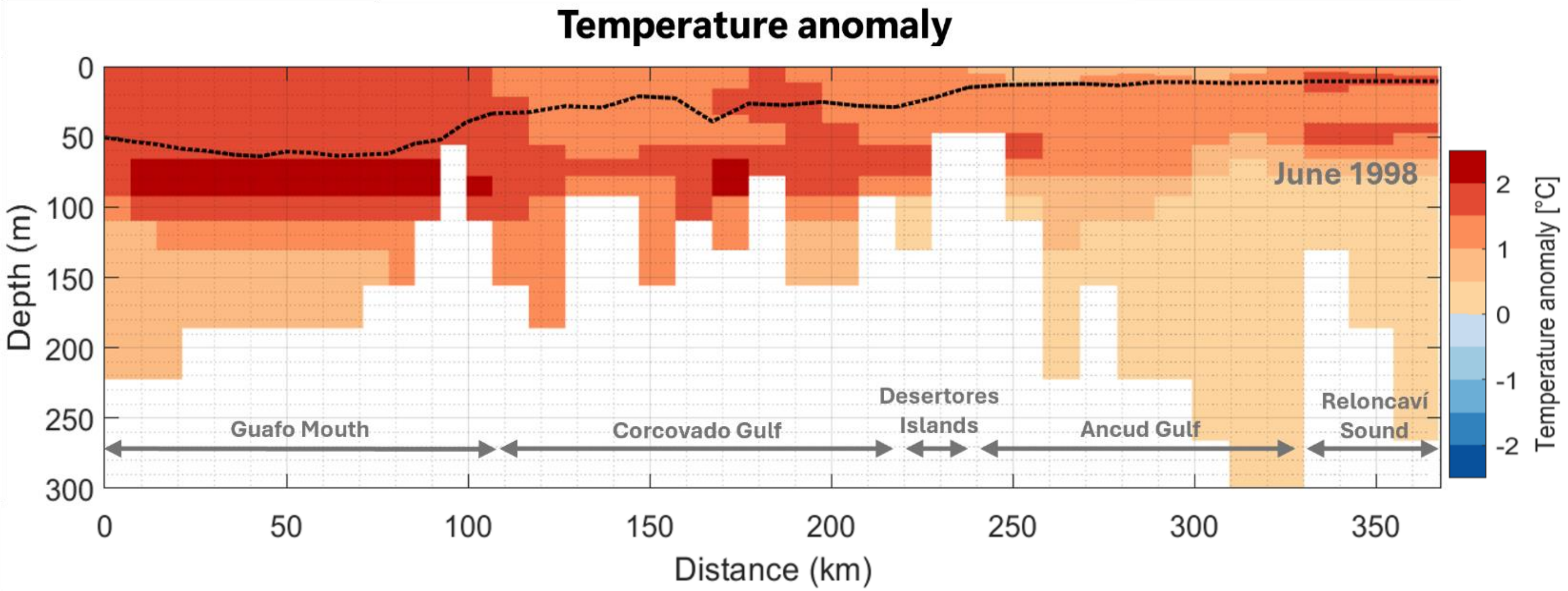
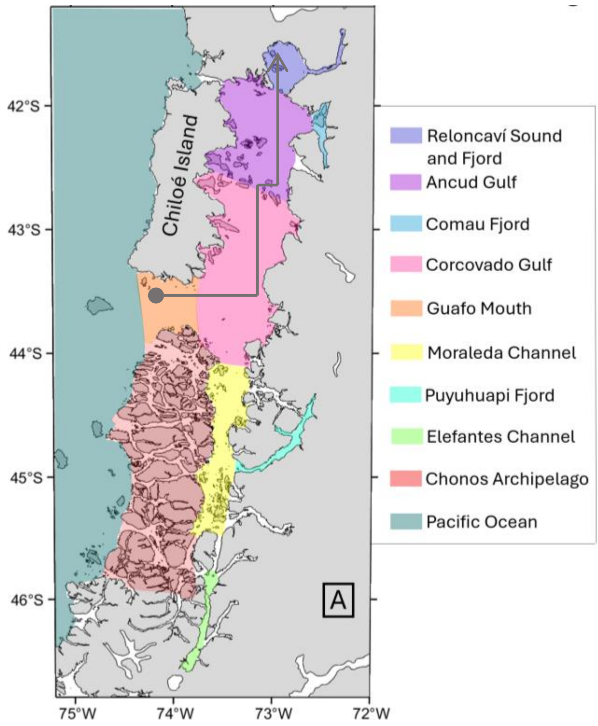


Fig. 38. Subsurface temperature in June 1998 from GLORYS model. Dotted line: mixed layer depth. Climatology: 1993-2024.



Fig, 32. Reminder of the study area.

- MHW over the entire water column
- Lasted for 8 months at 100 m depth
- Deepening of the mixed layer depth
- Very strong El Niño

Subsurface development: 2017 and 2024

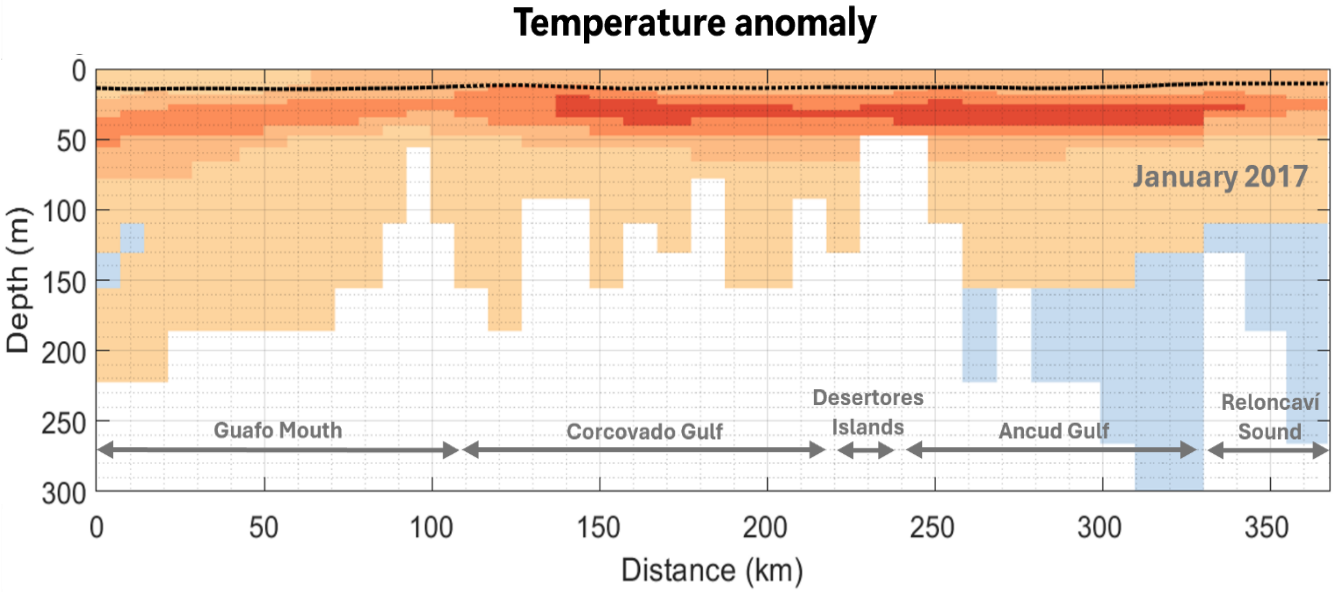


Fig. 39. Subsurface temperature in January 2017 from GLORYS model. Dotted line: mixed layer depth. Climatology: 1993-2024.

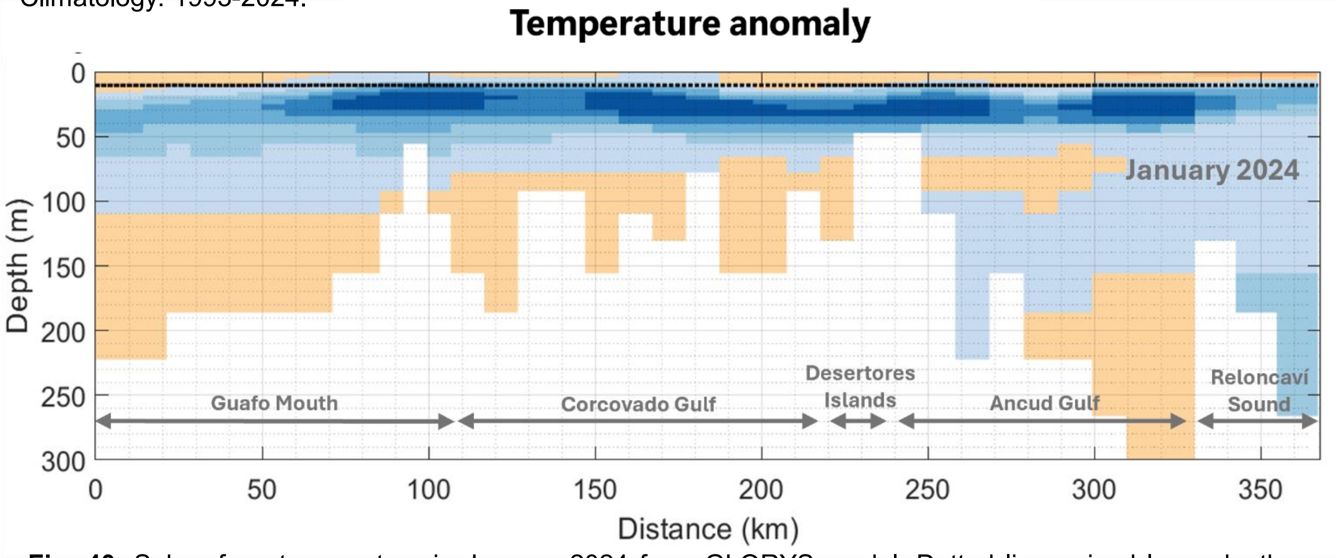
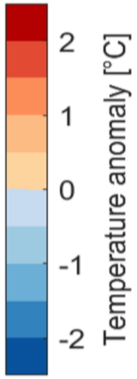


Fig. 40. Subsurface temperature in January 2024 from GLORYS model. Dotted line: mixed layer depth. Climatology: 1993-2024.



- MHW from surface to 50m
  - Positive heat fluxes & atmospheric heatwave
    - Coastal El Niño
- Stronger temperature below the mixed layer

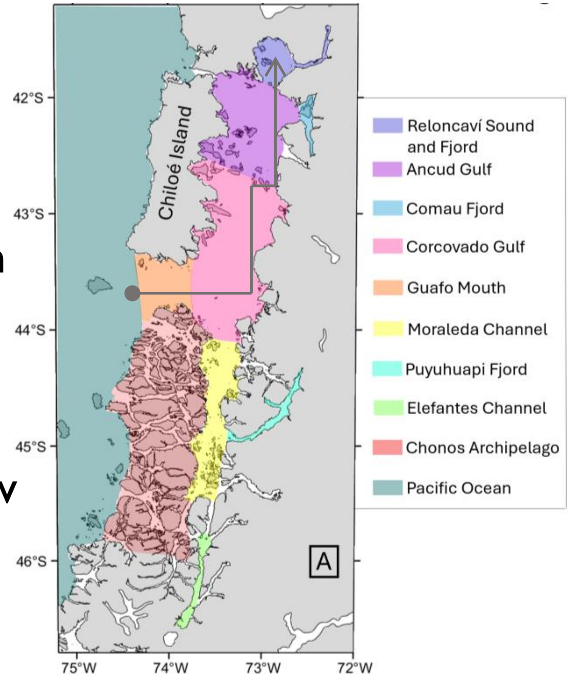
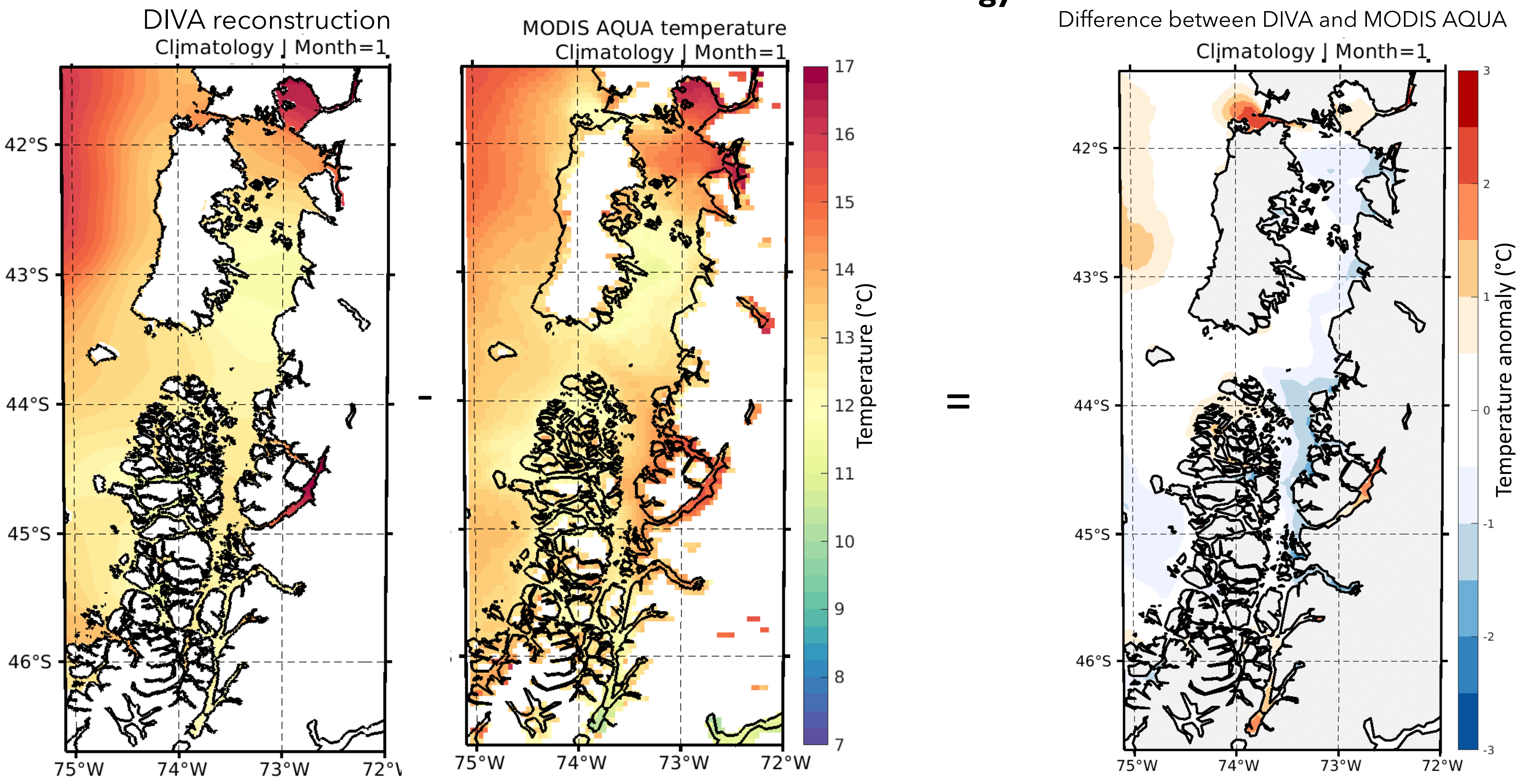


Fig. 32. Reminder of the study area.

MCS from surface to 50m
- Cold period context
- Low salinity period
- Lower anomalies below the mixed layer

Validation of the climatology



Summary and potential impacts of MCSs and MHWs

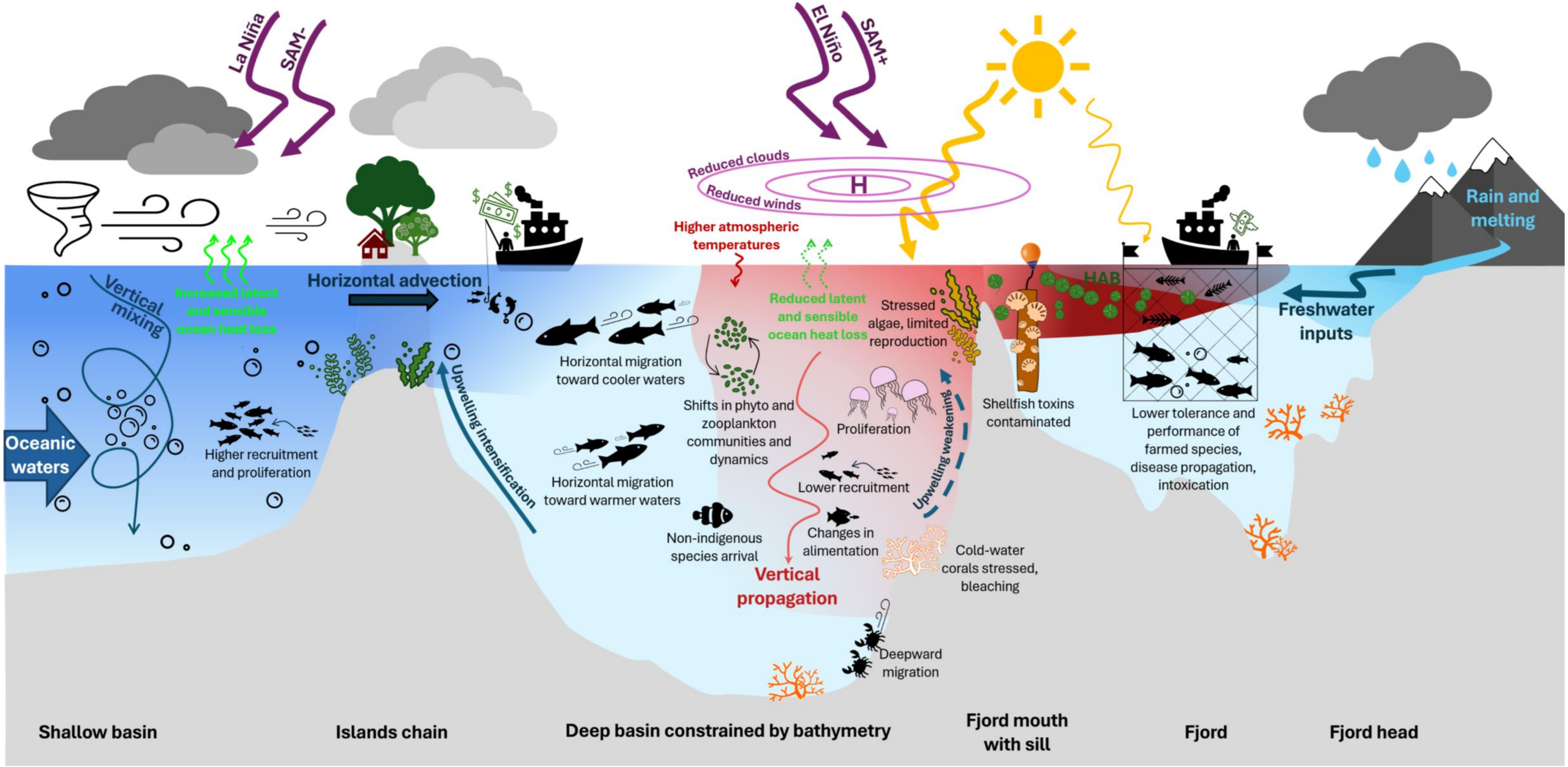


Fig. 52. Summary figure: drivers of MHWs and MCSs and potential impacts on ecosystems and human activities.