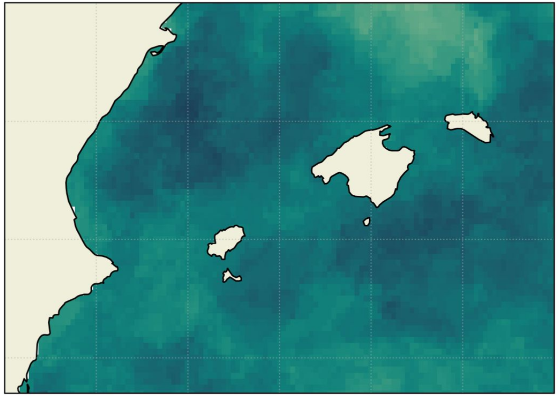
Internship Final Presentation - Master II Ocean Data Science

Marine heatwaves in the Balearic Islands region



Author: Arthur Gonnet, IMT Atlantique

September 2025

Supervisors: Mélanie Juza, Emma Reyes

SOCIB
Balearic Islands
Coastal Observing
and Forecasting System

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

iuem

ENSTA
IP PARIS

Outline

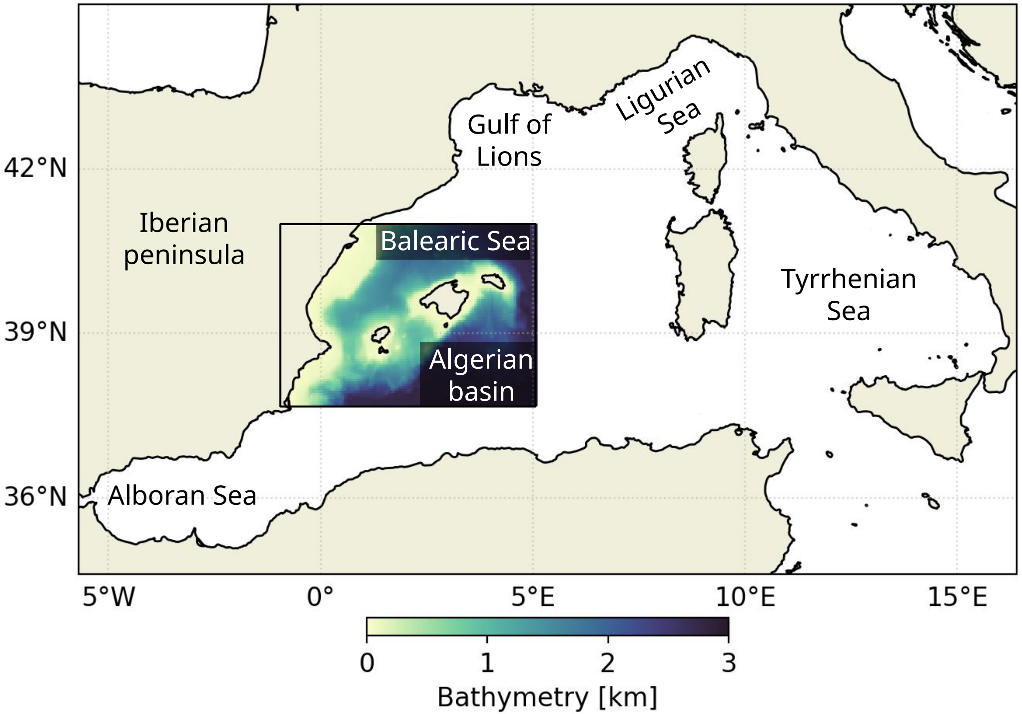
Introduction - Context of marine heatwaves

➢ Widely studied at global or regional scale, mostly using satellite SST

➢ Linked to a wide range of ecological and economic risks
(Garrabou et al., 2022)

➢ Global increase of MHW frequency, intensity and duration
(Frölicher et al., 2018; Oliver et al., 2018)

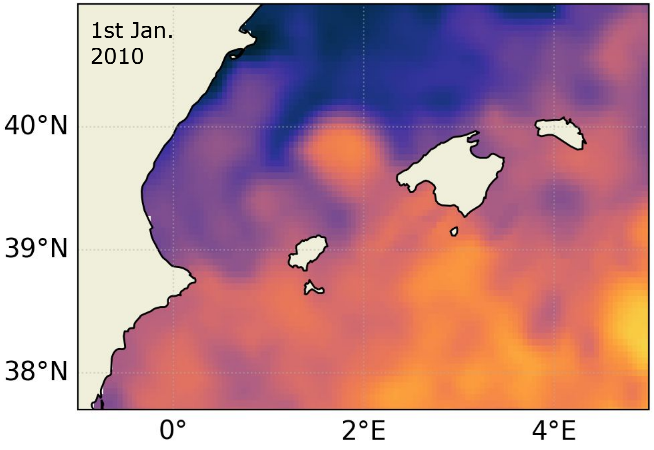
Introduction – Study Area



- ➤ The Mediterranean Sea is recognised as a climate change hotspot (Giorgi, 2006)
- ➤ The Balearic Islands is a biodiversity hotspot (Coll et al., 2010)
- ➤ Study of surface and subsurface marine heatwaves

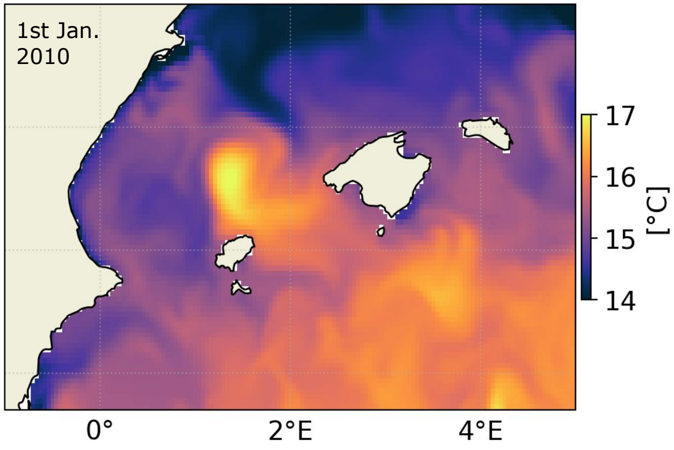
Data - Temperature datasets

REP (SST)



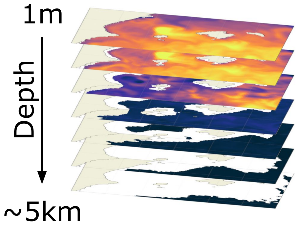
- Satellite observations
- Daily
- 1/20° (5-6 km)
- 1982-2023

MEDREA (at 1 m)



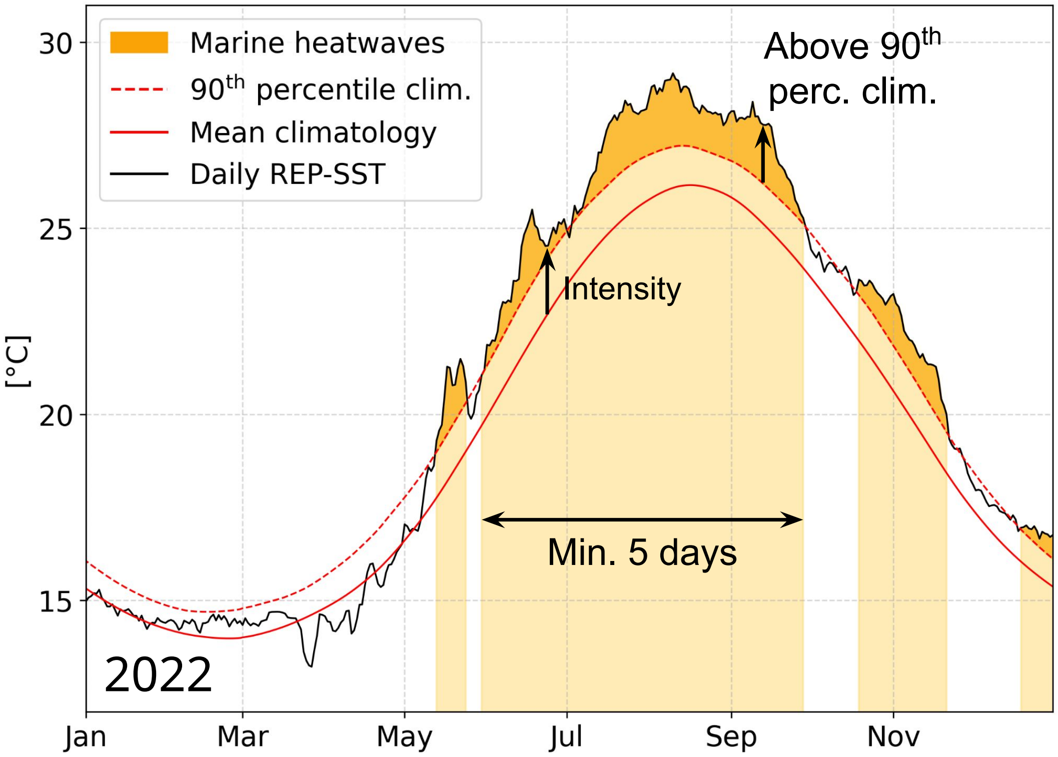
- Physical reanalysis
- Daily
- 1/24° (4-5 km)
- 1987-2022

- 141 levels

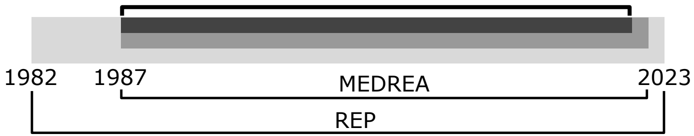


- Comparison of the two datasets at surface done in the report

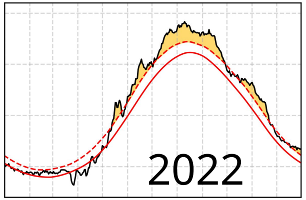
Methods - Marine heatwaves detection

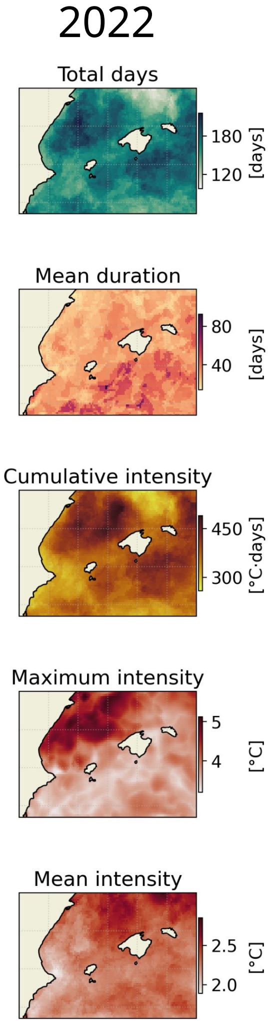


- **Marine heatwaves:** *"prolonged anomalously warm water event"*
- **Hobday et al. (2016):** *"temperature above 90th percentile climatology for more than five consecutive days" (ignoring two days gaps)*
- **Climatology period:** 1987-2021



Methods – 5 annual MHW metrics





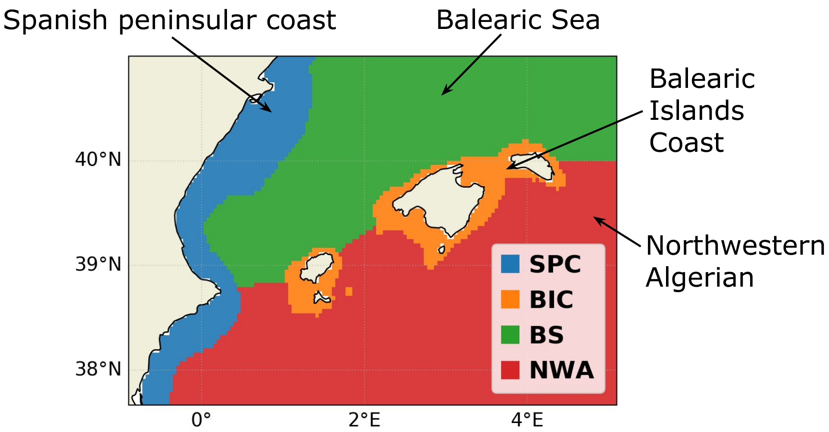
Annual metric	Definition
Total days	Number of MHW days
Mean duration	Average duration of MHW events
Cumulative intensity	Sum of MHW intensity over all MHW days
Maximum intensity	Maximum MHW intensity observed on a MHW day
Mean intensity	Average MHW intensity over all MHW days

➤ Study MHW events on a yearly basis

GitHub

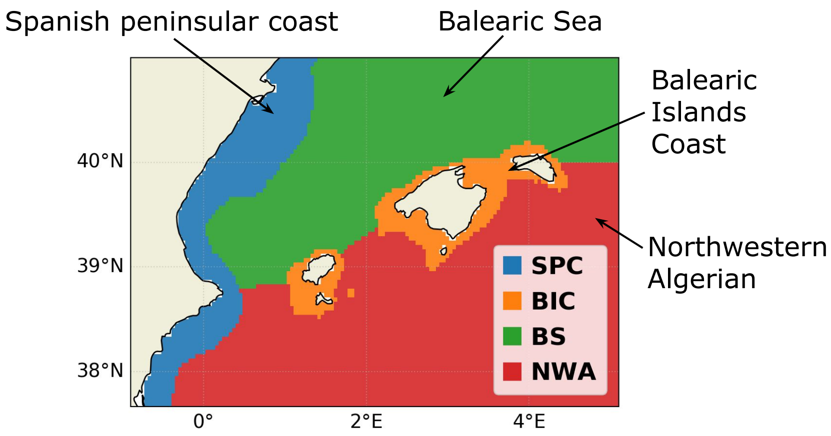
Note: All code used to produce the figures herein is open-source and available in GitHub
https://github.com/arthur-gonnet/balearic-mhws-study

Methods - Subregions & Levels



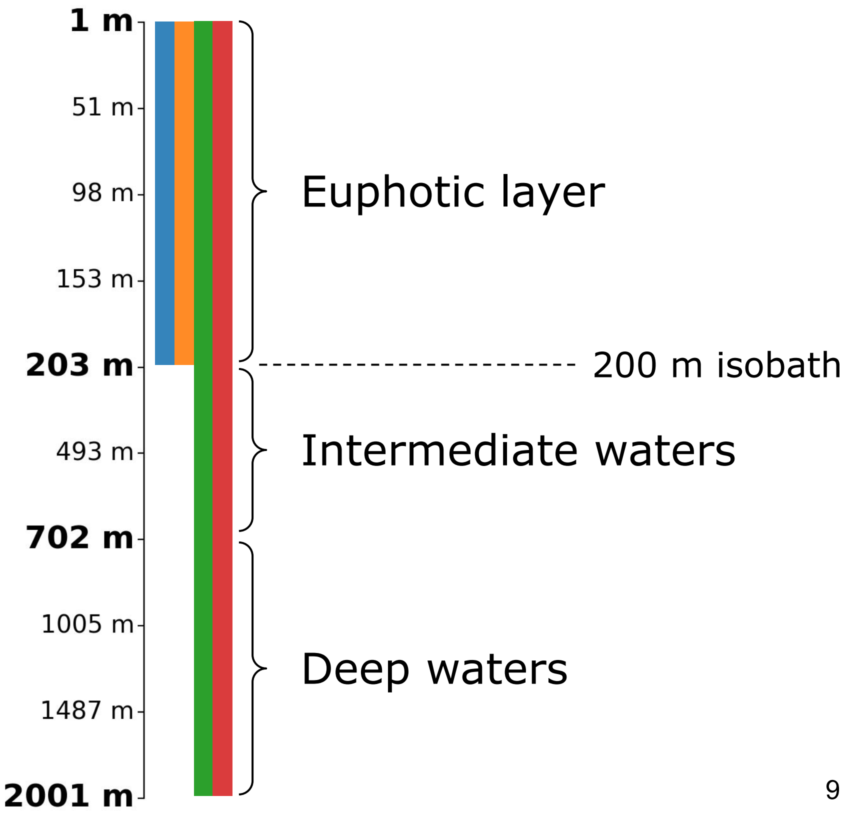
1. **Coastal / Open sea:**
   200 m isobath
2. **Peninsula / Islands**
3. **North / South:**
   Islands canals

Methods - Subregions & Levels



1. **Coastal / Open sea:** 200 m isobath
2. **Peninsula / Islands**
3. **North / South:** Islands canals

➤ **10 depth levels**



Surface MHWs - Balearic Islands region

Annual metric	Mean
Total days	**24** days
Mean duration	**10.5** days
Cumulative intensity	**45** °C·days
Maximum intensity	**2.28** °C
Mean intensity	**1.65** °C

REP over 1982-2023

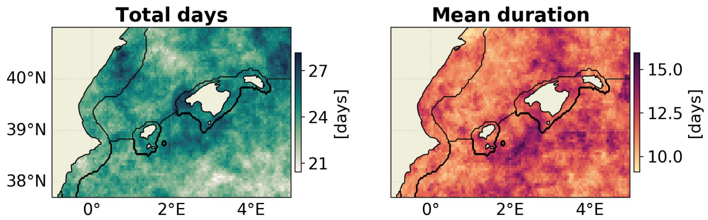
Surface MHWs - Balearic Islands region

Annual metric	Mean	Trend	Trend over 1982-2023
Total days	**24** days	**+ 8.5** days/decade	**+ 35.7** days
Mean duration	**10.5** days	**+ 1.07** days/decade	**+ 4.50** days
Cumulative intensity	**45** °C·days	**+ 15.0** °C·days/decade	**+ 63.0** °C·days
Maximum intensity	**2.28** °C	**+ 0.30** °C/decade	**+ 1.26** °C
Mean intensity	**1.65** °C	**+ 0.12** °C/decade	**+ 0.50** °C

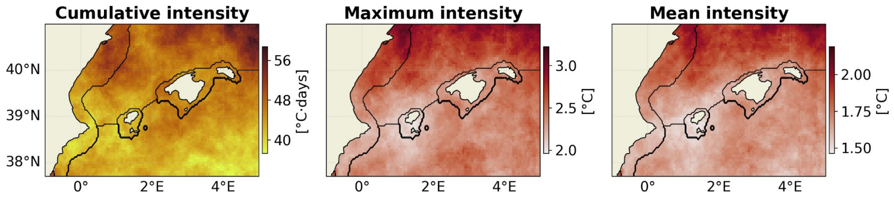
➤ All annual metrics shows significant and positive trends

Surface MHWs - Spatial variability

Mean | **Trend**



➤ No clear pattern in persistence-related metrics

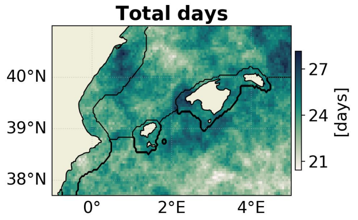


➤ North / South contrast in intensity-related metrics

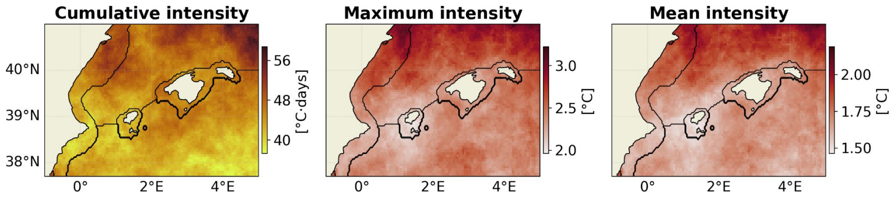
REP over 1982-2023

Surface MHWs - Spatial variability

Mean

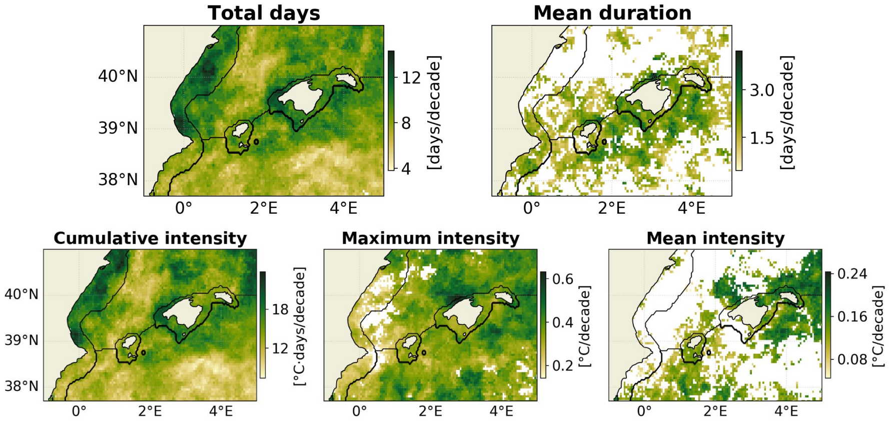


➢ No clear pattern in persistence-related metrics



➢ North / South contrast in intensity-related metrics

Trend

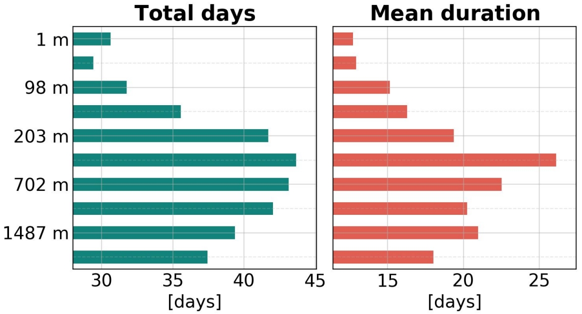


➢ Trends are all positive, but can be locally not significant

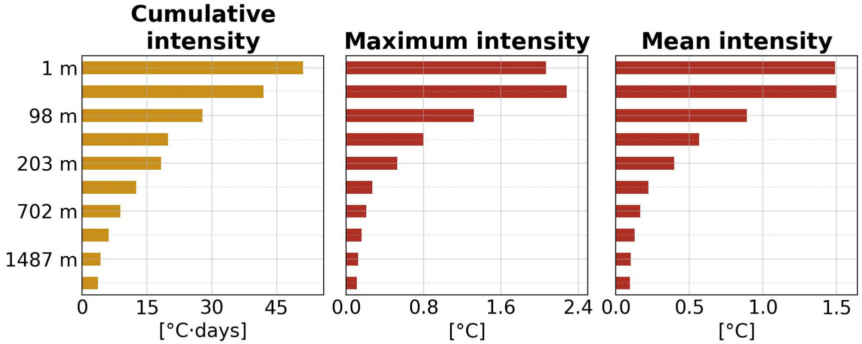
➢ Total days and cumulative intensity have higher trends in coastal areas

Subsurface MHWs - Balearic Islands region

Mean | **Trend**



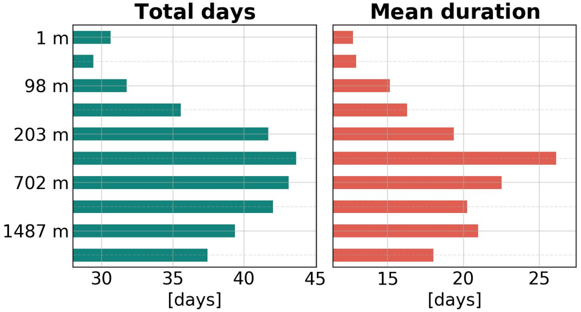
➤ MHWs are more persistent at 500 m depth



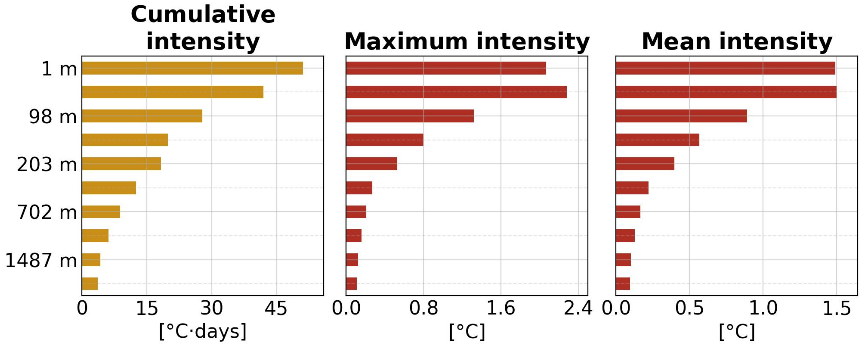
➤ MHWs are more intense at the surface

Subsurface MHWs - Balearic Islands region

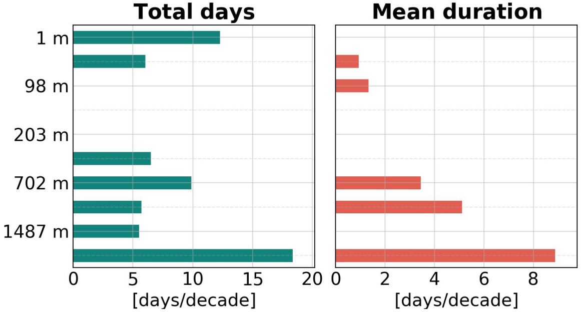
Mean | Trend



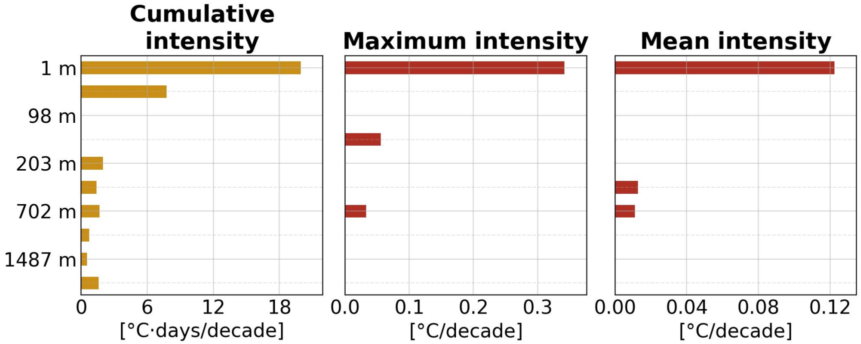
➢ MHWs are more persistent at 500 m depth



➢ MHWs are more intense at the surface



➢ Persistence -related metrics have higher trends at 2000 m

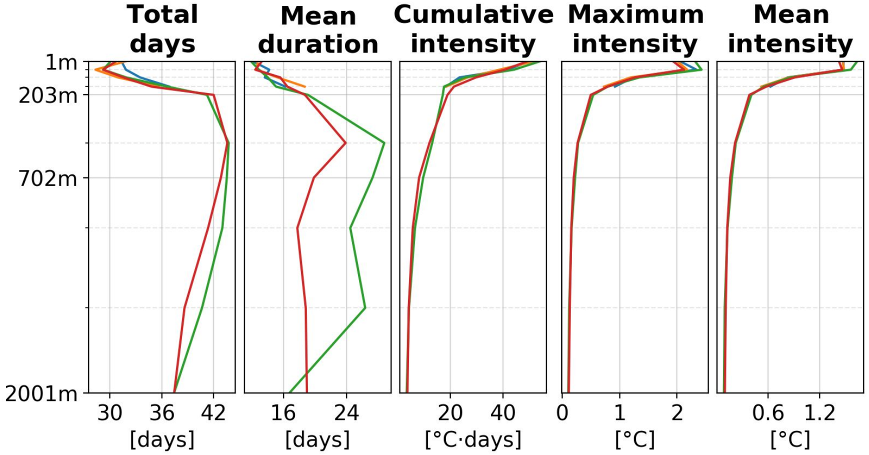


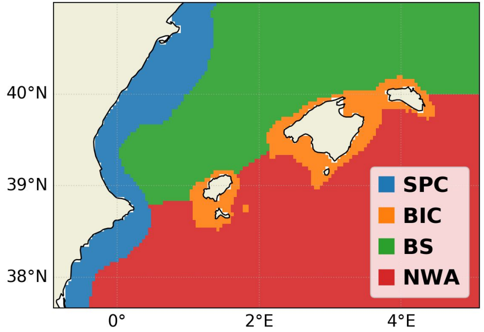
➢ Intensity-related metrics have higher trends at the surface

➢ Meaningful fraction of significant positive trends at subsurface

Subsurface MHWs - Subregions

Mean | Trend

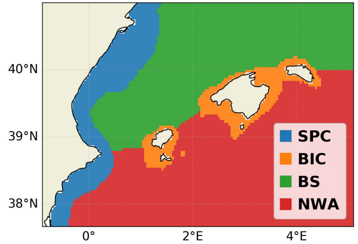




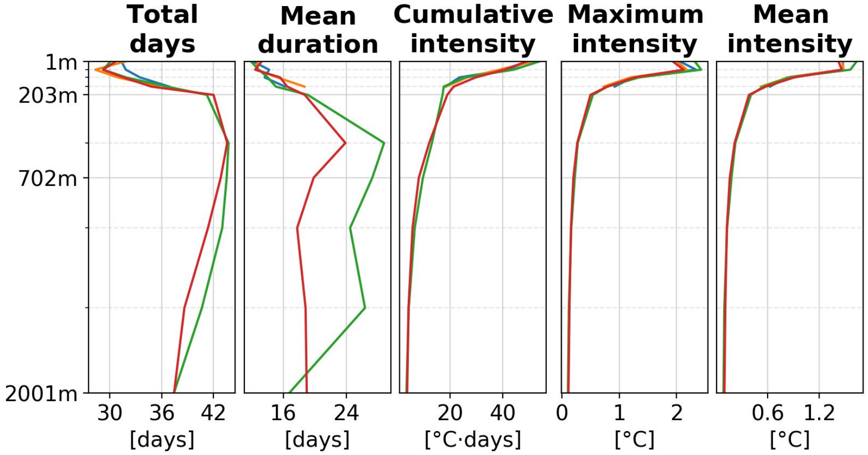
➤ BS (Balearic Sea) shows more persistent events at depth

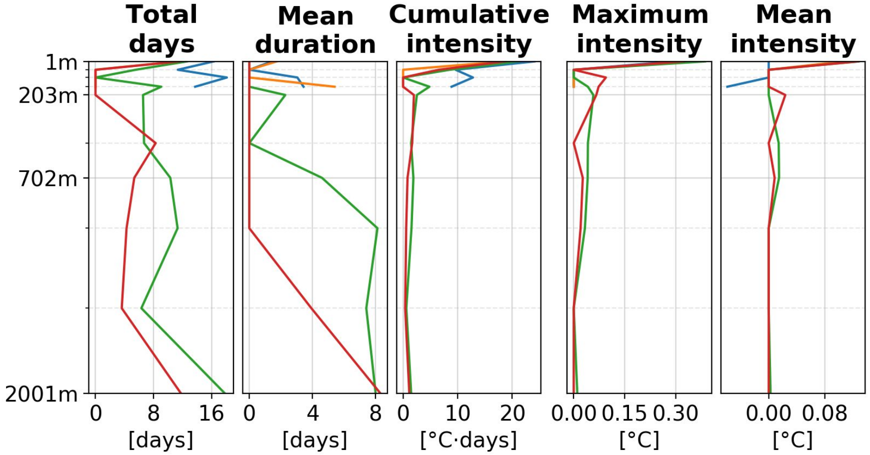
Subsurface MHWs - Subregions

MEDREA over 1987-2022



Mean | Trend



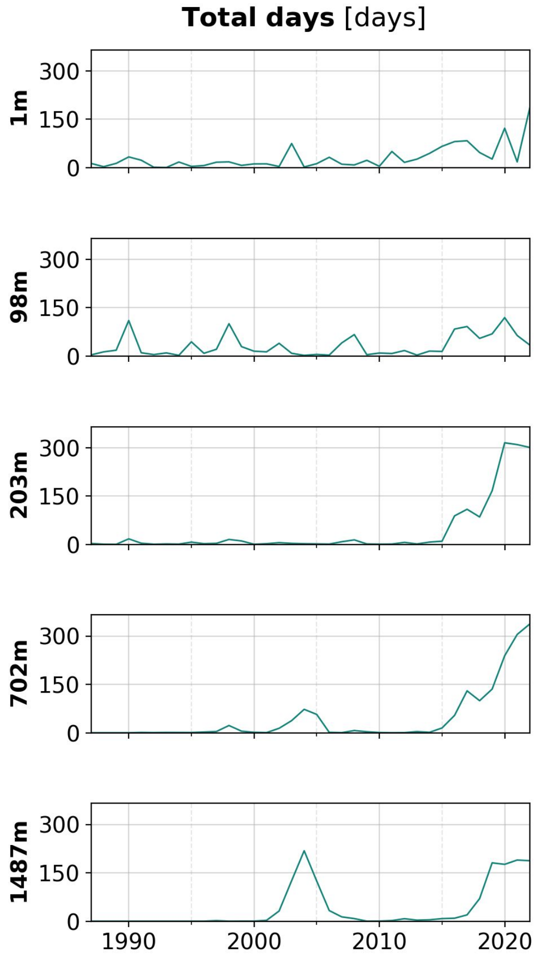


- ➤ BS (Balearic Sea) shows more persistent events at depth

- ➤ SPC shows highest trend of total days in the upper layer
- ➤ BS shows higher trends of persistence at depth

Drivers

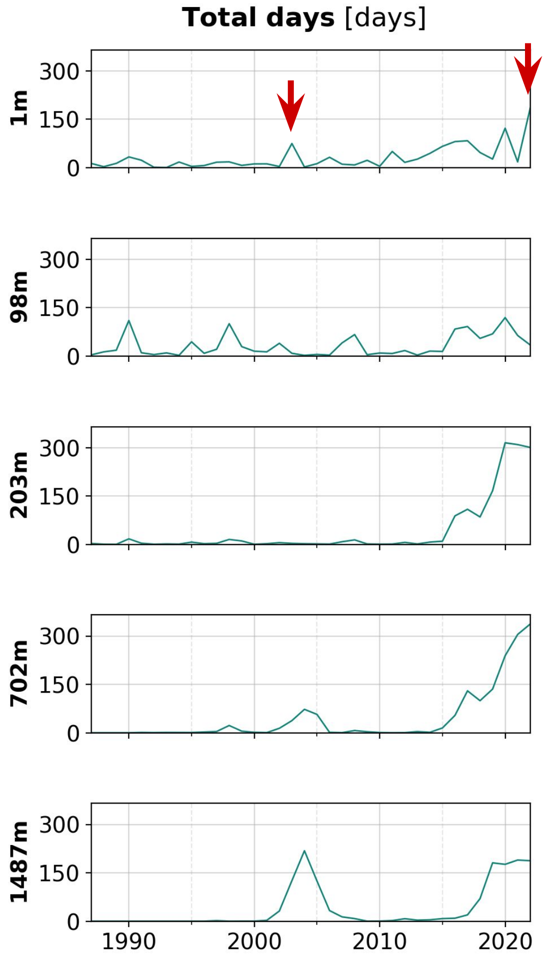
MHWs can be induced by various atmospheric and/or ocean processes

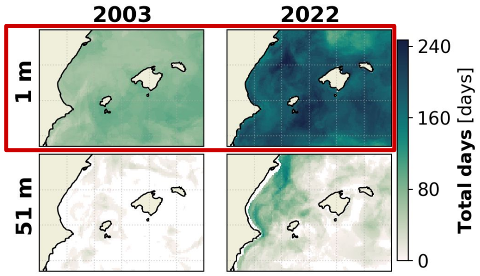


Drivers

MHWs can be induced by various atmospheric and/or ocean processes

➤ Atmospheric forcing



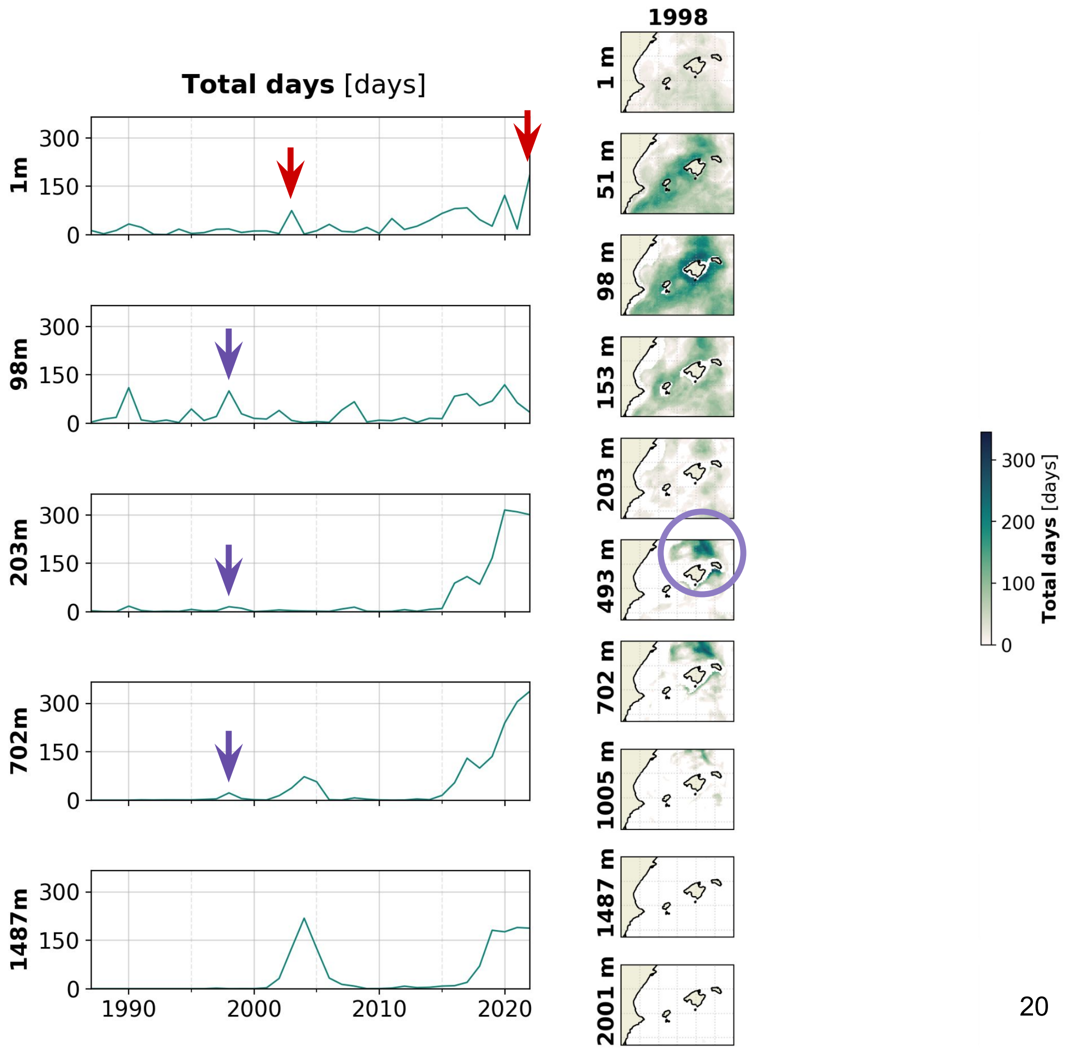


(Sparnocchia et al., 2006; Marullo et al., 2023)

Drivers

MHWs can be induced by various atmospheric and/or ocean processes

- Atmospheric forcing
- Anticyclonic eddies

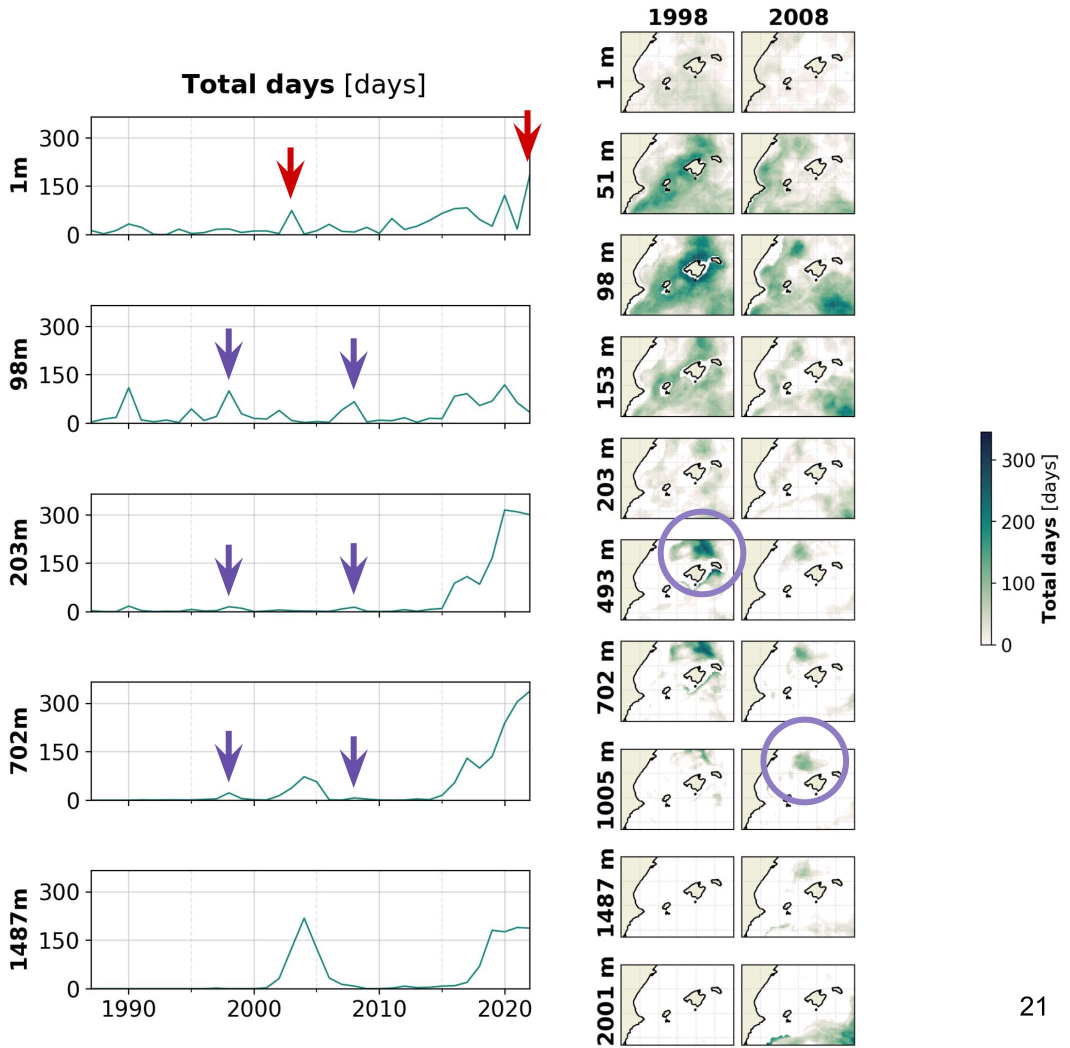


(Mason and Pascual, 2013; Aguiar et al., 2022)

Drivers

MHWs can be induced by various atmospheric and/or ocean processes

- Atmospheric forcing
- Anticyclonic eddies

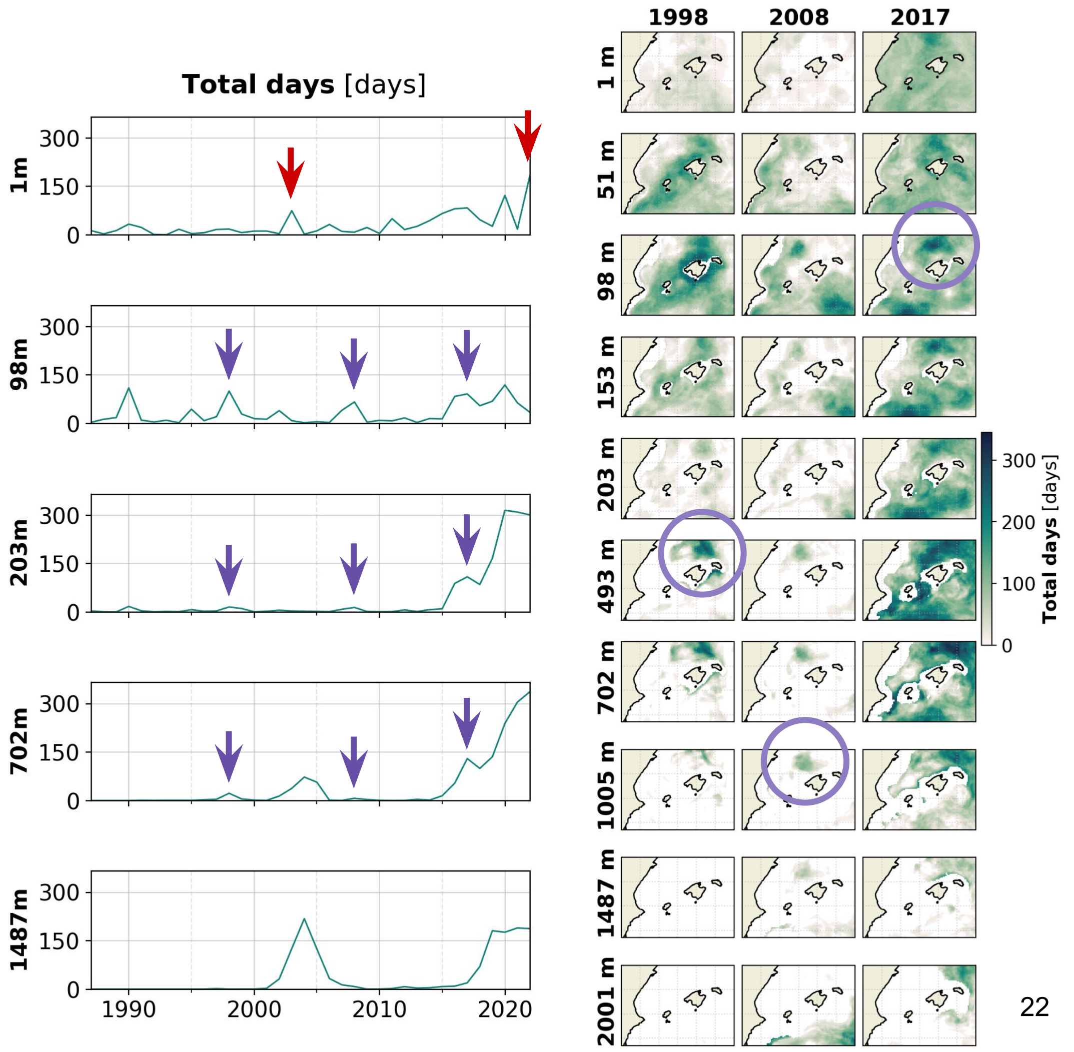


(Mason and Pascual, 2013; Aguiar et al., 2022)

Drivers

MHWs can be induced by various atmospheric and/or ocean processes

- ➤ Atmospheric forcing
- ➤ Anticyclonic eddies

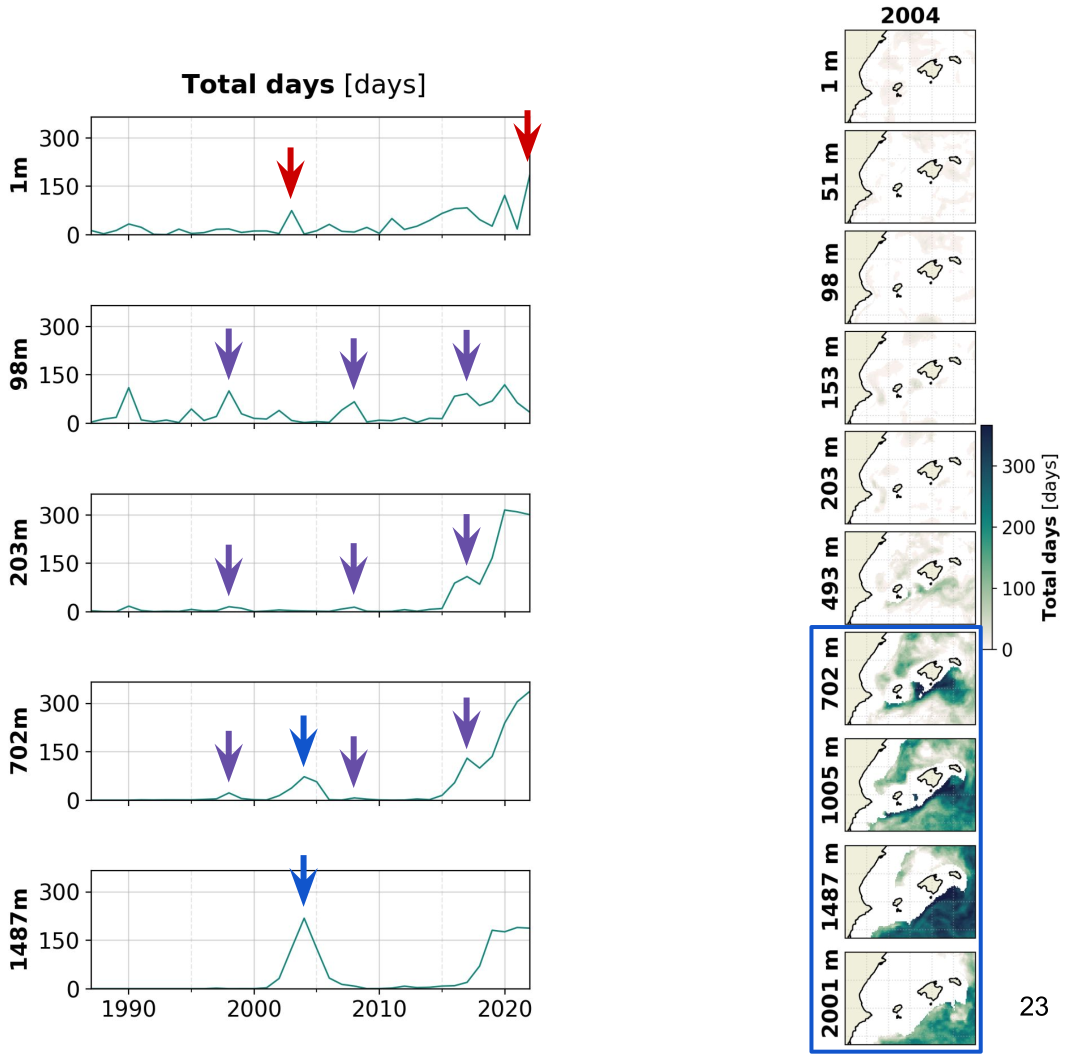


(Mason and Pascual, 2013; Aguiar et al., 2022)

Drivers

MHWs can be induced by various atmospheric and/or ocean processes

- Atmospheric forcing
- Anticyclonic eddies
- Other processes



Conclusion & perspectives

→ Positive trends of MHW annual metrics in the Balearic Islands region at the surface and over the water column for the periods 1982-2023 and 1987-2022, respectively

→ Strong spatiotemporal and vertical variability

→ Multiple drivers (atmospheric forcing, anticyclonic eddies)

→ Other baseline choices could be explored (Amaya et al., 2023)

→ Compare MHW activity to BGC data

References

Aguiar, E., Mourre, B., Alvera-Azcárate, A., Pascual, A., Mason, E., & Tintoré, J. (2022). Strong Long-Lived Anticyclonic Mesoscale Eddies in the Balearic Sea: Formation, Intensification, and Thermal Impact. J. Geophys. Res.: Oceans, 127(5), e2021JC017589. doi: 10.1029/2021JC017589

Amaya, D. J., Jacox, M. G., Fewings, M. R., Saba, V. S., Stuecker, M. F., Rykaczewski, R. R. et al. (2023). Marine heatwaves need clear definitions so coastal communities can adapt. Nature, 616(7955), 29–32. doi: 10.1038/d41586-023-00924-2

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J. et al. (2010). The Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats. PLoS ONE, 5(8), e11842. doi: 10.1371/journal.pone.0011842

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. Nature, 560(7718), 360–364. doi: 10.1038/s41586-018-0383-9

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R. et al. (2022). Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. Glob. Change Biol., 28(19), 5708–5725. doi: 10.1111/gcb.16301

Giorgi, F. (2006). Climate change hot-spots. Geophys. Res. Lett., 33(8), 2006GL025734. doi: 10.1029/2006GL025734

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J. et al. (2016). A hierarchical approach to defining marine heatwaves. Prog. Oceanogr., 141, 227–238. doi: 10.1016/j.pocean.2015.12.014

Marullo, S., Serva, F., Iacono, R., Napolitano, E., Di Sarra, A., Meloni, D. et al. (2023). Record-breaking persistence of the 2022/23 marine heatwave in the Mediterranean Sea. Environ. Res. Lett., 18(11), 114041. doi: 10.1088/1748-9326/ad02ae

Mason, E., & Pascual, A. (2013). Multiscale variability in the Balearic Sea: An altimetric perspective. J. Geophys. Res.: Oceans, 118(6), 3007–3025. doi: 10.1002/jgrc.20234

Oliver, E. C. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V. et al. (2018). Longer and more frequent marine heatwaves over the past century. Nat. Commun, 9(1), 1324. doi: 10.1038/s41467-018-03732-9

Sparnocchia, S., Schiano, M. E., Picco, P., Bozzano, R., & Cappelletti, A. (2006). The anomalous warming of summer 2003 in the surface layer of the Central Ligurian Sea (Western Mediterranean). Ann. Geophys., 24(2), 443–452. doi: 10.5194/angeo-24-443-2006

Data availability

All data used in this study are freely available on the Copernicus Marine Service platform (https://marine.copernicus.eu/).

REP: Mediterranean Sea - High Resolution L4 Sea Surface Temperature Reprocessed. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). doi: 10.48670/moi-00173 (Accessed on 5 Aug 2025).

MEDREA: Mediterranean Sea Physics Reanalysis. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). doi: 10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1 (Accessed on 5 Aug 2025).

Code availability

All analyses were performed using Python.

The original MHW detection code was written by Eric C.J. Oliver and is available through https://github.com/ecjoliver/marineHeatWaves.

The source code used for the analysis in this presentation is publicly available on the GitHub repository at https://github.com/arthur-gonnet/balearic-mhws-study. Please note that the repository is not in its final state at the time of writing. Modifications for enhancing the code readability are planned after this presentation.

For trend calculations, the Python module pyMannKendall was used (see https://github.com/mmhs013/pyMannKendall).

Thank you for your attention!

Appendix - Global overview of total days

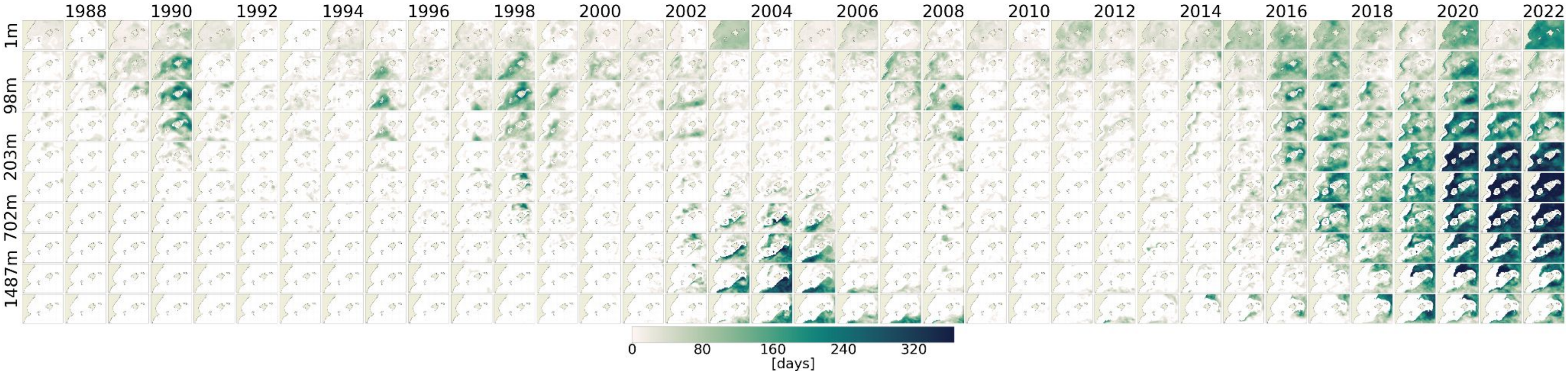


Figure: Annual maps of MHW total days, abscissa is the year (from 1987 to 2022), ordinate is the depth (from 1m to 2000m).

Appendix – Time series of temperature

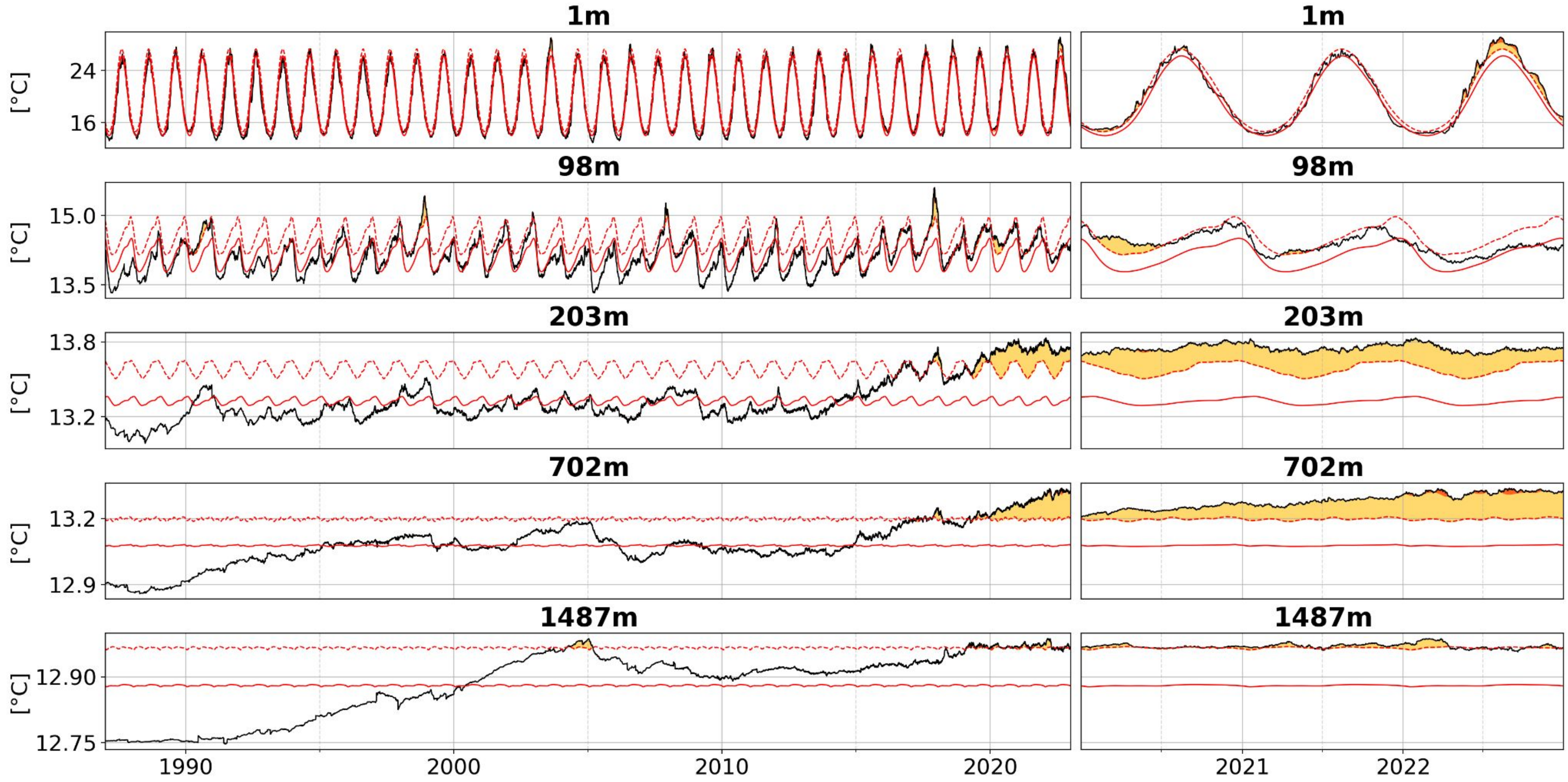
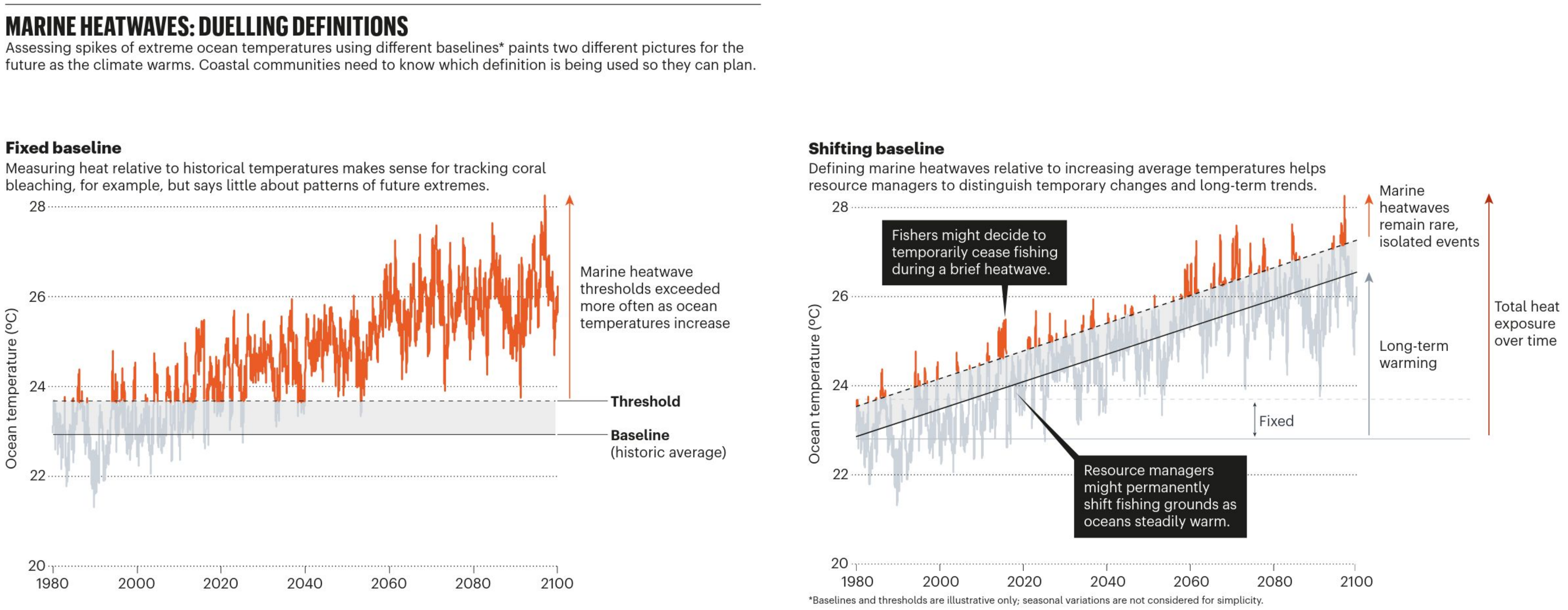


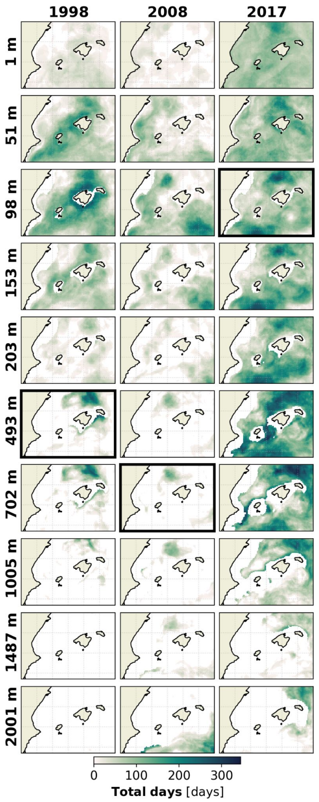
Figure: Time series of temperature from MEDREA averaged over the Balearic Islands region.

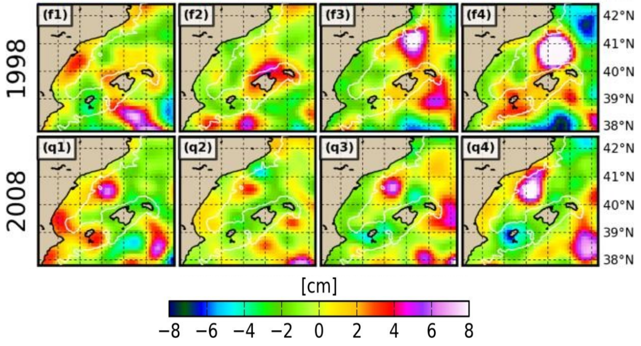
Appendix - Amaya et al., 2023



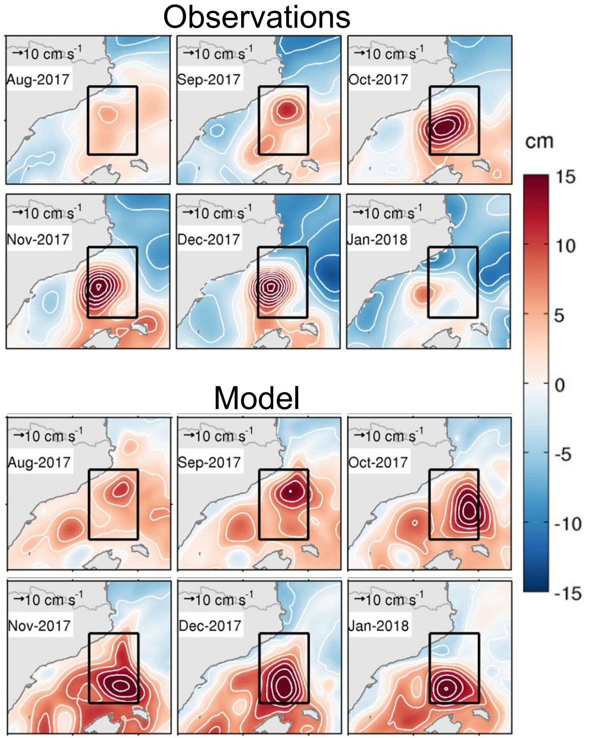
Appendix - Mesoscale activity

Comparison of total days and Sea Level Anomaly (SLA) maps in 1998, 2008, 2017.



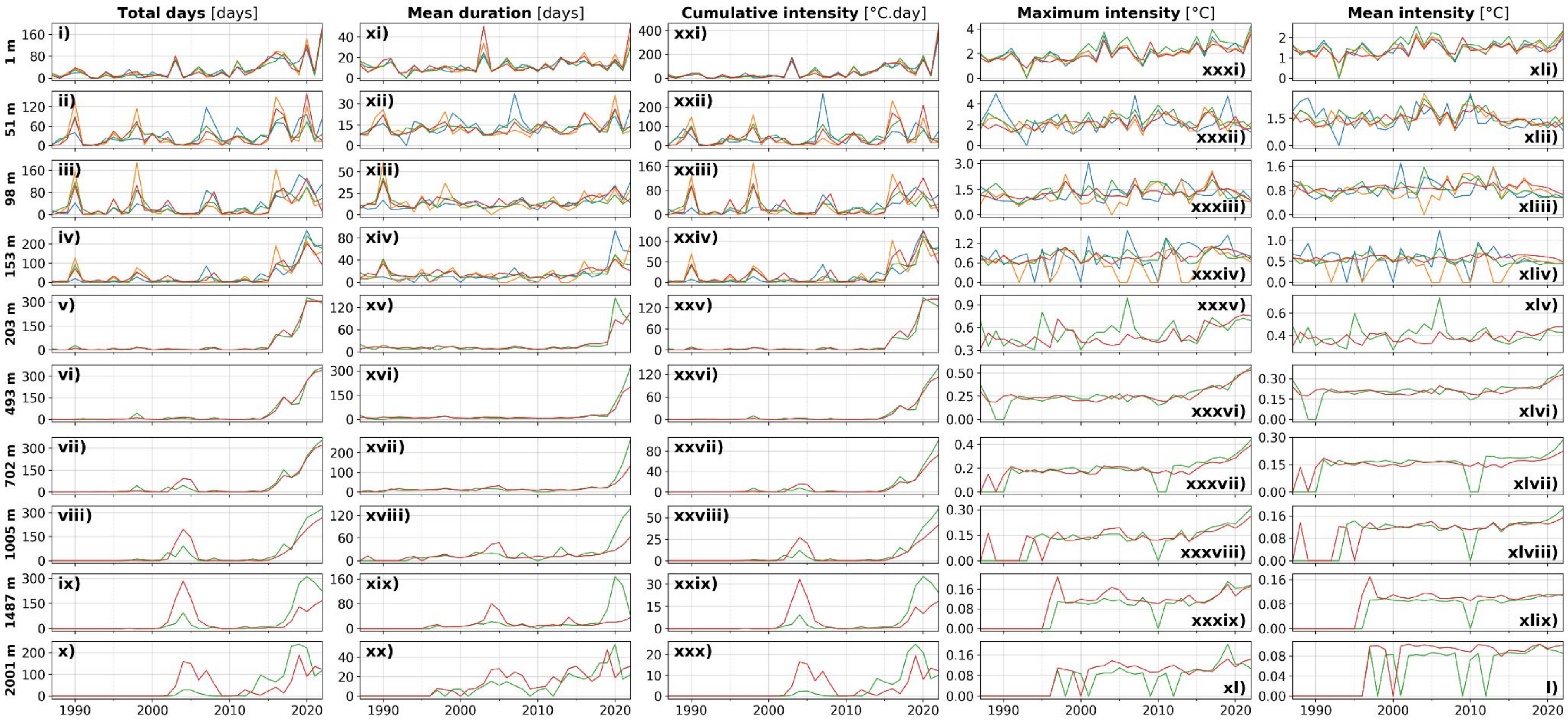


(Mason and Pascual, 2013)



(Aguiar et al., 2022)

Appendix – Time series of annual metrics



Appendix - Model assimilated data

Extracted from Copernicus Marine Service *Product User Manual* for MEDSEA_MULTIYEAR_PHY_006_004 (MEDREA)

Assimilated observations	In-situ vertical profiles of Temperature and Salinity from CTDs, XBTs, MBTs, bottles, ARGO floats; Sea Level Anomaly (SLA) from available satellites. Objective Analyses-Sea Surface Temperature (SST) fields are used to correct surface heat fluxes.

Extracted from Copernicus Marine Service *Product Quality Information Document* (QUID) for (MEDREA)

In the MEDREA24, the following observation datasets are assimilated: along track Sea Level Anomaly (SEALEVEL_EUR_PHY_L3_REP_OBSERVATIONS_008_061 from Copernicus Marine), and in-situ vertical temperature and salinity profiles, from a combination of INSITU_GLO_NRT_OBSERVATIONS_013_030 from Copernicus Marine and in-situ dataset from SeaDataNet.

Objective Analyses-Sea Surface Temperature (OA-SST) fields from CNR-ISA SST-TAC are used for the correction of surface heat fluxes with the relaxation constant of 110 W.m-2.K-1 applied close to midnight since the observed dataset corresponds to the foundation SST (approximately SST at midnight).

Appendix - Model accuracy

Extracted from Copernicus Marine Service *Product Quality Information Document* (QUID) for MEDSEA_MULTIYEAR_PHY_006_004 (MEDREA)

Table I-2: Temperature (in °C)

	RMSD	BIAS
Whole column	0.55	0.025
0-10 m	0.70	-0.068
10-100 m	0.85	0.071
100-500 m	0.28	0.010
500-1500 m	0.11	0.002

RMSD and bias are estimated using the 1987-2019 period. MEDREA is compared to a combination of INSITU_GLO_NRT_OBSERVATIONS_013_030 from Copernicus Marine and in-situ dataset from SeaDataNet. They are considered quasi-independent observations as “the evaluation is [...] performed on the observations before they are assimilated”.

Appendix - Model accuracy

Extracted from Copernicus Marine Service *Product Quality Information Document* (QUID) for MEDSEA_MULTIYEAR_PHY_006_004 (MEDREA)

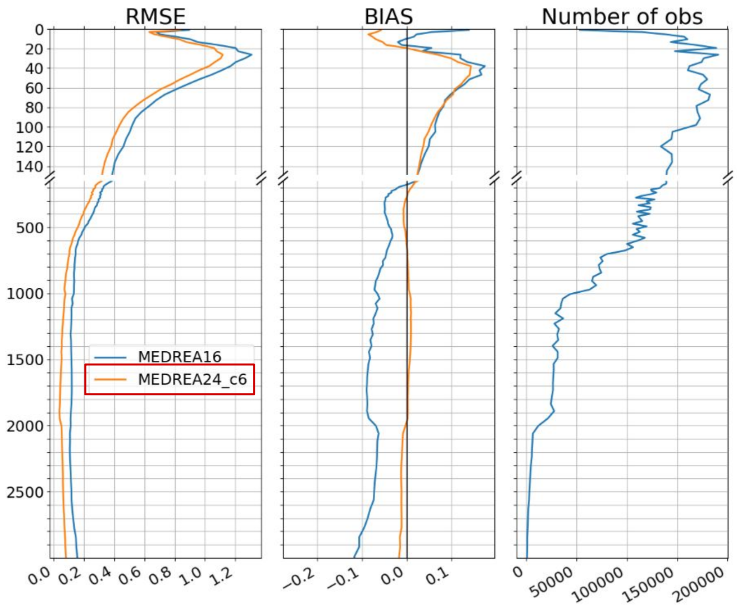


*Figure IV-16 Left: **T-PROF-32Y-CLASS4-ASSIM-RMSD-1DV,** Centre: **T-PROF-32Y-CLASS4-ASSIM-BIAS-1DV** Vertical profiles(in meters) of the same temperature statistics [°C].*

RMSD and bias are estimated using the 1987-2019 period. MEDREA is compared to a combination of INSITU_GLO_NRT_OBSERVATIONS_013_030 from Copernicus Marine and in-situ dataset from SeaDataNet. They are considered quasi-independent observations as “the evaluation is [...] performed on the observations before they are assimilated”.

Appendix - Categories