Marine heatwaves in the Mediterranean Sea

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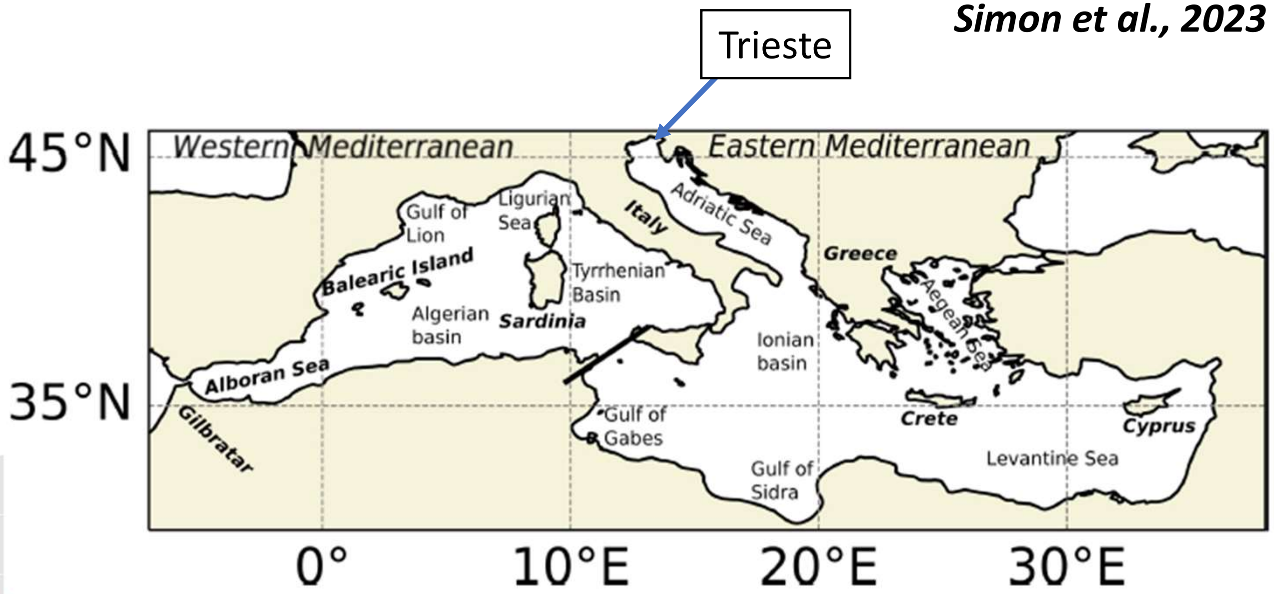
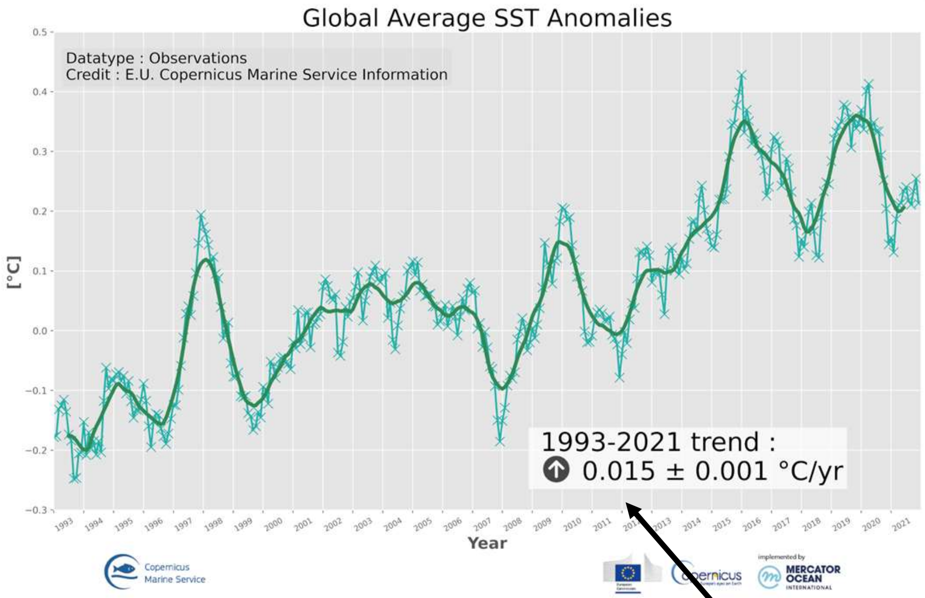
Outline

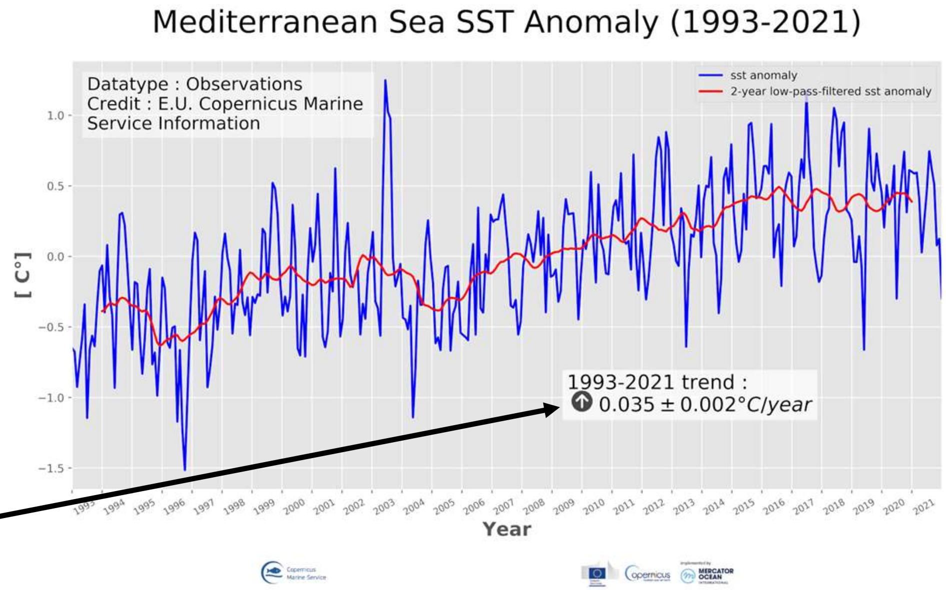
- **MHWs in the Med**
  - ➢past conditions and trends
  - ➢surface and subsurface conditions
- **Heat waves in the Med-European region: clustering technique and drivers**
- **MHWs in the Med: work in progress on drivers**
- **Extreme MHWs in the Med**
  - ➢The 2003 event in the Med-European region
  - ➢The 2022 MWH in the Med
  - ➢The present situation
- **Take home messages**

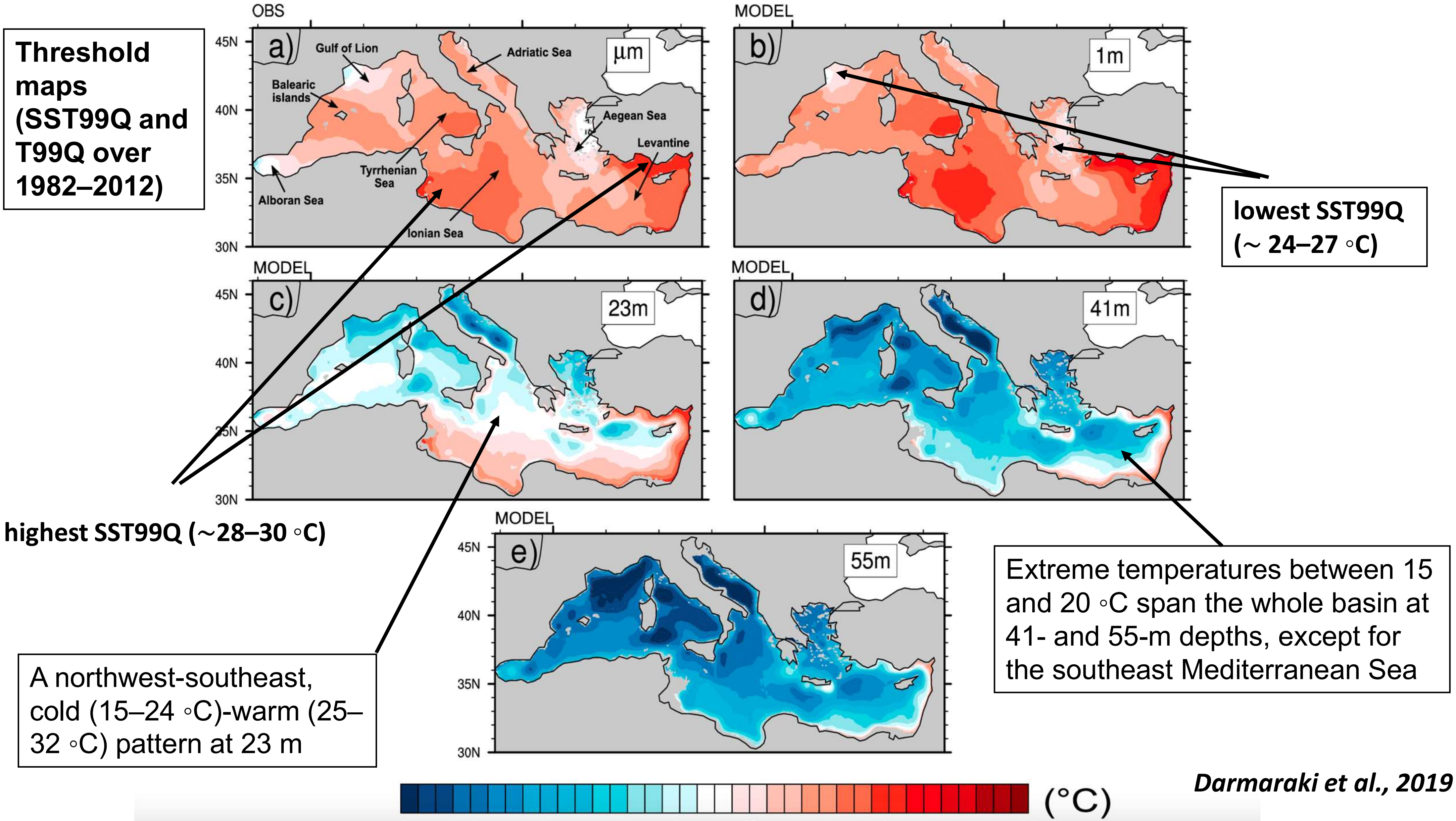
Where we are

Simon et al., 2023

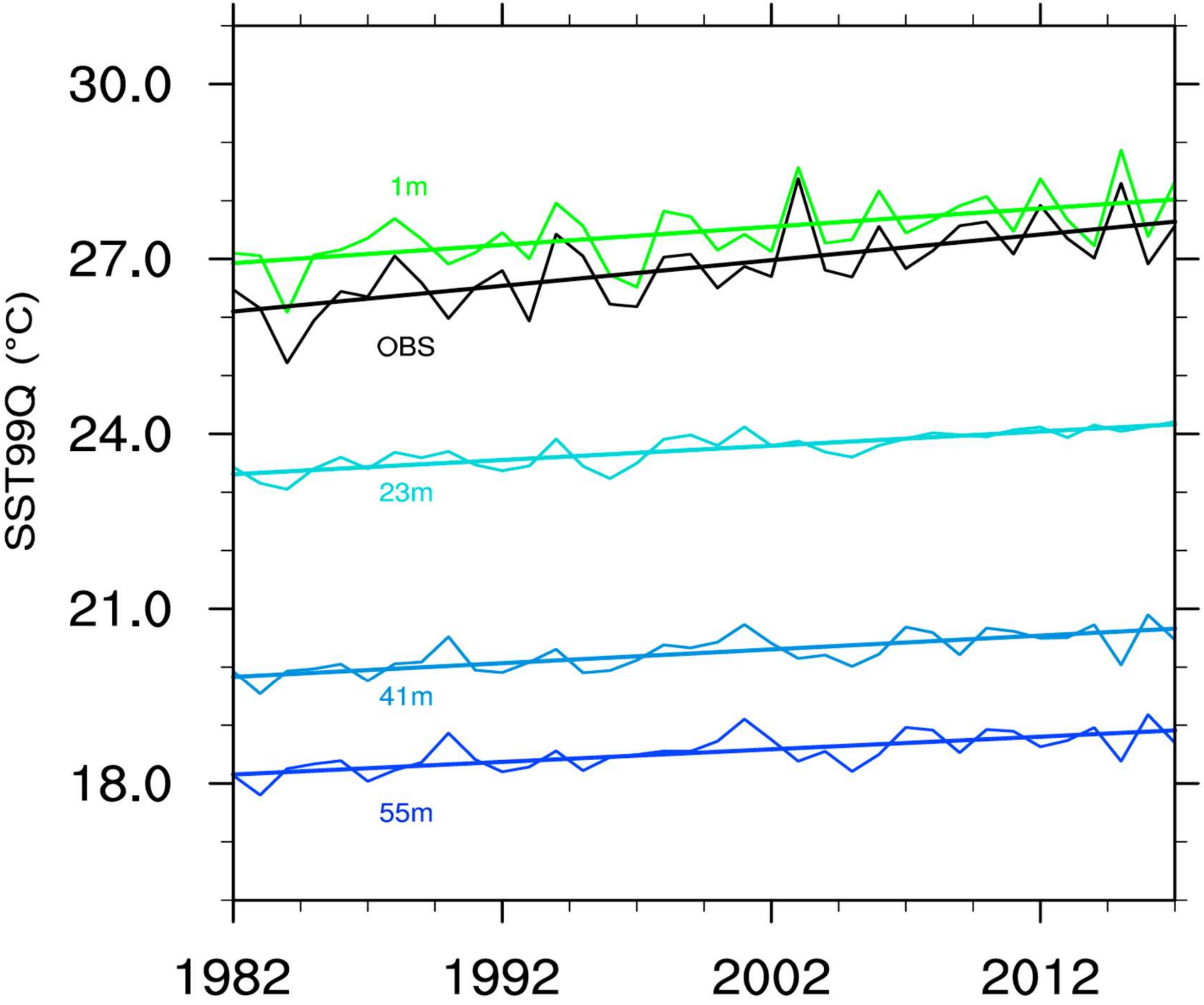








Threshold maps (SST99Q and T99Q over 1982–2012)
OBS
a)
μm
Gulf of Lion
Balearic islands
Adriatic Sea
Aegean Sea
Levantine
Tyrrhenian Sea
Alboran Sea
Ionian Sea
MODEL
b)
1m
lowest SST99Q (∼ 24–27 ◦C)
MODEL
c)
23m
MODEL
d)
41m
highest SST99Q (∼28–30 ◦C)
MODEL
e)
55m
Extreme temperatures between 15 and 20 ◦C span the whole basin at 41- and 55-m depths, except for the southeast Mediterranean Sea
A northwest-southeast, cold (15–24 ◦C)-warm (25–32 ◦C) pattern at 23 m
45N
40N
35N
30N
(°C)
Darmaraki et al., 2019

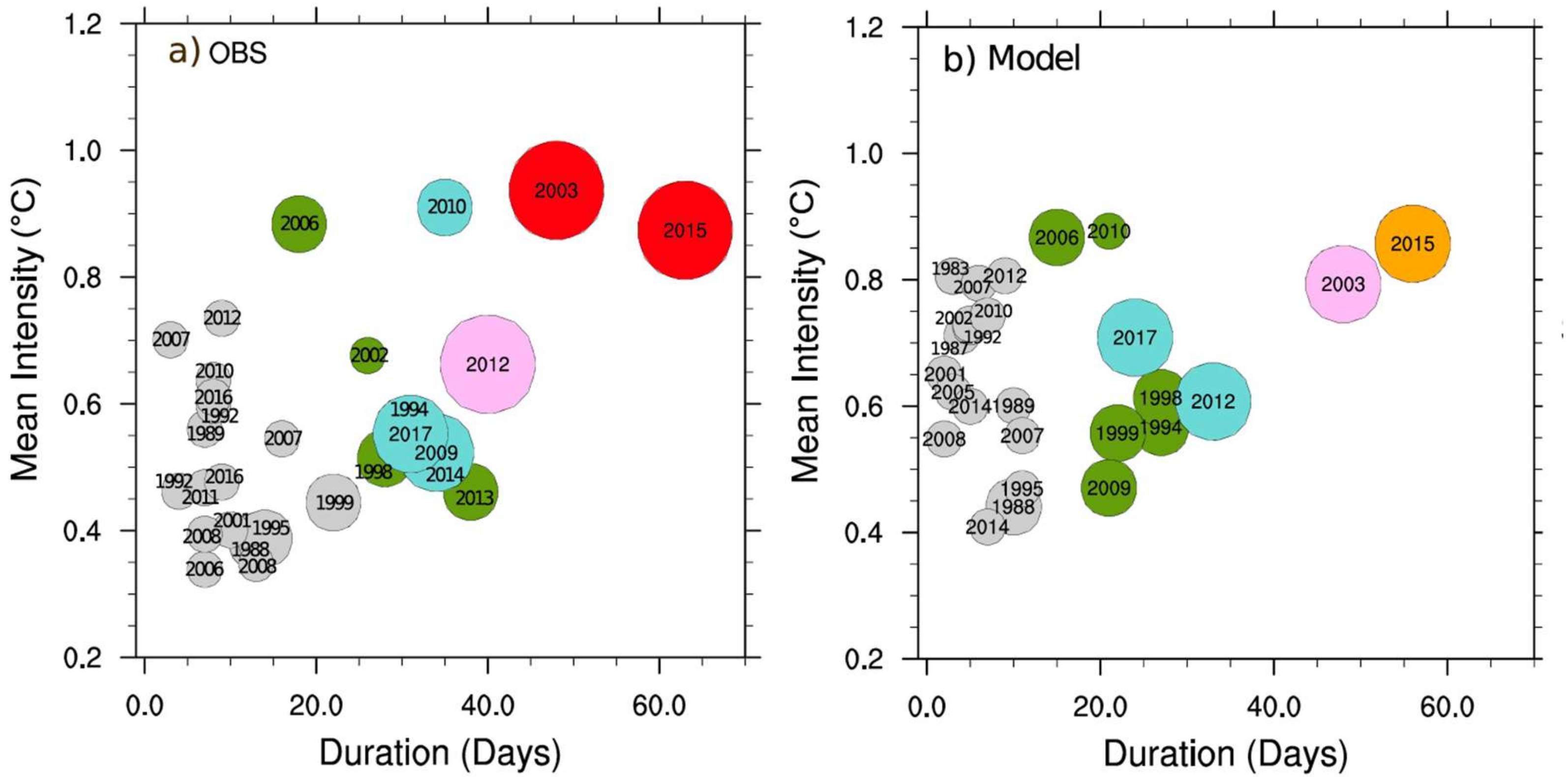


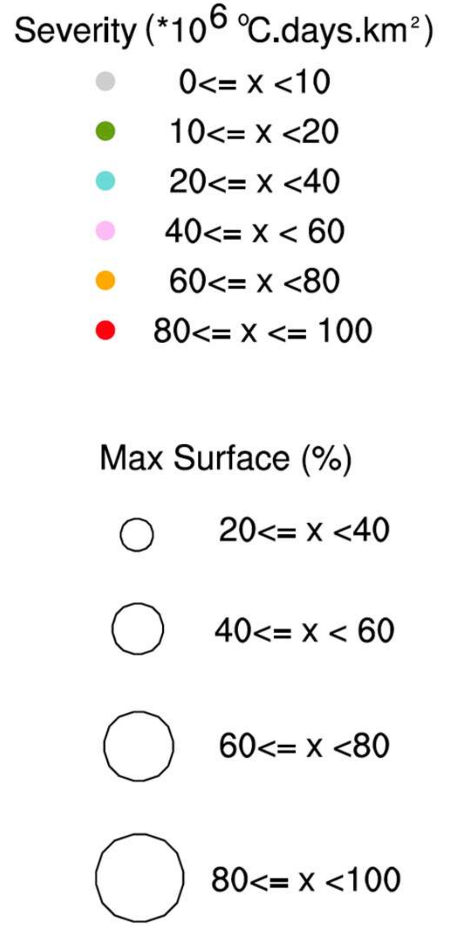
Annual, basin-mean observed and simulated SST99Q and T99Q values (◦C) and their linear trend for 1980–2017 for the different layers.

T99Q time series reveal a warming of about 0.02 ◦C/year at every layer, which decreases slightly with depth

Darmaraki et al., 2019

29 events over 1982–2017, 20 days long, Imean of about 0.6 °C, max of 44% of the Mediterranean Basin.

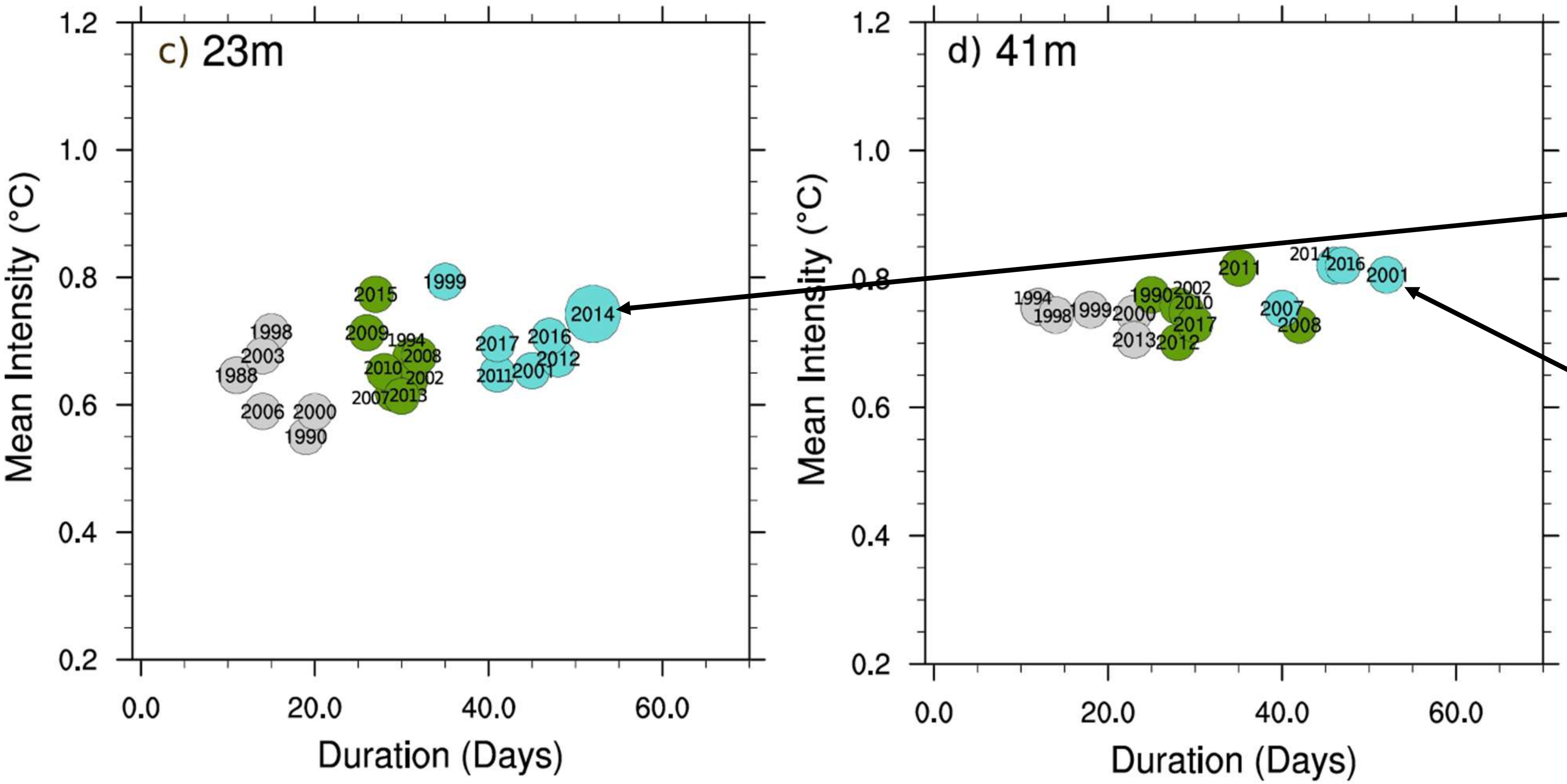




Model: surface MHW of 2015 displayed the highest duration, severity, and maximum spatial coverage (∼78.5%) of the period, while the MHW of 2010 the highest Imean (∼0.9 ◦C).

Observations: highest Imean, severity, and spatial coverage (89%) of the period correspond to the MHW of 2003 and the highest duration to the 2015 event.

Darmaraki et al., 2019



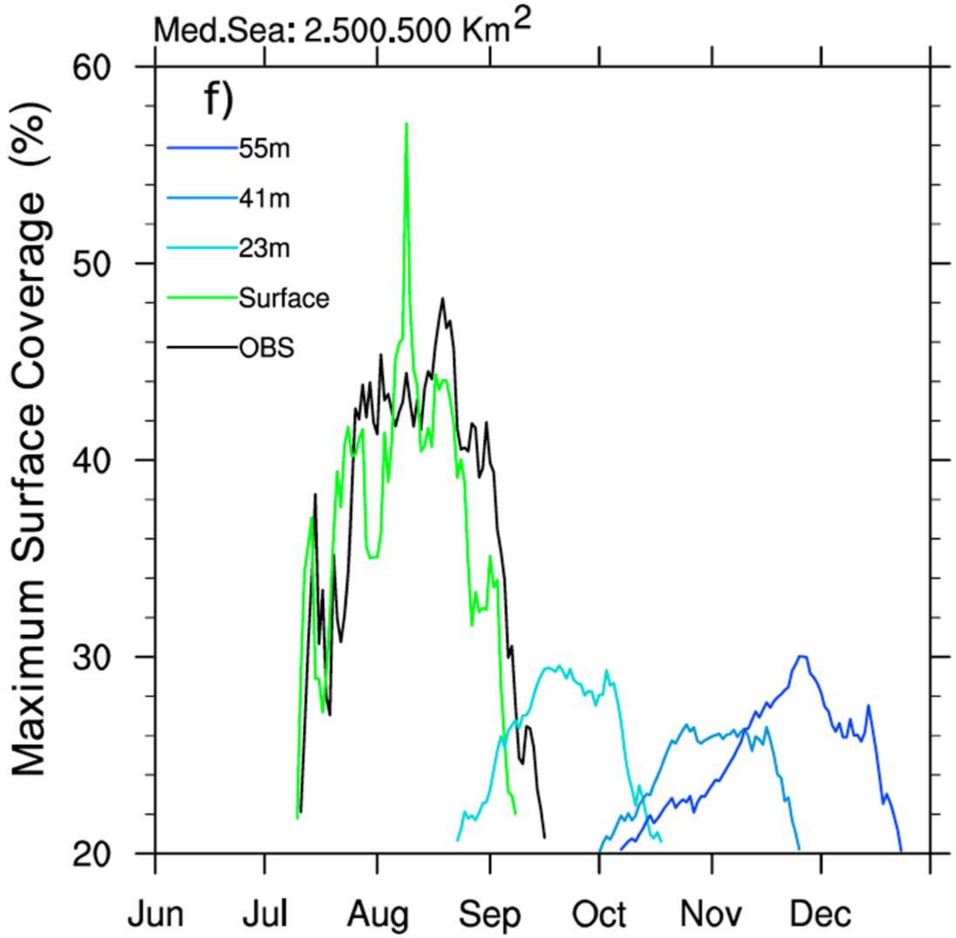
The subsurface **MHW 2014** was the longest (52 days), most severe and spatially largest (~43%) event of the period at 23 m.

The subsurface **MHW 2001** was the longest (52 days) and most severe event at 41 m.

Relative to surface simulated events, **frequency of subsurface MHWs reduces** as we go deeper in the water Column. Conversely, their **ensemble-mean duration and severity monotonically increase with depth**.

<u>Individually, the most notable MHWs at depth occur in different years from those at surface.</u>

Darmaraki et al., 2019



Seasonality follows the MLD deepening

In deep layer longer preservation of the heat content in smaller regions, and longest duration.
Surface temperature anomalies developed during the summer could propagate into the water column when it is weakly stratified.

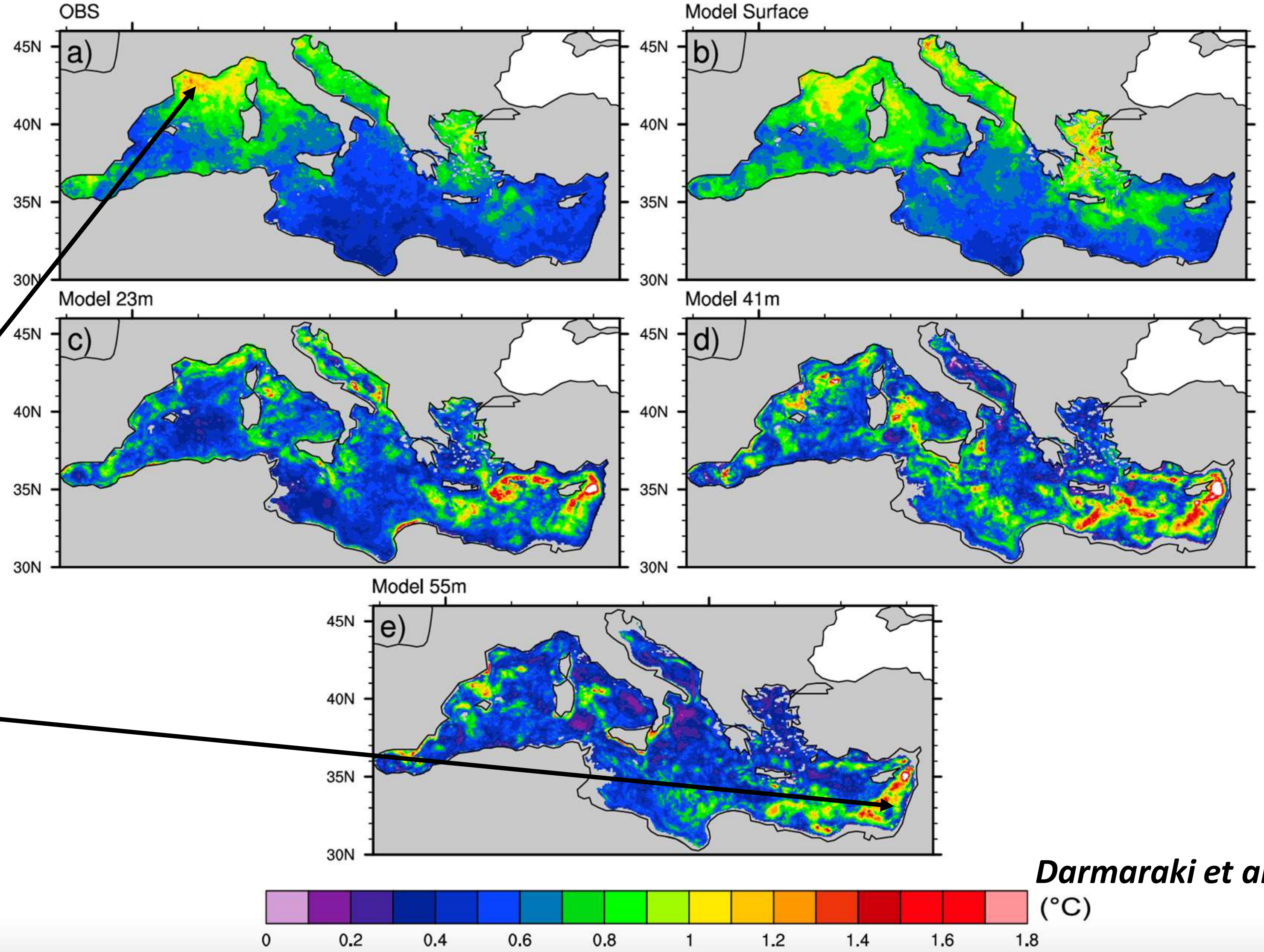
Darmaraki et al., 2019

Average marine heatwave intensity

Imean between ∼0.3 and ∼0.9 ◦C at every layer

North Mediterranean regions display the most pronounced surface Imean **(∼1◦C)**

In **deeper layers a local MHW intensification** (∼1–1.7 ◦C) displaced southward with depth.



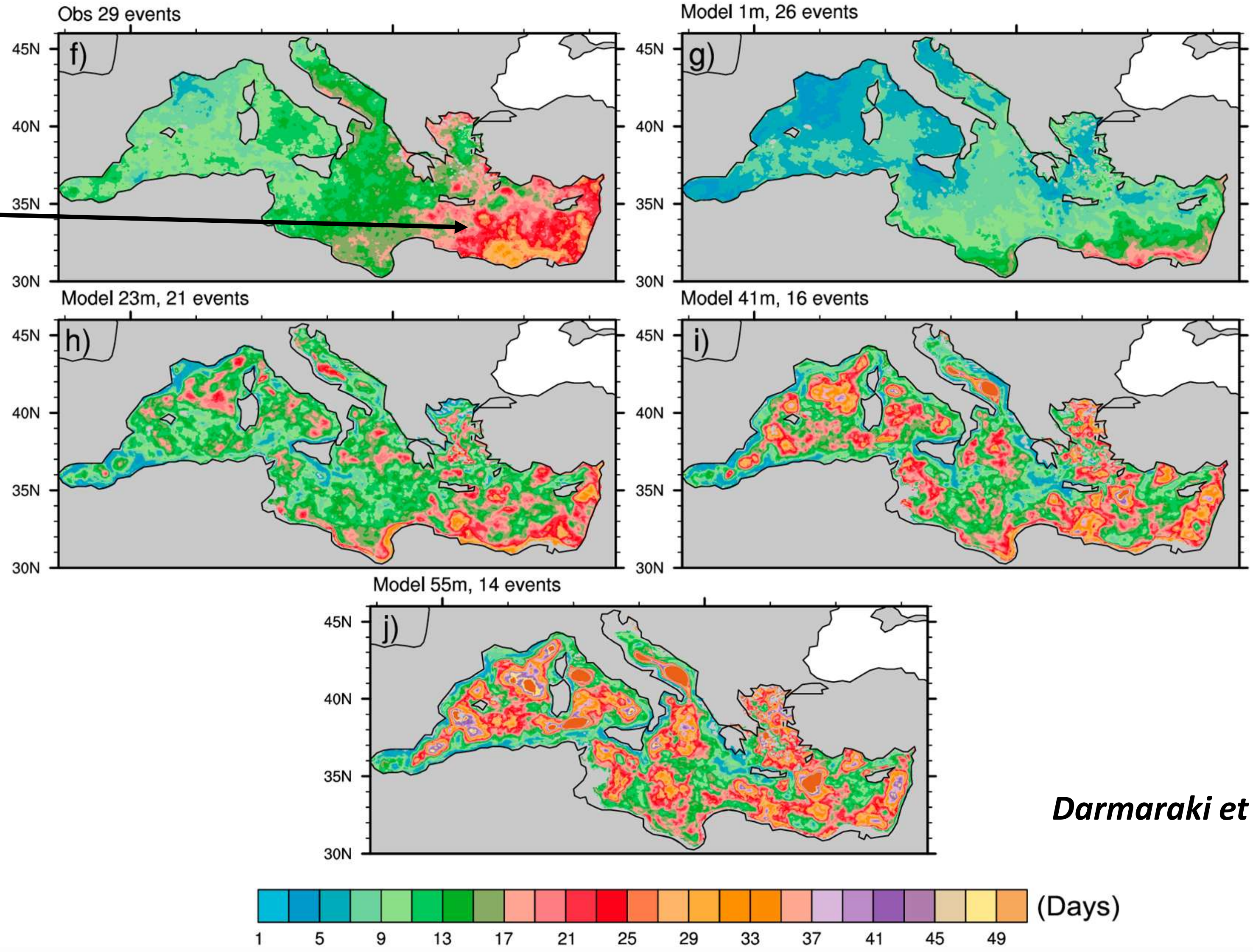
Darmaraki et al., 2019

Marked differences with depth.

At surface, **mean event duration between 8 and 13 days**, except for the **Levantine Basin (~20–70 days)** and some parts of the Aegean (~20 days) (model underestimates)

In deeper layers, average MHW duration increases progressively from 20 days at 23 m to 20–50 days almost everywhere at 41 and 55 m but far from boundary currents.

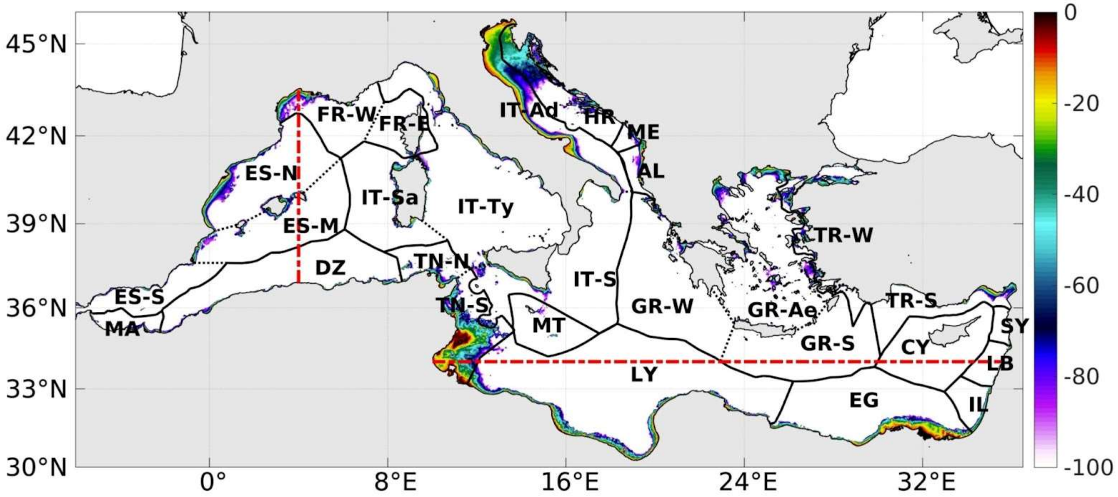
Average marine heatwave duration



Darmaraki et al., 2019

Towards stakeholder-relevant information

Exclusive Economic Zones (EEZs):
providing MHW information on a national-scale creates a direct narrative on needs for observations and provides background for stakeholder-specific interactions



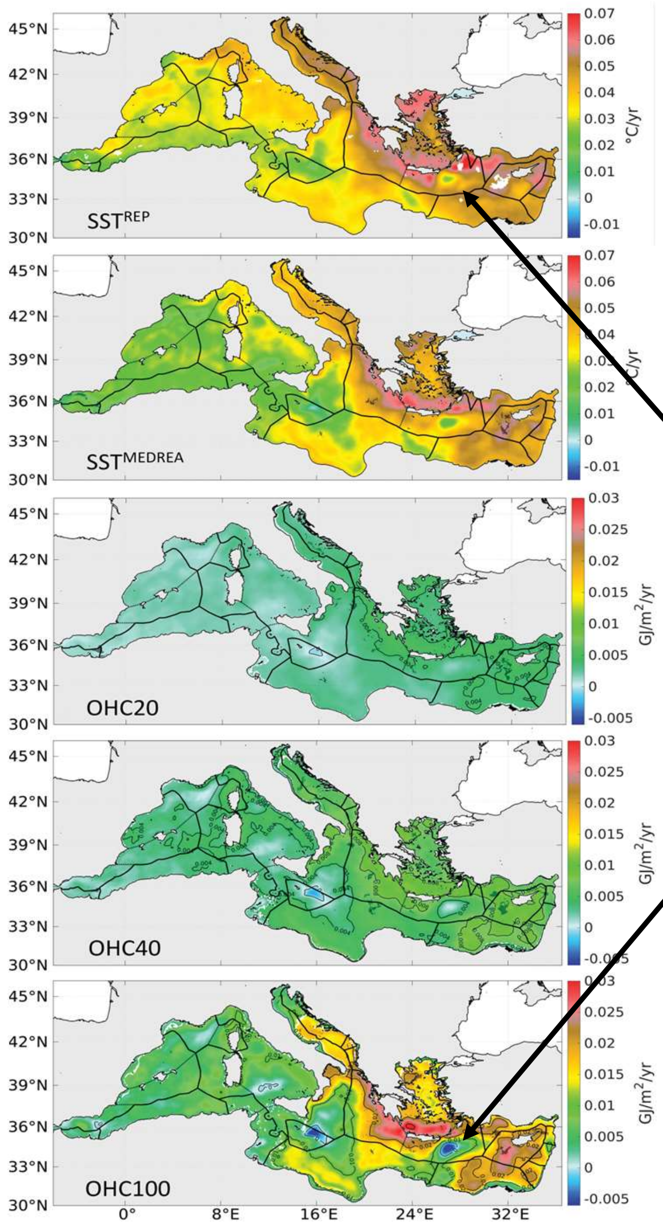
Dayan, H., et al. 2023.

We propose ocean heat content (e.g. 0-20 m, 0-40 m, 0-100 m)

$$H = \rho c_p \int_{z=0}^{z1} T(z)dz$$

T – temperature
ρ – density
c_p – specific heat capacity
z – depth

For the subsurface we use a regional REANALYSIS at 1/24 horizontal resolution (observations are assimilated into a model)



An assessment from the surface to the subsurface to meet national needs

Linear trends over the period 1987-2019 of SST (in °C/year)

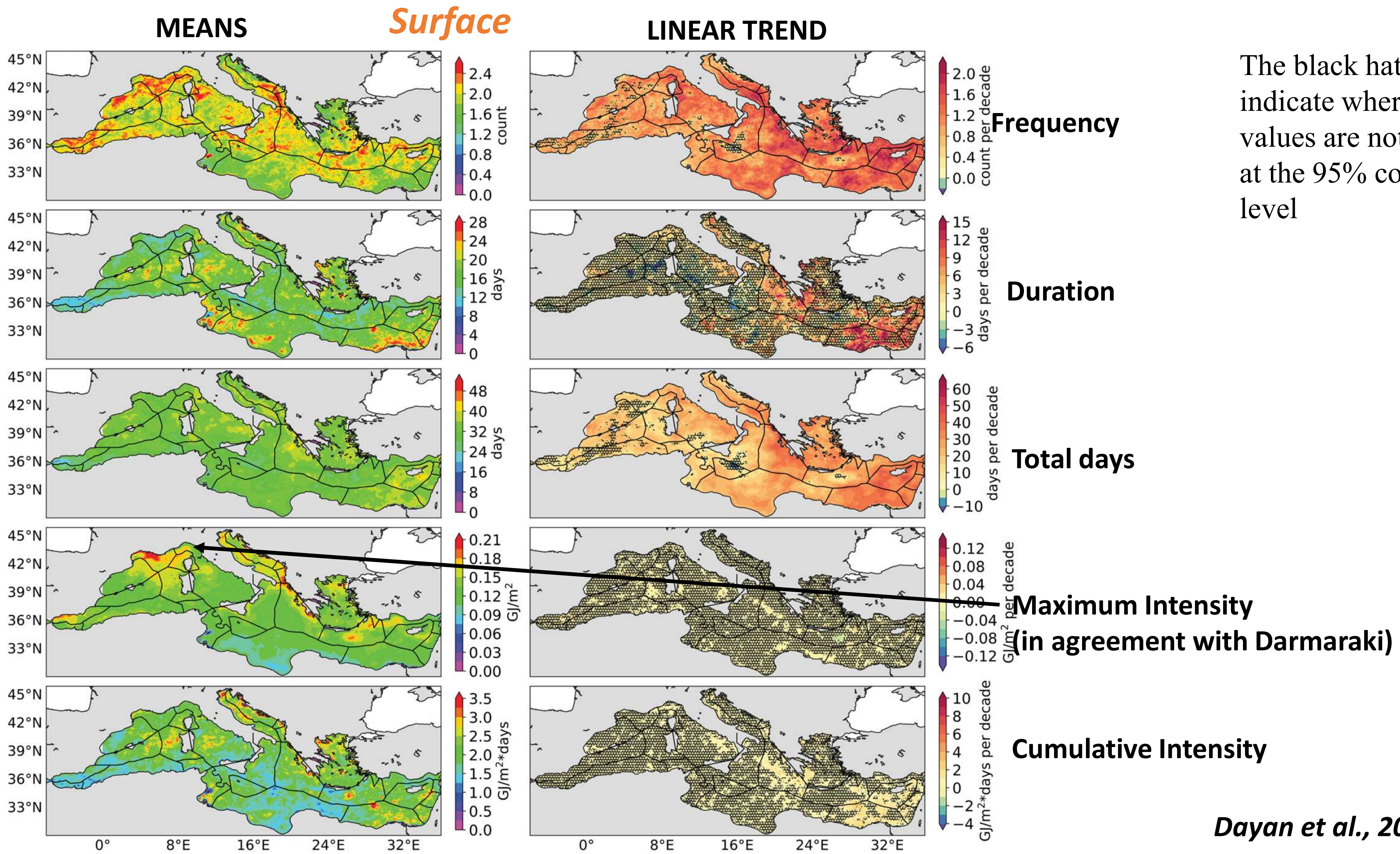
Even adjacent EEZs may experience very different average conditions and long-term trends.

Basin-scale patterns of trend are similar between SST and OHC (i.e. the peak warming occurs in the eastern part of the basin) but with notable exceptions (look at the negative cooling in Southern Greece)

It is not sufficient for national-level stakeholders to receive basin-scale information; a local viewpoint of ocean processes and changes is necessary.

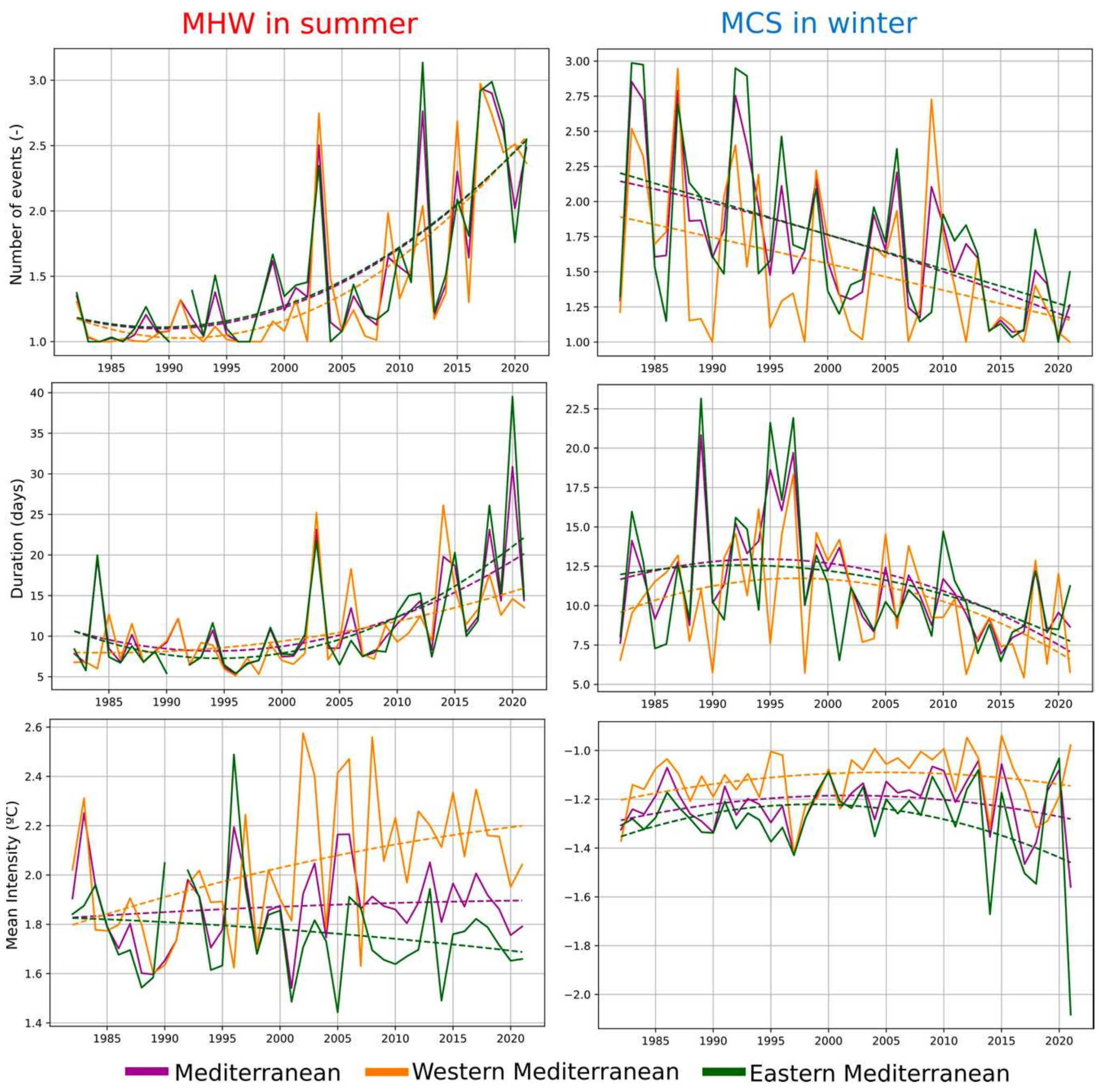
Dayan et al., 2023

Black lines: Exclusive Economic Zone (EEZ)



The black hatches indicate where trend values are not significant at the 95% confidence level

Dayan et al., 2023

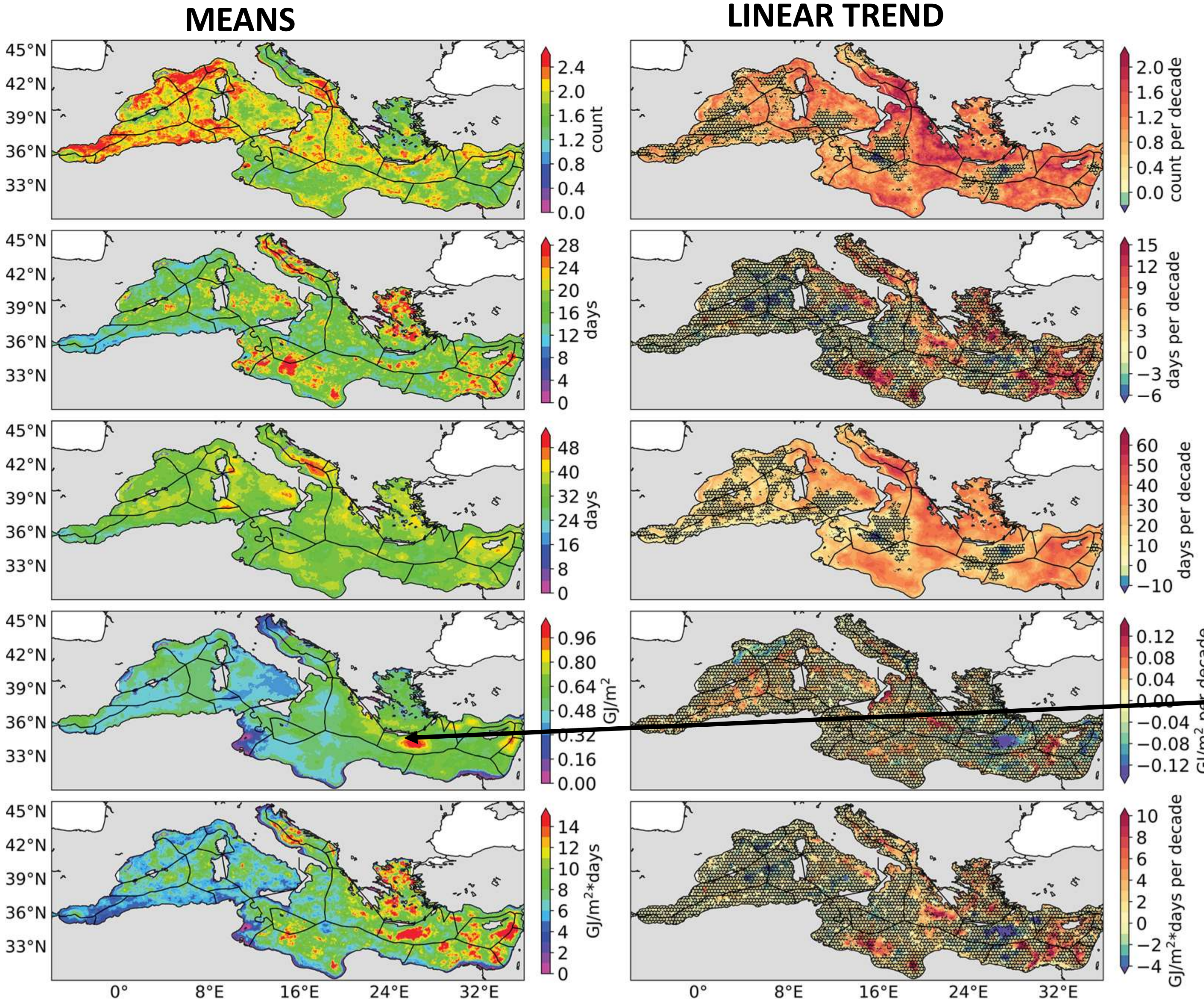


Daily sea-surface temperature (SST) from NOAAOISSTV2 (Reynolds et al., 2007; Huang et al., 2020) from 1° January 1982 to 23rd November 2021 at a regular resolution of 0.25°x0.25°

- **Summer MHW frequency and duration increase**
- Winter MCS a linear decrease
- **Positive linear tendency of mean intensity is observed only for the western Mediterranean**

Simon et al., 2023

Subsurface (OHC 0-100 m)



Frequency

Duration

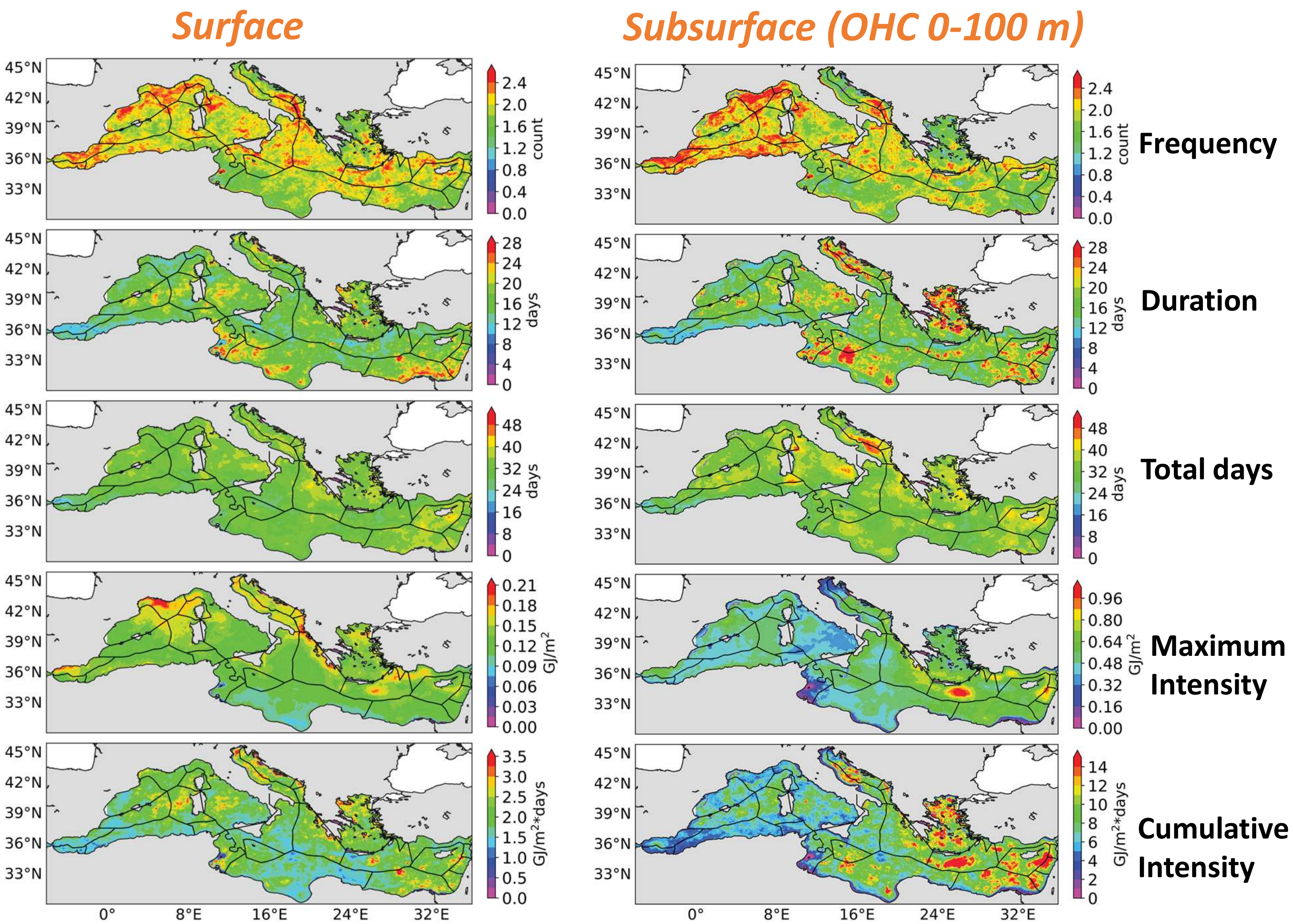
Total days

Maximum Intensity (in agreement with Darmaraki)

Cumulative Intensity

Since 1987, a substantial and significant increase in MHW frequency and total days across the basin at the surface and in the subsurface.

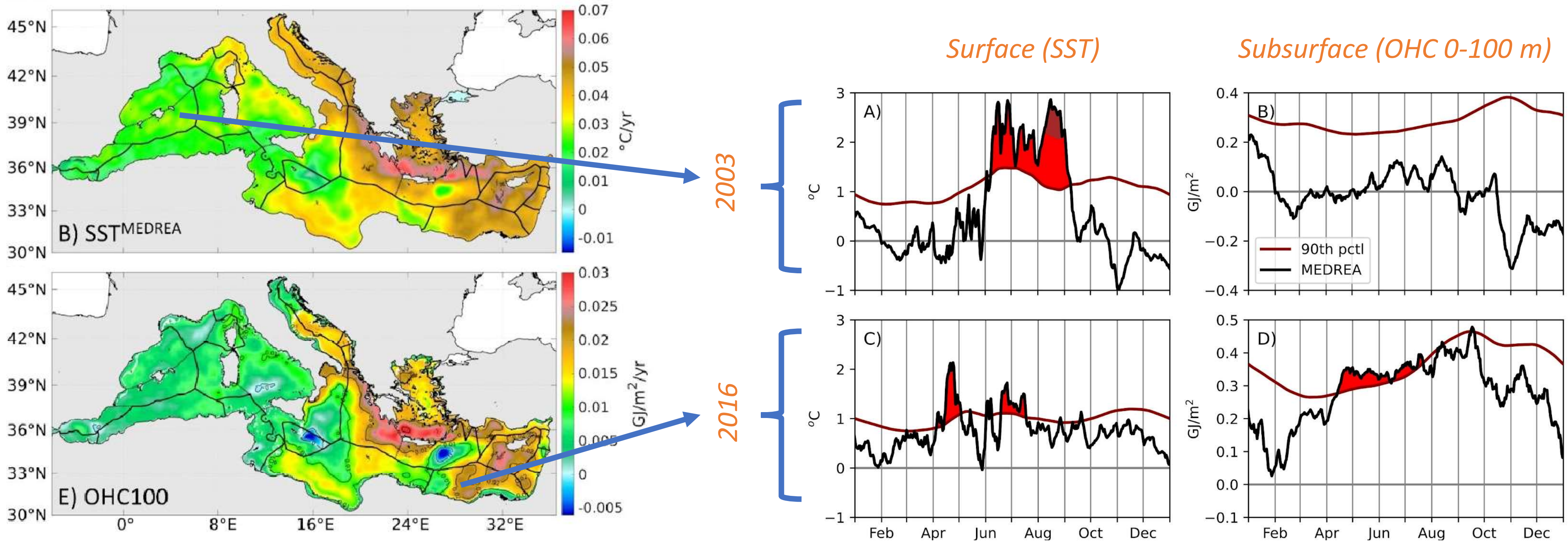
Dayan et al., 2023



MHW duration and total days values in the subsurface are substantially higher than at the surface

The peak of intensity is in the western Med at the surface and in the Levantine Basin at depth

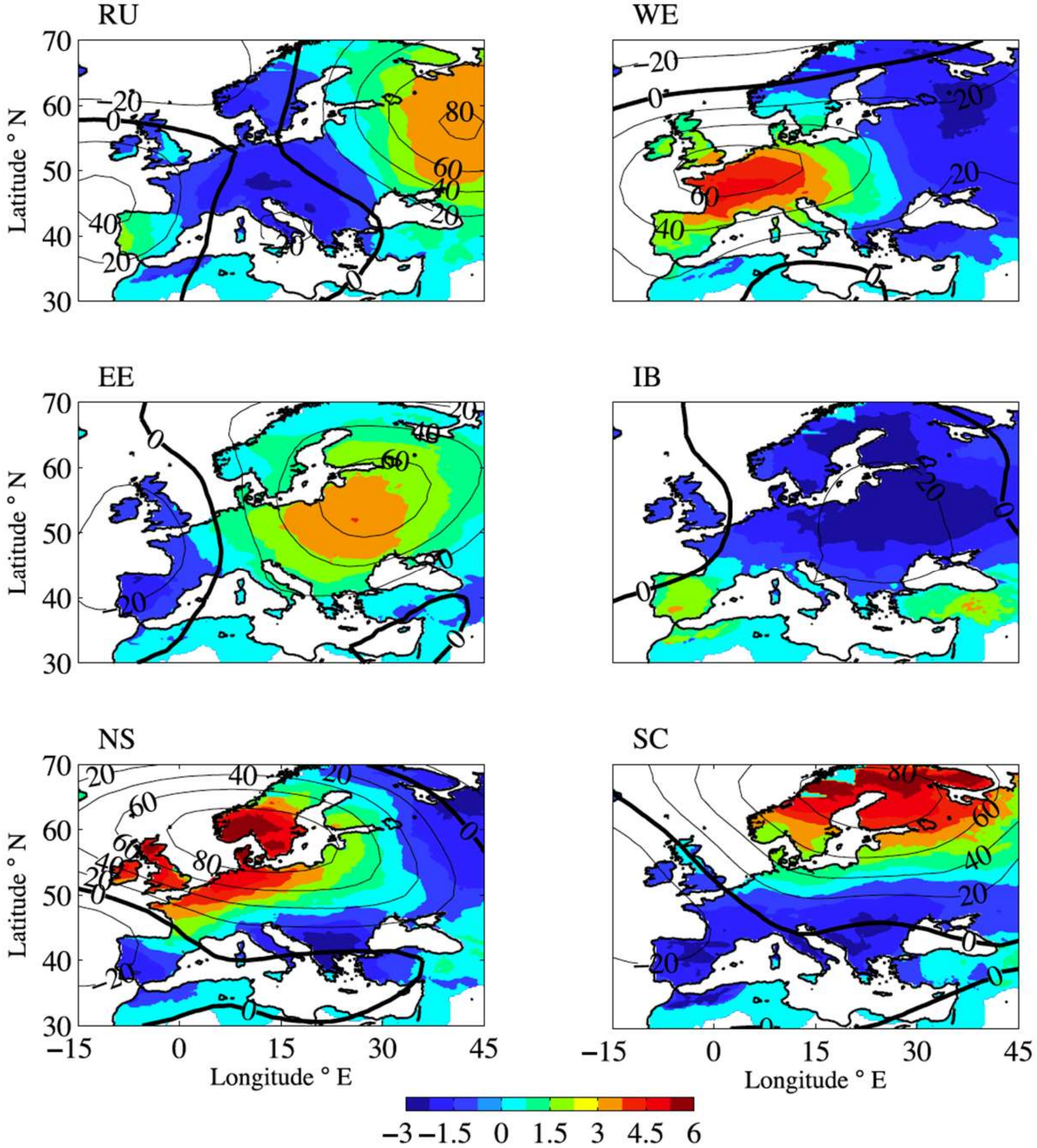
Subsurface manifestation of MHWs can vary hugely



MHWs which manifest at the surface do not always leave a signal on the depth-integrated indicators

Dayan et al., 2023

Heat waves in the Med-European region: clustering technique and drivers



Study period: 1950-2009

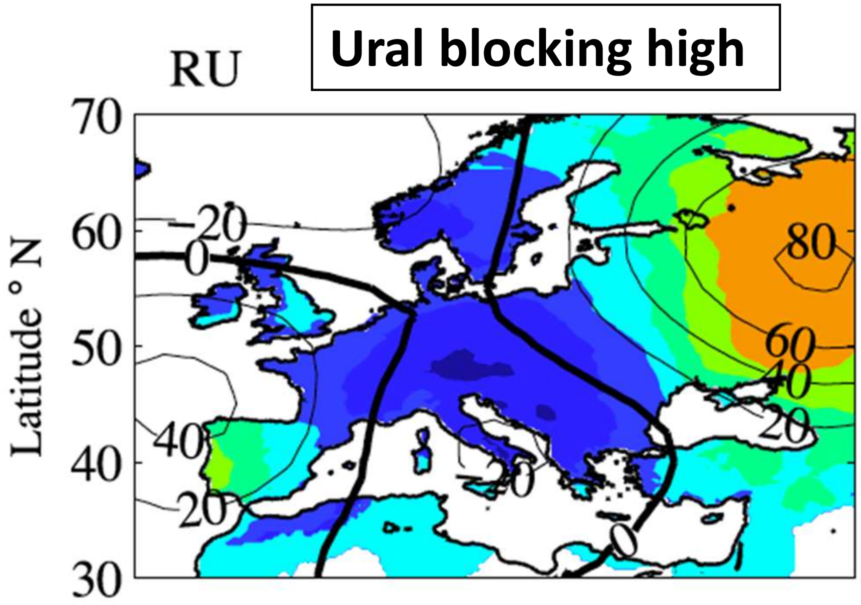
78 Heatwave events

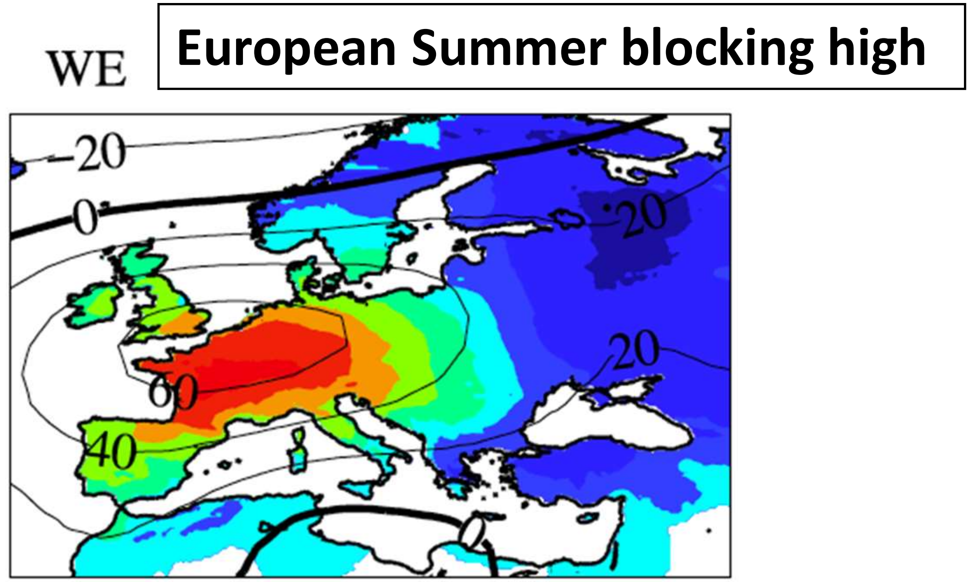
Six heatwave patterns obtained by a hierarchical clustering algorithm for the Euro-Mediterranean region:

(a) ‘Russian’ cluster (RU),
(b) (b) ‘Western Europe’ cluster (WE),
(c) ‘Eastern Europe’ cluster (EE),
(d) ‘Iberian’ cluster (IB),
(e) ‘North Sea’ cluster (NS),
(f) ‘Scandinavian’ cluster (SC).

Daily maximum temperature anomalies are in color and expressed in deg K and isolines are the 500 hPa geopotential height anomaly.

Stefanon et al., 2012





The Russian Cluster:

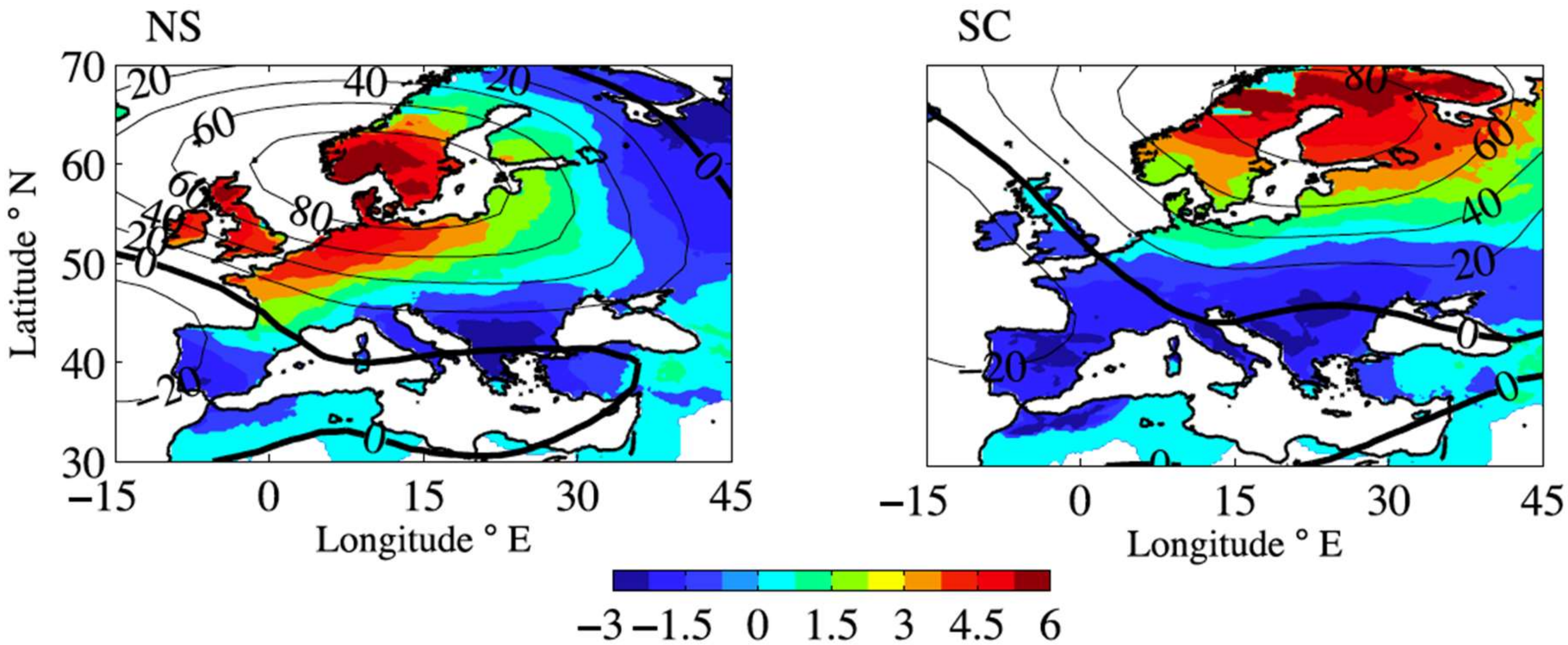
- T anomaly up to 4 °C
- 14 events
- Shape similar to the 2010 catastrophic event in Russia

(note that the 2010 is not included in the analysis period)

The Western Europe Cluster:

- T anomaly up to 5 °C
- 11 events
- The first half of the 2003 August event belongs to this cluster
- The T pattern of the 2003 event is very similar to this cluster

Stefanon et al., 2012



The North Sea Cluster:

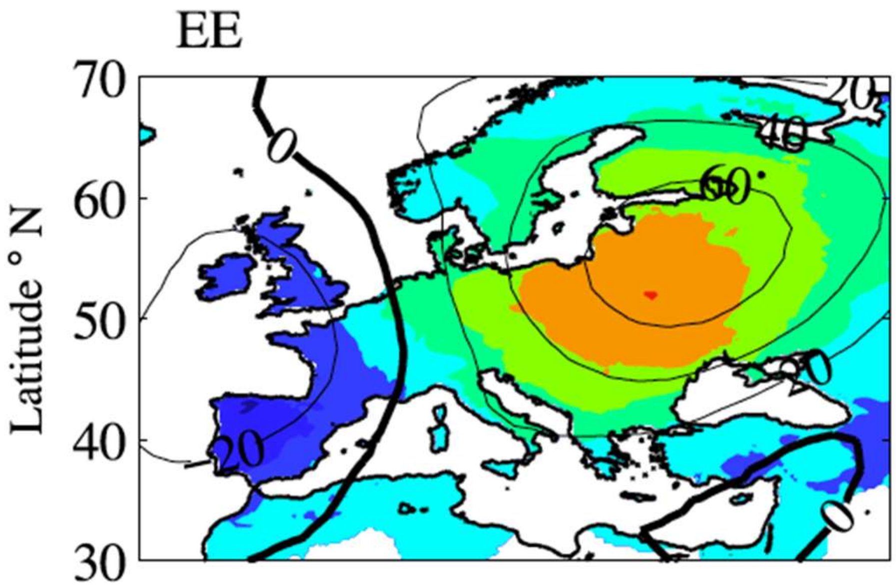
- T anomaly up to 6 °C (the hottest)
- 11 events
- Summer 1976 was very similar to this pattern

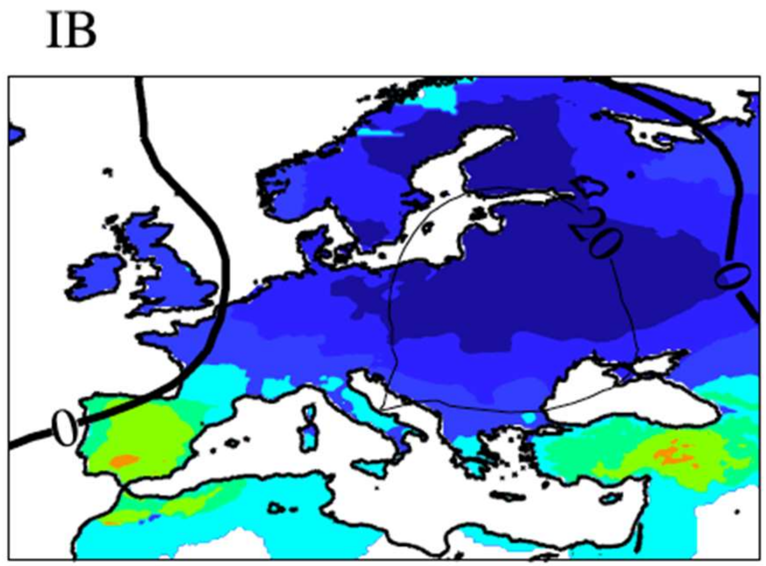
The Scandinavian Cluster:

- T anomaly up to 6 °C
- 10 events
- The first half of the 2003 August event belongs to this cluster
- The T pattern of the 2003 event is very similar to this cluster

Stefanon et al., 2012

The Iberian pattern is caused by warm air advection from Tropical Atlantic





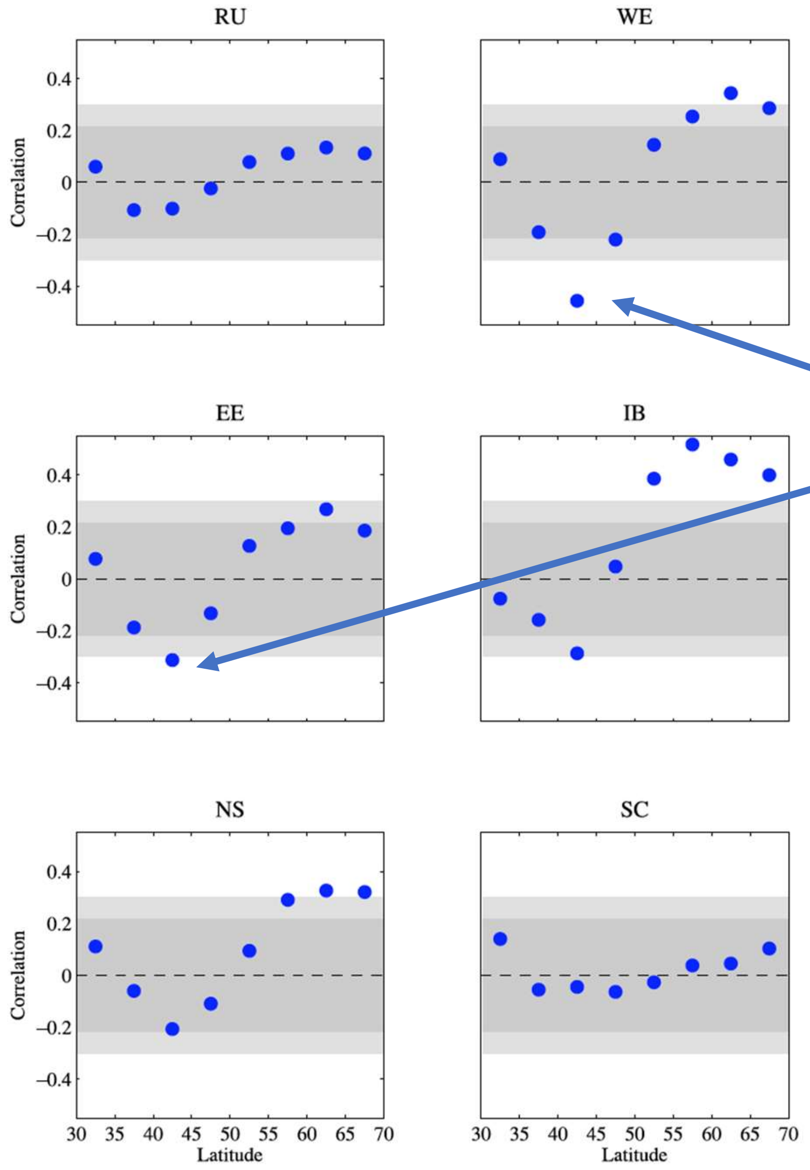
The Eastern Europe Cluster:

- T anomaly up to 4 °C
- 23 events
- Localized events around the Baltic and Black Sea

Stefanon et al., 2012

The Iberian Cluster:

- T anomaly up to 3 °C (weakest)
- 9 events
- Second center over Turkey
- **<u>The only exception to the phase lock between the anticyclone and the temperature anomaly</u>**



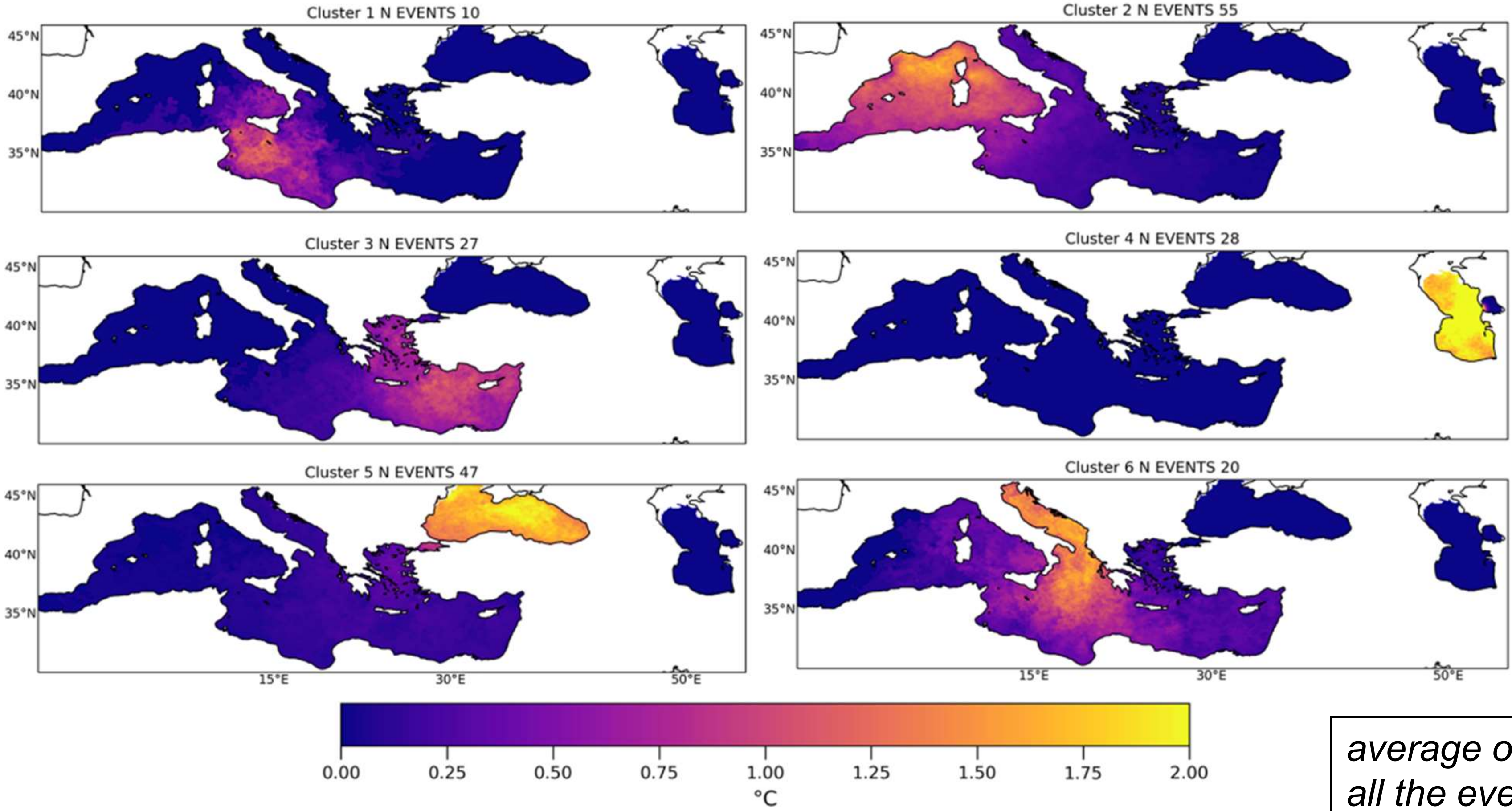
Correlation between the rainfall occurrence anomaly between January and May, and the detrended summer maximum temperature anomaly at the heatwave location.

In Western and Eastern Europe, a positive temperature anomaly in summer (heatwave) is associated with a precipitation deficit in winter and spring in Southern Europe.

Stefanon et al., 2012

A similar clustering approach for the SST

- Cluster analysis of ESA-CCI SST (1981-2016)
- 187 events
- Six marine heatwave patterns obtained by a hierarchical clustering algorithm for the southern Europe-and western Asia



average of the mean intensity of all the event maps which belong to that cluster

Bonino et al., 2023

The role of air-sea heat fluxes for Marine Heatwaves in the Mediterranean Sea …*work in progress*

as in Schlegel et al. (2021)

$$SST'_{t_2} - SST'_{t_1} = \int_{t_1}^{t_2} \frac{Q'}{\rho_o c_p h}\,\mathrm{dt} + \mathrm{R}$$

Q' is the daily anomaly of Q_{net}.

observed change in SST anomaly ($\Delta SST'obs$) relative to climatology, during a specific phase. Each phase starts at day t1 and ends at day t2

part of the $\Delta SST'_{obs}$ explained by Q' during this phase (ΔSST_Q)

contribution to $\Delta SST'_{obs}$ from other mechanisms

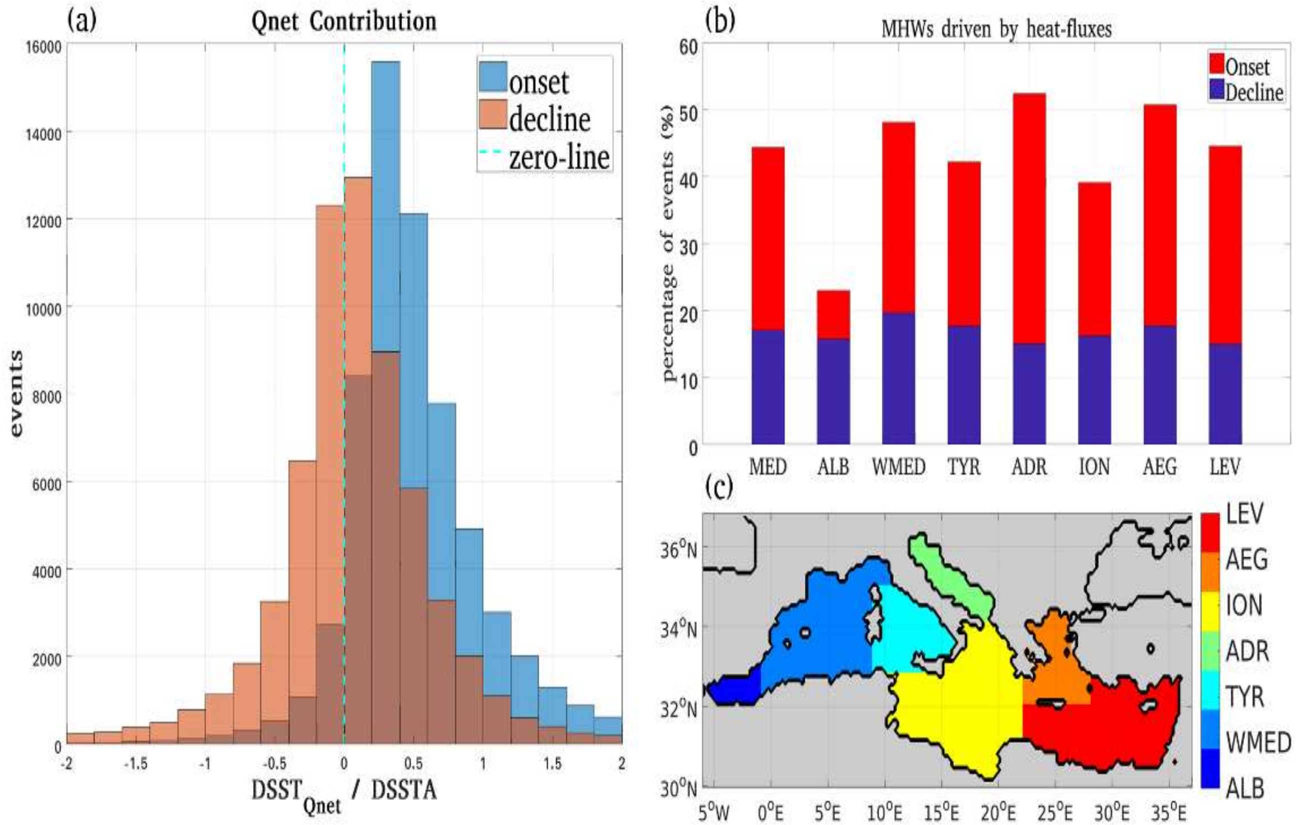
The contribution of Q' in driving a MHW onset/decline phase N is quantified through the following ratio of change

$$\mathrm{P(N)} = \frac{\Delta SST_Q(\mathrm{N})}{\Delta SST'_{obs}(\mathrm{N})}$$

a positive heat flux contribution value during a MHW phase indicates a favoring role of heat flux in the SST evolution, i.e., a warming (cooling) effect of heat flux during onset (decline). Analogously, a negative contribution value during either an onset or a decline phase, indicates that heat flux opposes the corresponding SST tendency.

Denaxa et al. Submitted to the State of the Planet in the context of OSR#8

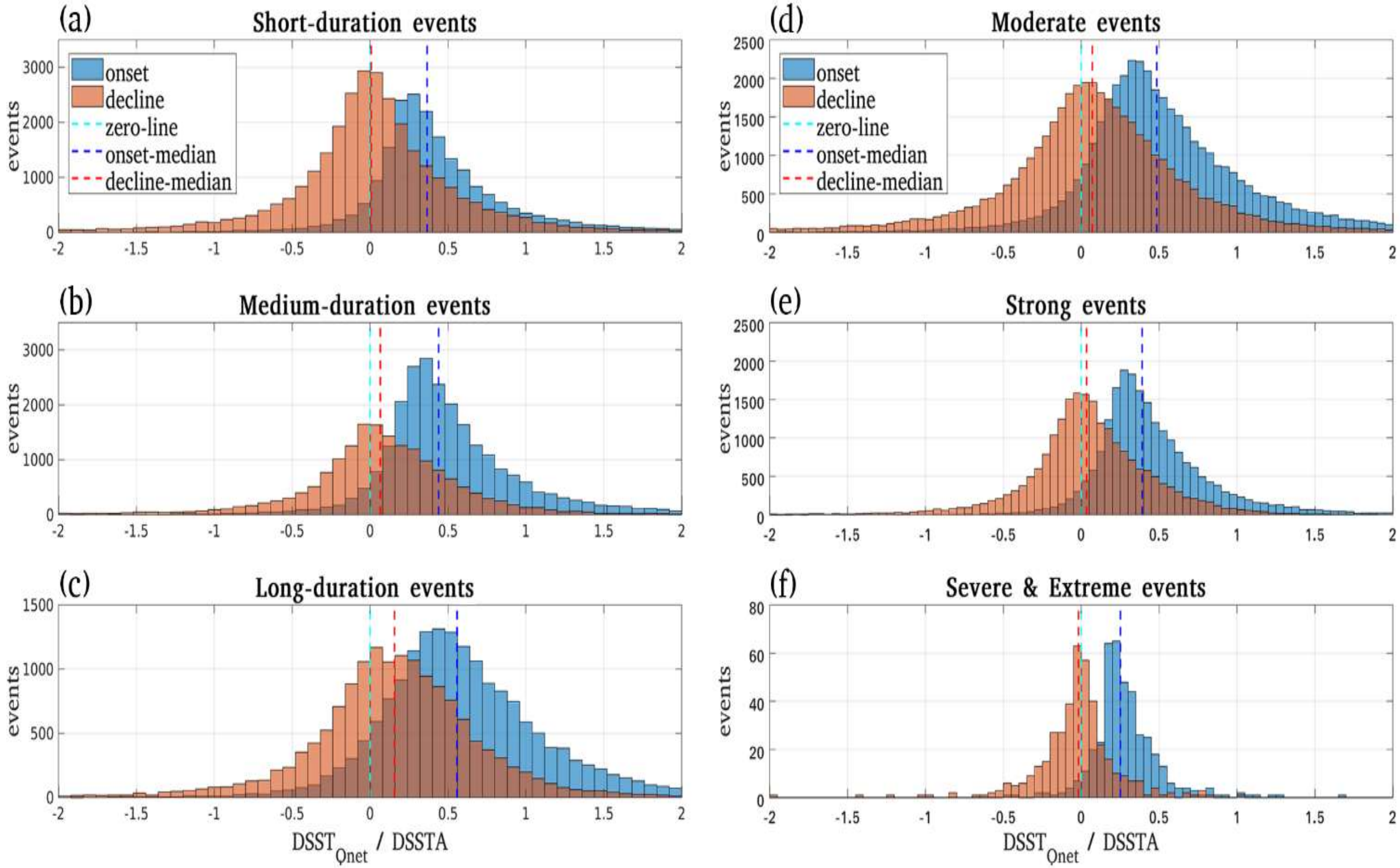
Surface heat fluxes contribute to the observed surface warming (cooling) during the onset (decline) in 92% (58%) events detected in the Mediterranean Sea



In 44% (17%) of the events, heat flux presents a major role during the development (decline) of MHWs, in terms of explaining more than half of the observed change in SST anomaly

Almost half (42%) of the observed MHWs in the basin decay under non-favorable heat flux conditions (i.e., heat flux opposing the SST decrease) → oceanic processes are the dominant driver of most MHW declines

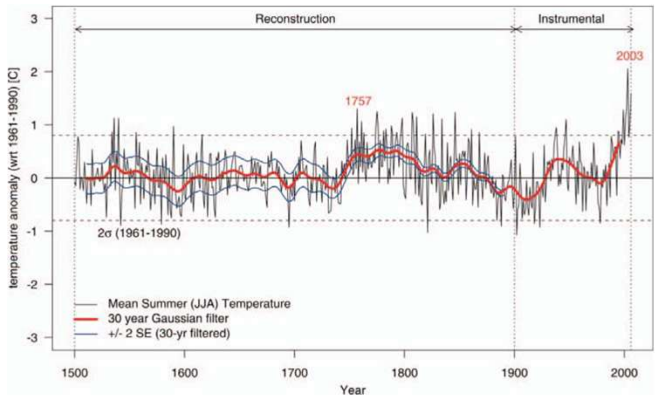
Denaxa et al. submitted

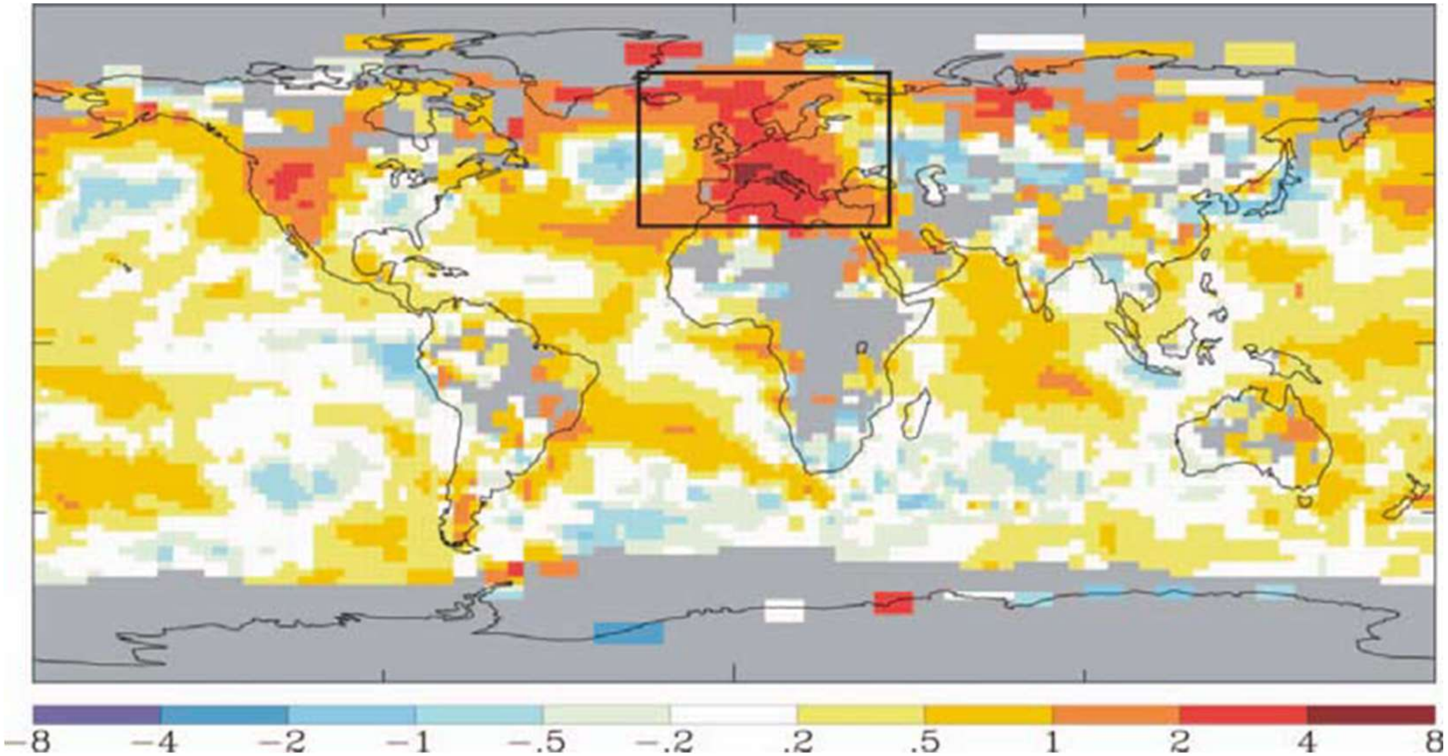


- Short-lasting onset/decline phases (shorter than 5 days) tend to experience a smaller contribution of heat flux in forming the SST evolution, compared to longer phases
- **There is an inverse relationship between MHW severity and the contribution of heat fluxes**

Denaxa et al. submitted

The 2003 HW Event



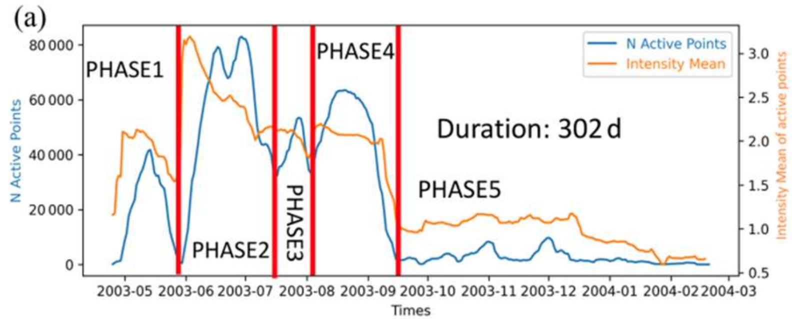


Surface air temperature anomalies (in ◦C, with respect to the 1961 to 1990 reference period), June–August 2003. Data source: Hansen et al., 2001; NASA/GISS

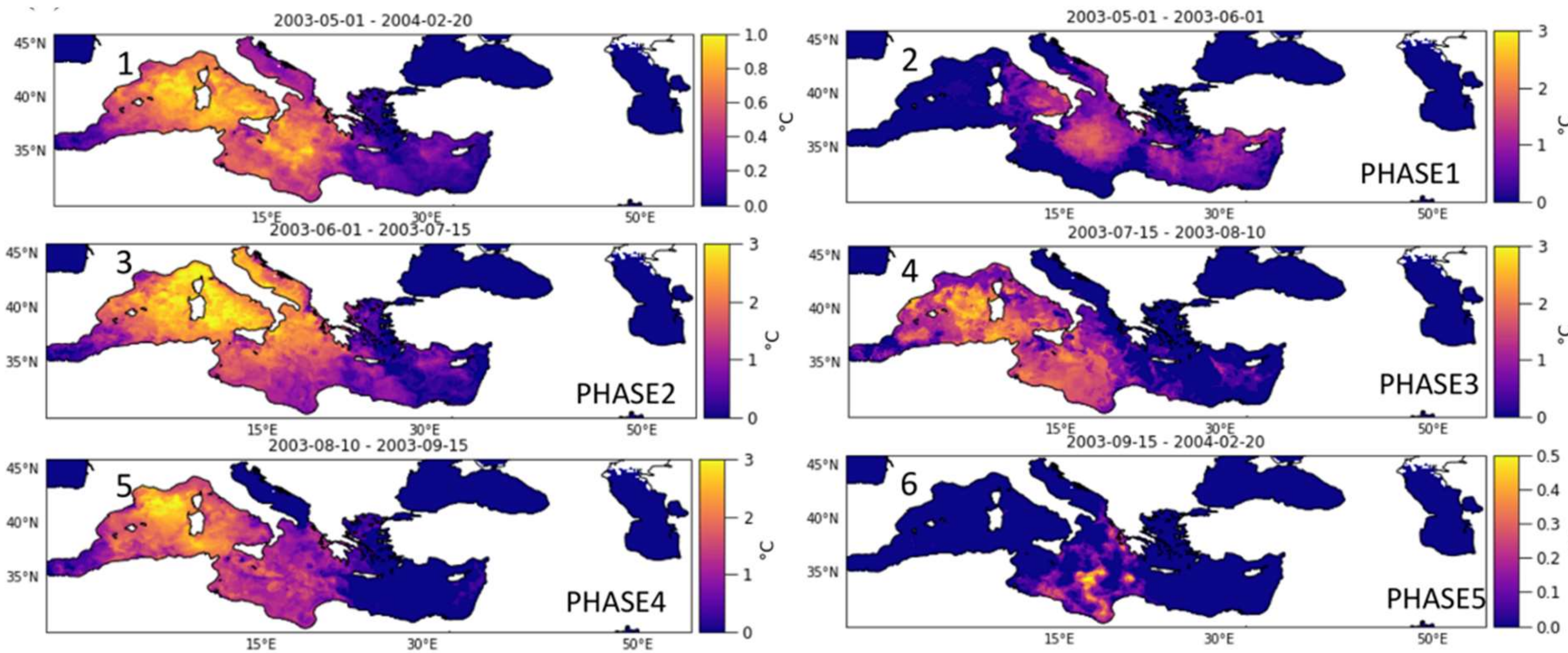
- At European scale, the temperatures exceeded +1.9◦C (around two standard deviations)
- Daily max temperature were 7.5◦–12.5◦C above average
- Estimate of around 40,000 deaths were registered in Europe

Garcia Herrera et al., 2010

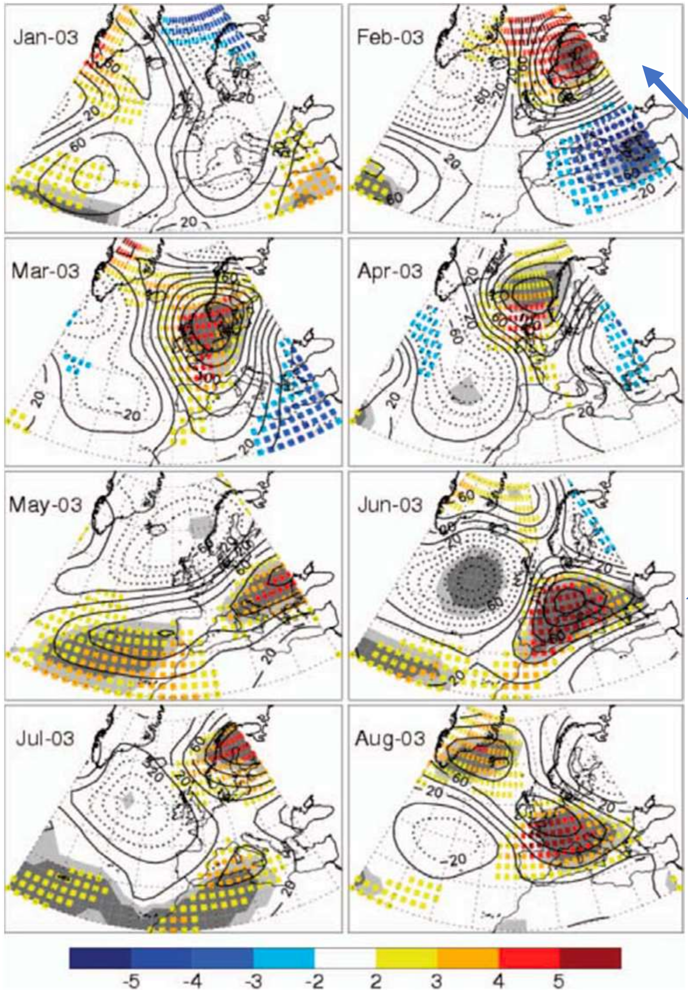
The 2003 MHW Event



Two distinct periods of exceptional heat occurred during the season: the first in June and the second during August



Bonino et al., 2023



Monthly anomalies of 500 hPa geopotential height and 850 hPa T anomaly (colored square)

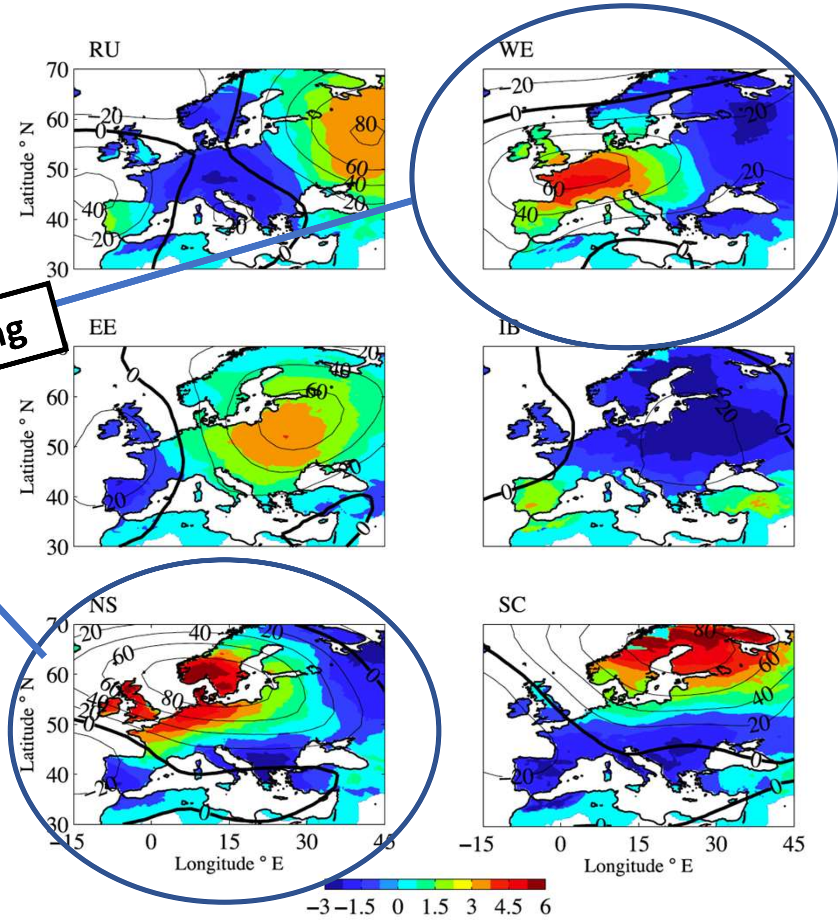
Garcia Herrera et al., 2010

Feb 2003

- Large positive T an. in the lower troposphere and at the surface between the British Isles and Scandinavia

European Summer Blocking

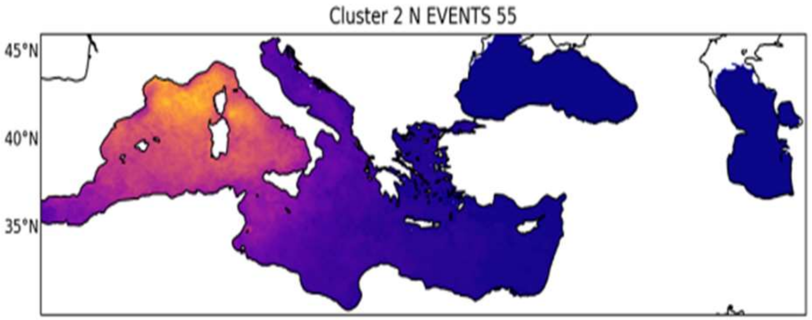
- Strong advection of cooler air from northern latitudes toward the eastern Med. 850 hPa T an. lower than –2◦C all over Western Europe.

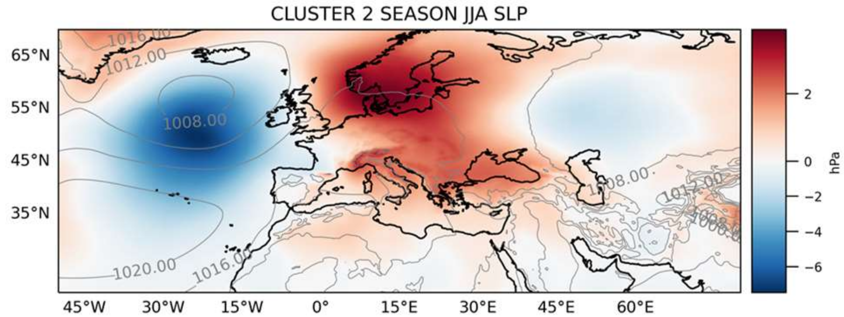


Stefanon et al., 2012

Mean of 5 days prior the first peak of cluster 2 events –> JJA season

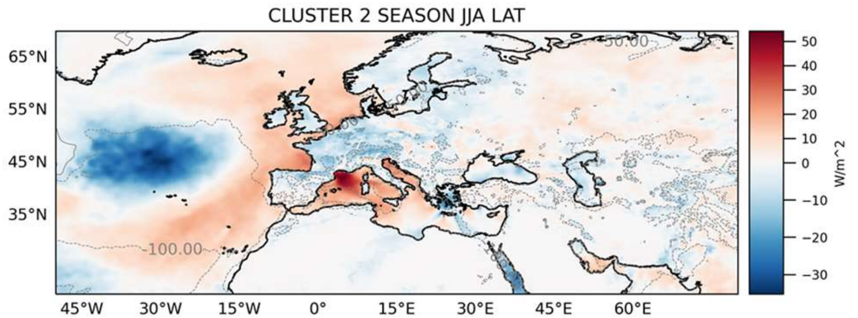
Work in progress…

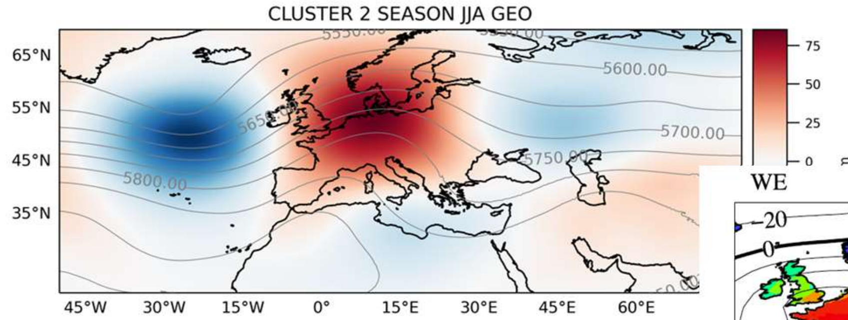


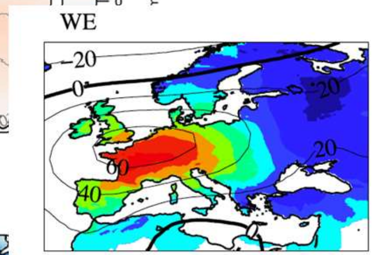


> SLP

> LAT
ocean is
loosing
less heat

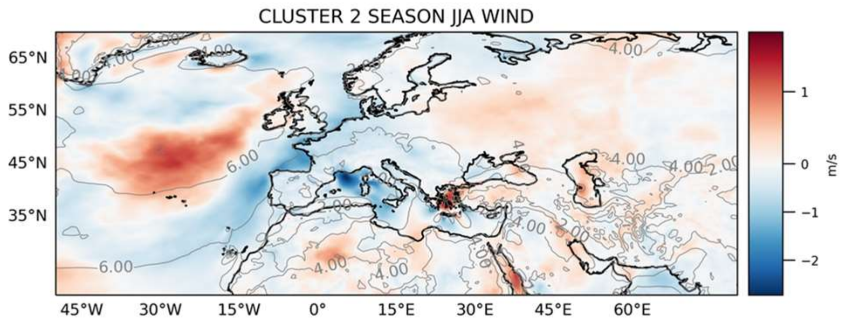


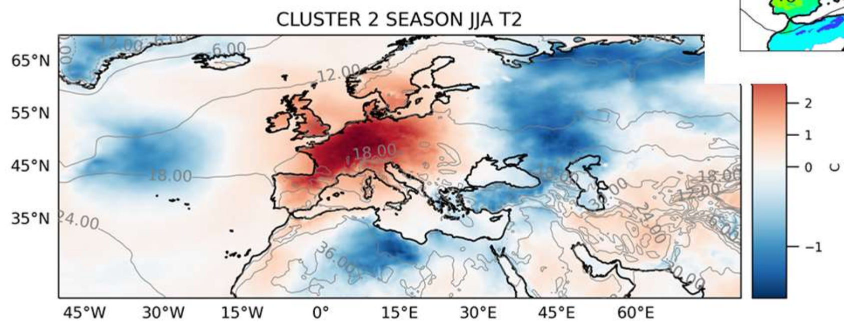




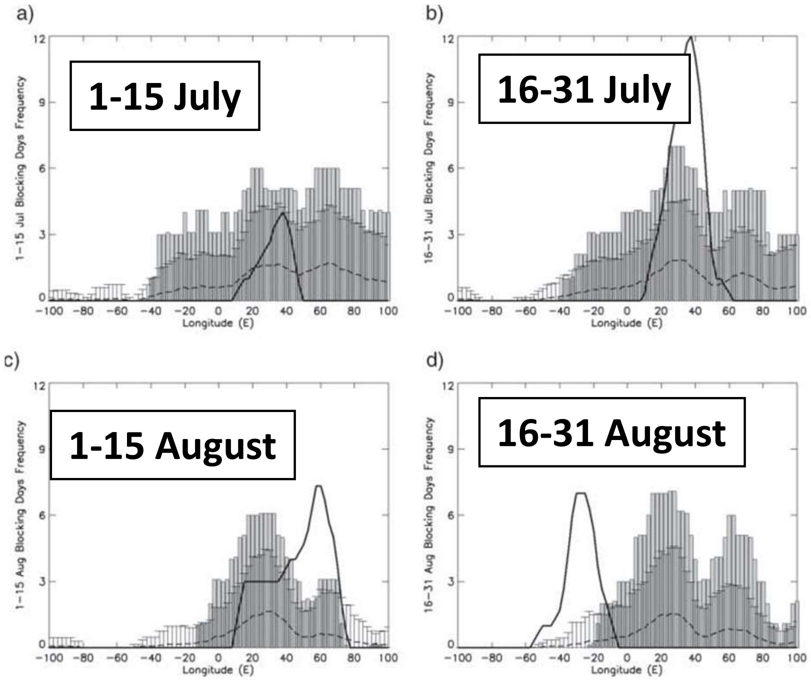
> GEO

< WIND





> T2

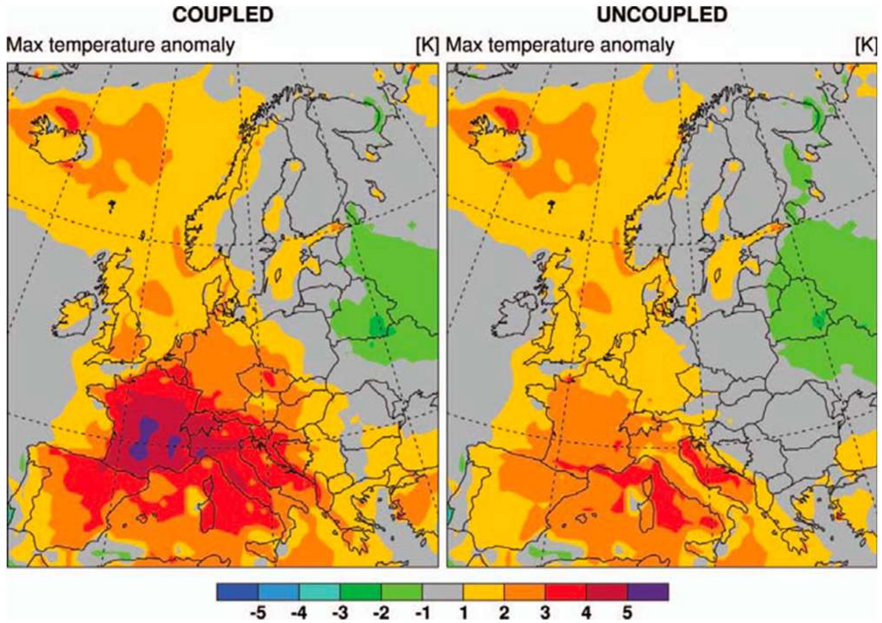


Longitudinal distribution for the frequency of blocked longitudes in July and August 2003 (thick solid lines) and the averaged distribution for the 1948–2005 period (dashed lines)

- **an extremely persistent blocking**

- **the intense negative soil moisture anomaly in central Europe**

2m T
JJA 2003

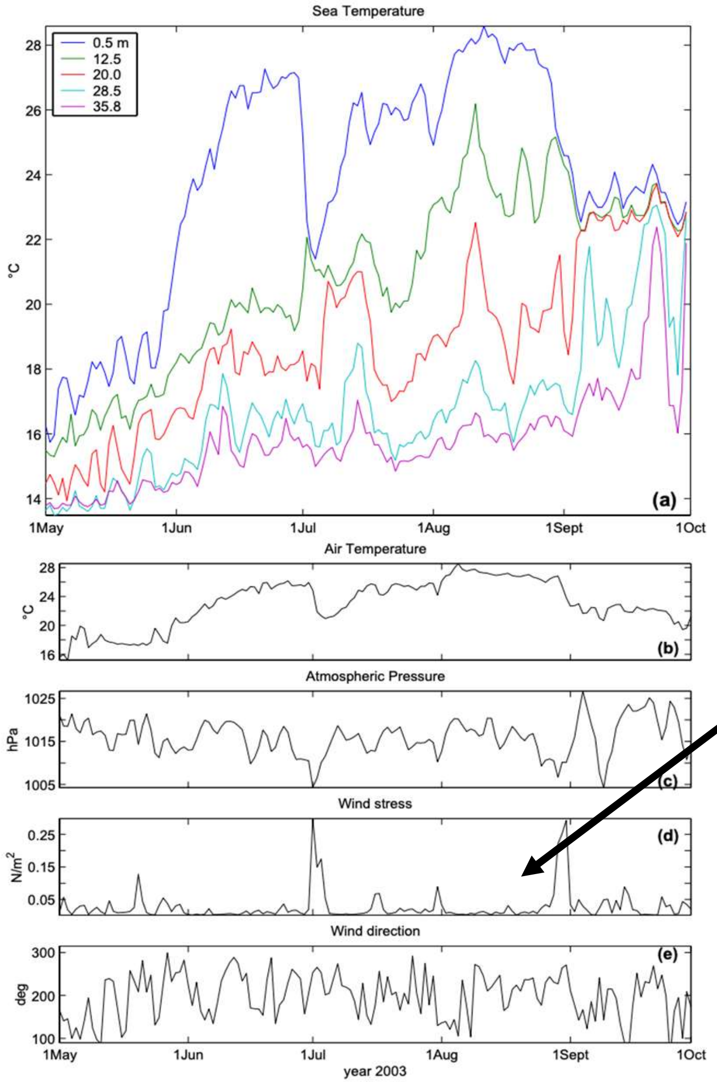


- **the prolonged high sea surface temperatures (SST) in the northern North Atlantic and the Med**

NO CONSENSUS on the driver/consequence contribution to the European Heat Wave

Garcia Herrera et al., 2010

The 2003 MHW Event in the Ligurian Sea

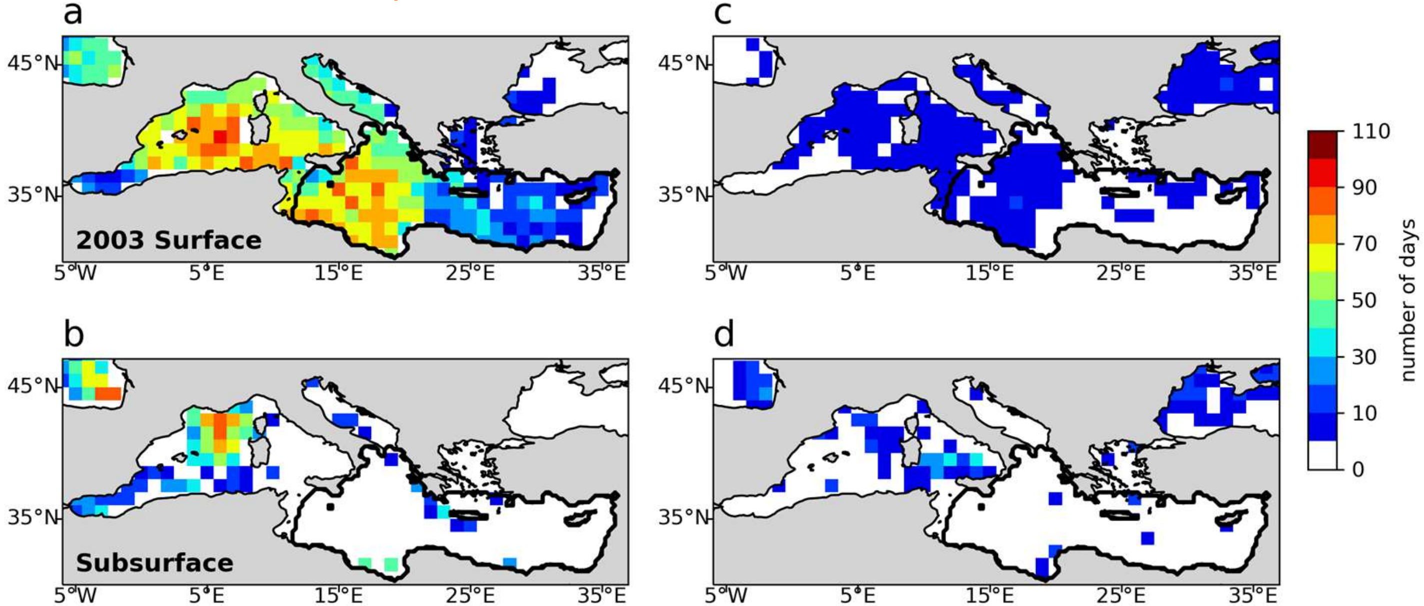


- **Data show that the anomalous warming was prevalently confined to within a few meters below the sea surface.**
- The limited vertical propagation of heat is ascribed to the high temperature difference that arose between the surface and the deeper layers due to protracted calm weather conditions.
- **Reduced wind activity may have been the principal cause of the temperature anomaly at the sea surface.**
- The analysis of the wind speed at the original time resolution (one hour) **from May to September revealed that the year 2003 was characterised by long periods with low wind speeds**, especially from June to August. Such long periods of persistently calm weather conditions are generally not observed during the summer months in this area

Sparnocchia et al., 2006

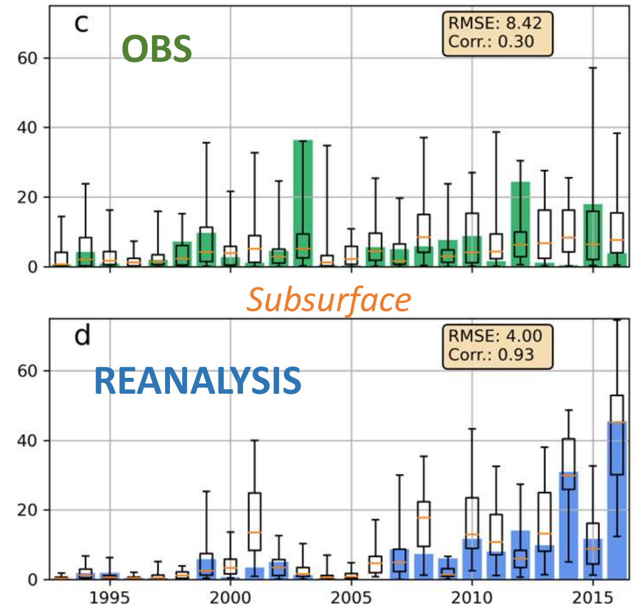
Seasonal Forecasts of Med 2003

Satellite/Reanalysis | *Forecasts*



Surface

Subsurface



Box plots represent the median, interquartile range, and range of the 40-member forecast ensemble.

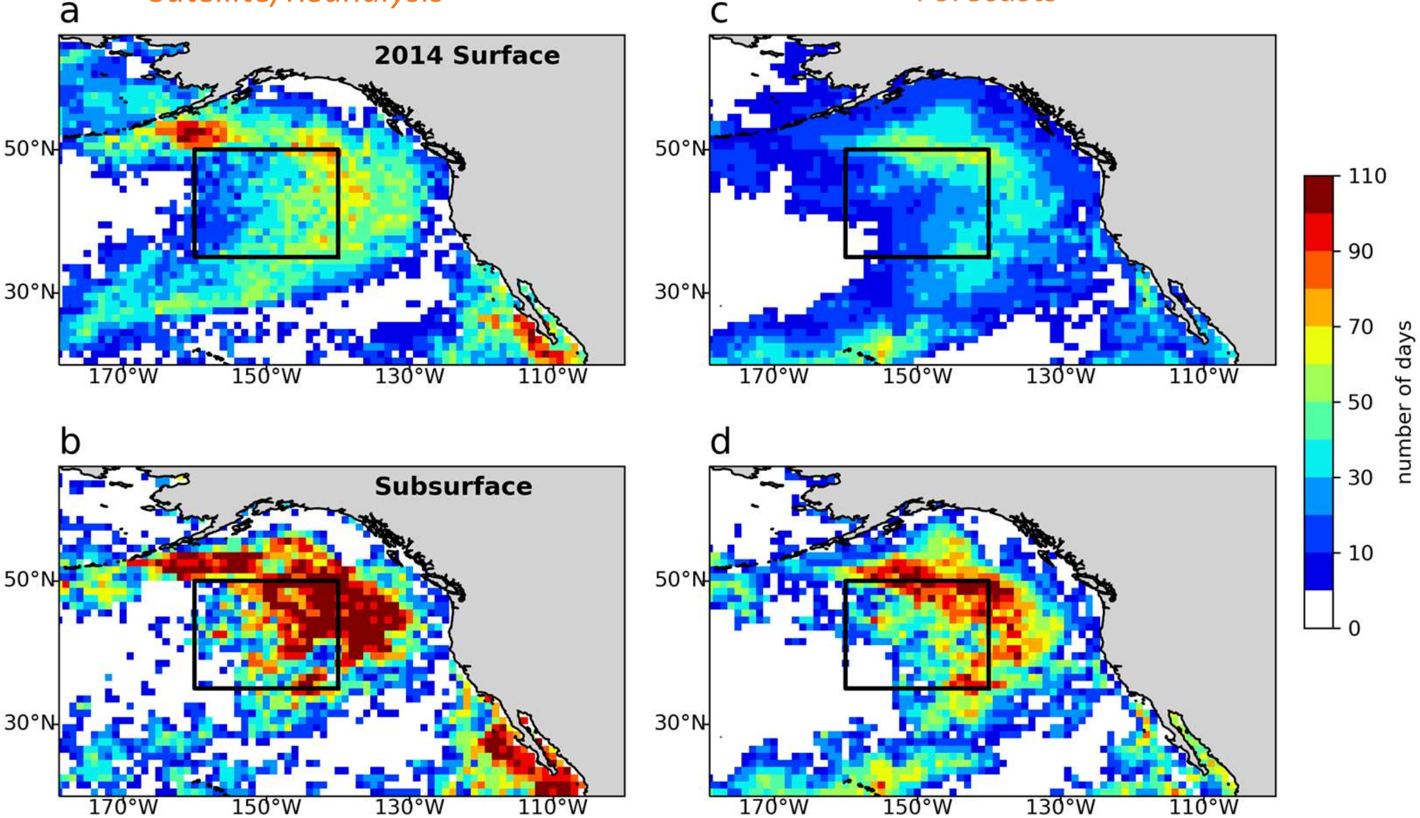
MHWs which manifest at the surface do not always leave a signal on the depth-integrated indicators

Subsurface extreme indicators are easier to predict than commonly-used surface indicators

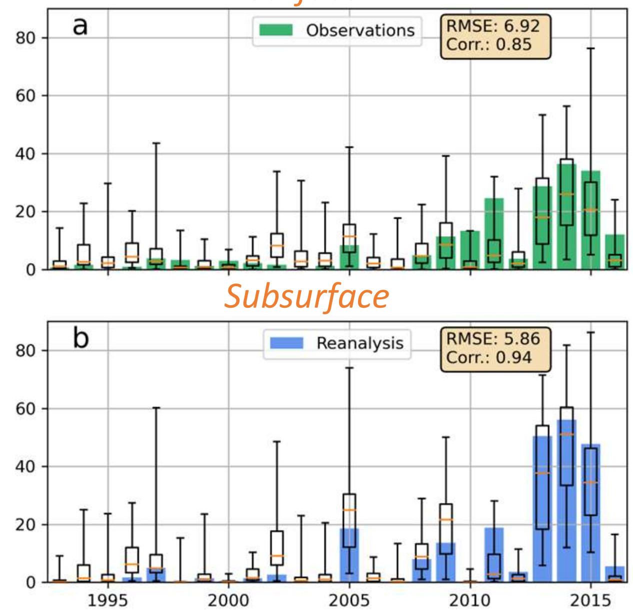
Mc Adam et al., 2023

Seasonal Forecasts of N.E. Pacific 2014

Satellite/Reanalysis *Forecasts*



Surface



Subsurface

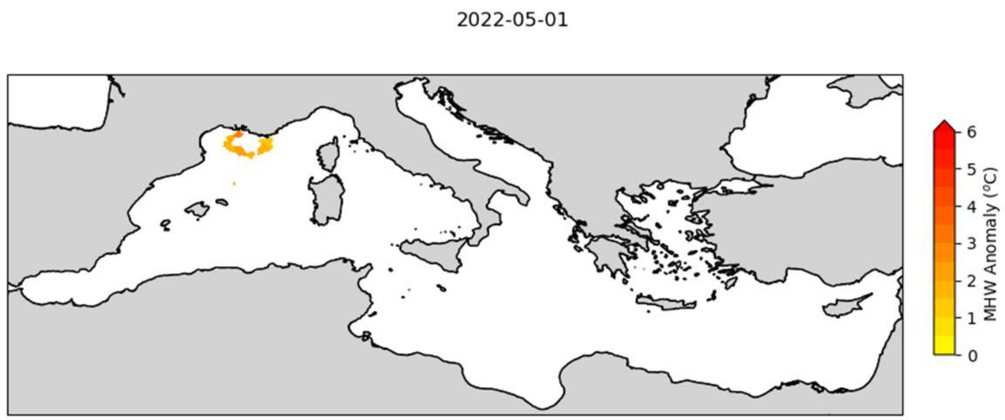
Subsurface extremes: there are general patterns (e.g., duration increases with depth)

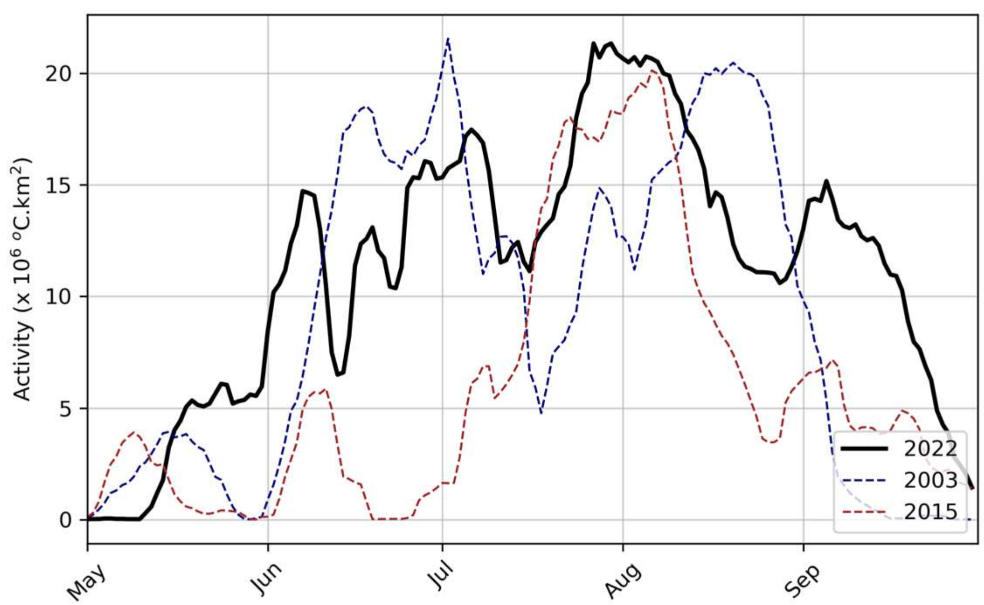
Mc Adam et al., 2023

MHW of Summer 2022

Reprocessed Mediterranean Sea Surface Temperature (REP)

- Mediterranean Basin
- Daily SST
- 0.05˚ res.
- 1982-2021 (+near real time)
- ESA CCI/C3S data + adjusted version of the AVHRR Pathfinder dataset version 5.3.

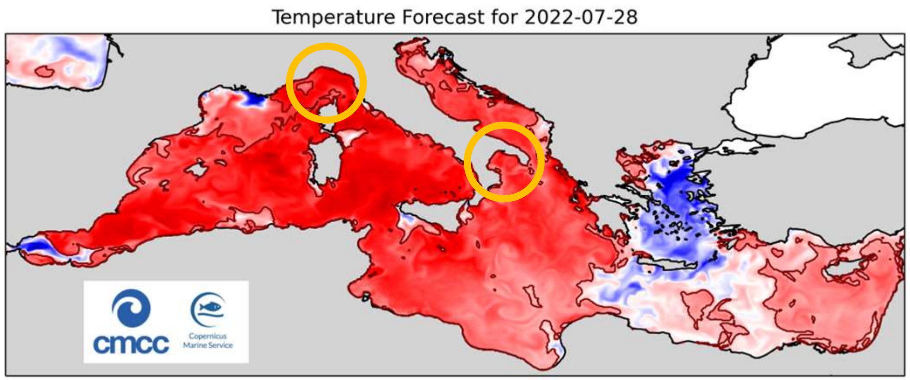


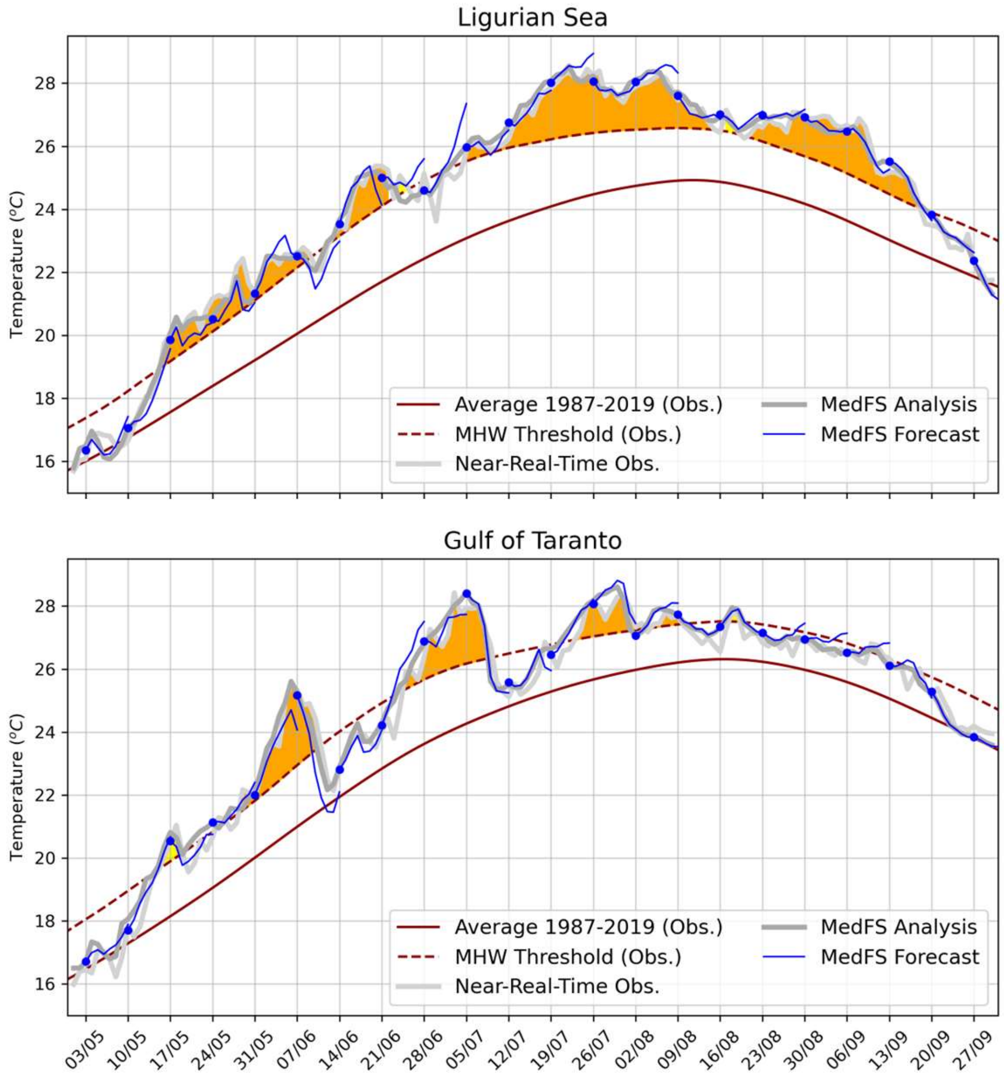


Short-term forecasting 2022

Mediterranean Forecasting System physical component: forecast & analysis (MedFS)

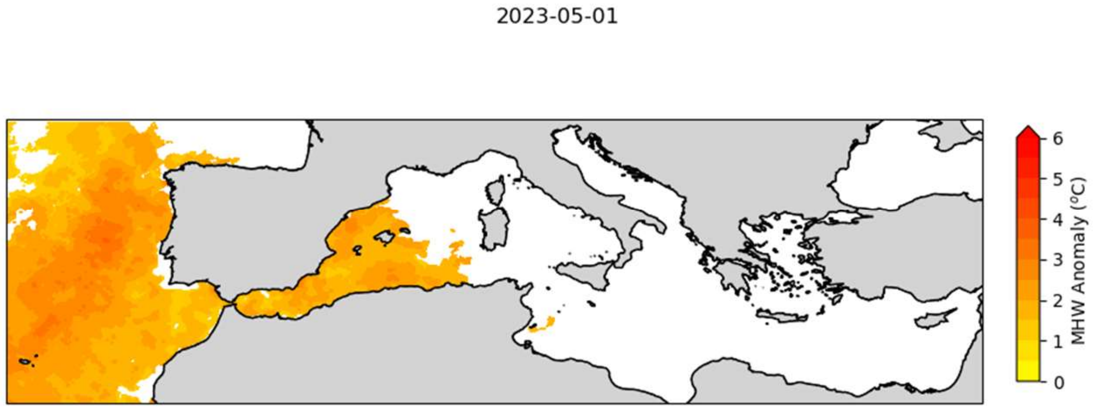
- **Coupled hydrodynamic-wave model including tides. 3DVAR assimilation scheme (OceanVar) of temperature and salinity vertical profiles and along track satellite Sea Level Anomaly observations.**
- **NEMOv3.6 + Wave Watch-III.**
- **Horizontal grid resolution is 1/24˚ (4-5 km).**
- **Vertical resolution: 141 unevenly spaced vertical levels.**
- **Analysis: Rolling dataset of previous two years.**
- **Forecasts: 10-day.**

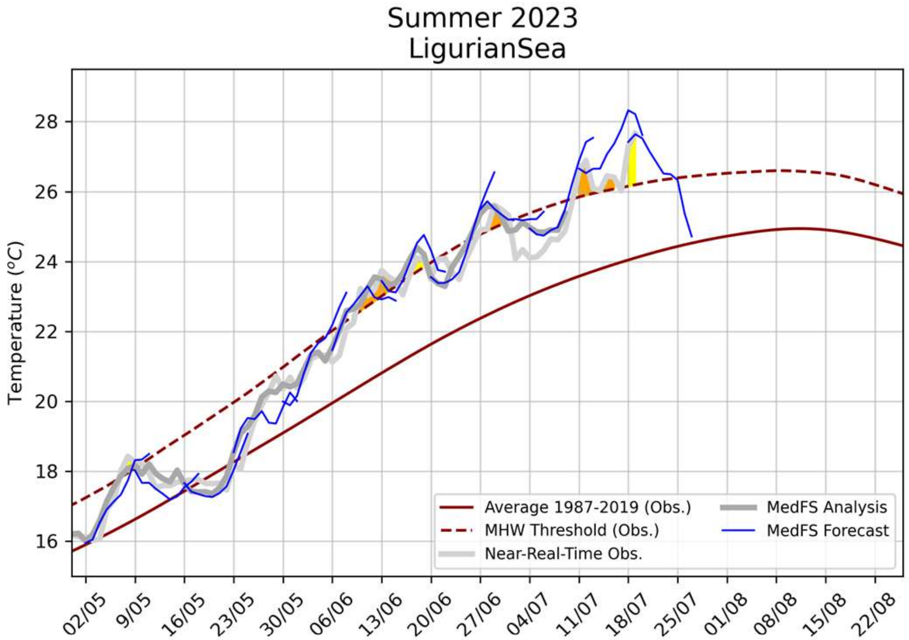


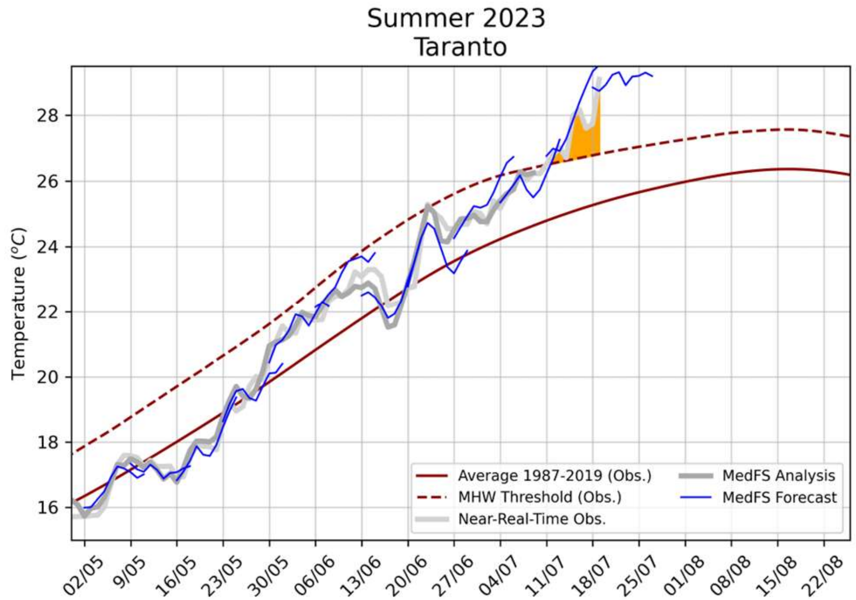


Summer 2022 in the Med: one of the largest/most intense on record (anomalies > 5^{o}C). CMCC/Copernicus **short-term forecasts** captured the **onset, eastward shifts, persistence and decay** of this event

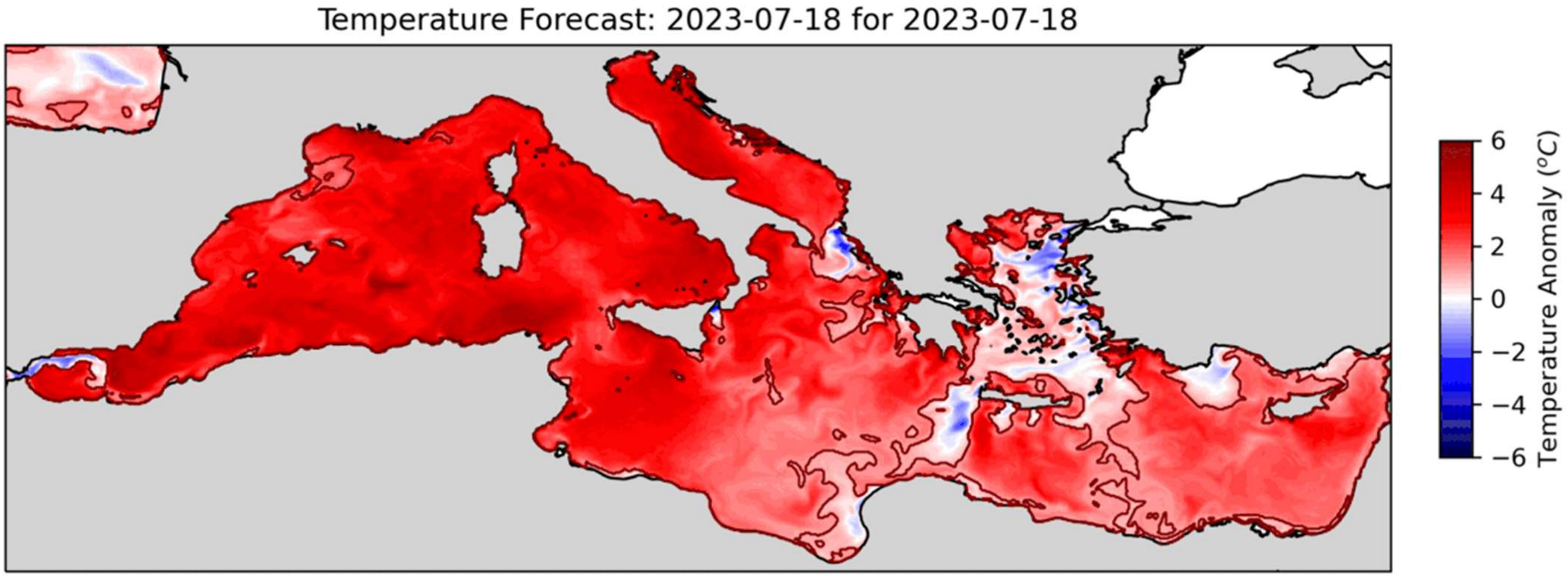
MHW of Summer 2023







This week forecast
July 18-27



Take home messages

- In the Med Sea **significant trends of increase** in most MHW properties since 1982 (number and duration, intensity mainly in the western Med)
- MHW **duration is longer in the subsurface** than at the surface, **MHW intensities decrease with depth and peak in different regions**
- **Subsurface extreme indicators are easier to predict than commonly-used surface indicators**
- **European heatwave events are primarily caused by the synoptic conditions** (persistent blocking). However, the pre-existing hydrological condition can influence the events by amplifying the temperature anomaly
- **Surface heat fluxes contribute** to the observed surface warming during the **onset phase** of the majority of the events (92%) detected in the Med Sea while **oceanic processes** are the dominant driver of most (83%) MHW **declines** (preliminary results…much more work needed on identification of drivers)
- **We need to work on the understanding of processes and drivers!!!!**