Response of the sea surface temperature to heatwaves during the France 2022 meteorological summer

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Abstract. Summer 2022 was a memorable and record-breaking event, ranking as the second hottest summer in France since the beginning of the measurements 1900, with a seasonal surface air temperature average of 22.7°CC. In particular, France experienced multiple record-breaking heat wavesheatwaves during the meteorological summer. As the main heat sink reservoir of the Earth system, the oceans are at the forefront of events of this magnitude , which enhance oceanic disturbances such as

- 5 marine heat wavesheatwaves. In this study, we investigated French maritime basins investigate the sea surface temperature to determine the ability of satellite (SST, hereafter) of French maritime basins using remotely-sensed measurements to track the response of surface waters to these events. the atmospheric heatwaves and determine the intensity of such feedback. Beyond the direct relationship between SSTs and surface air temperatures, we explore the leading atmospheric parameters affecting the upper-layer ocean heat budget.
- 10 Despite some gaps in data availability, we showed that the measured SSTs during the meteorological summer of 2022 was record-breaking, the mean sea surface temperature SST was between 1.3 C and 2.6 C above the long-term average (1982-2011). A focus on the heat wave from 31 July to 13 August was carried out and showed a significant sea surface temperature response to the heat wave and studied areas experienced between 4 and 22 days with average SSTs beyond the climatological maximum. We find out a significant SST response during heatwave periods, with maximum temperatures measured locally
- 15 locally measured at 30.8 C in the North-western Mediterranean sea. Beyond the response to intense surface air temperatures, the contribution of other atmospheric variables was not negligible. Thus, we have shown northwestern Mediterranean Sea. Our results show that France experienced an August with in August 2022 (July 31st to August 13th) above-average surface solar radiation correlated with below-average total cloud cover and anomalies in the distribution and intensity of wind speeds. The response to these different contributions depends on the hydrodynamic conditions, in particular the tides that ensure
- 20 turbulent mixing . This is why the response is more pronounced in the Mediterranean, where the absence of dynamic mixing (below-average surface wind speed) is associated with an absence of tides negative wind speed anomalies. Our attribution analysis based on a simplified mixed layer heat budget highlights the critical role of ocean-atmosphere fluxes in initiating abnormally warm SSTs while ocean mixing plays a crucial role in the cessation of such periods. We find that the 2-m temperatures and specific humidity are key variables across all regions studied that are consistently linked to the advection of
- 25 warm and moist air masses. Our results reveal that the influence of wind on heatwaves is variable and of secondary importance.

Moreover, we observe that the incident solar radiation has a significant effect only on BB and EC areas. Our results were are in line with previous studiesand we confirmed here, and demonstrate that even if the Mediterranean is known as a climate change hotspot, all maritime front the studied maritime areas are affected by a continuous warming of surface waters water and responded to extreme synoptic conditions.

30 Our study therefore demonstrated provide valuable insights into the complex mechanisms underlying the ocean-atmosphere interaction and demonstrates the need for an efficient and sustainable operational system combining polar orbiting and geostationary satellites to prevent monitor the alterations that threaten the oceans in the context of climate change.

Copyright statement. TEXT

1 Introduction

- 35 Anthropogenic influence on the climate is unequivocal and results in an Earth's global energy imbalanceas highlighted by the shifts in the leads to a global Earth's energy imbalance, as evidenced by changes in global average atmospheric temperatures distribution (?). The ocean's contribution to the energy balance temperature distributions (?). Furthermore, anthropogenic global warming is impacting climate variability, resulting in an increase in both the intensity and the frequency of extreme events (??). Regional projections, combining regional climate projections and historical observational constraints, predict
- 40 warming in France to range between 2.9°C and 4.8°C by 2100 in a medium emission scenario, with an increased impact on summer temperatures (?). These extremes, which affect every component of the Earth²'s system, in relation with the are primarily driven by atmospheric synoptic circulation (??).

The ocean plays a crucial role in the Earth's energy balance, with its extensive volume and the inherent thermal capacity , is making its contribution greater than that of any other component (continents, atmosphere, glaciers). As a matter of In fact, the

- 45 oceans absorb more than 90% of the thermal excedent of the system which leads excess, leading to an increase in their global heat content, thus to a rise in the global ocean temperatures (?). The ocean heat content (hereafter OHC) is a key indicator in the analysis of global warming (?). Although this increase is widespread, there are both horizontal differences, with a greater contribution from the Southern Ocean of the global heat uptake (?) and vertical discrepancies, with a greater uptake from the 0-700m depth layer (?). This global ocean heat content and temperatures (?). This internal energy imbalance in the ocean has
- 50 direct consequences on the properties of the system, its dynamics, its contribution to the water cycleand also as a , and its unique biotope. Such changes in the global OHC global ocean heat content have direct impacts on the sea-level rise (?), the total water vapor column (?), melting of continental glacier platforms melting (?) and decline in the ocean dissolved oxygene (?). In shorter time period, climate disruptions enhance the intensity and frequency of both atmospheric and oceanic extreme events. Among others oceanic events ocean dissolved oxygen (?). The ocean's tremendous heat capacity mitigates the surface
- 55 atmospheric warming, which is 50% higher over land than above the ocean (?). Among other oceanic events influenced by the context of climate change, marine heatwaves (hereafter MHWs), defined by ? which are defined as events of anomalously

warm water temperature having with specific characteristics (spatial extent, duration, intensity), have emerged as a key field of research due to their substantial impact on ocean ecosystems (?)(??). Although the extent of such events are is not limited to the ocean surface (?)), MHWs are mainly commonly detected and identified using sea surface temperatures (hereafter SSTs)

60 measurements (??) through sea surface temperature (SST) measurements (??) and the shift in their occurrence is directly linked to SST trends (?).

Beyond the detection of MHWs, SST is a fundamental variable in an oceanographic monitoring and forecasting system from daily to systems on both daily and climatic timescales. However, both SSTs are also key indicators of global ocean warming, which have increased since the beginning of the 20th century and are expected to continue on this pathway due to the direct

- 65 influence of near-surface atmospheric forcing changes (?). These shifts in SSTs also have implications in return, several studies demonstrating the contribution of warm SST anomalies in the enhancement of atmospheric heatwaves (???). However, the operational and the elimatic needs are based on elimatic needs for observations require a spatial and temporal coverage of observations that cannot be fulfilled achieved by *in situ* measurement means alone. Due measurements alone. Satellite SST measurements, due to their global spatial coverage and their usable spatial and temporal resolution, satellite SST measurements
- 70 meet these operational and climatic requirements and are now integrated in into forecasting systems (???).

During the This study focuses on two main objectives. First, we assess and characterise the response of SSTs over the French sea basins to the atmospheric heatwaves that hit France during the meteorological summer of 2022 meteorological summer (June-July-August), Western Europe and more specifically France have experienced a range of atmospheric heatwaves caused

- 75 by either a heat dome originating from an adiabatic compression of the Atlantic air particles (11th-25th of July and 31th-13th of August) or southerly advection of Saharian hot air masses called a heat plumes (15th 19th of June). As seen in the Figure ?? representing the anomaly in the 500 geopotential altitude, the first phenomena is associated to a planetary wave swell and enhanced by southerly warm advection while the June southerly advection is originating from an isolated cold pool over the Iberian Peninsula. These synoptics conditions resulted in anomalously changes in most of the variables influencing ocean
- 80 energy balance among them the 2m air temperature with anomalies that excedeed 5over Western-Europe (Fig.??). Among them, France experienced, during the using remotely-sensed SST observations. Finally, we diagnose the influence of atmospheric variables on the SST response and the relations between these variables based on a simplified mixed layer heat budget. We disentangle the role of the different atmospheric variables in explaining the anomalies in the surface flux and therefore their respective role in driving the mixed layer warming. The objective is to gain a better understanding of the relationship
- 85 between atmospheric conditions during the meteorological summer of 2022 elimatological summer, record-breaking surface air temperatures (in terms of both intensity and earliness), higher than average solar radiation (in combination with an unsual scattered cloud cover) and wind speed negative anomalies. and the underlying SSTs. In the following study, we assessed the capabilities of operational satellite SST measurements to describe the response to the atmospheric heatwaves that hit France during the
- 90 Section ?? provides a comprehensive overview of the data and methods used in this study. The synoptic conditions that triggered the heatwayes in Western Europe during the summer of 2022 meteorological summer and the influence of some of

are described in detail in Section ??. The main results of the study, including the characterization of the main components of the ocean energy balance on such impacts response of SST and its relationship with the physical processes at the air-sea interface, are presented in Section ??. Finally, in Section ??, we discuss these results, draw conclusions on their implications and the plan for future research.

ERA5 reanalysis of the mean geopotential height at 500 pressure level anomaly for a) June, b) July, c) August heatwaves as compared to the 1991-2020 climatology.

Same as Fig.?? for mean surface air temperature anomaly for a) June, b) July, c) August.

2 Data & Methods

100 3 Study sites

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2.1 Study sites

Although this studyfocuses-

In this study, we focus on the responses to the heatwaves that affected France , this meteorological extremes events during the meteorological summer of 2022. However, it is important to note that meteorological extreme events such as heatwaves

- 105 have a spatial extension that is not limited to extent beyond land borders. Thus, three distinct ocean areas In light of this, we have selected three distinct oceanic regions, including both coastal and open ocean zonesareas, as presented in the Figure ??, with inherent characteristics, have been selected in this study. Figure ??. These regions are characterized by distinct features and are as follows:
 - Area EC: The English Channel, characterized by strong tidal currents that enhanced the enhance water column mixing, thus help to hold cooler sea surface temperature, thereby helping to maintain cooler SSTs. This area is directly affected by the atmospheric zonal flux.
 - Area BB: Bay of Biscaye, The Bay of Biscay which is part of the Atlantic ocean and is composed of a deep abyssal plateau ending in underwater canyons, the most famous of which is that of Capbreton ending 300from the shoreplain connected to a shallow continental shelf by steep continental slopes. This area is also directly affected by the atmospheric zonal flux.
 - Area NWM: The North-Western Mediterranean Sea sub-basin(, including the Gulf of Lions& Balearie basin) used, the Ligurian Sea and the Balearie basin which are in the Copernicus Marine Environment Monitoring Service (CMEMS) Mediterranean Sea validation procedure as mentioned in ?. This area is directly influenced by Mistral and Tramontane regional winds influencing which drive recurrent upwelling phenomenaand is of particular interested in comprehensive studies of the Mediterranean water cycle and its implications for climate studies (??).

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Subdivision used in this study. The subbasins considered are the English Channel (EC), the Bay of Biscaye (BB) and the North-western Mediterranean Sea (NWM).

3 Data/Methods

125 2.1 Atmospheric reanalysis

The overview of the exceptional weather situation in France during the summer of 2022 is based on the systematic analysis of different meteorological variables influencing the upper-ocean energy balance (Equation ??). The forcing data used in the mixed layer heat budget were from the ERA5 reanalysis regridded to a regular latitude-longitude grid of 0.25 degrees (?). We also used an atmospheric forcing climatology to test the heat flux sensitivity the each variable in the model experiments.

130 In contrast to the SST products, we used a 1991-2020 time period reference, in accordance to the World Meteorological Organisation standards (hereafter WMO). Both hourly and monthly ERA5 data were used, the first to compute daily and weekly mean anomalies while the second were used to compute the 1991-2020 monthly climatological mean.

2.2 Sea surface temperature data

2.2.1 Operationnal SST product

The Advanced Very High Resolution Radiometer (AVHRR) on-board Metop satellites enables retrieval of SST twice daily at 1km resolution over the entire globe. The Ocean and Sea Ice Satellite Application Facility (OSI SAF) provides users with operational products of SST in near real time (https://osi-saf.eumetsat.int/). In particular it has been delivering operational Metop/AVHRR Advanced Very High Resolution Radiometer (AVHRR) SST products since 2007. In this study the specific OSI SAF product used is the level-3C (mono-sensor collated) from Metop-B labelled as OSI-201-b (https://osi-saf.eumetsat.
int/products/osi-201-b). It is a global 0.05° gridded product available twice daily.

SST retrieval from AVHRR data relies on MAIA version 4 cloud mask (?) and is based on a split-window algorithm using two infra-red bands at 10.8 and 12.0 μ m which coefficients are tuned so that the retrieved SST has a global zero bias against drifting buoy measurements at about 20cm depth, see for example ?. Since 2017, operational production of Metop SST includes an algorithm correction scheme. This scheme has been designed to mitigate the SST algorithm inherent biases due to

- 145 changing atmospheric conditions : negative biases with respect to drifting buoy measurements where and when the atmosphere is very wet such as in the Inter-Tropical Convergence Zone and positive biases where and when the atmosphere is very dry (see Figure 14 in ?). It is based on the use of Numerical Prediction model output of atmospheric profiles (pressure, temperature and humidity) and RTTOV radiative transfer model (?). This algorithm correction scheme is described in ? and in the OSI SAF Algorithm Theoretical Baseline Document (ATBD) for Low Earth Orbiter SST products (?)(??).
- As the product is operational, it is necessary to be aware of the biases inherent in the data. In order not to introduce biases related to the diurnal cycle, only night-time data have been analysed. However, these data are aggregated over a time window of 12 hours centered at midnight UTC. For the studied area, the night-time data are acquired at 21:30 local time, thus in the

westernmost part of the domain data are acquired at dusk in summer time. Therefore, data with a solar zenith angle smaller than 95° are removed to avoid analysing daytime SST. OSI SAF SST products are delivered along with a per-pixel Quality

155 Level (QL) which reflects the quality of the retrieval. This includes considerations about potential contamination by cloud and mineral dust aerosols. The QL is ranging from 0 (no data) to 5 (best available quality).

2.2.2 ESA CCI SST analysisproduct

An analysis of satellite derived SST was used to compute a daily climatology to compare to operational SST. It is For the purpose of climatological computations, the version 2.1 of the European Space Agency Climate Change Initiative (ESA CCI) level 4 Climate Data Record (??) which is (hereafter CDR) were used (??). These SST CDR measurements are based on the cloud-free reprocessed thermal infrared radiance from the AVHRR and the Along Track Scanning Radiometer (ATSR) sensors. It is a daily global gap-free product available from 1981 to 2016 on a regular latitude/longitude grid at 0.05 degrees resolution. This analysis represents the daily mean 20cm depth SST corrected by the diurnal cycle. Thus, this measurement is equivalent to the nighttime SST products developed under the OSI SAF framework.

165 2.2.3 SST climatology and anomaly

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The studyof SST anomalies requires, in a first step, the construction of a reliable monthly climatology for the period 1982-2011. Monthly elimatological averages were obtained by averaging the daily data presented in the section-

In the present study, we calculated both daily and monthly SST anomalies. To construct a reliable climatology for SST anomalies, we used a 30-year archive of data specifically dedicated to climate studies, in accordance to the standards set by the WMO.

We obtained monthly climatological averages by averaging daily ESA CCI CDR (Section ??) using the Climate Data Operator tool (?) for the 1982-2011 period. We then calculated daily (resp. monthly) anomalies by comparing the constructed daily (resp. monthly) ESA CCI climatology to the daily (resp. monthly) OSI SAF SST data.

In a second step, the daily OSI SAF data were filtered in order to reduce the biases of the analyses (especially on the calculation of spatial averages). In this study, only To reduce biases in the analysis, we filtered the operational OSI SAF SST data by only using data with a QL equal to Quality Level parameter of 3, 4, or 5have been used, as recommended in the Product User Manual (?). Following this first filtering, it is necessary to ensure Additionally, we ensured that the number of measured pixels is was representative of the area . To avoid biases in the spatial averages, only the days where the measurements concern by only keeping days where measurements covered at least 50% of the total surface areaare kept. Finally, to limit the. To limit

180 disturbances in the SST analysis, the daily analysis of the anomalies was done by taking we applied a sliding window over 3 days. This also limits the noise that might be and considered only lower frequencies, which also reduced the noise introduced by the diurnal cycleand to consider only lower frequencies. Any changes in

We also note that no changes were made to the SST retrieval process have been done during the study periodwhich proves, ensuring that the SST are homogeneously distributed in both space and time.

185 Anomalies are then calculating by taking the differences between the daily SST value-

2.3 Modeling framework

The aim of this research is to gain a deeper understanding of how SSTs react to the abnormal conditions of the summer of 2022 through examination of ocean-atmosphere interactions. We investigate the relationship between SSTs and specific atmospheric conditions, as well as the contribution of the inherent atmospheric variables. Generally, changes in SSTs are primarily the result

190 of small-scale processes occurring within the mixed layer that can be enhanced by climate modes such as the NAO (?). Among these local processes, ? found that the effects of a northward shift in the jet stream on SSTs are primarily driven by changes in the net heat flux at the ocean-atmosphere interface. Hence understanding the generation of warm SST conditions needs to be addressed by studying the atmospheric interactions with the ocean mixed layer.

2.3.1 Mixed layer heat budget

195 A mathematical approach to the mixed layer heat budget had been proposed by ? under the Boussinesq approximations, Reynolds averaging and diffusive closure assumptions for turbulent fluxes:

$$\frac{\partial T_m}{\partial t} = \underbrace{-\overline{\mathbf{u}} \cdot \nabla T_m}_{A} + \underbrace{\kappa_h \Delta T_m}_{B} - \underbrace{\frac{1}{h} \left[\kappa_v \frac{\partial T}{\partial z} \right]_{-h}}_{C} - \underbrace{\left(\frac{T_m - T_{-h}}{h} \right) \left[\frac{\partial h}{\partial t} + \mathbf{u}_{-h} \cdot \nabla h + w_{-h} \right]}_{D} + \underbrace{\frac{q_{rad} + q_{turb}}{\rho_0 c_w h}}_{E} \tag{1}$$

where T_m , h, ρ_0 and c_w are respectively the mean temperature, the depth, the mean density and the specific heat capacity of the surface mixed layer, **u** is the horizontal velocity vector and w is the vertical velocity. κ_h and κ_v are respectively the horizontal and vertical turbulent diffusivity coefficients. q_{rad} is the net radiative heat flux and q_{turb} is the net turbulent heat flux at the sea

and vertical turbulent diffusivity coefficients. q_{rad} is the net radiative heat flux and q_{turb} is the net turbulent heat flux at the sea surface, removing from the former the fraction that is radiated below the mixed layer. The mention -h refers to the bottom of the mixed layer as the vertical axis is oriented upward.

This equation helps to understand the contribution of each process to the mixed layer heat budget. The SST tendency is dependent on the horizontal advection (A), the horizontal eddy transport (B), the vertical turbulent mixing (C) and entrainment

205 (D) of heat at the mixed layer base and the ocean-atmosphere interface heat flux (E). One can notice the contributions of the solar shortwave radiation (through component E) and the wind speed through ocean currents (components A and D), vertical turbulence (component C) and air-sea heat fluxes (component E) on the SST evolution.

In this study, we aim at relating air-sea heat fluxes to the ocean mixed layer temperature trend. Therefore we write a simplified form of Equation **??** as:

(2)

$$\frac{\partial T_m}{\partial t} = \underbrace{\frac{q_{rad} + q_{turb}}{\rho_0 c_w h}}_{E} + \underbrace{\frac{Res}{A + B + C + D}}_{A + B + C + D}$$

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where only the air-sea heat flux (component E) is explicitly diagnosed, the remaining terms being merged into a residual *Res* deduced from the difference between the total trend and the air-sea heat flux trend. We interpret the latter term as a cooling

trend mainly driven by vertical turbulent exchanges (namely, components C and D), consistently with the literature on marine

215 <u>heatwave heat budgets (e.g. ?).</u>

Radiative air-sea heat fluxes are composed of shortwave incoming solar radiation (Q_{SWD}), shortwave radiation reflected at the surface (Q_{SWU}), longwave downward radiation (Q_{LWD}) and the longwave upward (Q_{LWU}) contribution from the ocean. Net radiative fluxes over the ocean can then be summarized as the sum of the net shortwave radiation (Q_{SW}) and the net longwave radiation (Q_{LW}).

Turbulent fluxes are composed of sensible and latent heat fluxes which are estimated, following the Monin-Obukhov Similarity Theory (MOST, ?), by the so-called Bulk aerodynamic formulas:

$$Q_S = \rho_0 C_p C_S |U_{10m}| \Delta T \tag{3}$$

$$225 \quad Q_L = \rho_0 L_v C_L |U_{10m}| \Delta q \tag{4}$$

with C_p the air specific heat capacity, C_s and C_L respectively the sensible and latent heat transfer coefficients, $L_v = 2.26$ MJ/kg the latent heat of evaporation, U_{10} the wind speed at 10m, ΔT the long-term value one (1982-2011) ocean-atmosphere interface temperature difference (K), Δq the ocean-atmosphere interface specific humidity difference ($g.kg^{-1}$). The specific humidity at the ocean surface is given by:

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$$q_s = 0.98 q^* (SST)$$
 (5)

with $q^*(SST)$ the saturating humidity at the sea surface temperature.

Under this decomposition, equation ?? becomes:

$$\frac{\partial T_m}{\partial t} = \frac{1}{\rho_0 c_o h} \Big(Q_{SW}(0) - Q_{SW}(-h) + Q_{LW} + Q_S + Q_L \Big) + Res$$
(6)

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2.3.2 Air-sea heat flux computation

To be able to assess the role of the different atmospheric variables in driving the net atmospheric fluxes and thereby the SST evolution, we have used the surface modeling platform SURFEX (VERSION 8) (Masson et al., 2013; Le Moigne et al., 2020),

240 developed at CNRM to calculate turbulent fluxes and radiative upward fluxes depending on incoming radiation and atmospheric variables. Turbulent fluxes are estimated using the COARE version 3.0 bulk formulae (?), radiative upward fluxes are calculated considering an ocean albedo of 0.065 and an emissivity of 0.96 respectively for shortwave and longwave radiation.

2.3.3 Mixed layer depth reconstruction

- 245 The mixed layer depth (MLD hereafter) is an oceanic variable that influences upper ocean variability and controls biogeochemical processes. While this variable is not specifically analyzed in the present study, it is necessary for the computation of the mixed layer heat budget. Therefore, we used the CMEMS mixed layer depth analysis for the summer of 2022 to compute an average mixed layer depth. Specifically, this value is the temporal average of respectively the hourly CMEMS Mediterranean Forecasting System (Med-Physics) for the NWM area and the CO5 configuration of the Atlantic Margin Model (?) over the
- summer of 2022 for EC and BB. Over the regions of interest, this averaged MLD is deeper than 10m (Figure ??), a depth for which typically 90% of the incoming solar radiation has been absorbed. therefore, for simplicity, we assume that the mixed layer absorbs all the surface solar radiation (hence $Q_{SW}(-h) \simeq 0$). Considering the low variability of the MLD (Figure ??) throughout the summer, we used a mean MLD of 12.5m for the NWM region and 11m for the BB region in our study. The outcome is different for the EC region with a strong spatial and temporal variability throughout the summer. For this specific area, we decided to prescribe the daily MLD directly in the analysis.

2.3.4 Model sensitivity experiments

Our simple model finally consists in estimating the air-sea fluxes depending on the atmospheric state using SURFEX and then estimating the SST evolution depending on these fluxes using the simple ocean bulk temperature equation (Eq. ??). We used SURFEX in offline mode utilizing ERA5 atmospheric variables as forcing data on the ERA5 grid. In all experiments, fluxes are calculated at an hourly time-step over the three months considered in the study using ERA5 hourly data. A reference experiment (CTL hereafter) is conducted in which all atmospheric forcings are prescribed according to their value in 2022.

To diagnose the influence of atmospheric variables on the SST response, an experiment in which all atmospheric parameters are modified to their values of the period 1991-2020 has been conducted (CLIM hereafter). This is done by estimating the flux taking atmospheric parameters from each summer of the period and then averaging the fluxes obtained over the full period. This gives an estimation of "climatological fluxes", assuming an unchanged SST. Integration of the ocean bulk model driven by these climatological fluxes provides a reference SST evolution that would happen if atmospheric parameters where climatological (CLIM). Based on this CLIM experiment, a set of sensitivity experiments has been conducted in which atmospheric parameters are modified individually to their 2022 value (as in CTL). All atmospheric variables used as inputs in the net heat flux equation

- 270 have been tested : temperature at 2 m (T2M hereafter), specific humidity at 2 m (HUS hereafter), 10 m wind speed module (WND hereafter), and incoming shortwave (RSS hereafter) and longwave (RLS hereafter) radiations. Experiments and their acronyms are listed in Table ??. Note that the air-sea flux computation also depends on SSTs. Here, we keep the SST as observed in 2022. The model set-up thus does not consider the feedback effect of SST on air-sea fluxes, which is out of the scope of this study.
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The contribution of each variable on SST was then determined by calculating the difference between SSTs of the respective sensitivity experiment and the CLIM experiment, similarly, the effect of all atmospheric variables is calculated as the difference CTL - CLIM.

280 **3** Synoptic conditions initiating heatwaves during the summer of 2022

During the meteorological summer of 2022 (June-July-August), France experienced the second warmest summer since 1900 with surface air temperatures that broke records in terms of both intensity and earliness (seasonal surface temperature average anomaly of +2,3C). The summer also set a record for the number of days spent under heatwaves, with 33 days split across three distinct events. The associated synoptic conditions resulted in anomalies in most of the variables influencing air-sea heat

- 285 fluxes. Among them, the 2m air temperature reached anomalies exceeding 5C over western Europe (Figure??). Particularly, all of the metropolitan French territory and its surrounding sea basins have been affected (Figure??). The first heatwave occurred between June 15th and 19th, and was caused by a shift in the weather pattern from a zonal regime to a summer blocking. This led to a stationary north-south meander of the jet stream and the formation of a cut-off low (hereafter CUL) over the Iberic Peninsula. This low-pressure system brought southerly winds that advected hot air masses, known as heat
- 290 plumes, over western Europe and France as seen in the Figure ?? representing the anomaly in the 500 hPa geopotential height. The second heatwave, which occurred between July 11th and 25th, and the third heatwave, which occurred between July 31st and August 13th, both had a similar dynamic of formation. They were linked to a north-south planetary wave swell that caused a meander of the jet stream. This led to adiabatic compression of subsiding air masses, which created a heat dome over the western part of Europe. In addition, the meander of the jet stream triggered the formation of another CUL, which further
- 295 enhanced the already abnormally warm surface air temperatures by advecting hot air masses from the Sahara. In all of the three heatwaves, the air mass advection occurred over the Mediterranean Sea or the Bay of Biscay which moistened the air mass which hence increased the specific humidity and had a strong effect on surface temperatures (?). These conditions have been well studied in previous research which indicates that these dynamics are usual in the occurrence of heatwaves over western Europe (?).

Table 1. List of model experiments with their respective forcing. CLIM refers to the average reference period 1991–2020.

| Experiment name | CTL | CLIM | T2M | HUS | WND | RSS | RLS |
|---|------|------|-------------|------|------|------|------|
| Temperature at 2 m | 2022 | CLIM | 2022 | CLIM | CLIM | CLIM | CLIM |
| Specific humidity at 2 m and surface pressure | 2022 | CLIM | CLIM | 2022 | CLIM | CLIM | |
| Wind speed at 10 m | 2022 | CLIM | CLIM | CLIM | 2022 | CLIM | CLIM |
| Incoming shortwave radiation | 2022 | CLIM | <u>CLIM</u> | CLIM | CLIM | 2022 | CLIM |
| Incoming longwave radiation | 2022 | CLIM | CLIM | CLIM | CLIM | CLIM | 2022 |





300 4 Results

4.1 Daily sea surface temperature evolution over the 2022 meteorological summer

The first primary objective of an operational product is to provide a daily usable daily monitoring for use by the forecasting services. However, these conditions are ideal cases and are therefore not basin-scale global coverage is dependent on several conditions described in the Section ?? which are not always met in all basins every day. Thus a significant part on a daily basis.

305 As a result, a significant portion of the data is not available depending on multivariate conditions (may not be available due to various factors such as clouds, aerosols, and low quality data). This share. The extent of missing daily SST data varies for each



Figure 2. Same as Figure?? for the mean geopotential height at 500 hPa pressure level anomaly for the a) June, b) July and c) August heatwaves compared to the corresponding period of the 1991-2020 climatology.

basin and is compiled in the as illustrated in Figure ??. One can note that the English ChannelEC, with 60% of missing data, is more impacted than the Bay of Biscaye basin (33BB (48%) and the North-Western Mediterranean Sea (22.7%) where the data are missing NWM (29%) areas where the missing data is significant only until the beginning of July. These missing data

310 do not follow a regular pattern and are rather related to the applied filtering conditions. Looking specifically at the heatwave periodsIn particular, the missing data do not allow for does not permit a systematic analysis of the response of the three basins to either the early heatwave in June 2022 (June 15th to 19th) and the July 2022 one(July 11th to 25th) heatwave. However, the response of the July 2022 heatwave is conceivable for BB and for NWM . Finally, only the BB and NWM areas. Only the response to the August 2022 heatwave is feasible for the all three basins. This is the reason why Therefore, the analysis of the Despite this lack of dataDespite this limitation, it is still possible to have an overview of the exceptional summer 2022 that affected these basins. It can be seen from of 2022. As seen in Table ?? and Figure ??that, all three basins have undergone experienced a range of warmer than average SSTs warmer than average SSTs, with the strongest response from the NWM

- 320 basin seen in the NWM area (mean daily anomaly of 2.6 C and maximum of 4.3C). More remarkable is there are not only one day, Notably, there were no days at the basin scale, where the temperatures are where temperatures were within the normal temperatures range or below. The summer of 2022 also a record for this basin with an average temperature of 26.1 C. Over the period of 1982-2011, the previous record dated back to 2003 with 25.6 C. Furthermore, the response of the NWM basin is clear with an increase of the average SSTs of 2.7C between the 6th of July and the 20th of July (among these July 6th and July
- 325 20th (during which the basin experienced 12 continuous days with an average anomaly over 3C) and of 1.4C between the 31th of July and the 11th of August (among these July 31st and August 11th (during which the basin experienced 9 continuous days with an average anomaly over 3CC during). The ocean surfaces are). Based on the available data, they were no days where SSTs were close or below the climatology on the EC and BB regions. 1.4C and 1.3C for EC and BB respectively, these regions experienced a warmer than usual summer. The BB basin showed a less pronounced response to the August heatwave, resulting

330 in a comparatively lower magnitude of warming.

Nonetheless, the surface ocean of all three regions was therefore anomalously warm throughout the summer. This is also highlighted by the variability which was kept, presented in the Table ??, which is comprised between 31% and 46% of the mean SST anomaly for a standard deviation between 0.5C and 0.8C revealing that, with . With the exception of specific episodes, SSTs remain in the same order of magnitude and stay close to the climatological maximum .One can say less about the daily

335 variability of the SSTs as this is dependent on the data availability. However, the response of the NWM on a daily timescale is evident during both July and August heatwaves of the period 1982-2011 (Figure??). In addition, it is noteworthy that the NWM experienced 22 days, EC experienced 19 days, and BB experienced 4 days of SSTs exceeding the climatological maximum. It should be noted that the previous temperature record in the NWM dated back to 2003, underscoring the historical significance of the observed response.

340

4.2 Response to the **2022** August **2022** heatwave

This section is focusing-

<u>This section focuses on the August heatwave 2022 heatwave</u>, as it is less affected by the low data availability and all three basins can be analysed. The August analyzed. The heatwave started on 31 July 2022-July 31st and ended on 13 August 2022.

345 <u>August 13th.</u> During this period, SSTs were abnormally highwith temperatures constantly, with temperatures consistently above the climatological norm (Table mean (as shown in Figure ??). The table Table ?? presents the spatial average and the maximum value for both SSTs and SSTs and their anomalies for each basin during the August 2022 heatwave. The mean SSTs by basin average (standard deviation inside the brackets(with temporal standard deviation in parentheses) over this period were respectively 18.718.5C (0.570.5C), 21.421.5C (0.480.5C), and 27.6C (0.460.4C) for the EC, BB and NWM while the

- 350 maximum SSTs on average were respectively 19.4the BB and the NWM basins, respectively. The maximum spatially averaged SSTs were 19.2C, 22.2Cand 28.4, and 28.0C. This is reflected by warmer than the average surface water, respectively. These results indicate warmer than average surface waters compared to the 1982-2011 period. As a matter of fact, 1982–2011 period. In fact, the mean SST anomalies were respectively 1.71.5C (EC), 1.2C (BB), and 3.1C (NWM).
- Positive temperature anomalies were found throughout the majority of the ocean surface and the trend of increase is spatially this anomaly was spatially relatively uniform (Figure??). 98% of the EC and 90% of the BB extent endured experienced warmer than average SSTs, while 100% of the North-western Mediterranean sea NWM area was warmer than the climatology during this event. Looking at individual value within each basin is also representative of Few coastal areas, mainly located on the west and south coast of Brittany and continuing along the north part of the Atlantic French coasts, experienced colder than average SSTs.
- 360 We investigated the local response of such phenomenon. For example, the maximum temperature reached to the marine heatwave in each basin by calculating the 1982-2011 daily climatology for every single point within each region. Our analysis revealed that the maximum recorded temperature was 30.8C on August 4th in the NWM basin on the 4th of August 2022. area, 23.6C on August 12th in the EC area, and 26.4C on August 11th in the BB area. In terms of anomalies, the minimal anomaly measured in the NWM during the event was NWM basin exhibited the minimal anomaly of 2.2C and the maximum one of a
- 365 whereas the EC and BB basins exhibited negative anomalies of -1.5C and -2.1C, respectively. The maximum anomalies were 7.9C - This reveals in NWM, 3C in EC, and 3C in BB, indicating the extensive response of the basin but also NWM basin and the range of SSTs variability sea surface temperature (SST) variability within and between each basin. The stronger SST variability in both BB and EC regions was notable.
- 370 <u>As mentioned in the section As previously mentioned in Section ??</u>, SSTs were already abnormally warm before the August event1st to August 13th heatwave. In order to identify the unique contribution of the heatwaveand prevent from any bias, the anomalies were debiased, the weekly variation of the anomalies were computed by subtracting the anomalies of the previous

Table 2. Nighttime SST analysis over the $\frac{01}{1000}$ June 1 st to $\frac{31}{2000}$ August 31 st 2022 period. Mean values hereafter refers refer to spatially averaged data. Maximum represents the highest daily spatially averaged value over the 2022 meteorological summer.

| | | SST | | | | Anomaly | |
|-------------|----------------------|-----------------------|-------------------------|---------------------|------------|-----------------------------|--------------|
| Sub-regions | Mean SST- | Max. SST - | Standard Std. deviation | Max. anomaly Mean | Max. | Mean anomaly_Std. deviation | Anomaly star |
| | (C) | (C) | (C) | (C) | (C) | (C) | |
| EC | 17.6 | 18.7 | 1.6 | 2.2 -1.4 | 2.2 | 0.5 | |
| BB | 20.3 | 21.8 | 1.1 | 2.4 1.3 | 2.4 | 0.6 | |
| NWM | 26.1 | 28.3 | 1.9 | 4.3 -2.6 | <u>4.3</u> | 0.8 | |

week (Figure ?????e and f). The bias-corrected anomalies anomalies variations show that the impact was pronounced in the English Channel EC, with an increase of 70% of the mean anomaly in a week (0.7C) while the Mediterranean basin, while the

375 <u>NWM area saw</u> a weaker response of only 15% (0.4C). The BC BB basin responded firstly by a warming of the SSTs, then a sharp decline of 1.4C between the August 3rd and the August 5thof August. The SSTs stayed steady until the remained steady until August 9th of August before starting to increase again. This impacted the response of the BB, with an increase of only 20% (0.2°C) compared to the previous week -

Response of the SSTs to the 31 July 2022 - 13 August 2022 heatwave: a) Mean SST anomaly, b) Maximum SST anomaly,
 380 c) Mean SST values and d) Maximum SST values. Anomalies are relative to the 1982-2011 average.

4.3 Observed variability of the atmospheric variables

4.4 Contribution of atmospheric/oceanic variables

In this sectionIn accordance with the previous analysis, the contribution of atmospheric and oceanic variables to the peristence persistence of abnormal sea surface temperature is analysed -only during the heatwave that occurred in August 2022. As

- 385 presented in the section Section ??, the atmospheric variables are derived from the ERA5 reanalysis. The heat wave in August 2022 occurred in an atmosphere that was already excessively energetic with a solar radiation anomaly stronger than the August 1991-2020 elimatology(As presented in Section ?? and ??, signature of atmospheric heatwaves can be found in atmospheric variables such as the surface air temperature and the mean sea level pressure. In addition, other atmospheric variables have the potential to enhance a situation that is already warmer than the climatology. As presented in
- 390 the Figure ??a).-, we looked, in the first place, at conditions of the surface solar radiation, windspeed and total cloud cover during the heatwave that occurred in August 2022. Apart from the extreme South East southeast of France, most of the area experienced mean anomalies over positive mean surface solar radiation anomalies exceeding 50 W.m⁻² (reaching 85 W.m⁻² in South southern Brittany). This anomaly The daily anomaly during the period of the heatwave is significantly correlated with the to the anomaly of SSTs in the NWM area with a Spearman coefficient of 0.8. These spatial mean anomalies are significantly
- 395 correlated with negative total cloud cover anomaly (anomalies (Figure??c, Pearson correlation coefficient of 0.90). The mean

Table 3. Nighttime average SST analysis over the July 31th - August 13th 2022 period. Mean values hereafter refers to spatially averaged data. Maximum represents the highest daily spatially averaged value over the time period. Weekly variation corresponds to the difference between the mean anomaly calculated during the August 2022 heatwave and the one calculated during the week before

| Sub-regions | $\underbrace{\text{Mean SST}}_{(\sigma)}$ | Mean SST anomaly | Max. anomaly | Max. SST | Weekly variation SST anomaly |
|-------------|---|------------------|--------------|--------------|------------------------------|
| | (°C) | (°C) | (°C) | (°C)_ | $(^{\circ}C)$ |
| EC | 18.5 (0.5) | 1.5 | 2.1 | <u>.19.2</u> | 0.7~ |
| BB | 21.5 (0.5) | 1.2 | 2.0 | 22.2 | 0.2 |
| NWM | 27.6 (0.4) | 3.1 | 3.6 | 28.0 | 0.4 |

anomaly over the whole domain total cloud cover anomaly over France reaches -17% while the North of France and specifically Brittany have undergone the maximum average anomaly of -37%.

As for Regarding the mean wind speed, two zones stand out (Figure ??b). On the one hand, the BB zone experienced stronger surface wind speed on its basin (with a maximum average anomaly of 1.9 m.s^{-1} during the heatwave events) compared to

- 400 the August 1991-2020 average. In addition to this, the average direction of the episode was oriented in a north-easterly flow, which accentuated both the mixing and thus the upwelling phenomenon on the coast. This mixing with colder deep waters accentuates accentuated the cooling of the surface waters (-1 C between on the August 12th and the 19th), which may explain the drop in SST in the basin from 10-11 Julythis area from August 10th to 11th (Figure??c) and the cold signal along the coast during the heatwave (Figure??).
- 405 On the other hand, the Gulf of Lions experienced a negative surface wind speed anomaly (with a minimum average anomaly of -3.7 m.s^{-1} during the heatwave events) due to a significant absence of the Mistral, oriented in a north flow, and Tramontane, oriented in a north-westerly flow, which are the main drivers of the Mediterranean turbulent mixing in the Gulf of Lions. In addition to the lack of turbulent mixing, the absence of wind results could lead to a reduced contribution of turbulent latent energy flux as an ocean energy sinks. The daily anomaly over the period of the heatwave is correlated to the anomaly of SSTs
- 410 in the NWM area with a Spearman coefficient of 0.6. The absence of wind could not explain in return the variability found in the Gulf of Lions. Thus this pattern can be related to the colder Rhone river outflows flowing into the Mediterranean sea. Results for the EC are more complex to interpret because of the dynamical response to the horizontal advection initiated by the tides. From the 10th-11th of August August 10th to 11th, the EC has been subject to high spring tides which initiated a effective turbulent mixing, thus a decrease in the SSTs.

415 4.4 Drivers of the 2022 SSTs response

5 Discussion/Conclusions

In this study, we investigated the response of sea surface temperatures to-

4.0.1 Summer 2022 air-sea interactions

The previous section showed a significant relationship between several atmospheric variables and the SST response. In the

420 upcoming section, the study aims at gaining a deeper understanding of the links between atmospheric variables and SSTs. The mechanisms behind the unusual warming of the SSTs are investigated using a mixed layer heat budget approach, as described in Section ??. The analysis is focused on the contribution of air-sea fluxes to the SST changes, with other terms deduced as a residual (see Eq.??).

As illustrated in Figure ??a, Figure ??a and Figure ??a, a control experiment (CTL) was performed to evaluate the influence

425 of air-sea fluxes on the mixed layer heat flux during the summer of 2022. The results indicate a significant contribution of atmospheric forcing to daily variability of heat flux in all three areas. Notably, the NWM exhibits the clearest response, with heatwave periods characterized by consistently high fluxes and in-between periods exhibiting stronger variability (mean

standard deviation is 14.5 $W.m^{-2}$ during heatwaves whereas it becomes 49.1 $W.m^{-2}$ outside). Specifically, the mean net heat flux was 156.7 $W.m^{-2}$ during heatwaves while the mean value over the summer is 125 $W.m^{-2}$. This pattern is repeatedly

- 430 observed throughout the summer, highlighting the significant contribution of atmospheric forcing. The results for EC and BB show more variability, with the net heat flux exhibiting stronger daily fluctuations. Nevertheless, the end of heatwave periods is consistently marked by a drop in air-sea fluxes, while the heatwave periods are associated with a local maximum in net fluxes. A comparison of the net air-sea heat flux anomaly to a reconstruction based on the daily 1991-2020 climatology of surface atmospheric parameters (CLIM simulations) reveals abnormally positive values during the three heatwaves in the EC and NWM
- (Figure ??b and Figure ??b). In the BB, the stronger daily variability is associated with few days with negative anomalies during heatwaves (Figure ??b). Over the summer months of 2022, the mean anomaly was 52 W.m⁻² in EC, 47 W.m⁻² in BB and 125 W.m⁻² in NWM. The net heat flux anomaly reached its highest value during heatwave periods, with a mean of 158 W.m⁻², 86 W.m⁻², and 74 W.m⁻² over the anomalous warm summer three heatwaves in NWM, EC, and BB, respectively.
- These findings underscore the crucial role of air-sea fluxes in heatwaves, and suggest that both increased atmospheric forcing
 and decreased cooling contributed to the anomalous mixed layer warming. Indeed, a systematic drop in the net heat budget is
 observed after each heatwave, with a rise before the start of the heatwave, emphasizing previous results.
 Overall, the results demonstrate the significant impact of atmospheric forcing on mixed layer heat flux during the summer of

2022over France using the OSI SAF satellite SST products. Accuracy of such products had been proved to be sufficient in an operational framework (?). We also assessed whether some of the main components influencing the ocean energy balance could

- 445 explain these anomalies (Equation ??). To our knowledge, this is one of the first study to examine the thermal response using only near-real time products at a country scale and by integrating sub-basins with distinct characteristics (English Channel, Bay of Biscaye and North-Western Mediterranean Sea). In comparison, ? studied the contribution of , and provide insight into the complex dynamics of air-sea interactions during heatwaves.
- This dynamic of the atmospheric fluxes has an impact on the average mixed layer temperature evolution (term E in Eq.??) as illustrated in the Figure ??c, Figure ??c and Figure ??c. In each of the areas, the air-sea flux-induced mixed layer temperature trend exhibited a continuous warming trend, resulting in a tendency of 0.12 C.day⁻¹ for EC, 0.23 C.day⁻¹ for BB and 0.16C.day⁻¹ for NWM over the summer period. By comparison, the observed SST trend (left-hand side term in Eq.??) was estimated to be 0.07 C.day⁻¹ for EC, 0.04 C.day⁻¹ for BB and 0.08C.day⁻¹ for NWM. The difference between these two terms represents the residual term, "Res", in Eq.??. Here this term is negative, indicating that ocean processes tend to cool
- the upper ocean. The mixed layer temperatures in the EC and BB areas were strongly influenced by residual term (the sum of all dynamic and diffusive terms), with a stronger contribution over longer periods, likely due to stronger cooling processes such as vertical mixing. The trends observed during the heatwaves provide valuable insights into the complex dynamics of different regions. For example, between July 12th and July 25th (July heatwave), the mixed layer temperature trend was weakly
- 460 positive for EC (0.04 C.day⁻¹) and even negative for BB (-0.01 C.day⁻¹). In contrast, during heatwave periods over NWM, the residual term remained relatively constant, while the mixed layer temperature trend slightly increased, demonstrating the significant role of surface fluxes in driving the warming. For instance, in the NWM, between July 12th and July 25th (July

heatwave), the air-sea flux contribution reached 0.18C.day⁻¹, and between July 31th and August 13th (August heatwave), it was 0.19C.day⁻¹, compared to a trend of only 0.07C.day⁻¹ between these two heatwaves. Thereby the air-sea fluxes implied a

465 clear warming trend suggesting the non-negligible contribution of ocean cooling processes to compensate for the atmospheric forcing and preventing SSTs from reaching record-breaking levels for longer periods. Almost invariably, the end of heatwave periods is associated with a cooling residual, suggesting a termination of events through vertical oceanic mixing while the air-sea flux budget becomes less effective.

470 4.0.2 Disentangling atmospheric variables contributions

To gain a deeper understanding of the processes contributing to the mixed layer temperature increase, we examined the contribution of atmospheric fields to the daily net air-sea heat flux (illustrated in Figure ??b, Figure ??b and Figure ??b and the associated air-sea mixed layer temperature trend (illustrated in Figure ??d, Figure ??d and Figure ??d in comparison to a reconstruction based on the daily 1991-2020 climatology of surface atmospheric parameters.

- 475 The sensitivity test results, displayed in Figures ??(c,d) and ??(c,d) reveals that the anomalous net air-sea flux in the EC and BB can be attributed mainly to the near-surface air temperature, the surface solar radiation and the near-surface specific humidity. In both basins, the 2003 heatwave on the Mediterranean sea SSTs using both satellite observations and a 3-D ocean model which needs computation costs that are limited and can be incompatible with the operational framework of monitoring SSTs. ? used a mix of SST satellite, Argo floats and cruise data to assess the Aretic sea ice decrease and warming SSTin response
- 480 to an atmospheric blocking episode. Although, most of the related studies investigated the warmer than average SST feedback on atmospheric temperatures (??) or assess the occurrence of marine heatwaves(??)radiative budget dominates the heat budget along with the contribution from surface air temperature. Specifically, in EC, SSR accounts for 39% of the total mixed layer temperature trend anomaly, while surface air temperature and specific humidity contribute 31% and 21%, respectively. In BB, surface air temperature is the largest contributor at 38%, followed closely by RSS at 35%, and specific humidity at 31%. These
- findings highlight the critical role of the radiative fluxes in shaping the heat budget and temperature trends in these regions. Our observations align with the positive anomalies in surface solar radiations recorded in both areas (Figure ??b). The contribution of specific humidity in the BB heat budget is explained by the moistening of the air mass during the advection of hot air masses from the northeast. Wind speed also plays a similar role in decreasing the net air-sea flux at the end of each heatwave in both EC and BB. However, the wind speed contribution to EC net air-sea flux is relatively low in the termination of heatwaves. In
- 490 contrast with EC, wind speed is a key factor in limiting the response of the SSTs in BB during heatwaves. For instance, the drop in the net air-sea flux anomalies during the heatwave of August is mainly attributed to an anomaly of wind speed that enhanced the turbulent fluxes and thus the heat loss. This results confirmed the effect of the positive wind speed anomaly in BB (Figure ??a) which increase the coastal upwellings and reduce the specific humidity contribution (north-easterly advection of continental air masses) As an example, both June and August heatwave endings are attributed to the negative anomaly of
- 495 the surface solar radiation in EC. The sensitivity test results, displayed in Figures ??b and ??d indicate that the anomalous net air-sea flux in the NWM can

be attributed mainly to the near-surface specific humidity, the near-surface air temperature and the near-surface wind speed anomalies. The specific humidity accounts for 43%, surface air temperature explains 33%, and wind accounts for 21% of the total mixed layer temperature trend anomaly. These three atmospheric variables have a significant impact on turbulent fluxes,

- 500 with the latent heat fluxes showing a stronger response (Figure ??). The effect of wind speed (WND) is twofold, it impacts the atmospheric heat fluxes but it also impacts the transfer of momentum to the ocean and therefore the ocean processes. Over the NWM in August, wind speed is weaker than normal and drives a reduced latent heat flux which tends to warm the ocean. We have not estimated its effect on momentum and ocean dynamics but a reduced wind speed in the region is most probably associated to reduced ocean surface cooling by mixing. This is consistent with Figure ?? that shows a negative correlation
- 505 between wind speed and SST. Conversely, wind speed was the main contributor (reaching a contribution of 63% on August 18th) to the drop in the net air-sea flux at the end of each heatwave, while 2-m air temperature (T2M) and 2-m specific humidity (HUS) have little effect. Wind speed may also contribute to the negative heat trend seen in the residual term at the end of heatwaves, likely linked to wind-driven turbulent vertical mixing and entrainment. Surface air temperature and specific humidity are closely linked to the synoptic conditions in this specific regions. As detailed in Section **??**, the observed increase
- 510 in specific humidity can be attributed to the moistening of the air mass linked to its southerly advection over a maritime region. Upon reaching the study area, the air mass was abnormally hot and humid, which in turn contributed to the air-sea flux forcing. The results demonstrate that while the record-breaking surface air temperature has a major impact on the area, the contributions of surface humidity and wind speed should not be underestimated. Contrary to the EC and BB areas, the contribution of the surface solar radiation is relatively low but to the overall net air-sea flux is consistent with the non significant anomaly of RSS
- 515 observed over the area in August (Figure ??b). Thereby, the surface solar radiation did not act as a key contributor to the SSTs response in NWM during heatwaves.

Despite a

5 Discussion & Conclusions

- 520 Using OSI SAF satellite products and an ocean mixed layer bulk model, we investigated the response of SSTs to the heatwaves that occurred during the summer of 2022 and the extent to which they could be attributed to changes in atmospheric variables. This is the first study to provide insights into the ocean thermal response to the exceptional summer of 2022 at a country scale, integrating sub-areas with distinct characteristics, including the English Channel (EC), Bay of Biscay (BB), and Northwestern Mediterranean (NWM) Sea.
- 525 Despite the significant lack of data, especially in particularly in the early summer and for in the EC area, we found a distinct clear warming signal of the SST in response to the atmospheric heatwaves that affected France during the SSTs during the summer of 2022 summerthat was evident in all studied areas. All three areas exhibited positive SST anomalies throughout the summer, with record-breaking daily anomalies indicating that 2022 was one of the warmest summers in terms of SSTs, which also started early in the season. The strongest response was found on the NWMbasin (with a maximum average in the NWM,

- 530 with a seasonal SST anomaly of 4.32.6 C, reaching 3.9 C during the heatwave that occurred in August and exceeding the climatological maximum for 22 summer days. It should be noted that the climatology takes into account summer 2003, which may be a record for SSTs in the NWM. Locally, these SSTs were even higher, with a peak measured at 30.8 C. A similar pattern is found for the EC area, which was consistently close to the daily climatological records, reaching a maximum anomaly of 2.2 C in August and 19 days over the climatological maximum, with a mean summer anomaly of 1.5 C. The response of the
- 535 BB area is lower in magnitude, even if the mean SST anomaly is 1.2° C) which is in line with observations (?) and modeled evolution (?) confirming-C and reaches a peak of 2.4 C, with only 4 days above the climatological maximum. This study demonstrates that the summer of 2022 was one of the warmest summers in terms of SSTs. In the specific case of NWM, this mark a record over the period 1982-2011 with a mean temperature of 26.1 C. The response of SSTs in the Mediterranean Sea is has been extensively studied and our results over this area are in line with previous studies investigating the contribution
- 540 of heatwaves to Mediterranean SSTs, such as the 2003 heatwave studied by ?. Focusing on the Central Mediterranean Sea, they found similar magnitudes in the SST warming with mean anomalies around 2C. The Mediterranean Sea is recognized as a "hotspot" for climate change (?)-, which will face warmer summer seasons (?). Our findings support the idea that the occurrence of heatwaves throughout the summer would cause the NWM Sea to respond strongly to these atmospheric forcings. Indeed, results indicate that even during non-heatwave periods, the SSTs in the NWM area were consistently warmer than
- 545 the climatological average, even when the net heat flux was close to normal. These results are also in line with the with observations (?) and modeled evolution (?) of the continuous warming of the Mediterranean Sea. Regarding EC and BB, this study contributes to the limited body of research on the responses of these areas to external factors. Our results align with previous studies that have emphasized the significant role of regional hydrodynamics in shaping SSTs (?)
 Atmospheric blockages have been shown to influence the multi-decadal variability of the North Atlantic (?). Here, we show
- that , in addition to atmospheric blockages, more dynamic phenomena, such as heatwaves initiated by cold drops off the Iberian Peninsula resulting from a static meander of the jet stream ("omega" atmospheric blocking system), can contribute to the variability of SST. Thus, in situations when there is an excess of solar radiation and a lack of cloud coverage, the increase in SSTs is modulated by regional effects such as wind anomalies that drive the turbulent mixing of surface waters. In such situation, a thermal stratification occurs, making impossible any exchange with the colder deep waters. This effect is
- 555 clearly visible as the Mediterranean is not subject to tides, unlike the English Channel where tides impact the The warming of upper layer ocean temperatures during summer is mainly driven by the occurrence of atmospheric blocking related to the multi-decadal variability of the North Atlantic (?). This implies that atmospheric forcings are a key contributor to the mixed layer heat budget in most ocean areas (??). Such events, which are characterized by an atmospheric blocking system associated with above-climatology surface air temperature and low surface wind speed, result in a warming of SSTs between 2°C and 4°C.
- 560 that is the range we found for the SSTs as seen in the Ushant Front (??). In such areas, the possibilities of mixing is limited and the SST warming is enhanced. However, some driving factors of anomalies during the summer of 2022. The associated fluxes are key indicators of the upper-ocean heat budget such as ocean's rapid response to extreme atmospheric conditions. Our findings suggest that the response of SSTs varies significantly between different ocean basins and is closely linked to the specific environmental characteristics of each region. While all areas respond strongly to record-breaking temperatures, the

- 565 turbulent heat flux, the vertical advection or the surface currents were not analysed in this study. A model analysis integrating the various possible drivers influencing the upper-ocean heat budgetwould help to prove the causality and found any other process or covariance that might influence the SSTs tendency. We found that SSTs responded to extensive and persistant heatwaves in July and August, however the response to shorter events like the one in June could not be studied.
- Developing such operational framework to measure daily SSTs might have several implications for monitoring essential oceanic variables and for ensuring a sustainable oceanic environment. Among them monitoring marine heatwaves(MHWs) and investigating their occurrence and impacts is one of the most straightforward outcomes of studying SSTs variability (?). These events have doubled in the last 30 years and are projected to increase both in term of frequency and intensity in the future (?). As seen in this study for summer 2022, MHWs are recurrent in the Mediterranean Sea (18 days in July advection of hot and humid air masses is the primary driver of SSTs in the NWM area, whereas areas such as EC and BB are more reactive to the variability
- 575 of surface solar radiation. In turn, the role of wind on air-sea heat fluxes is variable between basins and generally second-order. The increase of SSTs over NWM during the summer of 2022 and 12 days in August 2022 with can be attributed mainly to an increase in surface air temperature and specific humidity, and a decrease in wind speed, which reduced the effectiveness of turbulent heat fluxes as an ocean heat sink. Compared to a control experiment where all atmospheric variables are set to their 1991-2020 climatological values, the (positive) radiative heat fluxes increased slightly over the course of the summer, while the
- 580 (negative) turbulent heat fluxes reached minimum values during heatwave periods. For the EC and BB areas, the contribution to the warming of SSTs is dominated by surface air temperature and surface solar radiation, which in turn confer a stronger role to the radiative fluxes in the mixed layer heat budget. This is explained by the greater interannual variability of solar radiation in summer over these basins, whereas for NWM, radiation is close to its maximum value every summer. It should be noted that the contribution of specific humidity is not negligible and can be explained by the wind direction, which initiated
- 585 moistening of the air masses over these areas. As shown for the NWM area, the patterns of the different flux terms in BB and EC are similar, with negative anomalies of turbulent fluxes and positive anomalies of radiative fluxes during heatwave periods, while the opposite occurs in between. The observed pattern triggers a marked increase in positive anomalies of the MLD heat budget during heatwaves. Notably, our findings reveal that the MLD heat budget is unusually high in cases where turbulent heat fluxes fail to act as heat sinks, while radiative fluxes enhance atmospheric forcings. In addition, the pattern of SSTs elose
- 590 or over the maximum elimatology) in recent years and it remains one of the main impacted area with projected MHWs that will be 4 times more intense and 42 times more severe than current events (?)response is modulated by the residual terms which are reduced by atmospheric forcing during heatwaves. These terms are linked to oceanic cooling mechanisms such as vertical mixing. The observed trend of temperature extreme events highlights the crucial role of air-sea fluxes in the formation of record-breaking SSTs, with residual terms emerging as the dominant contributors by the end of each heatwave period. These
- 595 findings indicate that rapid warming of SSTs occurred during the summer months due to an imbalance in surface heat fluxes, which were intensified by specific atmospheric heatwave conditions and modulated by regional processes accounted for in the residual terms.

These trends are not consequence-free. They drive fundamental, irreversible modification of marine ecosystems and all the

ecosystem services provided to society (??). More generally, SSTs variability impactsbiological variables such as Chlorophyll-a,

600 main tracer of primary productivity (??). As such, extreme MHWs events like the "Blob" in-

Our results are consistent with the atmospheric circulation patterns observed during heatwaves. During the summer of 2022, atmospheric blocking occurred simultaneously with a southerly advection initiated by cold drops off the Iberian Peninsula, resulting from a static meander of the North-Eastern Pacific in 2013-2015 have had disastrous consequences on the fauna and flora of the ocean, but also on the ocean primary productivity (?). Daily monitoring of SSTs, as proxy, would, thus, be crucial

- 605 to understand and forecast changes in biological responses at regional and global scale (?). Among them the detection of harmful algal blooms that might endangered several coastal zone, shifts in community organisation (from temperate to tropical species) and prevention in mass mortalities of endemic species (??) jet stream, which enhanced the heatwaves that contributed to record-breaking SSTs. These high-pressure systems also have regional-scale impacts, such as modulating surface wind speed. Even though wind speed is not the main driver in all the areas in our study, negative anomalies in wind speed (and
- 610 corresponding latent heat negative anomalies) are correlated with the initiation, while positive anomalies are correlated with the cessation of marine heatwaves (?). In the presence of negative wind anomalies, the turbulent mixing of surface waters becomes less efficient and could result in thermal stratification that would limit exchanges with colder subsurface waters. This effect might be particularly pronounced in areas such as the Mediterranean, where tides are almost absent, as opposed to the EC, where tides influence SSTs, as demonstrated at the Ushant Front (??). The pattern of the radiative fluxes can be explained
- 615 by the atmospheric subsidence, which tends to lower relative humidity, reduce total cloud cover, and warm the surface air temperature. Besides the subsidence, the southerly advection, linked to the Iberian cut-off low, over the warm Mediterranean Sea enhanced the moistening of the air mass and increase the specific humidity thus the turbulent heat fluxes. The magnitude of anomalies can also be attributed to anthropogenic forcing, which can be quantified using singular event detection and attribution cutting-edge approaches (??).

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The main limitations of such approach is its sensitivity approach proposed in this study is sensitive to missing data due mainly to caused by cloud cover or atmospheric dust aerosols. To prevent anticipate the detection of anomalously warm SSTs, we could have used some combined products such as OSTIA (?) which produce Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) (?). However, interpolated gap-free global SST data - However these data are generally interpolated and thus products might end up hiding some specific trends or introducing biases in the SSTs-SST analysis (?). A possible way of improvements would improvement could be to combine these satellite observations to specific-model developed satellite observations with a specific model, such as the one developed by ?, to detect large-scale anomalously warm SSTsbased on the approach of ?. Currently, the detection model is unidimensionaland developments , and development of a simple dynamical two-dimensional model would helps to help track water temperature anomalies in the upper-ocean layer and to

630 understand temperatures feedbacks-understand temperature feedback within the mixed layer. More generally, development activities must pursue continue with the implementation of more advanced models capable of assimilating these observations and integrate dedicated physical /biogeochemical processes will accentuate both the precision and the reliability of this monitoring incorporating physical and biogeochemical processes, which will increase the accuracy and reliability of monitoring SSTs. This will provide a more general view of the processes and feedbacks involved, but also access to the responses of the surface layer

635 of the ocean where there is a systematic gap in observations. Daily monitoring of SSTs will be crucial for understanding and forecasting changes in biological responses at regional and global scales (?), including the detection of harmful algal blooms that might endanger several coastal zones, shifts in community organization, and prevention of mass mortalities of endemic species (??).

One of the levers for improvement should also come from an evolution of observation techniquesImproving observation

- 640 techniques will also play a role in enhancing SST monitoring. In this study, only data from the polar-orbiting satellite Metop-B were used. It will be judicious to use a consistent synergy between polar orbiting satellites Synergies between polar-orbiting and geostationary satellites in order to obtain will provide a significant gain for the monitoring of SSTs (??). Indeed, geostationary satellites , because of their SST monitoring (??), as polar-orbiting satellites have high spatial resolution but limited temporal resolution, ensure a systematic monitoring of surfaces but are limited in their contribution by their while geostationary satellites
- 645 <u>have high temporal resolution but limited</u> spatial resolution. Also, the The new generation of meteorological satellites with, such as Meteosat Third Generation and Metop-SGwill ensure a more precise monitoring in, will offer improved monitoring in both time and space with interesting nominal resolutions to locate systems with smaller characteristic lengths while being able to monitor larger scale systems with ideal temporal resolutions for operational purposes (?). This study focused on the 2022 meteorological summer which should not hide the fact that the meteorological situation in France is still abnormal with
- 650 continuous surface air temperature over long-term average. This situation have major implications on the Mediterranean Sea and a more systematic study of the response of the whole Mediterranean basin, including September, would help to assess the implications of persisting atmospheric heatwaves. All this confirms highlights the need to work on SST operational products such as the one operational SST products, such as those developed within the OSI SAF project, and to contribute to new products, such as ocean colorin the view of application frameworks linked to the, in the fields of biogeochemistry and physicsand
- 55 to prevent deep alterations that threaten to the oceans in the context of climate change.

Furthermore, in this study, we strictly analysed the atmospheric contribution. Here the aim of the study was to disentangle the respective roles of surface atmospheric variables in explaining the SST anomalies in a forced ocean context. However, we can speculate on the link between forcing and dynamic ocean processes. For example, the net heat budget variability is
driven by wind speed outside of heatwave periods associated with a decrease in SST anomalies. Therefore, we can hypothesise about its impact on cooling terms (referred to as residuals in the study) and the non-negligible role of other drivers, including turbulent vertical mixing and entrainment, vertical and horizontal advection by regional current systems, in the upper-ocean heat budget. Nonetheless, we did not assess how these atmospheric forcings could propagate inside the ocean and what would be the feedback from SSTs themselves. The mixed layer depth used has a lower bound of 10m, which might conceal important features that could explain the higher warming trend in mixed layer temperature in response to short-term atmospheric forcing ucriphility (2). For this purpose, we would need to have access to long term measurement means conclude of conturing processes.

variability (?). For this purpose, we would need to have access to long-term measurement means capable of capturing processes occurring below the surface in addition to complex unidimensional and 3D ocean models capable of representing turbulent mixing, entrainment, and complex features such as upwellings. The study did not quantify this impact and further development would be necessary to assess how much the turbulent and the advective oceanic heat fluxes have been lowered during the

670 summer of 2022. Although a comprehensive understanding of the mechanism between the atmosphere and the ocean can be gained with a coupled model analysis. Hence, a comprehensive model analysis constrained by subsurface observations is needed to integrate the various drivers influencing the upper-ocean heat budget.

This study provides insights into the response of SSTs during the 2022 meteorological summer and the link with synoptic conditions in France. However, it should be acknowledged that the abnormal meteorological situation persisted throughout most of the autumn season in France, with surface air temperatures continuously above long-term averages. Furthermore, a systematic study of the different areas, including additional months, could help assess the implications of persistent atmospheric heatwaves and their regional dependence.

680 *Code and data availability.* All post-processing codes are available on Zenodo in the following repository: https://10.5281/zenodo.7194099 (?).

Data used in this study are open-source and freely available. OSI SAF L3b can be found here: https://osi-saf.eumetsat.int/products/osi-201-b. ERA5 reanalysis can be found here: https://cds.climate.copernicus.eu/. ESA-CCI SST product can be found here: https://catalogue.ceda.ac. uk/uuid/62c0f97b1eac4e0197a674870afe1ee6. All these data were accessible on the date of the manuscript submission.



Figure 3. Time series of the summer 2022 daily SSTs measured by METOP-B spatially averaged over the sub-basin: a) the English Channel (EC), b) the Bay of Biscay (BB) and c) the northwestern Mediterranean (NWM). Atmospheric heatwave periods are represented with yellow shading. Brown line is representative of the 3-day SST moving average and compared to the 1982-2011 ESA-CCI climatological mean (black line).



Figure 4. Observed SSTs and anomalies fields. (a) Mean SST values, (b) Maximum SST values, (c) Mean SST anomalies and (d) Maximum SST anomalies during the July 31th 2022 - August 13th 2022 heatwave:. (e) Mean SST anomalies and (f) during the period from July 23th to July 30th. Anomalies are relative to the corresponding 1982-2011 monthly climatology. Areas of interest used in the study. The English Channel (EC), the Bay of Biscaye (BB) and the North-western Mediterranean Sea (NWM) used in to analyse SST pattern throughout the 2022 meteorological summer are plotted on the subplot (a).

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Figure 5. Same as figure ?? for Atmospheric variables conditions during the August 2022 heatwave; a) surface solar radiation anomaly, b) 10-m wind speed anomaly and c) mean total cloud cover anomaly over France. Anomalies are compared to the same period 23th - 30th July in the 1991-2020 climatology. Data originates from the ERA5 reanalysis.



Figure 6. Atmospheric variables conditions during Daily EC mixed layer heat budget and air-sea flux sensitivity tests for the August summer 2022 heatwave; compared to the corresponding 1991-2020 climatology. (a) surface solar radiation anomaly, Simulated net air sea flux for the summer 2022 (b) 10-m wind speed anomaly over FranceObserved SST variations (solid line), contribution of air-sea fluxes to the mixed layer heat budget (dashed line) and residual (dotted line) interpreted as cooling by vertical mixing and entrainment. Anomalies are (b) Sensitivity test of the spatially averaged net surface heat flux anomalies compared to the 1991-2020 climatology CLIM experiment. Data originate from ERA5 reanalysis(c) Same as (b) but time-integrated and expressed as an equivalent mixed layer temperature anomaly. For (b-c), RSS, T2M, WND, HUS and RLS stand for the effects of anomalous incoming solar radiation, 2-m temperature, 10m wind module 2m specific humidity and downward longwave radiation.



Figure 7. Same as the Fig ?? for the Bay of Biscay.



Figure 8. Same as the Fig ?? for the North-Western Mediterranean Sea

685 Appendix A: SST statistics over each studied basin

Appendix A: Supplementary figures

Nighttime average SST analysis over the 31th July - 13th August 2022 period. Mean values hereafter refers to spatially averaged data. Maximum represents the highest daily spatially averaged value over the time period. Sub-regions Mean SST (σ) Mean SST anomaly Max. anomaly Max. SST Bias-corrected SST anomaly ^{*a*}(°C) (°C) (°C) (°C) (°C) (°C) EC 18.7 (0.57) 1.7 2.5 19.4 0.65 BB 21.4 (0.48) 1.2 2.02 22.20.15 NWM 27.6 (0.46) 3.1 3.9 28.4 0.43-

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A1 <u>Heat budget terms sensitivity tests</u>

Appendix B: Upper-ocean energy balance

Several processes are key drivers of the SSTs variability, among them one can mentions horizontal and mixing or net surface heat flux. A mathematical approach of the upper-ocean layer heat budget had been detailed by ? as follows upon the hypothesis
 of the fluid incompressibility and the Boussinesq approximations:

$$\frac{\partial T_m}{\partial t} = \underbrace{-\overline{\mathbf{u}}\nabla T_m}_A + \underbrace{\kappa_h \Delta T_m}_B - \underbrace{\frac{1}{H} \left[\kappa_v \frac{\partial T}{\partial z}\right]_{-h}}_C - \underbrace{\left(\frac{T_m - T_{-h}}{H}\right) \left[\frac{\partial h}{\partial t} + \mathbf{u}_{-h}\nabla h + \omega_{-h}\right]}_D + \underbrace{\frac{q_{rad} + q_{turb}}{\rho_0 c_p H}}_E$$

where T_m , H, ρ_0 and c_p are respectively the mean temperature, the depth, the mean density and the specific heat capacity of the surface mixed layer, **u** is the 2-D horizontal vector and ω is the vertical velocity vector. κ_h and κ_v are respectively the norizontal and vertical diffusivity coefficients. q_{rad} is the net radiative flux and q_{turb} is the net turbulent flux. The mention -hrefers to the bottom of the mixed layer as the vertical axes is oriented in the direction ocean surface to the atmosphere.

This equation helps to understand the contribution of each component. The SST tendency is dependent on the horizontal advection (A), the horizontal (B) and vertical (C) mixing, the entrainment (D) and the ocean-atmopshere interface heat flux (E). One can notice the contribution of the solar shortwave radiation (through component E) and the windspeed (component B and C) on the SSTs evolution.



Figure A1. Decomposition of the net air-sea heat budget over the EC area during the summer 2022 for all sensitivity experiments compared to the CLIM experiment.



Figure A2. Decomposition of the net air-sea heat budget over the BB area during the summer 2022 for all sensitivity experiments compared to the CLIM experiment.



Figure A3. Decomposition of the net air-sea heat budget over the NWM area during the summer 2022 for all sensitivity experiments compared to the CLIM experiment.



Figure A4. Daily mixed layer depth analysis from the CMEMS Mediterranean Forecasting System (Med-Physics).

Author contributions. TG, SS and HR designed the satellite observation study, TG carried the observation analysis out. TG, AV and RB carried the modeling part out. AV produced the forcings dataset and carried out the numerical simulations. TG developed the code and performed the analysis of both observations and modelling outputs. TG wrote the manuscript with contributions from SS, AV and RB. All

710 co-authors took part on discussions and revisions of the manuscript.

Competing interests. The authors declare that they have no conflict of interest

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