means. We also include the regional (spatial) variance, which, together with the mean, gives an estimate of the distribution of values within the region – this may be useful for users concerned about how representative the regional mean is.

There are only a few variables on the NWS that are sampled with complete spatial coverage (SST being the exception). Therefore it is difficult to robustly validate the regional mean product. For sea surface temperature, it is possible to evaluate the regional mean time series with a spatially complete data set, such as the (largely satellite based) OSTIA analysis (Operational Sea-surface Temperature and sea-Ice Analysis; Roberts-Jones et al. 2012), however, as the reanalysis assimilates SST, this is circular. Instead, the regional mean time series are considered descriptors of the behaviour of the NWS reanalysis, rather than describing reality. The NWS reanalysis has been extensively evaluated in the Quality Information Documents (QUID), and given the data assimilation of observations, provides the statistical 'best guess' of the state estimate for the Northwest European Shelf Seas (Tinker et al. 2018). Here we use the relevant parts of the QUID to inform the user of the scale of the model errors and biases that will be propagate into the regional mean time series product.

The reanalysis temperature biases are generally smaller than ±0.5°C at all depths over the shelf. Reanalysis salinity biases are generally of magnitude less than ±0.5 PSU. In the coastal regions of the Southern Bight of the North Sea and around the Norwegian Trench, the reanalysis is typically too fresh, and is typically too saline in the Irish Sea, and further offshore in the Norwegian Trench. These errors are captured within the regional mean time series, and so provide qualitative error bounds of ±0.5°C and ±0.5 PSU for regions on the Northwest European Shelf Seas.

As these regional mean time series have only just been produced they have not been available to end-users, and so no examples of their use can be cited. However, similar Northwest European Shelf Seas regional mean time series and summary statistics have been used in a number of recent studies. Tinker et al. (2018) used regional mean time series of the previous NWS reanalysis, calculated on the Wakelin et al. (2012) regions (Figure 3.5.1(B)) to investigate seasonal predictability on the Northwest European Shelf. Tinker et al. (2015, 2016) used regional mean time series calculated from their Northwest European Shelf Seas climate projection to aid model evaluation, and to summarise their findings. The CMEMS Northwest European Shelf Seas regional mean time series product

will be released by Autumn 2019, and will include surface and bed (and surface-minus-bed) temperature and salinity, for the regional mean and its associated spatial variance. Once the new regional mean time series (introduced here) are released, work will continue to help raise awareness with MCCIP partners, and other policy users.

## 3.6. Using CMEMS and the Mediterranean Marine Protected Areas sentinel network to track ocean warming effects in coastal areas

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**Statement of main outcomes:** Systematic and sustained *in situ* sampling effort is being conducted in a growing number of Mediterranean Marine Protected Areas to track and assess climate change effects in marine coastal ecosystems. Considering the need for accurate observation at large geographical scale, we conducted joint analysis of CMEMS satellite derived high-resolution foundation sea surface temperature with T-MEDNet database of multi-year *in situ* temperature acquired nearshore in Mediterranean Marine Protected Areas. Statistical analysis of the match-up database (multi-year, 22 sites) demonstrated the applicability of the CMEMS satellite data to the nearshore areas and further documented associated uncertainties across temperature and variability gradients. Rapid and accelerated warming of sea surface temperature in the northwestern Mediterranean during the past decade is reported and compared to the 1982–2011 period (0.047 vs. 0.029°C/year respectively). Elevated and consistent warming rates were calculated at local scale from *in situ* and satellite observations. Combining CMEMS remote sensing and *in situ* monitoring systems, as shown in this study, is a pillar to enhance our understanding on climate change impacts in coastal areas.

**Products used:**

| Ref. No. | Product name and type | Documentation |
|---|---|---|
| 3.6.1 | SST_MED_SST_L4_REP_OBSERVATIONS_010_021 Remote sensing | PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OSI-PUM-010-021-022.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OSI-QUID-010-021-022.pdf |
| 3.6.2 | T-MEDNet consolidated *in situ* temperature time series. www.t-mednet.org (DOI pending) *In situ* | www.t-mednet.org/T-Database |

The coastal ocean is among the most dynamic and biologically diverse areas on Earth and supports a wide range of key marine ecosystems, which are providing goods and services to our societies. Climate change is one of the major threats for the conservation of marine coastal ecosystems through direct but also cumulative effects with other stressors (e.g. Coll et al. 2010; Hughes et al. 2017). Understanding how ocean warming is affecting the structure and functioning of marine ecosystems is crucial to support sound management and conservation policies and strategies. In the Mediterranean Sea, the occurrence of mass mortality events affecting the coastal macrobenthic biota and shifts in species distribution are the major effects of ongoing warming trend (e.g. Garrabou et al. 2009; Kersting et al. 2013, Bianchi et al. 2017). However, studies considering appropriate large-spatial and long-term scales on different climate change indicators are scarce. Representative data across biogeographic gradients are essential to enhance our capacity to evaluate current changes and impacts as well as to explore, through novel modelling approaches, future trajectories of ecosystems under different scenarios. Such information is required to establish vulnerability assessments and develop adaptation plans for the different management frameworks (from local to regional scales).

A systematic and sustained observation effort of Essential Climate and Ocean Variables (ECV/EOV), among which sea surface temperature and subsurface temperature, is essential to analyse changes and trends in marine ecosystems (IPCC, see Wong et al. 2014). Building sound knowledge of climate change impacts in the complex 3D marine realm might push requirements for sustained and accurate environmental data acquisition at relevant resolution both in time and space like never before (e.g. Bates et al. 2018).

Sea surface and subsurface temperature can be measured with different sensors and instrumental platforms, which have intrinsic differences, making it necessary to carefully assess errors and biases between them before merging data sets (Smale and Wernberg 2009). While satellites provide good spatial and temporal coverage of the surface layer of the ocean, the ability of gridded or operational satellite observations products in retrieving accurate sea surface temperature information in coastal areas has been repeatedly challenged (e.g. Smale and Wernberg 2009; Smit et al. 2013; Brewin et al. 2017, 2018). *In situ* measurements are needed to document the temperature variations beneath the surface, and they provide more reliable and accurate source of information on local conditions but show spatial and temporal limitations. In particular, one can note the scarcity of long-term series suited for climate change studies in the coastal zone. Indeed, long-term coastal observation is at the confluence of several challenges, among which are investment and maintenance costs, fieldwork constraints, data management, qualification and reporting.

Understanding the processes driving the ecological responses to climate change across different biological organisation levels (from the genes to ecosystems) is essential to address sound adaptation measures. High-resolution *in situ* measurements provide key information to characterise the variability of thermal regimes in which marine organisms thrive. In particular, these data have been key to characterise the thermal environment associated with the onset of mass mortality events that have affected the benthic biota during the past decades (e.g. Bensoussan et al. 2010; Crisci et al. 2011),
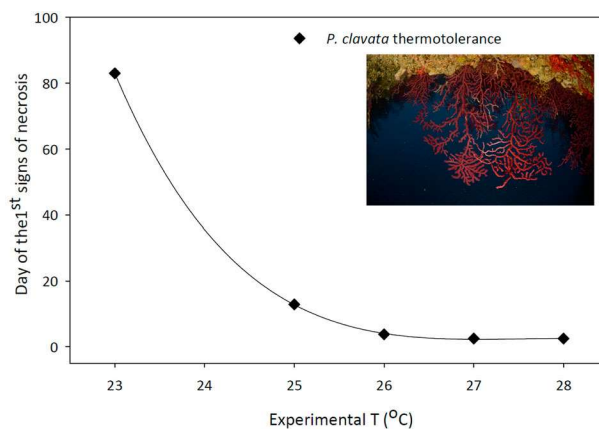


**Figure 3.6.1.** Thermotolerance response function of the red gorgonian *Paramuricea clavata*. The response curve shows the exposure duration to different temperature treatments (experimental T°C) leading to the first signs of tissue necrosis. Results were obtained from the compilation of different thermotolerance experiments and from *in situ* observations, combining local (at depth) information on thermal environment and necrosis. Figure modified from the data presented in Crisci et al. (2011, 2017) and Pairaud et al. (2014), integrating new experimental results.

and for the design of tailored field and laboratory experimental studies on the biological responses to warming of sensitive species (e.g. Ledoux et al. 2015; Crisci et al. 2017). For instance, comprehensive assessment of the thermotolerance response function of *Paramuricea clavata*, a habitat forming species, has been conducted from thermotolerance experiments and field observations (Figure 3.6.1). Non-linear response was evidenced, showing (sub-) lethal impacts across a range of temperature conditions, from sustained periods (months) of warm temperature to few days of extreme hot conditions. Such conditions might be detected using different and complementary approaches, like anomalies, extreme warm or hot conditions, and their integrative over different time scales, from event to season or year (see also sections 4.4 on Marine Heat Waves). This kind of information can provide empirical response functions to thermal stress that can be used to develop early warning systems and explore the risk of onset of mass mortality events under different climatic scenarios (e.g. Bensoussan et al. 2013; Pairaud et al. 2014; Galli et al. 2017).

In this study, we perform a joint analysis of multi-year to decadal high-resolution temperature time series acquired *in situ* from T-MEDNet network (www.t-mednet.org, product reference 3.6.2) with CMEMS remote sensing product of daily optimally interpolated foundation sea surface temperature at 4 km spatial resolution/smoothness (product reference 3.6.1) in the Mediterranean coastal zone. This joint analysis focuses on two main topics: characterisation of thermal regimes and warming trends. The results obtained advocate for the complementarity of these valuable date sets, from local to large scales in the coastal zone, by evaluating representativeness, uncertainties and limitations from which an improved framework on the assessment of climate change effects can be designed.

Instrumental development and a new generation of temperature data loggers now allow for deployment in multiple locations and depths over periods from months to years for high frequency (minutes to hours) characterisation of seawater temperature in a cost-effective manner. The origin of T-MEDNet network was set during the late nineties, when Mediterranean marine ecologists interested in climate change impacts on marine coastal ecosystems started to implement a standardised strategy to obtain *in situ* temperature data. This strategy consisted in temperature acquisition at high frequency (1 h) and high-resolution across the seasonal thermocline, using data loggers deployed every 5 m from surface to 40 m depth or more. Since then systematic and sustained sampling effort has been conducted in a growing number of sites, mainly Marine Protected Areas (Figure 3.6.2(a)). Same data loggers are being used at standard depth (Hobo U22, accuracy 0.21°C, resolution 0.02°C), are attached to rocky walls or moorings exposed to dominant winds and currents, and retrieved every 6–12 months by scuba divers. At present over 40 sites are being monitored, mainly in the north and central western Mediterranean but also in the Alboran Sea, southwestern Mediterranean, Tunisian, Adriatic and Aegean sub-basins (Figure 3.6.2(a)). T-MEDNet temperature monitoring sites span across a large range of Mediterranean Sea surface temperature (more than 7°C, from 2nd to 92th percentile of surface variability, Figure 3.6.2(b)). The monitoring strategy has proved its efficiency, with high return rates on observations (median return rate above 80%). Field surveys were complemented by the launch, in 2009, of a collaborative platform (www.t-mednet.org) for rigorous data management and quality check, allowing the building of unified consolidated database on *in situ* temperature in coastal waters consisting in more than $13 \times 10^6$ samples acquired at high frequency and standard depth levels. The development of this regional observation network was possible through sustained partnership between research institutions, Marine Protected Areas management bodies, Non-Governmental Organisations (e.g. IUCN, MEDPAN) and regional organisations (SPA/RAC). The ultimate goal is to contribute to a representative sentinel network on climate change effects in the Mediterranean Sea with the aim to maintain and enhance monitoring effort, also in terms of representativeness across the different sub-basins.

In Figure 3.6.2(c), we show an example of the time series acquired in the Marine Protected Area 'Reserve Naturelle de Scandola' (Corsica, France) over the period 2004–2018. From such long-term and high-resolution time series, robust baselines on coastal thermal regimes and seasonal stratification dynamics can be obtained (Figure 3.6.2(d)). The Marine climatology obtained from multi-year continuous monitoring shows some typical features of North Western Mediterranean thermal regimes. The annual cycle of the water column is governed by the seasonal cycle, which originate in seasonal vertical temperature stratification, and can display important variability depending on the area, due to the local wind regimes, bathymetry and topography (see for instance Bensoussan et al. 2010). The minimum temperature is observed in February–March (13.2°C) when the water column can become fully mixed. Spring and Summer surface warming induce seasonal vertical temperature stratification with the development and progressive deepening of the surface mixed layer. Maximum temperature occurs in August and generally, elevated daily temperatures are observed in the upper 15 m
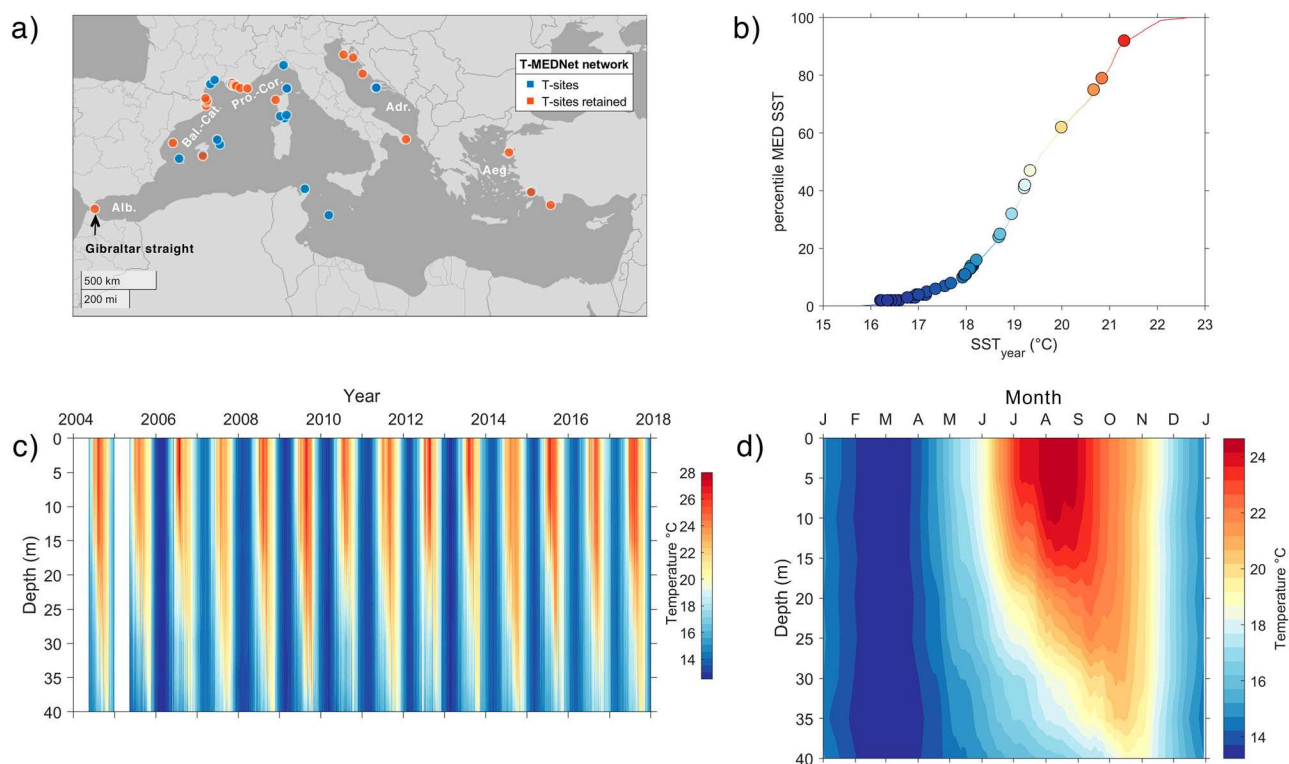
**Figure 3.6.2.** (a) Location map of T-MEDNet temperature monitoring sites in the Mediterranean Sea (Product reference 3.6.2). The sites retained for statistical comparison with satellite data are shown in orange, in the Alboran (Alb.), Balearic-Catalan (Bal.-Cat.), Provence-Corsica (Pro.-Cor.), Adriatic (Adr.) and Aegean (Aeg.) sub-regions. (b) Yearly mean sea surface temperature at the T-MEDNet sites and corresponding percentile relative to distribution over the entire Mediterranean Sea. Calculations were conducted over the period 1982–2011 from product reference 3.6.1. (c) Example of the high-resolution and long-term time series acquired *in situ* using data loggers set at standard depth levels (every 5 m from 5 to 40 m depth) in the Marine Protected Area of Scandola (Corsica, France) since 2004. (d) Climatological mean seawater temperature between the surface and 40 m depth at Scandola Marine Protected Area. The climatological mean was calculated over the period 2004–2017, for each depth and day of year using a 11-day moving window and additional smoothing on 31 days.

of the water column (mean maximum values ranging between 23°C and 26°C). The temperature difference between 5 and 40 m depth is 8°C on average in August. In late summer and fall, surface cooling and important (wind induced) vertical mixing occur, with subsequent deepening of the mixed layer depth to the bottom in late October or November. Benthic ecosystems dwelling between the surface and 40 m depth are thus exposed to contrasted environmental conditions, with strong differences in the magnitude and phasing of their hydrological cycle (e.g. mean amplitude of 12°C at the surface vs. 6°C at 40 m depth, maximum observed in August and October respectively). From the data series available, the different patterns of stratification and temporal variability were characterised across the network.

Regarding the *in situ* T-MEDNet network temperature database (product reference 3.6.2), a first subsample was obtained, retaining maximum depth of 5 m ($in\ situ_{5m}$) and more than one full year of measurements, for joint analysis with sea surface temperature from CMEMS (product reference 3.6.1). Out of these criteria,

22 time series were considered (median length 7.4 years), from the western and eastern Mediterranean basins where contrasted hydro-climatic conditions occur (Figure 3.6.2(a,b)). A matchup database of co-located satellite (nearest pixel) and $in\ situ_{5m}$ multi-year daily time series was built for statistical analysis of the observed differences over the annual cycle. Comparisons between remote sensing and $in\ situ_{5m}$ data were carried out using classical descriptors and analysis for bias, standard deviation, correlation and root mean square difference and results were synthetised in Taylor diagrams (Taylor 2001).

Important differences were evidenced from the 22 sites (Figure 3.6.3(a,b)). Overall, high correlation (>0.97) and low bias (<0.4°C) were shown for most sites (group A, $N = 15$) while lower agreement was evidenced for six sites distributed along 60 km of coastline in Provence (group B1) and on the southern coast of Gibraltar Straight (B2, Ceuta, Spain). From the observed variability in the correlation and standard deviation patterns, the 22 sites were clustered in six groups (groups A1
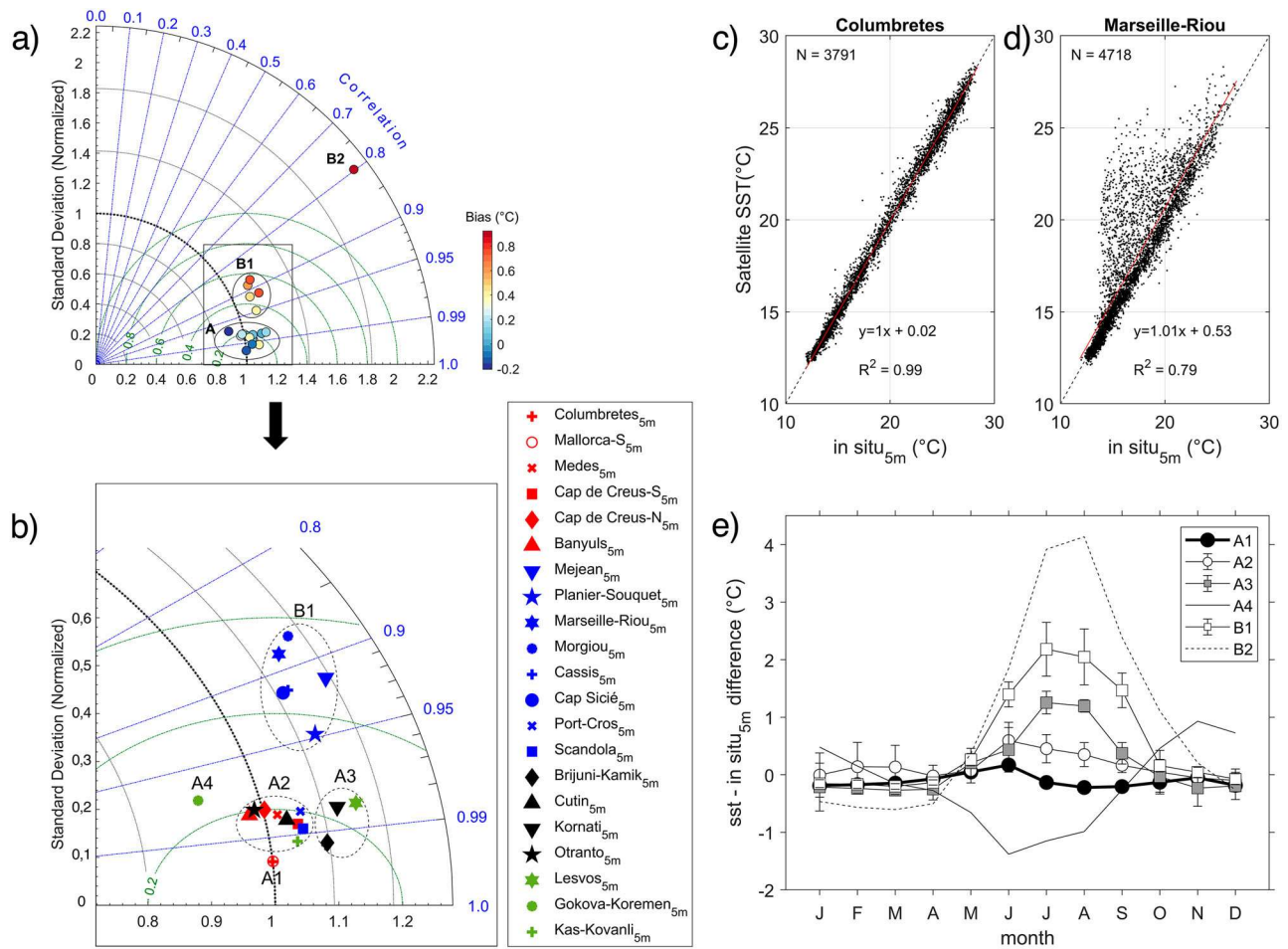
**Figure 3.6.3.** (a) Taylor diagram showing comparison between multi-year time series of satellite derived daily sea surface temperature from CMEMS (Product reference 3.6.1) and T-MEDNet *in situ* measurements at 5 m depth (product reference 3.6.2) considering all available samples over the 2004–2017 period. (b) Zoom on the box shown in panel a showing sites clustering along the standard deviation and correlation axes. Different symbol colours were used for sites from the Balearic-Catalan (red), Provence-Corsica (blue), Adriatic (black) and Aegean (green) sub-regions. (c–d) Linear regression analysis of daily temperature data in two sites from subgroups A1 and B1 (Columbretes Islands and Marseille-Riou respectively). (e) Average of the mean monthly bias for the different subgroups of stations show in the panels a–b.

to A4, B1 and B2). They were further analysed in order to quantify typical uncertainties and monthly bias during the annual cycle (Table 3.6.1, Figure 3.6.3(e)) and to better understand the determinants of the observed variability (e.g. Figure 3.6.3(c,d)).

Interestingly, highest and near perfect agreement in correlation ($R = 0.996$) and amplitude pattern (point lying on the unit standard deviation arc) was shown for two sites located off mainland coast, nearshore small islands in the Balearic Sea (group A1, Columbretes and Mallorca-S, distant by ca. 200 km, Figure 3.6.3(b,c)). The root mean square difference calculated over more than eight years of data was 0.44°C, i.e. comparable to typical accuracy of satellite measurement in non-near-shore area (0.5°C, Table 3.6.1, Pisano et al. 2016). These results demonstrate the high consistency and accuracy of multi-year local time series obtained from

the optimally interpolated satellite data in such near open sea conditions (product reference 3.6.1).

Comparatively, two to five-fold increase in root mean square difference was evidenced in typical coastal zone (mostly Marine Protected Areas, Table 3.6.1). Generally, low bias occurred in winter and fall but significant warm bias was shown in June (0.7°C for group A2) or during summer (Figure 3.6.3(e)). This pattern, consistent with the seasonal cycle, was amplified in sites within the clusters showing lower agreement, with summer bias >2°C to 4°C in groups B1 and B2 respectively (Figure 3.6.3(b,e), Table 3.6.1). However, a distinct seasonal pattern was shown in Gokova Koremen (A4, STD = 0.90, Figure 3.6.3(e), Table 3.6.1) where effect from the nearby Akyaka river is strongly suspected, which might explain the seasonal inversion in vertical temperature gradients in the top 5 m of the water column.

**Table 3.6.1.** Summary of the satellite – *in situ* matchup data over the Mediterranean Sea in the near-shore and off-shore as a function of sensor type.

| Data Type | Depth (m) | Bias (°C) | RMSD (°C) | Correlation | Standard deviation (Normalized) | Number of samples (and sites) | Reference period (median duration in year) |
|---|---|---|---|---|---|---|---|
| *Nearshore HF time series using benthic data loggers, coastal moorings - multi-year data sets from T-MEDNet - this study* | | | | | | | |
| A1 | 5.0 | -0.11 | 0.44 | 0.996 | 1.01 | 6 768 (2) | 2007-2017 (9.7) |
| A2 | 5.0 | 0.16 | 0.75 | 0.984 | 1.04 | 23 960 (9) | 2004-2017 (7.2) |
| A3 | 5.0 | 0.09 | 0.81 | 0.983 | 1.14 | 7 539 (3) | 2012-2017 (3.7) |
| A4 | 5.0 | -0.21 | 0.99 | 0.970 | 0.91 | 985 (1) | 2015-2017 (2.7) |
| B1 | 5.0 | 0.59 | 1.64 | 0.910 | 1.14 | 16 232 (6) | 2004-2017 (7.4) |
| B2 | 5.0 | 0.92 | 2.1 | 0.798 | 2.15 | 1 008 (1) | 2014-2017 (2.8) |
| Total | | | | | | 56 222 (22) | |
| *Source: Pisano et al. 2016* | | | | | | | |
| Drifter | 0.2 | -0.23 | 0.52 | | | 102 164 | 2004-2012 |
| TSG | 4.0 | -0.25 | 0.58 | | | 57 369 | 1990-2012 |
| CTD | 3.0 | -0.29 | 0.58 | | | 6 649 | 1982-2012 |
| XBT | 3.0 | -0.29 | 0.58 | | | 5 927 | 1990-2012 |
| ARGO Float | 3.0 | -0.18 | 0.54 | | | 769 | 1999-2012 |
| Total | | -0.24 | 0.55 | 0.992 | | 172 878 | 1982-2012 |

From group A2, a high agreement between the satellite and *in situ*$_{5m}$ data was achieved for nine sites from the different sub-basins, from cold to warm Mediterranean Sea surface temperature: in the Catalan, Provence-Corsica, Adriatic and S-Aegean Seas. The satellite data typically explained 96% of the variance observed *in situ*, with a root mean square difference $0.75 \pm 0.18°C$ (Figure 3.6.3(b), Table 3.6.1). Figure 3.6.4(a–d) shows how satellite and *in situ*$_{5m}$ data track each other during the entire annual cycle of year 2015 in Columbretes Islands (from group A1), and in three sites from group A2 accounting for large-spatial temperature gradients in the Mediterranean Sea (*in situ* data completeness index 99.6%). The high agreement allows fine analysis of the local subsurface annual temperature cycle and of such inter-site differences using satellite data. The

highest bias between satellite and *in situ*$_{5m}$ daily temperatures occurred during periods of strong sea surface warming (e.g. in June and warm summer events) which might be a sign of vertical temperature gradients, or during cold episodic events that were smoothed in the satellite data (up to 1°C in Columbretes, 2–3°C in other sites).

To take into account how complex coastal hydrological dynamics can affect satellite data, we considered a group of six T-MEDNet *in situ* monitoring sites (group B1), from the Gulf of Marseille to the East, to Cap Sicié to the West (Figure 3.6.5(c,d)). These sites displayed comparatively lower agreement between *in situ*$_{5m}$ and satellite data than other sites from the A groups. Since the hydrology in the area is under the influence of coastal upwelling cells triggered by
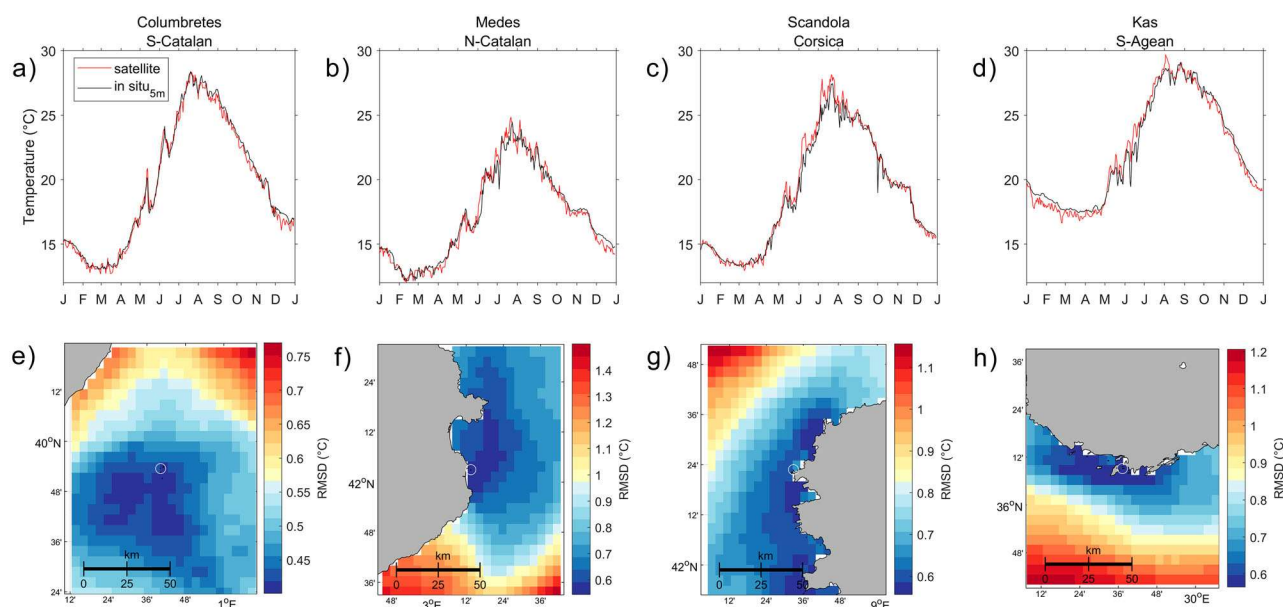


**Figure 3.6.4.** (a–d) Satellite and *in situ* temperature time series for year 2015 for sites from the Western and Eastern basin (Columbretes from group A1 and Medes, Scandola and Kas, from group A2). (e–h) Spatial maps of RMSD for match-ups (same day) of *in situ*$_{5m}$ data for all satellite sea surface temperature data from pixels in $1 \times 1°$ box. Reference of the products used: 3.6.1 and 3.6.2.
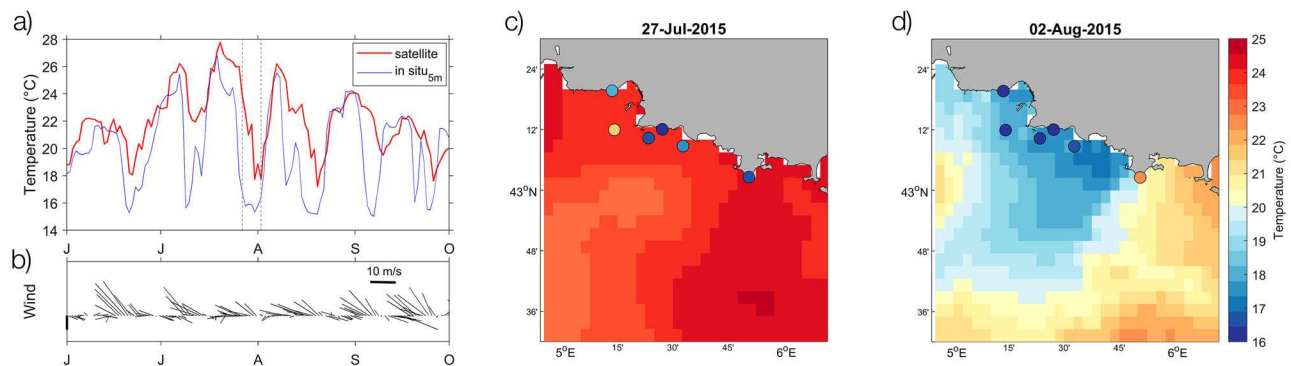
**Figure 3.6.5.** (a) Time series of satellite derived sea surface temperature and *in situ₅ₘ* in Marseille Riou (Provence France). (b) Wind data from local observations at Cap Couronne (Source Météo France). (c–d) spatial maps of sea surface temperature and *in situ* measurement during the set up and relaxation phase of the upwelling event observed at the end of July 2015 (dashed vertical lines in panel A).

alongshore Mistral winds (Millot and Wald 1981; Bensoussan et al. 2010), we related the oceanographic time series with independent wind data (Meteo France). We found that the degradation of matching patterns of group B1 could be attributed to satellite data which did not accurately resolve the surface temperature during the frequent upwelling events (Figure 3.6.5(a,b)). In fact, from their setup, when temperature decreased at rates up to 7°C/day, to their relaxation. Although most upwelling events were captured by the satellite data, time lag of few days was observed for their set up and their intensity was systematically underestimated. This was also illustrated in the spatial maps of sea surface temperature for the strong upwelling event that occurred at the end of July 2015. Local bias up to 8°C occurred on 27th of July 2015 (Figure 3.6.5(c)), while higher spatial agreement between satellite and *in situ* data was shown during the relaxation phase of this specific event whose influence was not limited to the nearshore but concerned broader areas (Figure 3.6.5(d)). These discrepancies are likely due to the satellite data quality check and interpolation procedures, which result in smoothing of such cold events.

Similarly, satellite smoothing of the summer high frequency variability was evidenced for sites of group A3. These three sites from the N-Adriatic and N-Aegean Seas share common features such as complex topography on large and shallow continental shelves and important wind forcing which drive episodic cooling events (Bora and Meltem winds). Contrarily in Ceuta (B2) warm bias was consistently observed during summer and the satellite derived sea surface temperature over the pixel area was not representative of local nearshore conditions, which might be interpreted as sign of spatial variability due to complex hydrodynamics along the southern coast in the Gibraltar straight.

Finally, in order to analyse the spatial representativeness of the *in situ* point measurements, statistics were computed considering all satellite data from pixels within boxes of 1° longitude and 1° latitude centred on the monitoring sites shown in Figure 3.6.4(a–d). The spatial maps of root mean square difference for year 2015 (Figure 3.6.4(e–h)) indicate smooth gradients, with highest agreement between satellite and *in situ* data for closest and adjacent pixels, though not necessarily alongshore (Figure 3.6.4(f–h)). Coherent spatial patterns were observed, for instance for Capes vs. Gulfs that further illustrate the interest of combining satellite and *in situ* data to enhance analysis of the spatial variability over coastal areas. In Columbretes, owing to the near open sea conditions and low horizontal sea surface temperature gradients (0.6°C annual difference over the S-Catalan Sea map, data not shown), high agreement concerned vast areas (100's km$^2$), south and east of the nearshore monitoring site (Figure 3.6.4(e)).

Warming can vary regionally and locally, with potential impacts on ecosystems. In order to evaluate the applicability of satellite data for representing subsurface trends in the nearshore area, nine time series from sites in the northwestern Mediterranean were selected from T-MEDNet database. The sites selection was based on the availability of a minimum number of seven years covered by data over the 2007–2016 period (Figure 3.6.6). The monthly average temperature, climatology and anomalies at each site were computed, out of which few were excluded from analysis when based on less than 15 days of observation. Finally, the average completeness index on monthly anomalies was 84 ± 9% (mean ± std), ranging from 73% to 96%. Warming rates (in °C per year) were calculated using the Sen's method to estimate the slope of the monthly anomalies time series (Sen 1968) over the 2007–2016 period. Warming trends over the northwestern Mediterranean Sea were calculated from satellite data (product reference 3.6.1) over the past decade (2007–2016) and at
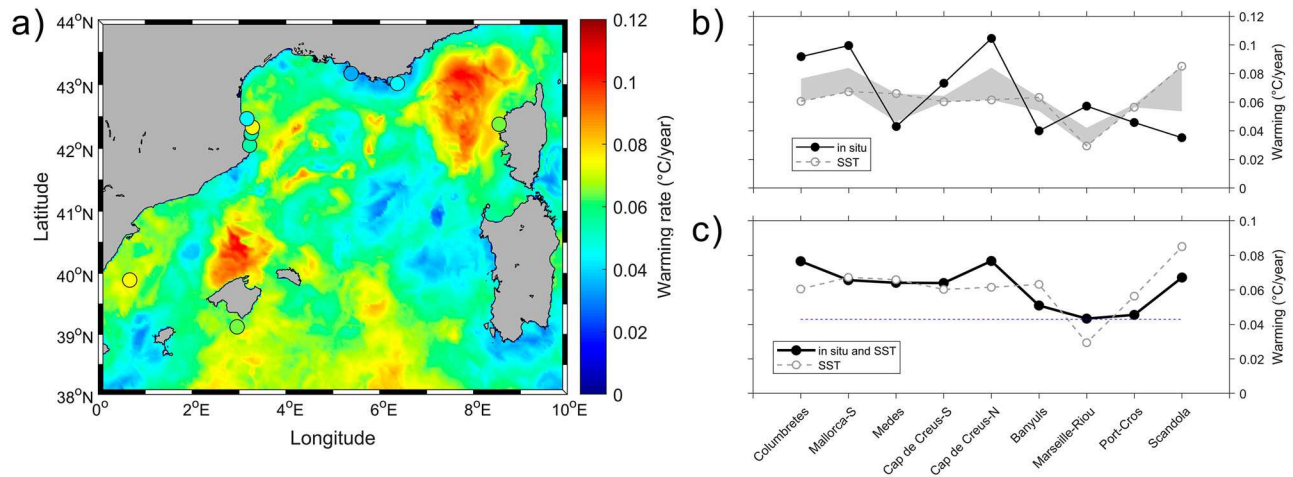
**Figure 3.6.6.** Sea surface warming trends over the past decade (period 2007–2016) in the northwestern Mediterranean Sea. (a) Trends over the north western Mediterranean Sea from high-resolution satellite data and combined *in situ* and satellite data from nine coastal sites (see panel (c)). Results show accelerated warming over the area compared to the 1982–2011 period (0.047 ± 0.031°C/year vs. 0.029 ± 0.003°C/year respectively) (b) Comparison of surface warming trends in the 9 coastal sites shown on map calculated from *in situ* or satellite sea surface temperature data. The effect of missing data on trends calculation is also shown (grey shaded area). (c) Best estimates of surface warming trends in the nine coastal sites obtained by combining *in situ* and satellite data (black curve). Trends from satellite data at the coastal sites and over the entire area are indicated by the grey curve and blue line respectively.

climatological time scale (1982–2011). For comparison at local scale, satellite data from nearest pixel to the nine T-MEDNet sites were considered, retaining the complete data sets over the 2007–2016 period, and also sub-samples by retaining only matching dates with *in situ*$_{5m}$ in order to evaluate the potential incidence of missing data.

Analysis conducted on satellite data from CMEMS (product reference 3.6.1) attest to rapid and accelerated warming of sea surface temperature in the northwestern Mediterranean during the past decade compared to the 1982–2011 period (0.047 ± 0.031°C/year vs. 0.029 ± 0.003°C/year respectively, Figure 3.6.6(a)). Strong spatial variability is obvious and elevated warming rates (>0.1°C per year) occurred in the Balearic Sea and the Provence-Corsica Sea, mostly offshore. Rapid warming was also evidenced from the analysis of the T-MEDNet *in situ* time series to the coast (Figure 3.6.6(b)). Local warming rates calculated from *in situ*$_{5m}$ and satellite data showed comparable values on average (0.065 vs. 0.061°C/year respectively), but important differences arose when comparing pair of values at each site (mean of absolute difference 0.024 ± 0.014°C/year). We must also note the stronger inter-site variability of warming rates, at the various spatial scales, from *in situ* time series when compared to satellite data (Figure 3.6.6(b)).

We further evaluated the effect of missing data which is a characteristic of most, if not all, *in situ* time series, on estimation of trends. Trend calculation is known to be highly sensitive to the length of the time window, as well as the start and end dates considered. Here we showed

that even minor change in the completeness index of the data set (e.g. for Columbretes, retaining 96% vs. 100% of the satellite data over the 2007–2016 period) can result in significant variability/uncertainty in warming trends estimates (grey shaded area, Figure 3.6.6(b)). Overall, we assume that missing data may account for a 50% or more of the observed differences in the warming rates obtained using satellite and *in situ*$_{5m}$ data. Considering the statistical analysis conducted above, *in situ*$_{5m}$ data gaps were filled by satellite data with high confidence for all sites (from group A1 and A2), except for Marseille-Riou (upwelling area as discussed above).

Interestingly, the new estimates combining *in situ* and satellite data showed fair agreement with trends derived from the complete satellite data (Figure 3.6.6(c)). These results showed overall elevated warming rates (0.043° C/year in Marseille to 0.077°C/year in the Catalan Sea) among which most are higher than the average warming at sub-regional scale (blue dotted line, Figure 3.6.5(c)). These results further demonstrate the interest of combining satellite and *in situ* observations to enhance and validate analysis on thermal regimes and warming trends in the vital coastal and nearshore area.

Climate change is expected to have significant impacts in the coastal areas. Integrated Coastal Zone Management and Ecosystem Based Approach strategies are being implemented to deal with current and long-term climate change as well as other drivers of change. Through these strategies, integrated and adaptive approach to coastal zone planning and management are developed in order to achieve Good Environmental

Status and sustainable development of coastal areas. Marine Protected Areas are one of the main instruments being implemented in this framework. Besides Marine Protected Areas are recognised as nature-based solutions to cope with climate change in many frameworks (e.g. Convention on Biological Diversity, Sustainable Development Goal 14). In this study we showed the relevance of joint effort with Marine Protected Areas in tracking and informing on ongoing changes associated to climate change in coastal areas.

The statistical analysis of the satellite and *in situ* matchup database (22 sites, multi-year) firstly determined that high agreement in terms of correlation (0.98), RMSD (0.5–0.8°C) and bias (year = 0.3°C, month < 0.8°C) was attained in most Marine Protected Areas in the different sub-basins, from cold to warm Mediterranean Sea surface temperature. Secondly the large variability in matching patterns, with higher uncertainty in the nearshore compared to offshore and significant warm bias during summer, largely reflects the underlying coastal oceanographic processes that determine the local seawater temperature variability. Our results, consistent with the literature (e.g. Smale and Wernberg 2009; Smit et al. 2013; Brewin et al. 2018), further document uncertainties associated to such approach in the Mediterranean Sea and highlight potential limitations, especially in upwelling areas, that may inform user uptake and future product improvement. These results also demonstrate the interest of considering multi-year time series acquired nearshore using benthic data loggers in complement to other sensors platforms/classically used for satellite data validation (surface drifter, thermosalinograph, CTD, XBT, Argo float, Table 3.6.1, Pisano et al. 2016). Future work could focus on the validation of different sea surface temperature products but also high-resolution models and reanalysis, by considering the hourly and high vertical resolution of T-MEDNet *in situ* measurements. This analysis also informed on the spatial representativeness of *in situ* point measurements from which adaptive and cost-effective sampling strategy could be designed across environmental gradients in the Mediterranean coastal regions and potentially offshore, considering small islands. We advocate that in coastal areas where poor knowledge on oceanographic features, systematic *in situ* measurements over a complete annual cycle should be considered in order to maximise the potential of use and interpretation of satellite derived sea surface temperature at local and broader spatial scales relevant for coastal management (e.g. Gulfs, Marine Protected Area and coastal networks). Indeed, the long-term remote sensing data series (since 1982) can be of particular relevance for broad scale ecological studies (e.g. for computation of climatological

means), analysis of extreme warm or hot events based on anomalies to the climatological mean (see for instance Sections 4.4 on Marine Heat Waves) and warming trends.

Combining remote sensing and *in situ* monitoring systems as shown in this study is a pillar to enhance our understanding of climate change impacts and improve 3D modelling approach in hydrologically complex coastal areas. Supporting the development of a representative coastal monitoring network at Mediterranean scale, e.g. across the network of Marine Protected Areas, while pursuing the enhancement and delivery of CMEMS products to provide accurate and high-resolution information offers a unique opportunity to address vulnerability and adaptation plans to climate change over broad ecological and economic settings.

### 3.7. Combined analysis of Cryosat-2/SMOS sea ice thickness data with model reanalysis fields over the Baltic Sea

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**Statement of outcome:** The satellites Cryosat-2 and SMOS provide a new insight for accurate estimation of the sea ice thickness in the Baltic Sea, a heavily trafficked seasonally ice-covered boreal sea. In this study, we demonstrate that combined Cryosat-2/SMOS ice thickness product correlates with the high-resolution model ice thickness values with correlation coefficient of 0.41 and root mean square difference of 0.30 m. Model and Cryosat-2/SMOS data accuracy is good during the ice growth period when ice thickness is below 0.6 m. Cryosat-2/SMOS data captures inter-annual variations of ice thickness, volume and concentration as well as regional differences between Baltic Sea basins. Moreover, Cryosat-2/SMOS data provide added value to the ice thickness estimations based solely on the model during the ice melting period. Therefore, including Cryosat-2/