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The Copernicus Marine Services State of Pacific Ocean analysis of available data demonstrates that the ocean surrounding the Pacific Islands is warmer, has higher heat content, with sea level rising at rates higher than the global mean and a decline in chlorophyll content.

### *3.2. Review of the use of ocean data in European fishery management and monitoring applications*

**Authors:** Mark R. Payne, Patrick Lehodey

**Statement of main outcome:** Operational oceanographic data is potentially of great value for use in the monitoring and management of marine living resources due to the close coupling between the physiology of marine organisms and their environment. However, while oceanographic data is invaluable in understanding the processes governing the dynamics and behaviour of these organisms from a historical perspective, it has generally not been used in the day-to-day management of fisheries resources. We discuss the reasons for this situation and highlight emerging results, such as dynamic ocean management and marine ecological forecasting, that are starting to reverse this tendency. Finally, we discuss what can potentially be done to improve the uptake of this information.

| Ref. No. | Product name and type | Documentation |
|---|---|---|
| 3.2.1 | SST_GLO_SST_L4_NRT_ OBSERVATIONS_010_001<br>SST_GLO_SST_L4_REP_ OBSERVATIONS_010_011 | PUM:<br>http://marine.copernicus.eu/documents/PUM/CMEMS-OSI-PUM-010-001.pdf<br>QUID:<br>http://marine.copernicus.eu/documents/QUID/CMEMS-OSI-QUID-010-001.pdf |
| 3.2.2 | GLOBAL_ANALYSIS_FORECAST_ PHY_001_024_MONTHLY<br>Model | PUM:<br>http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-024.pdf<br>QUID:<br>http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-024.pdf |

Marine organisms are coupled to their physical environment in a way that, as terrestrial mammals, is hard for us to comprehend. Most marine organisms are ectotherms (‘cold blooded’), meaning that their body is at the same temperature as the surrounding environment: as a consequence, their metabolisms, and therefore their food requirements, growth rates, reproductive development and activity rates are all directly modulated by the temperature of their surroundings (Pörtner 2002). In addition, the concentration of dissolved oxygen at the surface is strongly temperature-dependent (higher temperature waters contain less oxygen) while below the surface the consumption of oxygen by other organisms can lead to areas of critical oxygen depletion (Breitburg et al. 2018). Salinity can play an important role in limiting the fitness and distribution of organisms, particularly in and around regions of transition between fresher and saltier waters e.g. from the high salinity North Sea (surface salinity of approximately 33–35) to the low salinity Baltic Sea (surface salinity 2–15) (Pecuchet et al. 2016). Variations in seawater pH and its resulting impacts on carbonate concentration have also been shown to affect both shell-forming organisms (e.g. coccolithophores, shellfish) and higher organisms (e.g. fish) (Dupont and Pörtner 2013).

This tight linkage between the physical environment and marine organisms has long been recognised within both the science and management of living marine resources. Oceanographic data therefore can potentially play an important role in informing these activities (Tommasi et al. 2017). Here we review how operational oceanographic products are currently used in these fields, with a particular focus on the CMEMS product catalogue. We focus on three different applications of this information, according to the timescale in question, i.e. understanding the historical perspective, evaluating the current state of the system and looking towards the future. Finally, we examine potential future directions and how collaboration between these two fields can best be fostered.

Firstly, historical oceanographic data play a key role in developing our scientific understanding of marine organisms and ecosystems: indeed, an entire sub-discipline of oceanography (‘fisheries oceanography’) has evolved at the interface of fisheries science and physical/chemical/biological oceanography that focuses on resolving these questions. One of the most prominent applications of such historical data is in cataloguing and understanding changes in the context of climate change and climate variability: a review performed in the lead up to the last IPCC report (AR5) identified 1700 such examples of observed responses to climate change in marine systems, including around 800 in European waters (Poloczanska et al. 2013). Large-scale indices have been used to link climate variability to ecological consequences in the ocean, including the North Atlantic Oscillation, the Atlantic Multidecadal Oscillation (Nye et al. 2014), the North Atlantic Subpolar Gyre intensity (Hátún et al. 2009), the El Niño Southern Oscillation (Chavez et al. 2002) or the Indian Ocean Dipole (Saji et al. 1999). The oceanographic data sets underlying these studies are diverse in nature and often reflect what is available to the authors, rather than being selected from either the global marketplace or from a systematic catalogue such as the CMEMS portal. In particular, the most impactful and important results are those that are based on long time series of both biological and physical observations (e.g. Boyce et al. 2010). Nevertheless, the satellite record is now starting to be of sufficient length to drive analyses on its own to, for example, link temperature to changes in fish distributions (e.g. MacKenzie et al. 2014) (Figure 3.2.1) or to study changes in lower trophic levels based on ocean colour (Racault et al. 2012).

Historical environmental data are also key inputs to develop empirical statistical (correlative) models with direct applications for marine management and conservation. Amongst the most common of these are the so-called species distributions models (also known as environmental niche models or bioclimatic envelope models) that link the distribution of a target species to environmental variables such as temperature, salinity, bathymetry, chlorophyll and primary productivity (e.g. Brunel et al. 2018, Raudsepp et al. 2019: Section 2.5 of this report). Other biological responses are also commonly correlated with environmental variables, in particular recruitment (the number of juveniles produced by a fish stock each year), growth and phenology (the timing of key biological events). Despite the limitations associated with correlative approaches these models have been used in two ways. Firstly, they help to understand the processes that are controlling the response of interest. Secondly they can be used to both project changes into the future under climate change e.g. Bruge et al. (2016), and, more recently, to drive near-term predictions (e.g. Figure 3.2.2). In all cases, long time series of synoptic oceanographic data, matching at least the temporal range of the biological observations, are critical to developing this work, and their lack can often represent a bottleneck in the analysis.

While oceanographic data is critical to scientific investigations of historical changes in marine populations and ecosystem, this data has seen little uptake on the near-term timescale and in the management of living marine resources. A review of the management practices of around 1250 fish populations globally (Skern-Mauritzen et al. 2016) showed that just 24 used ecosystem drivers to inform their short-term decision-making about setting fishing quotas: of these, 15 populations (1.2%) used oceanographic variables while 10 (0.8%) used the abundances of either the species' predators or prey. In essence, oceanographic information is simply not used in setting quota.

This result may seem surprising to the reader, given the prior discussion about the importance of the environment for the dynamics of biological systems. However, it reflects the current state of the art in this field. In spite of aspirations to move towards the more holistic 'ecosystem-approach to fisheries management' and 'ecosystem-based management' (Rice 2011), the majority of fisheries management systems today remain firmly rooted in the traditional single-stock paradigm that considers one population largely in isolation from both all other species and the environment (Skern-Mauritzen et al. 2016). Nevertheless, many fisheries are managed effectively today based on these simple approaches, supplemented with regular monitoring of changes in the populations and their productivity (Daan et al. 2011).

Why is this? An important factor limiting the uptake of oceanographic data is the paucity of quantitative, reliable and robust relationships between the environment and biological responses that can be used in a management context. This point is particularly well illustrated by a review paper from the late 1990s, that revisited published relationships between the environment and recruitment, to see whether they were still being used in a management context (Myers 1998). Of the 49 published relationships reviewed, the author found just one that was in use 10 years later: results that were, in his own words, 'dismal'. While many factors

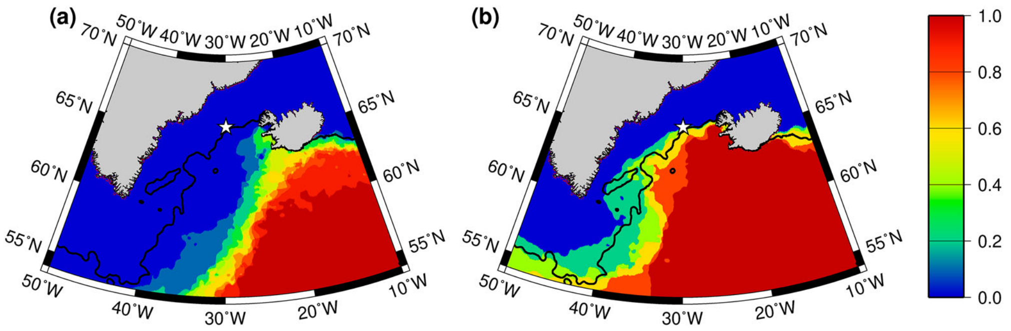

**Figure 3.2.1.** Using remote sensing data to understand changes in the distribution of Atlantic bluefin tuna (*Thunnus thynnus*). In August 2012 bluefin tuna were caught in Denmark strait (location marked by a star on both plots) for the first time in recorded human history. Bluefin tuna are generally restricted to waters warmer than 11 degrees. The plot here shows the proportion of years where August SST > 11°C for (a) 1985–1994 and (b) 2007–2011, while the contour line shows location of the 11°C isotherm for 2012. A clear expansion in the amount of thermally suitable habitat is seen in recent years, providing a corridor whereby tuna can access Denmark strait. From MacKenzie et al. (2014). Reprinted by permission of John Wiley & Sons, Inc. SST Data source is ref. 3.2.1.

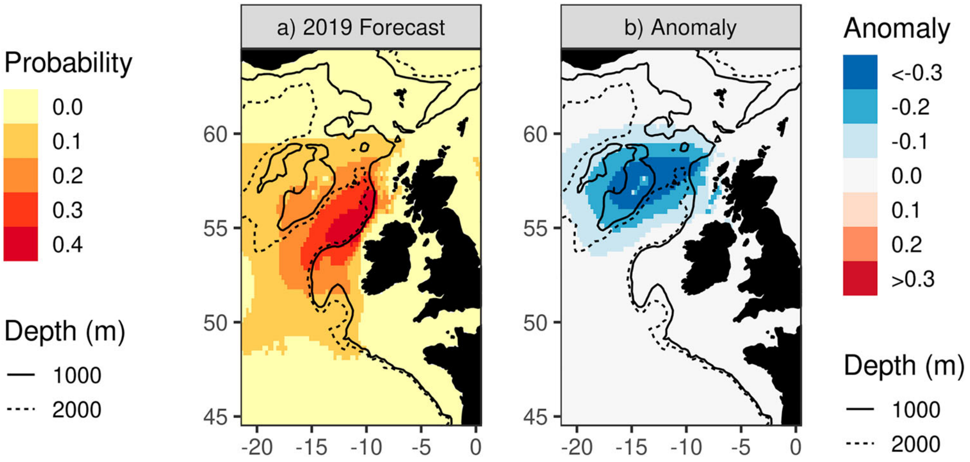

**Figure 3.2.2.** Forecasts of the spawning distribution of blue whiting (Micromesistius poutassou) in March 2019, issued in January 2019. The forecast is based on a species distribution model (Miesner and Payne 2018) linking spawning distribution of this species to salinity at 300–600 m and a range of geographical covariates. Distribution is represented here as the probability of observing blue whiting larvae and is plotted as (a) the value and (b) the anomaly relative to the climatological probability (1960–2010). Probabilities > 0.4 can be considered as the core spawning habitat. The 1000 and 2000 m isobaths are added for reference. The EN4 data product (Good et al. 2013) provides the basis for the historical development of the model, while the CMEMS PSY4 reanalysis provides the most recent estimates of the state of the system (product ref. 3.2.2). The original model of Miesner and Payne (2018) has been applied here to show the most recent estimates of spawning distribution.

contribute to this situation, the essence of the problem is the sheer complexity of marine biological dynamics together with a lack of appropriate data (e.g. predator and prey fields) that means that the majority of processes that impact recruitment are not and cannot be parameterised in models. This results in the phenomenon of ‘non-stationarity’, where the apparent relationships between the environment and the biological response appears to shift over time, leading to the abandonment of published correlations that Myers (1998) uncovered.

While this situation may appear bleak for the providers of operational oceanographic products, it is important to remember that there are other important uses of this information beyond setting quota. Both the commercial fishing industry and recreational fishers are acutely aware of the link between physics and biology, and have the flexibility and profit/enjoyment motive to take advantage of this information: indeed, commercial services have sprung up providing this information to end-users for a fee (e.g. ‘Roffers Ocean Fishing Forecasting Service’, www.roffs.com). Similarly, the scientific monitoring of the abundance and distribution of marine species also operates within a different framework to that of fisheries management, and can and at times does take advantage of oceanographic information to design their surveys. Changes in fish distribution and productivity, often associated with trends in the physical environment, have consequences for geographically linked fisheries management plans and international quota agreements. Furthermore, the new field of dynamic ocean management (Maxwell et al. 2015) places a high weight on oceanographic data. Rather than fixing marine protected areas in time and space, this new paradigm makes them dynamic, following the movement and distribution of protected species. Oceanographic data is key to dynamically defining these habitats and regions of interest. The first such tools that implement this approach are now emerging e.g. EcoCast (Hazen et al. 2018) and have shown tremendous potential for improving the way that the ocean is managed.

The tendency of oceanographic data getting greater uptake away from the goal of setting fisheries quota can also be seen when looking into the future. Advances in the ability to observe and forecast the ocean over recent years have paved the way for the creation of marine ecological forecasts for use in the management of living resources. A recent review of these forecast systems globally (Payne et al. 2017) revealed around 10 operational forecast products (Figure 3.2.3). The majority of these forecasts were of the spatial distribution of species, while only one, for salmon on the US West Coast, was directly related to setting quota, highlighting again the point that there are valuable uses for oceanographic observations and forecasts beyond setting quota (Tommasi et al. 2017). A second key point from this review was that Australia and the USA are currently leading the world in the development of such products, while there were no such marine ecological forecast products available in Europe, even though European waters, and particularly the NE Atlantic, are amongst the most predictable waters in the world (Langehaug et al. 2017). However, since that review the first such

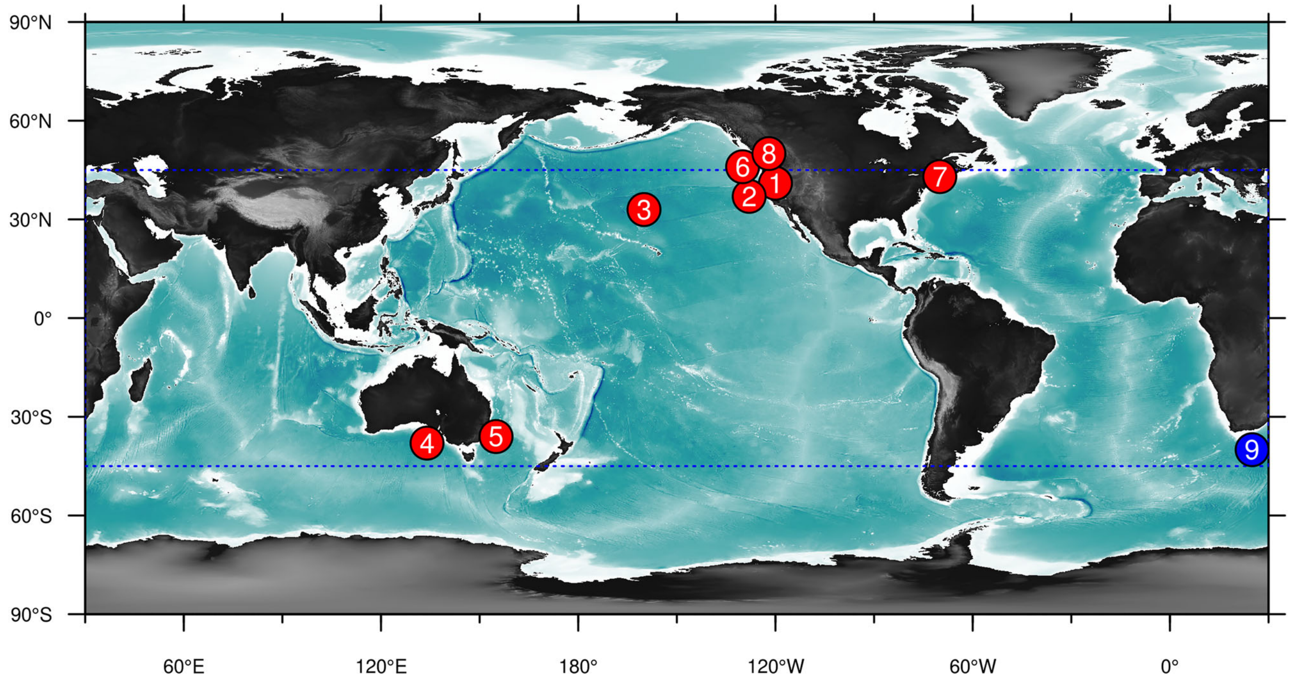

**Figure 3.2.3.** Distribution of marine ecological forecasts products globally. (1) Return rates of salmon along US West Coast. (2) Whale-watch – distribution and numbers of blue whales in California Current. (3) Turtlewatch – spatial areas where there is a high risk of loggerhead turtle bycatch. (4) Distribution of southern bluefin tuna in the Great Australian Bight. (5) Forecasts of areas closed to the SE Australian long-line tuna fishery. (6) Distribution of California Sardine. (7) Timing of Gulf of Maine lobster landings. (8) Timing of salmon run on the Columbia River. (9) Coral Reef Watch's Heat Stress Outlook. Reproduced from Payne et al. (2017).

European product has come online (Payne 2018) (Figure 3.2.2) and we can expect to see more of these types of products develop in the future.

The final time scale we consider is that of future climatic change. Here, oceanographic and climatic data clearly plays a critical role, as it forms the basis for future projections. Much of the work referred to above that is performed in a historical context can also be used to inform projections of future change (Drinkwater et al. 2010). As the focus of such work is primarily to develop scenarios about the impacts of climate change, rather than trying to make specific estimates or predictions for use in management, weak biological knowledge is only one of a number of other sources of uncertainty that need to be considered (Payne et al. 2016). Much debate exists around the usefulness and reliability of these biological projection models (e.g. Cheung et al. 2012; Brander et al. 2013) and this field is still maturing.

In spite of the poor historical uptake of operational data, the field is emerging rapidly. A particularly promising example of what can be done is provided by the recent implementation of a regional operational model for the Indonesian Ministry of Fisheries. The system couples ocean circulation model and primary production derived from satellite ocean colour data with a model of intermediate trophic levels on the top of which are simulated the spatial dynamics of three exploited tuna species (Tranchant et al. 2016; Lehodey et al. 2018). Boundary conditions of the regional model are provided by the CMEMS global operational model. The biological component of the model is a complete population dynamics model allowing monitoring of the effects of environmental variability on the stocks (e.g., related to the Indian Ocean Dipole), and the estimation of the fishing impacts. The success of this application relies on the strong multidisciplinary approach adopted covering physical and biogeochemical oceanography, numerical modelling and engineering, marine biology, fisheries oceanography and fish population dynamics modelling. In addition, the low and mid trophic levels (zooplankton and micro nekton) simulated from realistic ocean physics and primary production directly derived from, or assimilating satellite data appear promising potential key explanatory variables to develop other applications, including recruitment indices or species habitat models.

In conclusion, the direct use of operational oceanographic data in the management of living marine resources is currently very limited. Nevertheless, oceanographic data have an important role to play in the science that currently supports management, particularly in understanding the changes that have taken place in the past, and in projecting the response to climate change in the future. Furthermore, emerging fields such as dynamic ocean management and marine ecological forecasting lean heavily on oceanographic data as their foundation. There is also a clear desire to rectify the underutilisation of environmental information in the management of both fisheries and the entire ecosystem, with a move towards more integrated and environmentally informed management approaches. It therefore seems reasonable to expect significant increases in the uptake of operational oceanographic data in the future for use in the management of living marine resources.

**Box:**

What can operational oceanographers do to support fisheries management?

There is little doubt that operational oceanography can make an important contribution to fisheries management: as noted above, the relationship between physics and biology in the ocean is well recognised. However, there are numerous hurdles that need to be overcome to help these two closely related fields work together more effectively.

Perhaps the most important barriers are the simple differences between the practitioners of the two fields. It is easy to overlook the fact that the background, training, skill sets, tools and often the motivations and career paths of the people working in each of these fields can be wildly different (e.g. Berx et al. 2011). These differences in the way of working can limit both the uptake of data and the quality of science and decision-making: clear, effective and continued communication between the fields is therefore essential.

Re-evaluating the way oceanographic data are presented to the rest of the science community can help the communication. Data portals such as CMEMS have tremendous potential to both guide and educate end-users in making choices about the appropriate data product for their needs, but need to take the end-users perspective. For example, product descriptions are often primarily oriented towards the technically literate user and can therefore be difficult to penetrate for the non-specialists. Further developments in the guidance to finding and selecting the appropriate dataset (e.g. NCAR's Climate Data Guide (Schneider et al. 2013) could be highly beneficial for many end-users.

Providing tools and products that are compatible with the wide variety of end-users skills and requirements is also critical. For example, subsetting and online processing tools that allow the users to drive the data extraction and processing process themselves (e.g. by defining areas/polygons of interest, calculating averages and statistics on the server side and providing outputs in a variety of formats) are particularly useful for those not used to handling large datasets. It is however important that these tools work well with the current toolsets of users: while fisheries scientists work primarily in Excel and R, the current script-based subsetting tools provided by CMEMS are based on Python and NetCDF. Fortunately, technological developments, such as the emergence of robust standards for metadata and web access services following the 'FAIR' principles of Findable, Accessible, Interoperable, and Reusable data (Wilkinson et al. 2016) are helping to pave the way and ease the challenge of moving data between scientific disciplines.

Finally, and most importantly, there is a need for greater understanding and collaboration between the fields. Education and outreach activities, including training courses, are critical but also need to work in both directions, not just to increase the skill-set of potential end-users, but also to educate operational oceanographers in the principles of marine science and fisheries management. Co-development of new products by oceanographers and marine biologists working together is a particularly important and productive approach that can help to bring the two fields closer. Indeed, much can be learnt from the newly developing climate services community, for example, where co-development and co-production of climate services helps to overcome the challenges associated with differences between the producers of climate data and the information needs of end-users (Bruno Soares and Dessai 2016). In the same way, it is hoped that a greater dialogue between operational oceanographers and fisheries scientists can lead to improvements in the state of the marine ecosystem and benefit those that depend on the ocean, whilst at the same time realising the tremendous potential offered by operational oceanographic products.

## 3.3. Synergy between CMEMS products and newly available data from SENTINEL

**Authors:** Joanna Staneva, Arno Behrens, Gerhard Gayer, Lotfi Aouf

**Statement of main outcome:** This study explores the synergy between the CMEMS Monitoring and Forecasting Centres model products and the newly available satellite data. Working with these complementary sources of reliable information is useful not only for validation and assimilation purposes but also to explore in depth both the temporal and spatial scales of variability in European seas. The quality of the newly available Sentinel-3A (S3) data is assessed in comparison with data from Jason-3 (J3) at regional scales. The general performance of the wave products is very good and fairly