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Description	This document demonstrates the capability of seasonal forecasting systems to predict observable and user-relevant ocean climate indicators.
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Comments	

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1. Executive summary

Predictions of anomalous seasonal conditions provide industries and society time to manage resources and mitigate against ecological and economic damage. Seasonal forecasts of the physical environment are freely available and employed by many users, but traditionally the focus has been on land-based or atmospheric variables. Given the importance that ocean conservation and the Blue Economy has to societies across the world, the uptake of seasonal forecasts of marine variables will be crucial for the sustainable use of the marine environment. Through this deliverable, EuroSea aims to increase the validation, provision and, eventually, the uptake of seasonal forecasts of the marine environment.

This deliverable presents the skill of user-relevant marine indicator forecasts in two operational seasonal forecasting systems contributing to the Copernicus Climate Change Service. Forecasts, of up to 2 seasons ahead, of indicators over the period 1993-2016 are compared to satellite-derived records from the Copernicus Climate Change Service (C3S) and a global reanalysis from the Copernicus Marine & Environmental Monitoring Service (CMEMS). Marine indicators assessed here are derived from either sea surface temperature (SST), ocean heat content (OHC) or sea surface height (SSH), and include: regions of direct interest to marine industries (such as upwelling regions for fisheries); indicators of climate variability (e.g., Indian Ocean Dipole), which have a large influence on regional and global oceanic and atmospheric conditions; sea level change; and summer marine heat waves and winter cold spells.

This report presents extensive results of indicator forecasts across seasons, highlighting where the exploitation of forecasts has the potential to benefit users but also where further improvements in forecast systems are necessary to make them useful. Examples of encouraging results are shown for regions prone to devastating marine heat waves, and for sea level change near island nations. Seasonality of skill is also considered here; for example, extreme winter conditions in European seas are more accurately forecast than extreme summer conditions.

In summary, this report demonstrates the capability of seasonal forecast systems to predict marine indicators and is the first step towards the creation of marine-focused climate services.

2. Introduction

2.1. Seasonal Forecasting in EuroSea

A major goal of EuroSea is to improve ocean climate and health forecasting, with the aim of aiding marine-based stakeholders to make science-based decisions about their resources and activities. Seasonal forecasts are included in this because they have the potential to play a key role in the sustainable management of the marine economy and environment, by providing information on conditions several months in advance. This deliverable presents an assessment of the quality of forecasts of user-relevant indicators in seasonal forecasting systems.

Seasonal forecast systems, including those made freely available via the Copernicus Climate Change Service[1] (C3S), provide many land-based and atmosphere-based variables (e.g., precipitation, sea level pressure). The "maturity" of seasonal forecasting application can be seen in the progress made by other European projects. There are many examples of various stakeholders, from the energy and agriculture industries to water services companies, working with seasonal forecast output of land-based variables; see, for example, the case studies of the H2020 SECLI-FIRM[2] and MED-GOLD[3], projects, and the sectoral impacts of C3S[4]. Wind speed, solar radiation, and 2 m temperature, to name but a few, are already used in demonstrator case studies and active climate services. The application and operational usage of seasonal forecasts are not as mature for marine variables as it is for land-based variables. For example, C3S provides only one marine variable: sea surface temperature (SST).

A major aim within EuroSea was to promote the uptake of seasonal forecasts of marine variables by marine stakeholders. This deliverable presents an assessment of the skill of state-of-the-art seasonal forecast systems in predicting user-relevant indicators in the ocean. It is the final part of a chain of milestones and deliverables which describe EuroSea's marine seasonal forecasting development:

- Milestone 7: User-driven indicators defined and selected EOV/ECV from ensemble of seasonal forecasts verified
- Milestone 11: Definition of ocean indicators for seasonal forecasts
- Deliverable 4.3: Derive observable ocean climate indicators from seasonal forecasts
- Deliverable 4.6: Skill assessment of Essential Ocean/Climate Variables from seasonal forecasts

Milestone 7 proposed definitions of climate indicators useful to a range of marine stakeholders, some of which are used here. Milestone 11 introduced our data-sharing approach and preliminary analysis of system skill. D4.3 introduced our forecast validation methods and metrics. Lastly, D4.6, released alongside this deliverable, presents the global scale validation of three essential ocean/climate variables: SST, ocean heat content (OHC) & sea surface height (SSH). While both this deliverable and D4.6 cover the skill of forecast systems, D4.6 covers marine variables while this deliverable covers marine indicators. Moreover, much of the work presented here has been published in various scientific journals (McAdam et al. 2022a; McAdam et

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[1] https://climate.copernicus.eu/seasonal-forecasts
[2] https://www.secli-firm.eu/
[3] https://www.med-gold.eu/it/home-page-it/
[4] https://climate.copernicus.eu/sectoral-impacts

al. 2022b; von Schuckmann et al. 2022). Combined, we believe they state the case for an increase in marine seasonal forecasting validation and application.

Table 1: Brief description of datasets used for analysis in this deliverable.

Validation Datasets		
ESA CCI SST	European Space Agency Climate Change Initiative Sea Surface Temperature (https://doi.org/10.48670/moi-00169) (Good S.A.; Embury 2019)	Satellite-derived SST records of the period 1981 onwards, provided on a 0.05° grid.
C3S SSH	Copernicus Climate Service Reprocessed Sea Surface Heights https://doi.org/10.48670/moi-00145	Derived from the DUACS delayed-time altimeter gridded maps of sea level anomalies. It covers the period 1993 onwards, using a reference period of 1993-2012, provided on a 0.25° grid.
GREP	Global ocean Reanalysis Ensemble Product (https://doi.org/10.48670/moi-00024) (Storto et al. 2019)	4D reconstruction (model + assimilation of observations) of the global ocean covering the period 1993 onwards, with a 0.25° horizontal resolution.
Seasonal Forecast Systems Available via the C3S Store (DOI: 10.24381/cds.68dd14c3)		
ECMWF-SEAS5	Ensemble size: 51; Forecast Period: 7; Atm. Model: IFS; Atm. Model Res.: 36 km; Ocean Model: NEMO v3.4; Ocean Model Res.: 0.25°; Ocean Model Vertical Levels: 75.	
CMCC-SPS3/3.5	Ensemble size: 40; Forecast Period: 6; Atm. Model: CAM; Atm. Model Res.: 0.5°; Ocean Model: NEMO v3.4; Ocean Model Res.: 0.25°; Ocean Model Vertical Levels: 50.	

2.2. User-relevant indicators

Ocean indicators are tools used to monitor the state and health of the marine environment. They consist of maps, time series or trends of essential ocean and climate variables. More complex analyses of these variables, such as identification of extreme events, are also indicators. The Copernicus Marine Environment Monitoring Service[5] (CMEMS) provides dozens of indicators of European seas and the global ocean. They are derived from a range of historical climate data records (e.g., in-situ data, satellite-derived products, reanalyses) and provide a comprehensive view of the ocean of the last few decades. Past variability and trends in the marine environment are important not just for scientific understanding but also for economic, recreational and conservation activities (von Schuckmann et al. 2021). Accurate prediction of future changes to indicators is equally important and is the focus of this deliverable.

How have we picked "user-relevant" indicators? We have adopted three approaches to this question, each of which is covered in the following sections. Firstly, we have employed a stakeholder engagement strategy to understand what potential users consider relevant to their activities (Section 2). Secondly, we produce time series of SST, OHC & SSH for regions in which crucial marine activities occur; examples include the Eastern Boundary Upwelling Systems (EBUS) where nutrient productivity drives thriving fishing industries (Pauly and Christensen 1995)(Section 2). Lastly, we focus on a particular marine phenomenon which causes

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[5] https://marine.copernicus.eu/access-data/ocean-monitoring-indicators

huge ecological and economic damage across the globe, namely marine heat waves (Smith et al. 2022) (Section 3).

2.3. Aims

The aims of this deliverable are both scientific and stakeholder-orientated, and are to:

- Verify the forecast indicator based on past performance, calibrating where necessary and comparing different forecast systems when possible
- Expand on existing validation methods by testing the skill of new and marine-specific indicators
- Design and test user-relevant and user-defined products
- Demonstrate the end-to-end connection from climate and seasonal forecast products to a wide variety of stakeholders

3. Stakeholder engagement and user-needs

3.1. Communicating and visualising forecasts and forecast skill

Understanding the skill of a seasonal forecasting system requires much information which must be carefully communicated to potential stakeholders. The crucial first step is to communicate the skill of the system, which is quantified in a step known as “validation”. Validation involves comparing seasonal forecasts of past years (re-forecasts or hindcasts) with the “true” ocean state of this target period. To validate over a global scale for a period which covers the seasonal forecast period (in this case, 1993 onwards), climate data records are required. For surface variables like SST and SSH, satellite-derived products (Good S.A.; Embury 2019) are the best and most widely used options. For subsurface variables (e.g., OHC), a 4D reconstruction of the ocean, known as a reanalysis, must be used; reanalysis are models which assimilate in-situ and satellite data to provide the most realistic recreation possible. Table 1 introduces the validation datasets used here.

Moreover, for each start date, an ensemble of re-forecasts is provided. As there are uncertainties in the initial conditions used to initiate the forecasts, many forecasts are run using slight perturbations to the initial conditions to represent these uncertainties. The ensemble, therefore, represents the corresponding error in forecasts. Often, the ensemble mean is used, to cancel out individual errors in ensemble members. Table 1 lists the ensemble size and model configurations for the two forecast systems used here. A more detailed explanation and presentation of forecast validation and metrics can be found in D4.3 and D4.6.

Presenting a forecast to stakeholders means also conveying information on the forecast ensemble and the skill relative to validation data. Climagrams are a way to present an ensemble forecast with additional information about the climatology of the forecast model for context. Figure 1 shows an example of area-averaged SST forecasts for the Nino 3.4 region, a standard indicator for monitoring the El Nino Southern Oscillation (ENSO) phenomenon. The ensemble forecast is initialized on 1st May 2015 and predicts strong warming of SSTs over the subsequent 7 months (forecast distribution plotted in orange). The distribution of the forecast ensemble is clearly extreme with respect to the climatology of the forecasts (distribution shown in blue). Since this example is a hindcast, the climagram also includes observed SSTs which confirm that this was a successful forecast of the strong El Nino event of 2015/16 (see figure legend for details on the climagram).

While the climagram compactly conveys information about a single forecast start date, the Receiver-operator-curve (ROC) diagram is a way to visualize statistics of the forecasts of certain events (typically defined by crossing a certain percentile). The ROC diagram plots false positive against the true positive rates of occurrence of the event in question, where each point on the diagram represents this ratio for a given forecast probability. The diagonal represents the line of no skill (where false and true positive rates are equal). The ROC curve of a skilful ensemble system is expected to lie over the diagonal, and the area under the computed ROC curve (AUC) is often used as a metric to quantify the performance of the forecast system (AUC of the diagonal is 0.5). Figure 1 shows the ROC curve for extreme El Nino events (SSTs in Nino 3.4 exceeding the 90th percentile) over lead months 1-3 of forecasts initialized in May. The forecasts are clearly skilful, with an AUC of 0.99.

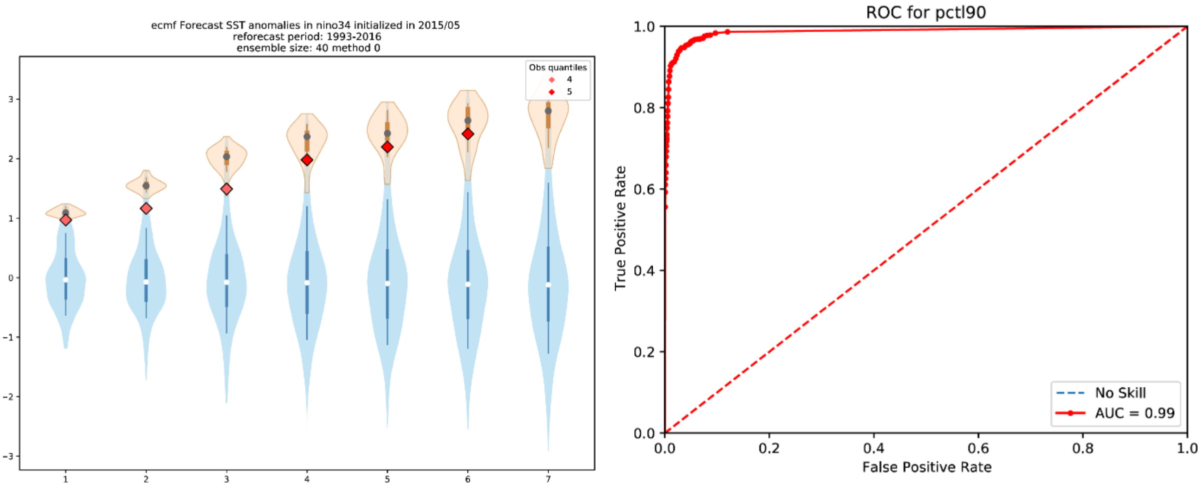

Figure 1. Visualising forecast ensemble information and skill. Left: climagram for forecasts of SST in the Nino 3.4 region initialized on 1st May 2015 as a function of lead time (x-axis). The forecast ensemble is shown in orange, with the thick line indicating the middle tercile, the thin line the lower and upper decile, and the shading the estimated distribution of the forecast. The median of the forecast is shown with green dots. The forecast climatology (i.e., the distribution of all forecasts initialized on 1st May 1993-2016), is shown in blue (median represented by white dots). The diamonds represent observed SSTs in 2015, with colour indicating the quintile w.r.t. observation climatology. Right: ROC diagram for forecasts of the 90th percentile of SST in the Nino 3.4 region, initialized in May 1993-2016.

3.2. Preliminary stakeholder discussions

Prior to developing a stakeholder engagement strategy, EuroSea collaborators from CMCC presented marine seasonal forecasting activity to representatives of the *Istituto superiore per la protezione e la ricerca ambientale* (Italian Institute for Environmental Protection and Research, ISPRA). The focus of the discussions was to identify how seasonal forecasting of SST and OHC might benefit the aquaculture industry, in Italy and the Mediterranean basin. Initially, they suggested other variables might be of more use; for example, wave activity forecasts would indicate when nets would be most susceptible to damage. However, they did not rule out that temperature-related variables would be useful and shared with us examples of mass mortality in aquaculture farms in Italian waters which were linked to warmer-than-average conditions.

3.3. Stakeholder engagement strategy: surveys on seasonal forecasting knowledge and adoption

We found two immediate issues to deal with when beginning marine stakeholder engagement. First, we had to initiate interactions with target sectors of stakeholders and individual companies/activities. Then, we had to understand their knowledge of seasonal forecasting as well as their concerns and needs. To begin tackling both issues simultaneously, we chose to send out a survey to networks and associations which represent the chosen sectors. The aim was that the survey would bring seasonal forecasting to the attention of the targets and bridge the gap between their needs and our expertise.

We targeted two sectors we believed would benefit from seasonal forecasts: marine protected areas (MPAs) and the aquaculture industry. The surveys sent out to each sector were nearly identical in content but differed in wording (e.g., “marine protected area” changed to “area of operations”)[6][7]. In both cases, the survey aimed to:

- demonstrate the potential for forecasts of the marine environment
- understand concerns, needs and targets
- directly contact the potential users
- identify indicators and products that are directly tailored to the needs and requirements of their activities
- begin the process of co-developing these products

The survey features an introductory page explaining our aims, while the main part was split into 4 sections:

(1) Describe your MPA/area of operations
(2) An introduction to EuroSea’s work on marine seasonal forecasting
(3) Marine phenomena of interest
(4) Tools for monitoring and predicting the environment – what do you use?

The second section (“An introduction to EuroSea’s work on marine seasonal forecasting”) included an example forecast of SST in the Mediterranean Sea during the summer of 2015 (Figure 2). This period was chosen because of the occurrence of mass mortality of mussels in the Gulf of Taranto (Section 2.2). The seasonal forecasts made in May 2015 correctly predicted the spread across the Mediterranean and the exceptional nature of this event (Figure 2). Highlighting one encouraging example, however, is not sufficient to gain stakeholder trust. It is also necessary to quantify the skill of predictions over a longer time period. We included the correlation skill score of OHC 0-40 m between CMCC-SPS3.5 and GREP, to highlight how skill decreases throughout the forecast period (Figure 3). We chose OHC 0-40 m with the aim of proposing this new indicator to stakeholders (see Section 4 for its application to marine heat waves). In the example shown for forecasts initiated in May, forecast skill decays to statistically insignificant values in parts of the western Mediterranean within 2 months (Figure 3). This behaviour is expected, as SST and several atmospheric variables are more predictable in the eastern part of Mediterranean Sea than in the western part (Deliverable 4.6; Calì Quaglia et al. 2022).

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[6] https://www.surveymonkey.com/r/CMCCsurvey4aquaculture

[7] https://www.surveymonkey.com/r/CMCCsurveyMPAs

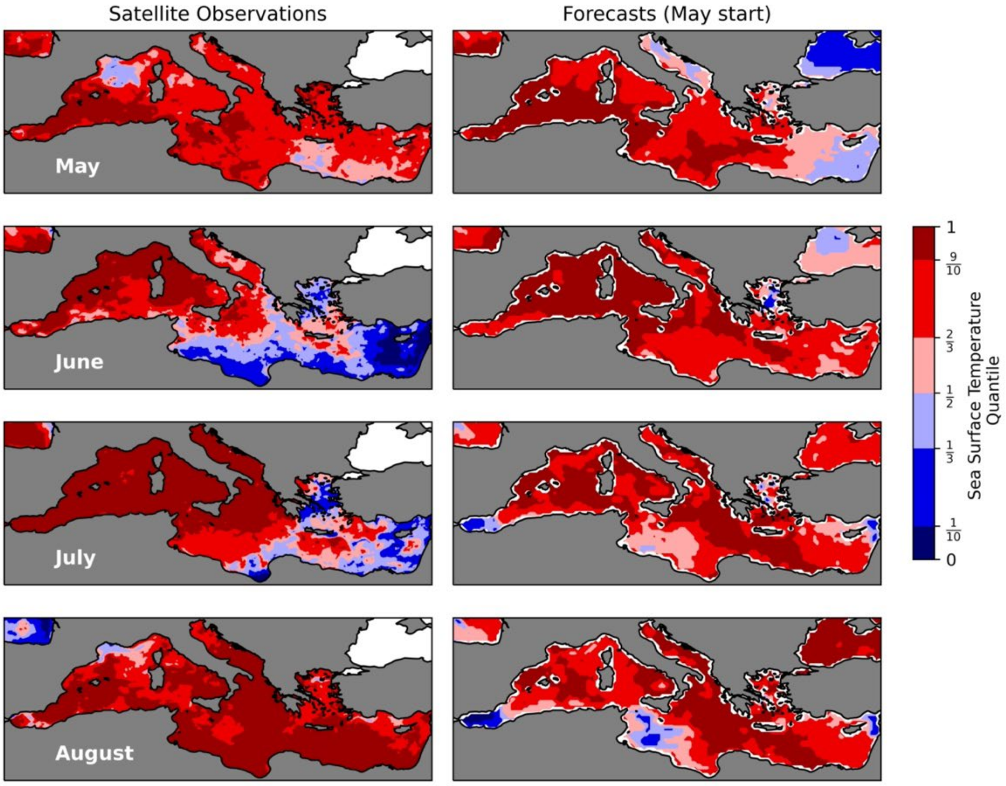

Figure 2. SST in the Mediterranean Sea in the summer of 2015. Satellite observations (left) show exceptional temperatures spreading throughout the Mediterranean Sea during the summer (May to August). The temperature quantile shows how exceptional each month was compared to the long-term monthly climatology: for example, between 9/10 and 1 (dark red) shows where the 2015 temperature was in the upper 10% of monthly-averaged temperatures experienced.

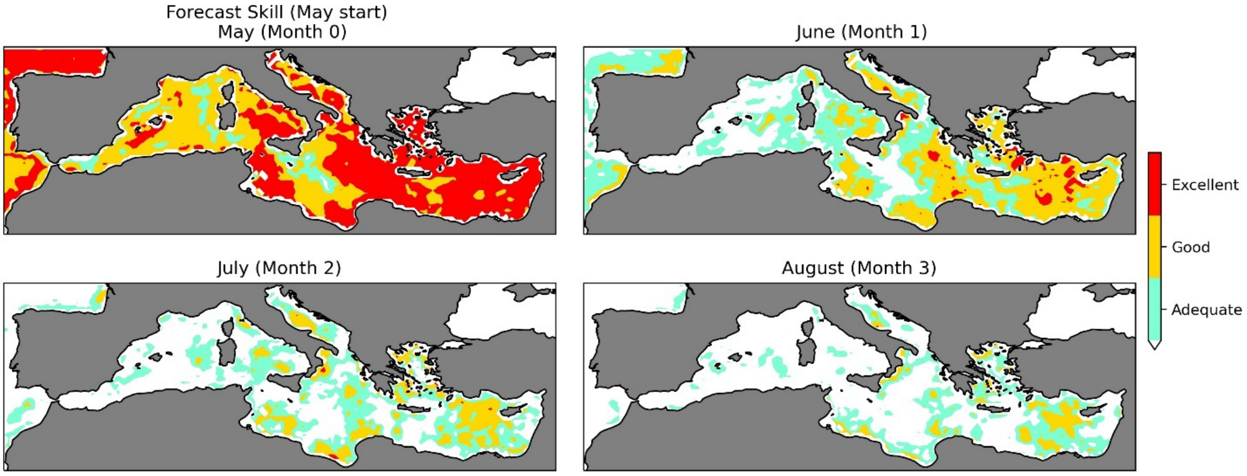

Figure 3. Forecast skill of OHC 0-40m in the Mediterranean Sea. CMCC-SPS3.5 is validated against GREP. Skill is quantified here by measuring the correlation between forecasts and observations; forecast anomalies (differences compared to average conditions) are compared to the anomalies which were observed to take place (over the 1993-2016 period).

First, the survey was sent out to individual MPAs (with whom collaborators at the CMCC had previous contact) and shared on social media through the CMCC's Facebook, Twitter and Instagram pages. MedPan, a network of Mediterranean-based MPAs, was also contacted to help disseminate the survey. Unfortunately, this means of dissemination proved to be ineffective. We received no response from email requests, and social media only led to one survey response.

Engagement with the aquaculture sector was approached differently and was more successful. In September 2022, CMCC and ISPRA collaborators presented a poster on EuroSea seasonal forecasting activities at the annual European Aquaculture Society Conference in Rimini, Italy. It was already clear from the conference content that the physical variables forecast by our systems, such as temperature, salinity, and sea level, provide vital information to the planning and running of aquaculture farms. Contact was made with two organisations representing aquaculture farms in Europe and the Mediterranean Sea, who shared our survey through their networks. Given the proximity to the release of this deliverable, we do not yet have enough results to analyse in a statistical manner. However, initial responses already provide information which can direct our effort to make user-relevant indicators.

Here we list some examples of feedback and how each example might affect our future development of seasonal forecasts. First, extremes of physical stressors (e.g., high temperature) seem to be considered as much of a concern as extreme biological stressors (e.g., algal blooms). The current state-of-the-art of seasonal forecasting does not include a biochemical component. However, there exist correlations between physical variables and biological indicators in some cases (e.g., between temperature and chlorophyll), which may be exploited to provide proxy indicators. Next, depths of interest cover the range of aquaculture nets, typically 5-15 m. It may be more useful to explore forecasts of subsurface conditions and rely less on SST as a key indicator. Lastly, there are also concerns about the funds and expertise at the micro-enterprise level (i.e., individual fish farms) which is required to maintain prototype services. Forecasting centres would therefore have to work with regional/continental representative bodies, rather than directly with farms.

As previously stated, although the following sections cover indicators which are known to be useful to a wide range of sectors and applications, they have not been co-designed with the target stakeholders described here. However, we strongly believe that the feedback received, and the lessons learnt will become a key legacy of EuroSea and will focus on future seasonal forecasting activities and research. We will return to this point in Section 5. The indicators described in the following sections are, however, of known interest to the target stakeholders and more.

4. Ocean Climate Indicators

The use of indicators aims at making the output of seasonal forecasts more accessible to users, and to communicate ideas behind probabilistic forecasts in terms of skill and uncertainty. The approach followed here is relatively simple: To define a series of area-averaged indices, which can be easily verifiable by targeting a reduced number of sectorial applications. The following sectorial applications have been identified:

- Seasonal Forecasts of atmospheric variables. (**SF**)
- Climate Variability and Change: changes in circulation, heat absorption, and sea level change. (**CVC**)
- Coastal Sea Level Change (**CSL**)
- Marine Health: large-scale conditioner for Marine heat waves (**MH**)
- Marine Productivity: upwelling regions (**MP**)

The definition and calculation of indicators were provided in deliverable D4.3. For completeness, their names, coordinates, and relevance for applications are provided in Tables A1-5 of the Appendix. The probabilistic skill of the seasonal forecasts, in terms of AUC for the different percentiles, is also given in Figures A1-3, for SST, OHC and SSH. Overall, the seasonal forecasts have positive values of AUC for all the initialization times at both 1 and 2 seasons ahead. This means that they outperform the climatological information. In what follows we discuss specific examples.

4.1. Marine Productivity: Upwelling regions

The set of indicators include some major upwelling areas, such as the Canary and Benguela upwelling systems in the Atlantic, Northern/Southern Californian and the Humboldt upwelling systems in the Pacific. Instead of vertical velocity, which is difficult to validate, we use temperature-related variables (SST and OHC), since the chlorophyll and nutrients depend on temperature, and in turn temperature variations are highly influenced by upwelling.

The relevance of the seasonal forecast information depends on its skill and timeliness. Decision makers may need the information for some specific seasons only. In addition, the decisions needed in preparation for a productive season (e.g., cold events in the case of an upwelling region may imply mobilization of the fleet) is likely to be of different nature than for the preparation for a poor season (e.g., warm events may require additional regulations on quotas). To cater for these needs, the different categories of outcomes have been verified: extreme cold (10th percentile: lowest 10% of the climate distribution), cold (lower tercile: lowest 33.3 %), warm (upper tercile, warmest 33.3%) and extreme warm (90th percentile: warmest 10%). The probability offered for these different categories by the ensemble of seasonal forecasts has been verified, using the Area Under the Curve (AUC) of Relative Operating Characteristics, for the different initialization times (February, May, August, and November) verifying at 1 and 2 seasons ahead.

These results for the upwelling indicators are illustrated in Figure 4, which shows the AUC of the forecasts compared with the climatological values (which have an AUC of 0.5). Thus, the positive values in Figure 4 imply that the forecast information is more skilful than climatology. A perfect forecast would have a value of 0.5. The seasonal forecasts beat the climatology for all starting dates, verification seasons and percentiles. The skill in the first season is, as expected, greater than in the second season. While in the first season the skill is relatively uniform across percentiles, in the second season the skill is more dependent on the forecast category and initial conditions. For instance, large values of AUC for SST forecasts over the CANAYC region initialized in November verifying in FMA. The skill in both SST and OHC is consistently high.

Although the skill scores are important for quantifying skill and objectively feeding cost-loss ratio models (Richardson 2001) used for decision-making, it is also important for the user to build up expertise on information from individual seasonal forecasts. Figure 5 shows two individual examples of seasonal forecasts for the ECMWF model from the Canary area (CANARYC). The left panel shows forecasts initialized in May 2010. In this case, the three variables SST, OHC and SSH show probabilities of high values for the three quantities for all forecast ranges, which are verified by the observations. The right panels show the case of forecasts initialized in May 2013. In this case, the SST values (both forecast and observations) decay quickly after the first month, while the values for OHC and SSH remain high, signalling that the cooling is relatively shallow; such information is relevant for fisheries which deal with a range of ocean depths.

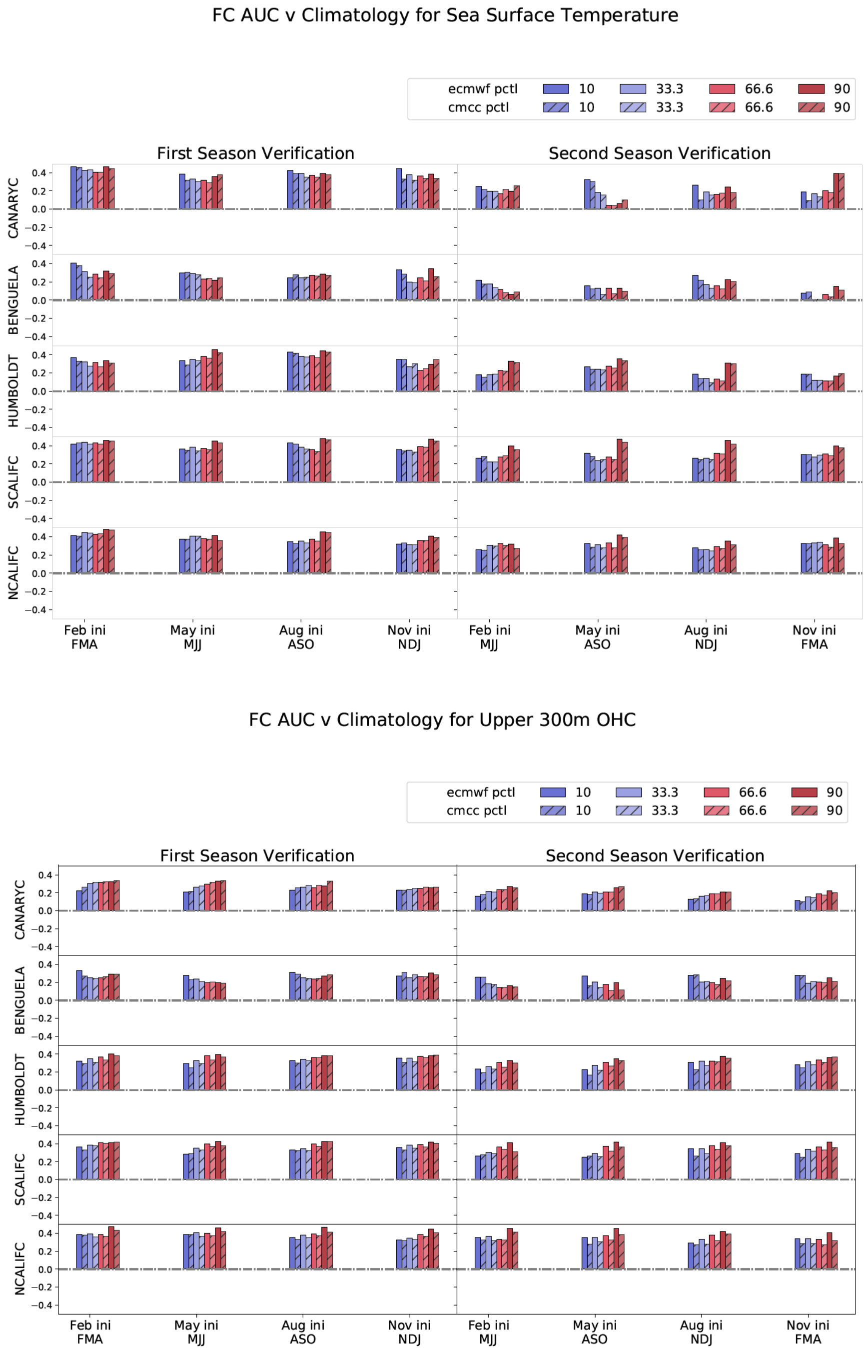

Figure 4. Summary of probabilistic skill for the Upwelling Areas. Shown is the AUC skill of ECMWF (plain bars) and CMCC (stapled) compared with climatology, for SST (left) and OHC (right). The forecasts have been evaluated for different categories (extreme cold, cold, warm, extreme warm, see text for explanation). The skill is shown for forecasts verifying 1 and 2 seasons ahead, and for the different initialization times. Positive values indicate that the forecasts are better than climatology. In this score, a perfect forecast would have a value of 0.5. The skill has been estimated for the period 1993-2016.

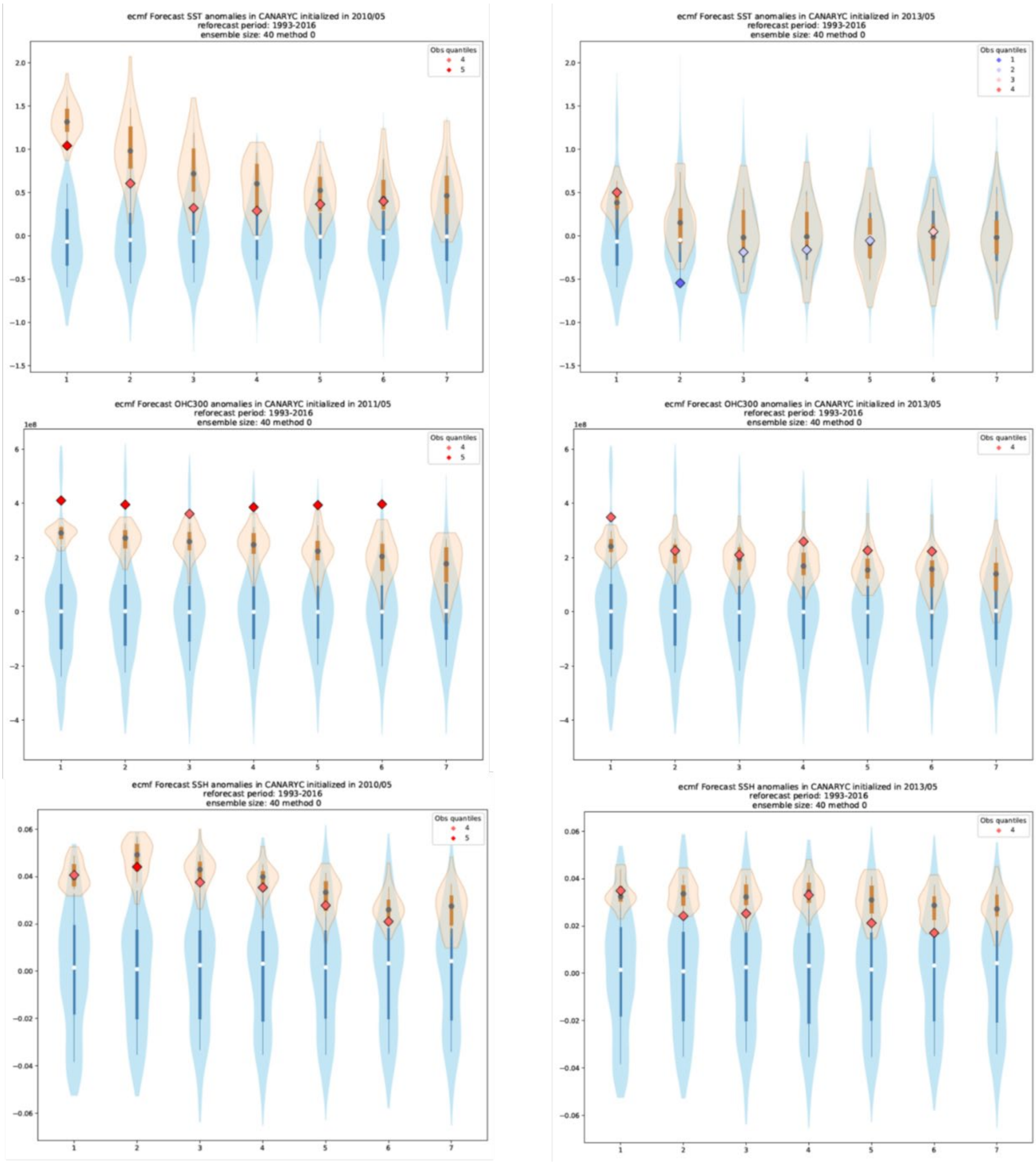

Figure 5. Climagrams for the Canary Upwelling Region, from ECMWF forecast initialized in May 2010 (left) and 2013 (right). The figures show forecasts of SST (top), OHC (middle) and SSH (centre). The blue violins represent the pdf of model climatology, and the orange violins represent the distribution of the specific forecasts, with the tercile/quintile range represented by thick/thin bars, and the ensemble mean by the circles. The verifying observations are shown by the diamonds, which colour represents the quantile category (red representing the upper quintile). The forecast spread is larger for SST than for OHC/SST. In 2010 the three variables indicate the occurrence of extreme warm anomalies, while in 2013 the OHC/SSH remain high while the SST cools down early in the forecast.

4.2. Sea Level Change

Sea level rise has serious implications for populations living in low-level coastal areas, increasing the risk of flooding. In addition, there are areas where the sea level is rising faster than average. This is the case in the Caribbean, with an average increase of 3.6 mm per year, between 1993-2020 (WMO report -1272, 2021[8]). In these areas, interannual climate fluctuations that affect the sea level on top of the climate trend can have a damaging impact on human activities, and seasonal forecasts of these hazards can be useful as an early warning system for preparedness.

The ability of seasonal forecasts to predict fluctuations in sea level has been evaluated, and results show that it compares favourably to climatology (see scores in Figure A 3 of the Appendix). Figure 6 shows examples of climagrams for the Caribbean region from ECMWF and CMCC seasonal forecasts initialized in November 2013. The forecasts, which start from relatively neutral initial conditions, successfully capture the increase in sea level in the subsequent months.

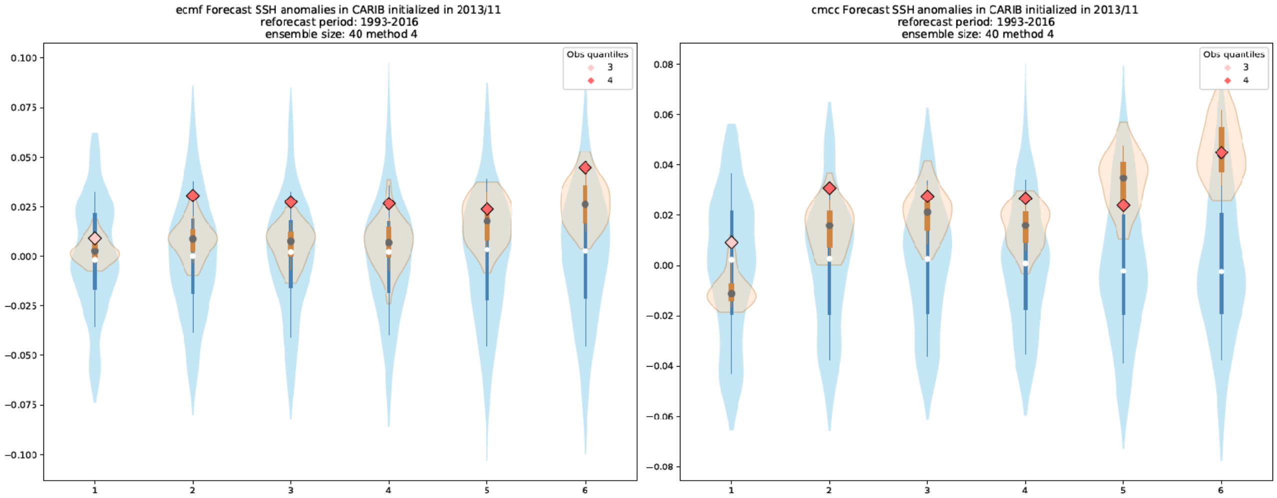

Figure 6. Climagrams for SSH in the Caribbean region. The figures show forecasts of SSH from ECMWF (left) and CMCC (right), initialized in November 2013. The blue violins represent the pdf of model climatology, and the orange violins represent the distribution of the specific forecasts, with the tercile/quintile range represented by thick/thin bars, and the ensemble mean by the circles. The verifying observations are shown by the diamonds, which colour represents the quantile category (red representing the upper quintile). Both models, starting from relatively neutral conditions, successfully capture the increase of the SSH during the subsequent months.

4.3. Climate Variability

Several EuroSea indicators target Climate Variability and Change. In addition to well-established indicators such as Nino3.4 or the Indian Ocean Dipole, we have also defined indicators specific to the Atlantic basin. Figure 7 shows the AUC scores of the seasonal forecasts compared to climatology for the tropical Atlantic basin climate indicators for SST and OHC. It shows that the seasonal forecasts are more skilful than climatology for all initial dates and verifying seasons. Among them are the Caribbean area and the Mean Development Region (MDR) in the central subtropical Atlantic, which are relevant for tropical cyclone prediction.

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[8] https://library.wmo.int/index.php?lvl=notice_display&id=21926#.Y1o--C8RqWa

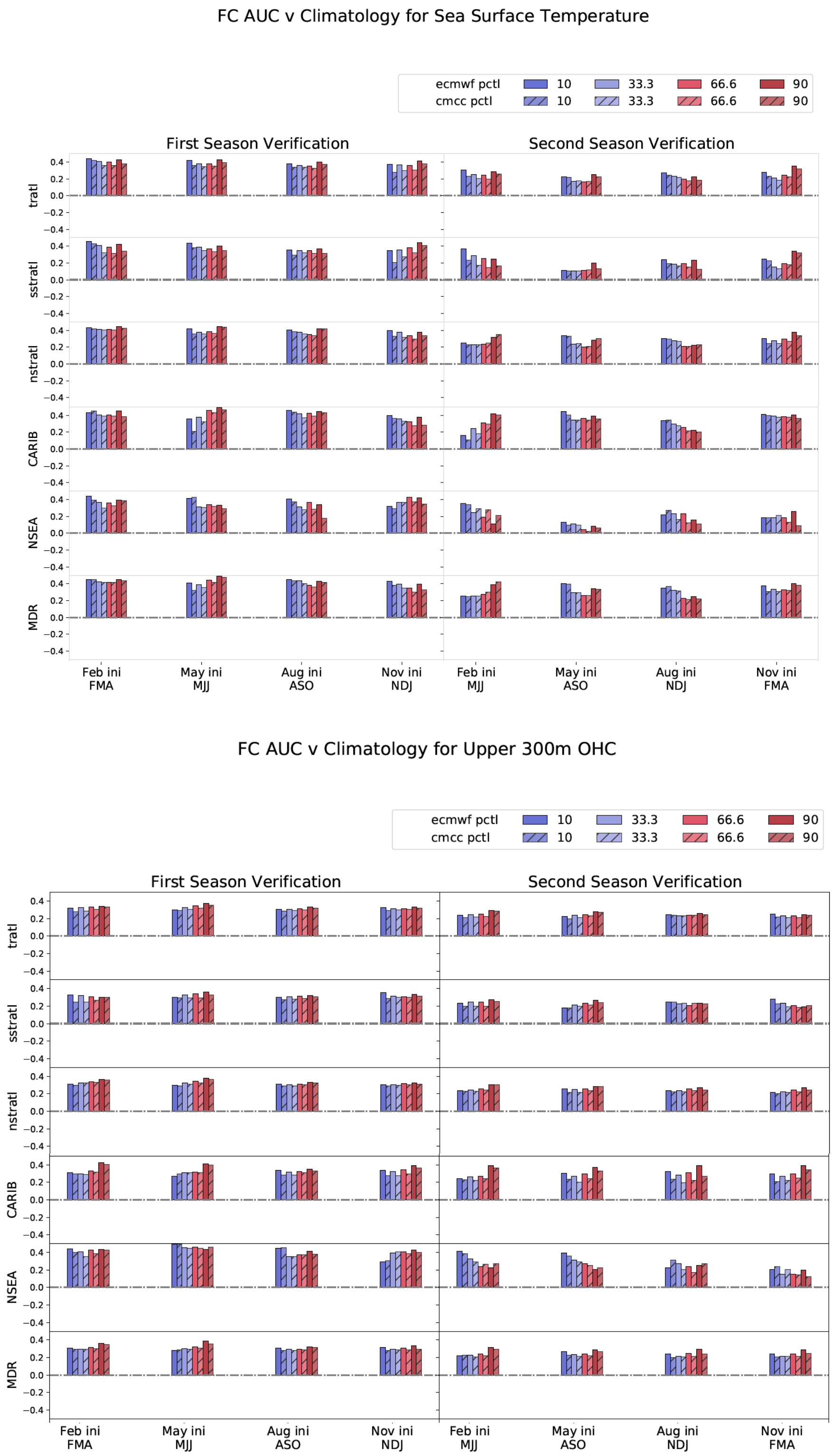

Figure 7. Summary of probabilistic skill for the CVC indicators over the Tropical Atlantic. Shown is the AUC skill of ECMWF (plain bars) and CMCC (stapled) compared with climatology, for SST (left) and OHC (right). The forecasts have been evaluated for different categories (extreme cold, cold, warm, extreme warm, see text for explanation). The skill is shown for forecasts verifying 1 and 2 seasons ahead, and for the different initialization times. Positive values indicate that the forecasts are better than climatology. In this score, a perfect forecast would have a value of 0.5. The skill has been estimated for the period 1993-2016.

Figure 8 shows an example of a prediction for the SST over the Caribbean. It corresponds to predictions of SST in forecasts initialized in May 2010. 2010 was one of the most active seasons for tropical cyclone activity in the Atlantic, with 19 named tropical storms (12 of which were classified as hurricanes). The 2010 season also started unusually early, with hurricane Alex[9] making its appearance in June. The activity in 2010 was heightened due to a very strong La Niña[10] in the Pacific. Because hurricanes rely on warm water to release heat into the upper atmosphere, any additional energy coming from local SST warming can result in increased intensity. The figure shows that the Caribbean was unusually warm during this season, and the forecasts were able to successfully capture these unusual conditions.

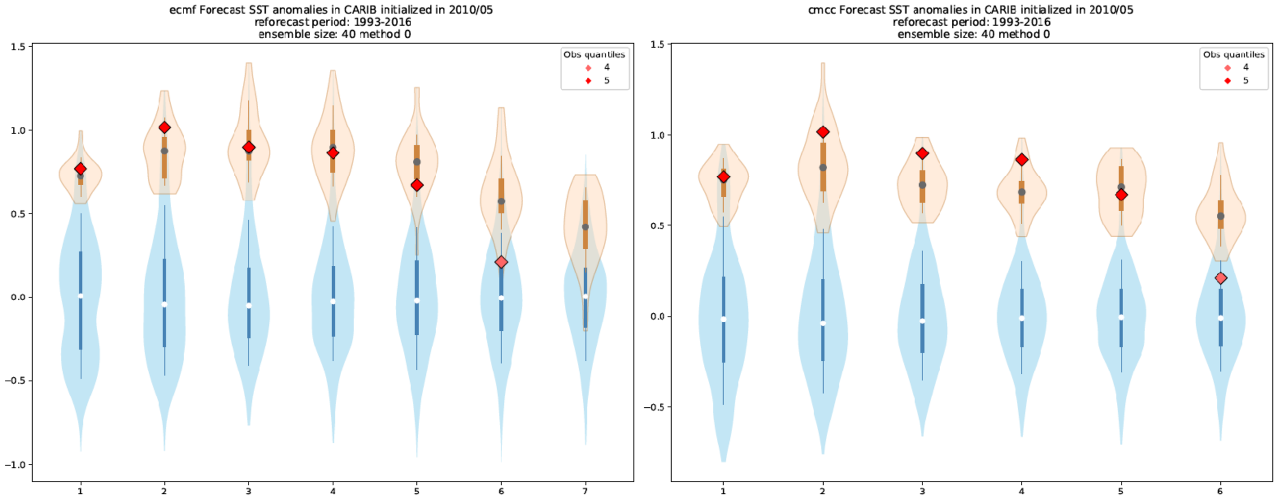

Figure 8. Climagrams for SST in the Caribbean region, for forecasts initialized in May 2010.

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[9] https://en.wikipedia.org/wiki/Hurricane_Alex_(2010)

[10] https://en.wikipedia.org/wiki/2010–2012_La_Niña_event

5. Marine Heat Waves & Cold Spells

Marine heat waves (MHWs) are defined as temperature conditions above a certain threshold which last for 5 days or longer (Hobday et al. 2016). Since their first formal scientific definition in 2016, scientific literature has determined the most severe and long-lasting events (Oliver et al. 2021), presented in detail regional characteristics (Juza et al. 2022), identified potential physical drivers (sen Gupta et al. 2020), studied impacts on marine wildlife (Garrabou et al. 2022; Smith et al. 2022) and ocean processes (Mignot et al. 2022), and begun to assess the ability of various forecasting systems to predict their occurrence (Jacox et al. 2022).

Within EuroSea, MHWs factor into many actives, such as including MHW-tracking in the design of new observational platforms and networks, and tailored aquaculture farm monitoring (Deliverable 6.1). A cross-work package collaboration has led to detailed regional and local analyses of MHW characteristics across the Mediterranean basin (Dayan et al. 2022). Meanwhile, public awareness of their occurrence and potential impacts has also begun to grow; in the summer of 2022, several EuroSea scientists shared their expertise on MHWs in various European media outlets[11][12][13][14].

Given their potentially devastating impact on marine ecosystems and industries, we gave a particular focus to MHWs in our seasonal forecast validation work. MHWs can be considered a cross-cutting indicator in many ways, as their occurrence impacts many temporal and spatial scales, and motivates various ocean sciences, from the physical to the biological. Meanwhile, the development of MHW prediction tools is an urgent and ongoing task for research institutions across the globe (Caputi et al. 2016; Liu et al. 2018; Jacox et al. 2022). Thus, there are many justifications to focus heavily on this specific indicator.

Here, we present: (1) an introduction to the definition of this indicator; (2) a case study using CMEMS and C3S products to monitor and forecast a long-lasting MHW which occurred in the North Pacific in 2020; (3) a comparison of the forecast skill of surface and subsurface MHWs; (4) a look at the skill of marine cold spells.

5.1. Definition of MHW indicators

The definition of the marine heat wave indicator is flexible. In practice, the "indicator" consists of information on event duration and intensity, or on cumulative metrics over a target time frame (i.e., number of MHW events or days over a summer). Moreover, the parameter used to define MHWs differ. First, the climatology period, against which MHWs are detected, differs from study to study based on the period of interest of the availability of data (Oliver et al. 2021). Then, the threshold used to define MHWs may be statistical (based on the 90th percentile, as used widely in the literature) or correspond to species-specific thermal tolerances (Galli et al. 2017a). As a result, there is no strict definition for the MHW indicator.

Seasonal forecast systems are not built to predict the precise conditions on particular days, but instead, capture average conditions over timescales from months to seasons. In this context, we do not propose to

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[11] https://www.bloomberg.com/news/articles/2022-06-29/how-extreme-heat-impacts-sea-temperatures?sref=FUtuEW8l

[12] https://www.ilpost.it/2022/06/28/estate-2003-caldo/

[13] https://www.repubblica.it/green-and-blue/2022/07/02/news/caldo_mare_effetti_taranto-356183802/?ref=RHVS-VS-I271182744-P3-S5-T1

[14] www.lemonde.fr/planete/article/2022/07/29/en-mediterranee-la-canicule-marine-accelere-le-remplacement-des-especes_6136530_3244.html

use seasonal forecasts to depict precise onset, peak and decay times of individual events. Instead, we aim to predict the propensity for MHW occurrence (Prodhomme et al. 2022). Specifically, we propose and use two MHW indicators, inspired by work on atmospheric heat waves:

- number of marine heatwave days
- strongest intensity event

Both indicators correspond to a particular time period i.e., the summer period in the Northern Hemisphere from May to September.

5.2. Case Study: North Pacific Ocean 2020

Recent NOAA ecosystem assessment reports (Ferriss and Zador 2021; Harvey et al. 2021) showed that the second largest marine heatwave observed in the North Pacific occurred in 2020 with subsequent signs of habitat compression, harmful algal blooms and changes in population types and local species behaviours. EuroSea partners provided a case study for the Copernicus Ocean State Report 7 on the representation of this MHW event in the ECMWF ocean reanalysis system (Zuo et al. 2019) and its predictability in the seasonal forecast system ECMWF-SEAS5 (Johnson et al. 2019). This event took place in a North-Eastern Pacific region that was previously affected by ‘the Blob’, a long-lasting event off the west coast of North America and Alaska over the 2014–16 period that decimated populations of Pacific cod, seabirds, salmon, and other species while toxic algae prospered (Laurel and Rogers 2020; Trainer et al. 2020). The ‘Blob’ vanished in 2016 but signs of the resurgence of extremely warm conditions over the North-Eastern Pacific appeared as soon as 2018 and were confirmed by consecutive events in 2019 and 2020.

The 2020 case study showed that current ocean reanalysis systems are able to capture MHW events and accurately reproduce their observed characteristics (Figure 9). This study also provides first-order verifications of the ECMWF seasonal ensemble predictions of MHW properties for the spring, summer and autumn seasons in the forecast range from 1 to 4 months. The ocean reanalysis showed that 2020 has the highest number of MHW days of the past 10 years in the North-Eastern Pacific. The seasonal predictions showed skill in predicting both number of MHW days and intensity, in particular of the most intense phase of the event in summer and autumn (Figure 10a, b). Forecast probabilities of the occurrence of the 2020 MHW events are the highest for the summer season (Figure 10c) when the upper ocean is already preconditioned by the late spring warm SST anomalies (Figure 9b).

The time series of MHW properties over the past 10 years highlight both the long-lasting ‘Blob’ and the intense recent events in 2019 and 2020 (Figure 10d, e). The seasonal hindcasts show a mixed level of skill. On the one hand, the seasonal forecast missed the start of the Blob in spring 2013 and wrongly predicted a strong event in summer 2018. On the other hand, both 2019 and 2020 events are well forecasted probably because initial conditions at the air-sea interface were preconditioned for the occurrence of MHW.

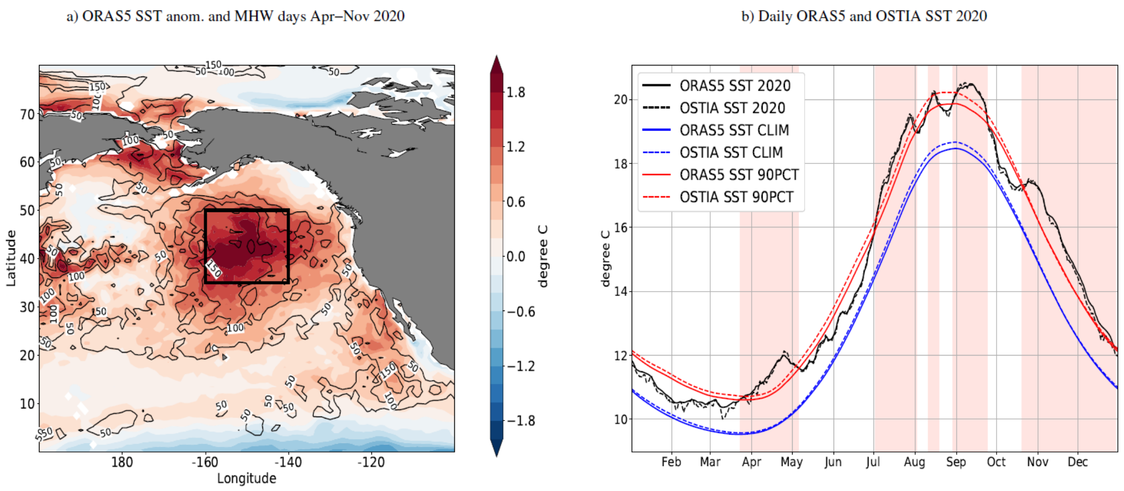


Figure 9. 2020 MHW spatial pattern and SST time series. a) corresponds to the April-November 2020 SST anomalies (wrt the 1996-2016 reference period) in the ECMWF ocean reanalysis with contour showing the total number of MHW days during that period. The warmest anomalies are located in the black-framed North-Eastern Pacific box (35-50N and 140-160W); b) corresponds to the daily 2020 SST time series (black), the daily mean (blue) and 90th percentile (red) in both ocean reanalysis (solid lines) and observations (dashed lines).

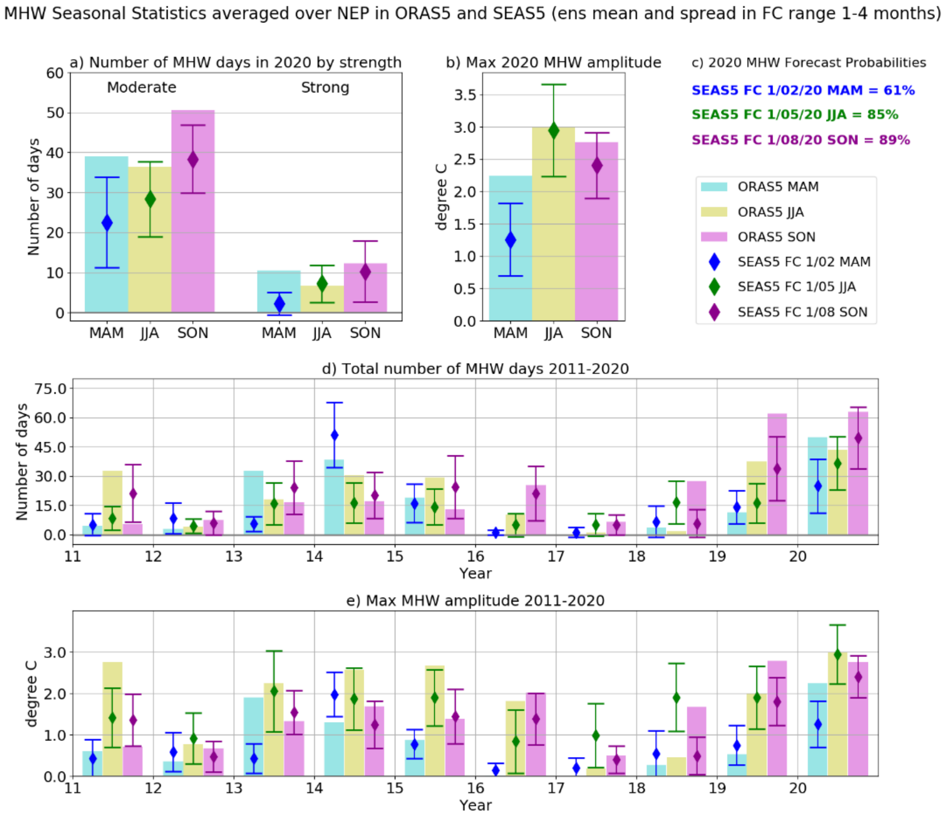


Figure 10. MHW characteristics in the North-Eastern Pacific over the 2011-2020 period in both ocean reanalysis and seasonal forecasts. a & b) correspond to the number of MHW days (discriminated by their intensity) and their maximum amplitude in the North-Eastern Pacific (35-50N and 140-160W), respectively, for the spring (MAM), summer (JJA) and autumn 2020 seasons in both ocean reanalysis (bars) and seasonal forecast ensemble mean (diamonds) and spread (errorbars); c) corresponds to seasonal forecast probabilities of MHW in spring, summer and autumn 2020; d & e) correspond to the total number of surface MHW days and their maximum amplitude in both ocean reanalysis and seasonal forecast ensemble mean and spread over the 2011-2020 period.

5.3. Global forecast skill of MHW indicators: from surface to subsurface

Marine heat waves have mostly been studied with data of the surface of the ocean due to the widespread spatial and temporal coverage of satellite-derived SST products. Such products allow us to track surface MHW events and trends over the last 3-4 decades. However, marine wildlife of all shapes and sizes, from plankton to large predators, migrates vertically through the upper ocean waters repeatedly throughout the day (Hays 2003; van Haren and Compton 2013; Andrzejaczek et al. 2019; Lavender et al. 2021). Few, if any, species, are restricted to the upper 1 cm of the ocean, which is often the range represented by satellite products. Although SST products may be indicative of near-surface conditions, subsurface manifestation and spreading of MHWs cannot be taken for granted and must be studied specifically. In this deliverable, we propose a complementary MHW indicator constructed from the ocean heat content over a target depth range.

To demonstrate the potential of this indicator, we use the upper 40m as a target depth range. The range 0-40 m covers depths frequently passed through by various species. 40 m is also deeper than the summer mixed layer depth in most of the ocean (de Boyer Montégut et al. 2004), meaning we can capture more than atmospheric-driven signals alone, and thus expect to see different characteristics from surface-defined events. In practice, different stakeholders may be interested in different depth ranges. The main caveat of using OHC is that we cannot rely on satellite or observation-based datasets (which are available but not as daily means) as we would for surface temperatures. Instead, we use the GREP ocean reanalysis.

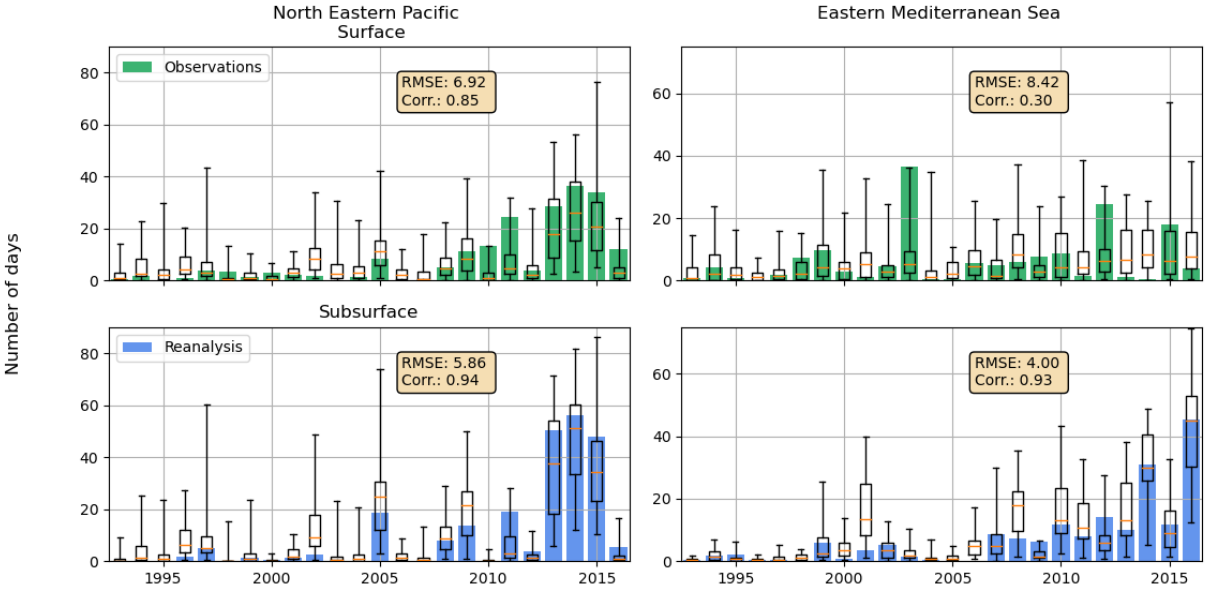


Figure 11. Record of surface and subsurface MHWs in two regions of high MHW activity. Left: the number of surface and subsurface MHW days in the North-Eastern Pacific. Right: The Eastern Mediterranean Sea. A fixed baseline climatology is used. Box plots represent the median, interquartile range, and range of the 40-member forecast ensemble. Bar charts represent either the surface MHWs in the observations (green) or the subsurface MHWs in the reanalysis (blue). The average number of days in all cells within the regions is used, including cells with zero values. Root-mean-square error (RMSE) and correlations between forecast ensemble medians and observation/reanalysis values are shown inset.

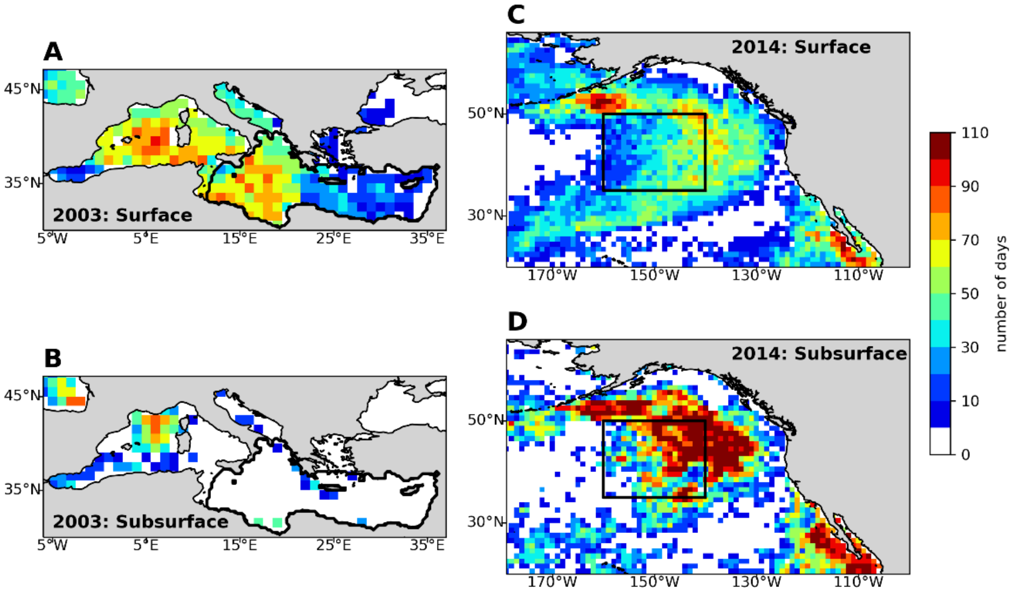


Figure 12. Examples of surface and subsurface manifestations of MHW activity. The number of MHW days during the summer months is shown for the Mediterranean Sea in 2003 (A & B) and for the North-Eastern Pacific in 2014 (C & D). Surface values are taken from observed SST (A & C), while subsurface values are taken from reanalysis (B & D). The black contours indicate the regions used for area-averaging in Figures 1 and 4.

To demonstrate how records of subsurface MHWs differ from surface records, we use two examples of regions in which occurred MHWs with noted ecological impacts: the North-Eastern Pacific and the Eastern Mediterranean Sea. In the North-Eastern Pacific, both the surface and subsurface experienced peaks of MHW days between 2013 and 2015, during the multi-annual warm anomaly known as the “Blob” (Figs. 11 & 12). Using SST alone, however, would have underestimated the amount of MHW days in those summers by roughly 50% (Figure 11 & 12).

In the Eastern Mediterranean Sea, however, the surface and subsurface MHW records do not resemble each other. In 2003 there was a peak in the number of surface MHW days relating to the infamous summer-long event (Figure 12). We find it left no signal on the subsurface indicator in the Eastern Mediterranean Sea; the subsurface signal of this event is restricted to the North-Western part of the Mediterranean Sea (Figure 12). Instead, subsurface MHWs have occurred more frequently in recent years. Thus, not only can the characteristics of events, such as duration, differ between definitions, but the occurrence can too. Surface MHWs, therefore, do not provide a complete picture of MHW activity.

Across the global ocean, the forecast skill of two MHW indicators (number of MHW days and strongest intensity) is encouragingly high for the subsurface events (Figure 13). Significant positive correlation between the forecasts and validation, for both indicators, is found in approximately 3/4 of the ocean between 60ºS and 60ºN. The tropics (between 30ºS and 30ºN) are the most skilfully predicted, with an average skill score of approximately 0.65 for both indicators. Overall, global patterns of skill resemble those of SST (Jacox et al. 2022). The forecasts system generally predicts well the interannual variability of both MHW metrics used here (strongest MHW intensity as well as the number of days).

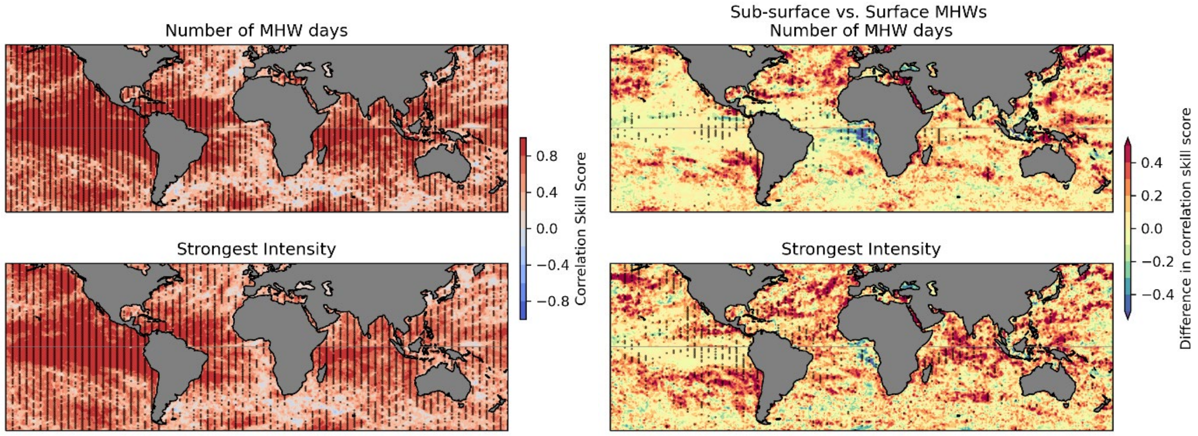


Figure 13. Improved skill of subsurface MHW Indicators. Left column: Correlation skill score between subsurface MHW indicators. Right column: Difference between subsurface and surface MHW indicator skill. Positive values in left column represent improvement in subsurface event detection. All scores correspond to the hemisphere-specific summer season and the 1993-2016 period. Black stippling indicates statistically significant correlation (left column) or differences in correlation (right column).

Subsurface MHW forecast skill is generally higher than or statistically indifferent to surface event skill (Figure 13). Scores between surface and subsurface are similar in regions where surface skill is already high, so the improvements in subsurface skill are clearest away from the tropics. In the Indian Ocean, surface forecasts display significant skill for the number of MHW days but not the strongest intensity; the subsurface forecasts display skill in both indicators. In the European seas, skill is relatively low; statistically, significant skill is found only in the eastern Mediterranean and the open Atlantic Ocean.

5.4. Cold Spells

Cold spells are characterised by temperatures which fall below the lower 10th percentile for a period of 5 consecutive days or more; they can be considered the “inverse” of MHWs. Here we present the skill of capturing cold spells in the winter months in European seas. Forecast skill varies seasonally, with changes in variability and occurrence of different phenomena. Previous studies have highlighted the greater predictability of atmospheric conditions during winter months over Europe, as the variability of atmospheric conditions is reduced, and the North Atlantic Oscillation plays a key role in modulating the European climate in these months (Scaife et al. 2014; Dunstone et al. 2016). The poor skill in capturing surface MHWs in the summer, therefore, is not indicative of poor skill in capturing extreme events in winter.

Across the North Atlantic and Mediterranean Sea, the correlation between MHW activity in CMCC-SPS3.5 forecasts and satellite observations is rarely statistically significant, indicating inadequate skill. However, correlations for winter cold spells are relatively high across the North Atlantic and the Eastern Mediterranean. Across the domain shown here, winter cold spells are more reliably predicted than summer heat waves (Figure 14). Both are extreme temperature events, but the increase in forecast capability is large and encouraging for winter-time applications.

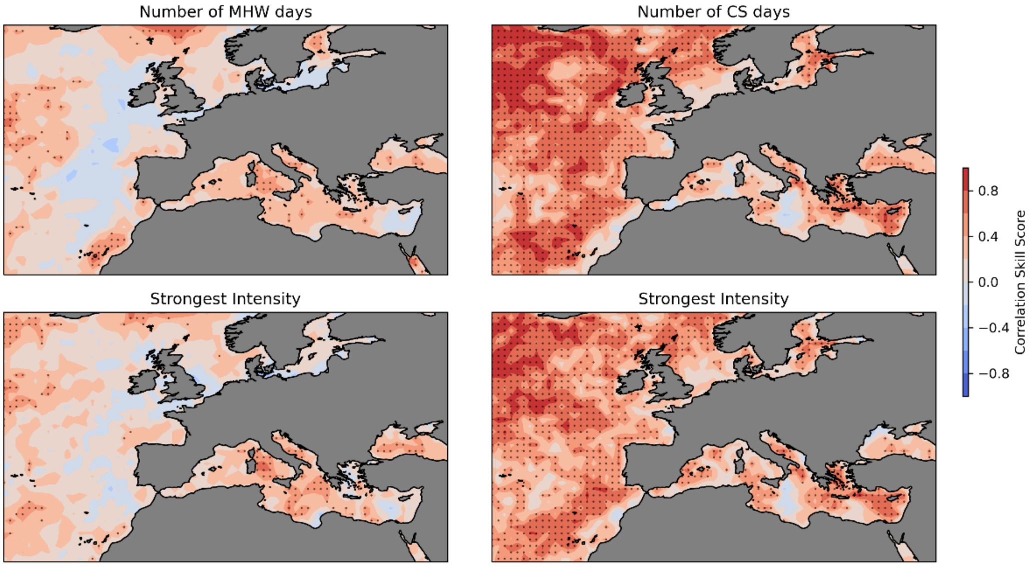


Figure 14. Skill of seasonal forecasts of surface MHWs and Cold Spells in European Seas. Black stippling indicates statistically significant correlation.

6. Conclusion and Recommendations

6.1. Main results

This deliverable has identified the seasonal forecast skill of a range of marine indicators across the global ocean. We have identified several encouraging examples of reliable indicators which may provide useful forecasts to stakeholders, while also highlighting where further progress is required. We find no reason why marine variables are overall any less predictable or useful than land-based variables, which are already adopted by a range of land-based industries such as energy production and agriculture. After all, a forecast system does not need to provide reliable forecasts everywhere and all the time to be useful and to be used. We believe this deliverable, representing the culmination of three years of work in EuroSea, is the first step in widespread adoption and use of marine seasonal forecasts.

We have shown examples of accurate individual forecasts which have the potential to aid a range of marine stakeholders: sea level rises around island nations; surface temperature increases in a region of tropical-cyclone genesis; changes in SST, SSH & OHC which imply changes to upwelling and therefore to nutrient concentrations relevant to fishing activities; long-lasting and expansive marine heat waves. These examples have communicated as concisely as possible the information needed to interpret forecasts and the anomalous nature of the target events. Employing a common diagnostic used in seasonal forecast validation, the ROC diagram, we quantified the forecast reliability for indicators in the Atlantic and across the global ocean. This extensive validation effort was not discussed in detail in this deliverable, but we hope it will be used for future studies and applications of marine seasonal forecasting.

Crucially, the two seasonal forecast systems used nearly always here outperform climatology. This is a reassuring result because it demonstrates that our dynamical systems contain valuable information about ocean processes which shape our climate and economic activities. Generally, forecast skill decays with lead time, and the indicators shown here are no exception. Forecast skill of different events (e.g., temperatures in the upper tercile), however, depends on initial conditions and seasonal variability.

A special focus was given to marine heat waves because of the increased scientific and social awareness of their destructive nature in recent years. Extreme or rare events are difficult to predict but we identified sources of skill in detecting marine heat waves. A preconditioned ocean state (in which there has recently been anomalously high warming) is more susceptible to MHWs, and the ECWMF system forecast benefitted from signals of preconditioning in its initial conditions. Moreover, using subsurface indicators for MHWs may not only be more practically useful for certain marine stakeholders but are easier to predict on seasonal timescales.

6.2. Making seasonal forecast data and indicators available

A key scientific result of EuroSea's activity on seasonal forecasting is that OHC and its derivative indicators are generally reliably forecast on seasonal timescales (McAdam et al. 2022a). Skill is high due to reduced variability on the seasonal timescale. Shallow OHC (e.g., 0-40 m) may find use for near-surface stakeholders such as fisheries and aquaculture farms, while intermediate range OHC (e.g., 0-300 m) indicate longer-term changes in ocean climate. OHC is perhaps less understood than temperature and sea level but is already a widely used indicator in oceanography and is used to communicate the profound effect of anthropogenic climate warming. SST alone describes a negligible fraction of the water column depth. Important economic and ecological activity occurs below the surface, and we believe that OHC can become a more commonplace indicator for marine stakeholders. We believe this is a strong motivation for seasonal forecasts of marine variables to be made freely available, for example via C3S or CMEMS.

The seasonal forecast output which C3S provides is produced by a range of forecasting centres which use different model configurations. All these systems are regridded to a rectangular 1° grid for sharing via C3S. This is a necessary practical step for two reasons: (1) it ensures conformity between products which have different original grid structures and (2) there are limits on how much data can be provided via online servers (the finer the resolution, the greater the size of each file). Practically, this means ocean phenomena of local areas smaller than the grid cell area are not visible to users. To appeal to a wider range of stakeholders, it will become necessary to provide forecasting data at a finer resolution which can capture local and coastal processes. The systems used here both use an ocean model with 0.25° horizontal resolution, and could, in theory, provide much higher resolution output.

Extreme event tracking tools, in particular those for MHWs, are growing in number. Copernicus has the unique position of providing historical and near-real-time data, as well as forecasts covering weekly to annual time scales. Together, these tools could be used to build a "complete" indicator or event-tracking tool on a national, continental, and global scale. We believe this Deliverable shows that seasonal indicators can and should play a big role in any such tool. A lack of awareness of products is a major obstacle to their uptake but, for example, a MHW tracking tool would be a timely, high-profile resource which could gain lots of interest in Copernicus products.

6.3. Defining and co-developing indicators

An important practical issue to highlight is that the definition of indicators may continue to be inconsistent between different studies and applications. For example, within EuroSea alone, several different groups produced MHW indicators, yet the definitions and methods of analysis all differ. The most common difference between studies is the study period, which depends on the temporal coverage of data available. For example, the GREP reanalysis begins in 1993 while satellite-derived SST extend into the 1980s. The study period affects the number of MHWs detected and the average values calculated. However, each dataset has its own merits and, as a result, we envisage that MHW research will continue without a uniform definition for the indicator. Moreover, species-specific applications will require species-specific temperature thresholds (Galli et al. 2017), as opposed to the statistical definition commonly used. The "MHW Indicator", for example, will continue to differ between future potential applications.

In EuroSea, we have ambitiously attempted to make progress along the entire value chain of seasonal forecasting, from the validation of forecasts to the creation of indicators. The progress made in producing climate services based on seasonal forecasts of land-based variables has been a benchmark for this work. The next important progression for marine applications would be to move from "user-relevant" to "user-defined" indicators, which is a level of maturity not reached during this 3-year project. In this deliverable, we have demonstrated many indicators which are, to the best of our knowledge, relevant to users. For example, we have suggested using the integrated heat of the upper 40m to define MHWs, based on the habitat and behaviour of marine life. We appreciate that such an indicator may not be useful for all stakeholders; direct engagement with fish farms has indeed informed us that shallower depths (~15 m) are more relevant to them. It will take much collaborative effort and time between stakeholders and forecast providers to achieve this.

Nonetheless, we believe EuroSea's efforts to close the loop between producers and users have been encouraging. Prior to stakeholder engagements, a solid understanding of forecast skill was necessary; the validation comprised the largest portion of the work performed for EuroSea and is vital to any future engagements. Our task, as a EuroSea “demonstrator” activity, was to propose and demonstrate new indicators. The stakeholder engagement strategy defined in this deliverable is ongoing, has already provided important feedback, and will eventually lead to sectorial applications.

References

Andrzejaczek S, Gleiss AC, Pattiaratchi CB, Meekan MG (2019) Patterns and drivers of vertical movements of the large fishes of the epipelagic. Rev Fish Biol Fish 29:335–354. https://doi.org/10.1007/s11160-019-09555-1

Calì Quaglia F, Terzago S, von Hardenberg J (2022) Temperature and precipitation seasonal forecasts over the Mediterranean region: added value compared to simple forecasting methods. Clim Dyn 58:2167–2191. https://doi.org/10.1007/s00382-021-05895-6

Caputi N, Kangas M, Denham A, et al (2016) Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot. Ecol Evol 6:3583–3593. https://doi.org/10.1002/ece3.2137

Dayan H, McAdam R, Juza M, et al (2022) Marine heat waves in the Mediterranean Sea: an assessment from the surface to the subsurface to meet national needs. In review at Frontiers in Marine Science

de Boyer Montégut C, Madec G, Fischer AS, et al (2004) Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. J Geophys Res 109:. https://doi.org/10.1029/2004JC002378

Dunstone N, Smith D, Scaife A, et al (2016) Skilful predictions of the winter North Atlantic Oscillation one year ahead. Nat Geosci 9:809–814. https://doi.org/10.1038/ngeo2824

Ferriss B, Zador S (2021) Ecosystem Status Report 2020: Gulf of Alaska. Resource Ecology and Fisheries Management, Alaska Fisheries Science Center, NOAA.

Galli G, Solidoro C, Lovato T (2017) Marine Heat Waves Hazard 3D Maps and the Risk for Low Motility Organisms in a Warming Mediterranean Sea. Front Mar Sci 4

Garrabou J, Gómez-Gras D, Medrano A, et al (2022) Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. Glob Change Biol n/a: https://doi.org/10.1111/gcb.16301

Good S.A.; Embury O; BCE; MJ (2019) ESA Sea Surface Temperature Climate Change Initiative (SST_cci): Level 4 Analysis Climate Data Record, version 2.1. Centre for Environmental Data Analysis, 22 August 2019. https://doi.org/doi:10.5285/62c0f97b1eac4e0197a674870afe1ee6.

Harvey CJ, Garfield NT, Williams GD, Tolimieri N (2021) CALIFORNIA CURRENT INTEGRATED ECOSYSTEM ASSESSMENT (CCIEA)CALIFORNIA CURRENT ECOSYSTEM STATUS REPORT, 2021

Hays GC (2003) A review of the adaptive significance and ecosystem consequences of zooplankton diel vertical migrations. In: Jones MB, Ingólfsson A, Ólafsson E, et al. (eds) Migrations and Dispersal of Marine Organisms. Springer Netherlands, Dordrecht, pp 163–170

Hobday AJ, Alexander L v, Perkins SE, et al (2016) A hierarchical approach to defining marine heatwaves. Prog Oceanogr 141:227–238. https://doi.org/10.1016/j.pocean.2015.12.014

Jacox MG, Alexander MA, Amaya D, et al (2022) Global seasonal forecasts of marine heatwaves. Nature 604:486–490. https://doi.org/10.1038/s41586-022-04573-9

Johnson SJ, Stockdale TN, Ferranti L, et al (2019) SEAS5: the new ECMWF seasonal forecast system. Geosci Model Dev 12:1087–1117. https://doi.org/10.5194/gmd-12-1087-2019

Juza M, Fernández-Mora À, Tintoré J (2022) Sub-Regional Marine Heat Waves in the Mediterranean Sea From Observations: Long-Term Surface Changes, Sub-Surface and Coastal Responses. Front Mar Sci 9:

Laurel BJ, Rogers LA (2020) Loss of spawning habitat and prerecruits of Pacific cod during a Gulf of Alaska heatwave. Can J Fish Aquat Sci 77:644–650. https://doi.org/10.1139/cjfas-2019-0238

Lavender E, Aleynik D, Dodd J, et al (2021) Environmental cycles and individual variation in the vertical movements of a benthic elasmobranch. Mar Biol 168:164. https://doi.org/10.1007/s00227-021-03973-1

Liu G, Eakin CM, Chen M, et al (2018) Predicting Heat Stress to Inform Reef Management: NOAA Coral Reef Watch's 4-Month Coral Bleaching Outlook. Front Mar Sci 5:

McAdam R, Masina S, Balmaseda M, et al (2022a) Seasonal forecast skill of upper-ocean heat content in coupled high-resolution systems. Clim Dyn 58:3335–3350. https://doi.org/10.1007/s00382-021-06101-3

McAdam R, Masina S, Gualdi S (2022b) Seasonal forecasting of subsurface marine heat waves. Submitted to Nature Communications

Mignot A, von Schuckmann K, Landschützer P, et al (2022) Decrease in air-sea CO2 fluxes caused by persistent marine heatwaves. Nat Commun 13:4300. https://doi.org/10.1038/s41467-022-31983-0

Oliver ECJ, Benthuysen JA, Darmaraki S, et al (2021) Marine Heatwaves. Annu Rev Mar Sci 13:313–342. https://doi.org/10.1146/annurev-marine-032720-095144

Pauly D, Christensen V (1995) Primary production required to sustain global fisheries. Nature 374:255–257. https://doi.org/10.1038/374255a0

Prodhomme C, Materia S, Ardilouze C, et al (2022) Seasonal prediction of European summer heatwaves. Clim Dyn 58:2149–2166. https://doi.org/10.1007/s00382-021-05828-3

Richardson DS (2001) Measures of skill and value of ensemble prediction systems, their interrelationship and the effect of ensemble size. QJR Meteorol Soc 127:2473–2489. https://doi.org/10.1002/qj.49712757715

Scaife AA, Arribas A, Blockley E, et al (2014) Skillful long-range prediction of European and North American winters. Geophys Res Lett 41:2514–2519. https://doi.org/10.1002/2014GL059637

sen Gupta A, Thomsen M, Benthuysen JA, et al (2020) Drivers and impacts of the most extreme marine heatwave events. Sci Rep 10:19359. https://doi.org/10.1038/s41598-020-75445-3

Smith KE, Burrows MT, Hobday AJ, et al (2022) Biological Impacts of Marine Heatwaves. Annu Rev Mar Sci. https://doi.org/10.1146/annurev-marine-032122-121437

Storto A, Masina S, Simoncelli S, et al (2019) The added value of the multi-system spread information for ocean heat content and steric sea level investigations in the CMEMS GREP ensemble reanalysis product. Clim Dyn 53:287–312. https://doi.org/10.1007/s00382-018-4585-5

Trainer VL, Kudela RM, Hunter M v, et al (2020) Climate Extreme Seeds a New Domoic Acid Hotspot on the US West Coast. Frontiers in Climate 2:

van Haren H, Compton TJ (2013) Diel Vertical Migration in Deep Sea Plankton Is Finely Tuned to Latitudinal and Seasonal Day Length. PLoS One 8:e64435. https://doi.org/10.1371/journal.pone.0064435

von Schuckmann K, le Traon P-Y, Smith N, et al (2021) Copernicus Marine Service Ocean State Report, Issue 5. Journal of Operational Oceanography, 14:1–185. https://doi.org/10.1080/1755876X.2021.1946240

von Schuckmann K, le Traon P-Y, Smith N, et al (2022) Copernicus Marine Service Ocean State Report, Issue 6. Journal of Operational Oceanography, 15:1–225. https://doi.org/10.1080/1755876X.2022.2095169

Zuo H, Balmaseda MA, Tietsche S, et al (2019) The ECMWF operational ensemble reanalysis–analysis system for ocean and sea ice: a description of the system and assessment. Ocean Science 15:779–808. https://doi.org/10.5194/os-15-779-2019

Appendix I. Definition of Indicators

Table A1. Coordinates of the EuroSea Indicators for Seasonal Forecasts

Short Name	Long Name	Longitudes (°East)	Latitude (°North)
nino12	Nino 1+2	270.,280.	-10., 0.
nino34	Nino 3.4	190., 240.	-5., 5.
atl3	Atlantic 3	340., 360.	-3., 3.
atl2	Atlantic 2	0. ,10.	-3.,3.
ATL60NA	Subpolar Gyre North	260., 9.13	59., 61.
ATL40NA	Subpolar Gyre South	260., 358.	39., 41.
NATL	North Atlantic	290., 15.	30., 70.
NEATL	North East Atlantic	320., 15.	30., 70.
NWATL	North West Atlantic	260., 320.	30., 70.
TRATL	Tropical Atlantic	280., 20.	-20., 30.
NSTRATL	North Subtropical Atlantic	280., 20.	5., 28.
SSTRATL	South Subtropical Atlantic	300., 20.	-20., 5.
EQATL	Equatorial Atlantic	290., 30.	-5., 5.
SATL	South Atlantic	290., 20.	-70., -30.
NPAC	North Pacific	100., 260.	30., 70.
NEPAC	North East Pacific	210., 260.	30., 70.
NWPAC	North West Pacific	100., 210.	30., 70.
TRPAC	Tropical Pacific	125., 280.	-30., 30.
NSTRPAC	North Southtropical Pacific	105., 270.	10., 30.
SSTRPAC	South Southtropical Pacific	105., 270.	-30., -10.
TREPAC	Tropical East Pacific	210., 270	-30., 30.
TRWPAC	Tropical West Pacific	100., 210	-30., 30.
EQPAC	Equatorial Pacific	130., 280.	-5., 5.
SPAC	South Pacific	150., 290.	-70., -30.
IND1	W. Indian Ocean Dipole	50., 70.	-10., 10.

Short Name	Long Name	Longitudes (°East)	Latitude (°North)
IND2	Eastern Indian Ocean Dipole	90., 110.	-10., 0.
EQIND	Equatorial Indian Ocean	40., 120.	-5., 5.
TRIND	Tropical Indian Ocean	40., 120.	-30., 30.
SIND	Southern Indian Ocean	20., 150.	-70., -30.
NXTRP	Northern Extratropics	0., 360.	30., 70.
TROP	Tropics	0., 360.	-30., 30.
SXTRP	Southern Extratropics	0., 360.	-70., -30.
CANARYC	Canary Current	330., 350.	11., 31.
BENGUELA	Benguela	-35., -15.	5., 20.
HUMBOLDT	Humboldt	275., 290.	-40., -5
NCALIFC	Northern California	225., 240.	34., 45.
SCALIFC	Southern California	235., 250.	22., 34.
MDR	Mean Development Region (tropical cyclones)	275., 340.	10., 20.
CARIB	Caribbean	275., 300.	10., 20.
GMEX	Gulf of Mexico	260., 280.	20., 30.
WMEDI	Western Mediterranean	0., 15.	35., 44.
EMEDI	Eastern Mediterranean	15., 30.	30., 40.
NSEA	Northern European Seas	-3., 8.	51., 61.

Table A2. Definition of Seasonal Forecast Indicators for the Atlantic-Mediterranean basins.

Index Short Name	Index Long Name	Sectorial Application	Relevance
CANARYC	Canary Current	MP, MH	Major upwelling region
BENGUELA	Benguela	MP, MH, SF, CVC	Major upwelling region
GMEX	Gulf of Mexico	MH, SF, CVC	Warm pool region relevant for tropical cyclones with vulnerable marine ecosystem.
CARIB	Caribbean	MH, SF, CVC	Warm pool region relevant for tropical cyclones with vulnerable marine ecosystem.
WMEDI	Western Mediterranean	MH, SF	Vulnerable marine ecosystems
EMEDI	Eastern Mediterranean	MH, SF	Vulnerable marine ecosystems.
MDR	Mean Development Region for Tropical Cyclones	SF	Mean area of Tropical Cyclogenesis.
NSEAS	Northern European Seas	CSL, SF, MH, MP	Relevant for marine ecosystems, sea level raise, fisheries and marine ecosystems.
ATLSPG	Atlantic Subpolar Gyre. ATL60NA-ATL40N	SF, CVC	Proxy for AMOC and decadal variability. Possible application to heat heaves.
NATL	North Atlantic	SF, CVC	Monitor ocean heat content and sea level
NEATL	North East Atlantic	CVC, CSL, MH	SST relevance for heat waves affecting Europe. Climate indicator for circulation. Sea Level rise in Western Europe.
NWATL	North West Atlantic	SF, CVC	Affected by Gulf Stream. Climate indicator for circulation. Influences atmospheric circulation.
TRATL	Tropical Atlantic	SF, CVC	Climate indicator of heat absorption and circulation. Influences atmospheric circulation.
NSTRATL	North Subtropical Atlantic	SF, CVC	Influence on hurricane season, atmospheric circulation, Atlantic ITCZ (Africa and Brazil climate).

Index Short Name	Index Long Name	Sectorial Application	Relevance
SSTRATL	South Subtropical Atlantic	SF, CVC	Large influence on atmospheric circulation, Atlantic ITCZ (African Monsoon, Brazil).
DTRATL	Tropical Atlantic Dipole NSTRATL-SSTRATL	SF, CVC	Atlantic Meridional model climate indicator. Influences atmospheric circulation (Atlantic ITCZ, African Monsoon).
EQATL	Equatorial Atlantic	SF, CVC	Climate and seasonal indicator.
ATL3	Atlantic El Nino Index	SF, CVC	Climate and seasonal indicator. Ocean variability.
ATL2	Gulf of Guinea	SF, CVC, MP	Upwelling. Climate and seasonal indicator.
SATL	South Atlantic	CVC	Climate indicator.

Table A3. Indicators for the Pacific Ocean Basin

Index Short Name	Index Long Name	Sectorial Application	Relevance
HUMBOLDT	Humboldt Upwelling Area	MP, MH	Major upwelling area.
NCALIFC	Northern California Upwelling	MP, MH, SF, CVC	Major upwelling area.
SCALIFC	Southern California Upwelling	MP, MH, SF, CVC	Major upwelling area.
NPAC	North Pacific	CVC	Climate indicator.
NEPAC	North Eastern Pacific	SF, CVC, MP, MH	Relevant for Marine heat waves. Marine Productivity. Climate variability and change. PDO.
NWPAC	North Western Pacific	CVC, MP	Relevant for Marine productivity. Climate variability and change.
TROP	Tropical Pacific	SF, CVC	Climate indicator. Affect worldwide atmospheric circulation. Heat uptake and distribution.
NSTRPAC	North Subtropical Pacific	SF, CVC	Climate indicator for the Pacific Meridional Mode. Affects ocean and atmosphere climate circulation.
SSTRPAC	South Subtropical Pacific	SF, CVC	Climate indicator for the Pacific Meridional Mode. Affects ocean and atmosphere climate circulation.
TREPAC	Tropical Eastern Pacific	SF, CVC	Decadal and Interannual atmospheric variability. Link with the Atlantic variability.
TRWPAC	Tropical Western Pacific	SF, CVC, CSL	Decadal and Interannual variability. Links with Indian Ocean. Sea level change.
EQPAC	Equatorial Pacific	SF, CVC	Relevant to ENSO and ocean circulation
NINO3.4	ENSO index	SF, CVC, MP, MH	ENSO affects atmospheric climate, but also marine health and productivity via remote impacts.
NINO1.2	Coastal ENSO index	SF, CVC, MP, MH	Marine productivity and upwelling area. Climate variability. Atmospheric Impact.
SPAC	South Pacific	CVC	Climate indicator.

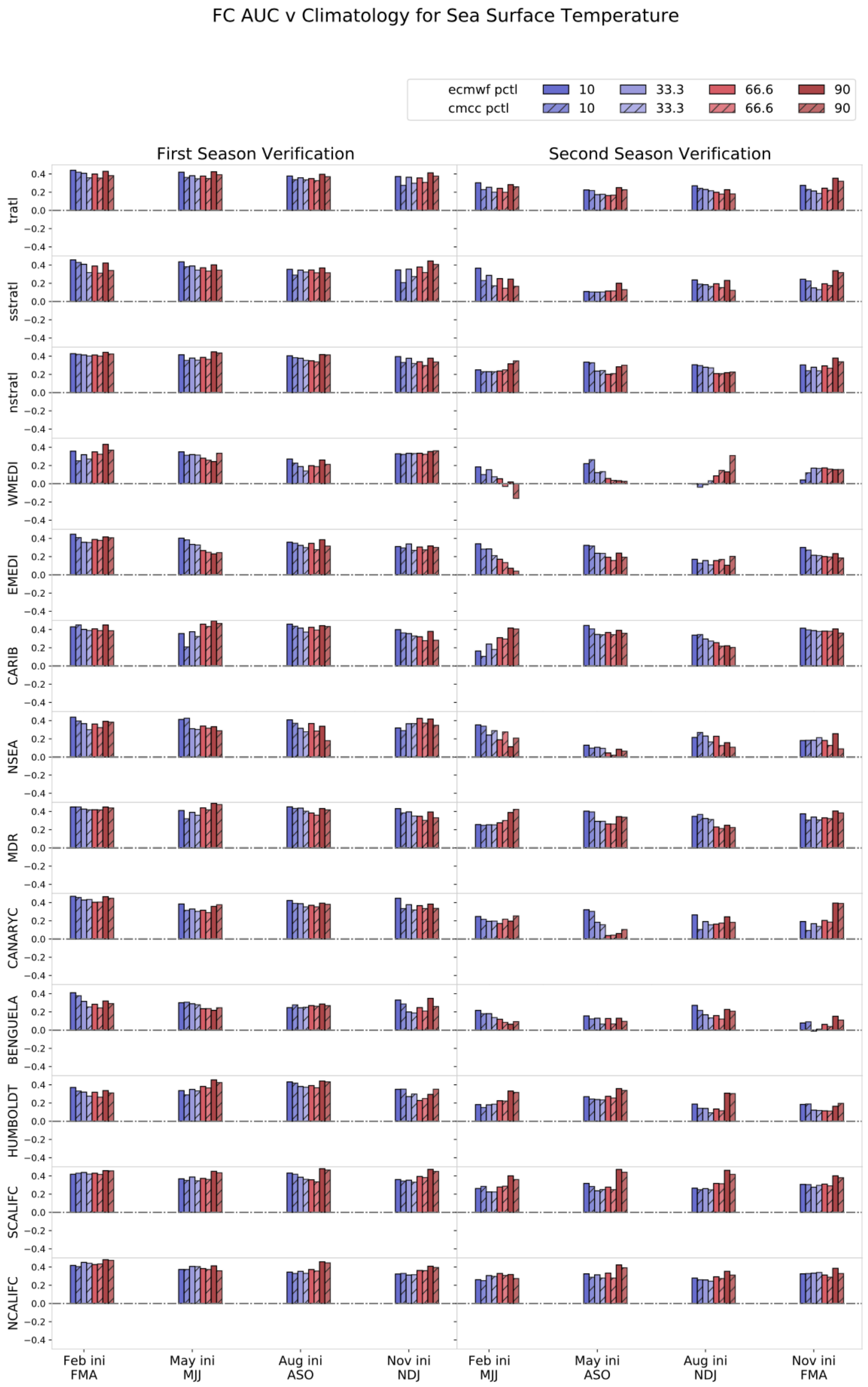
Table A4. Indicators for the Indian Ocean basin

Index Short Name	Index Long Name	Sectorial Application	Relevance
IND1	Eastern Node of the Indian Ocean Dipole	SF, CVC, CSL	Atmospheric Circulation. Climate Indicator. Coastal Sea Level.
IND2 (SETIO)	Western Node of Indian Ocean Dipole	SF, CVC, MP, CSL	Marine Productivity. Atmospheric circulation. Climate indicator. Coastal Sea Level.
INDPL	Indian Ocean Dipole IND1-IND2	SF, CVC	Atmospheric circulation. Climate variability.
EQIND	Equatorial Indian Ocean	SF, CVC	
TRIND	Tropical Indian Ocean	SF, CVC	Atmospheric circulation. Climate variability. Heat absorption and sea level change.
TRWIND	West Tropical Indian Ocean	SF, CVC	Related to the interannual and decadal changes in the ocean-atmosphere coupled system.
TREIND	East Tropical Indian Ocean	SF, CVC	Related to interannual and decadal changes in the ocean-atmosphere coupled system.
SIND	Southern Indian Ocean	CVC	Interbasin connection. It helps to monitor how the Southern ocean affects other basins.

Table A5. Latitudinal band indicators

Index Short Name	Index Long Name	Sectorial Application	Relevance
NXTRP	Northern Extratropics	CVC	Climate change indicator. Complements NPAC, NATL.
TROP	Tropics	CVC	Climate indicator of variability and change. Complements TRIND, TRATL, TRPAC.
SXTRP	Southern Extratropics	CVC	Complements SPAC, SIND, SATL.

Appendix II. Forecast Skill of Indicators



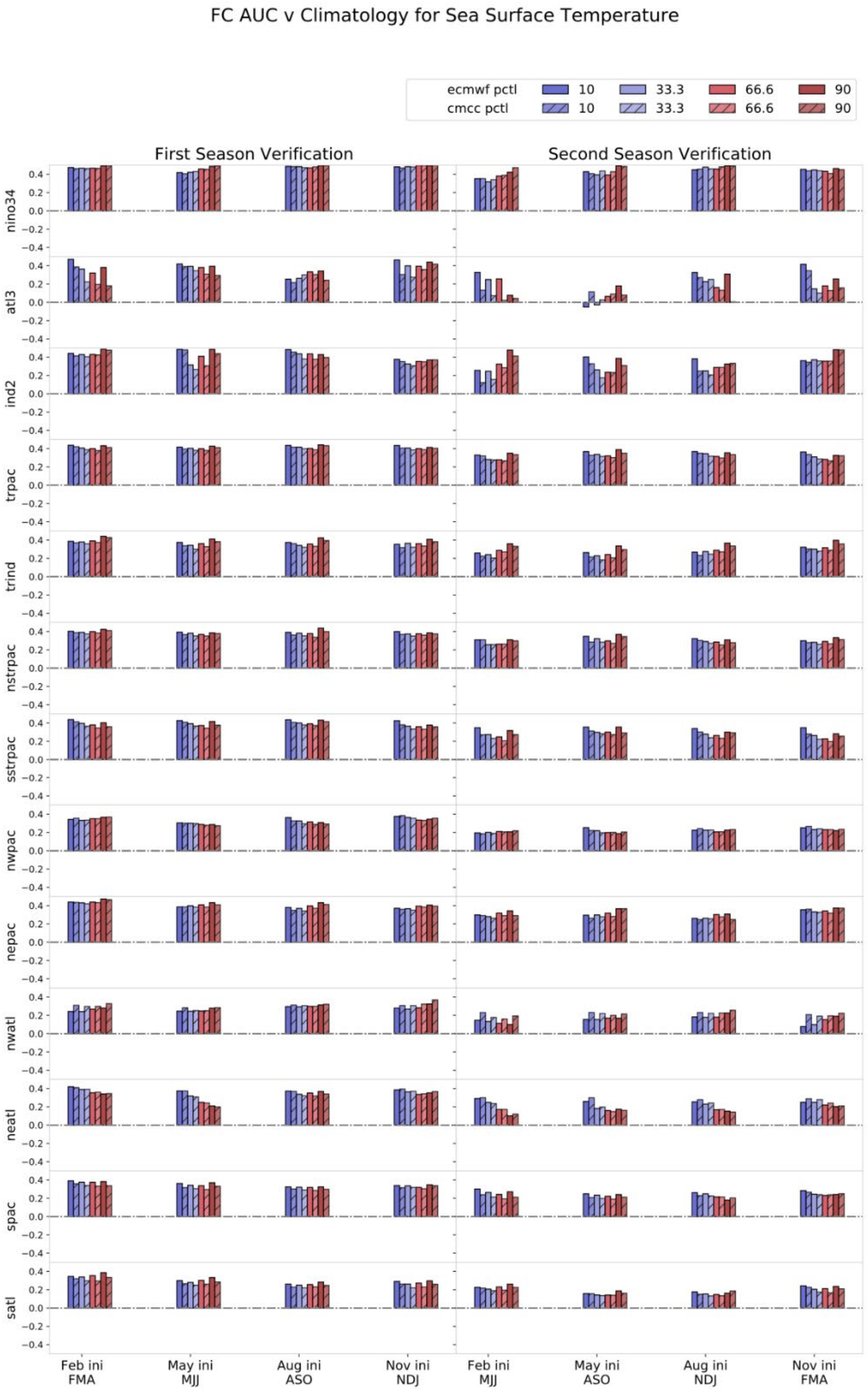
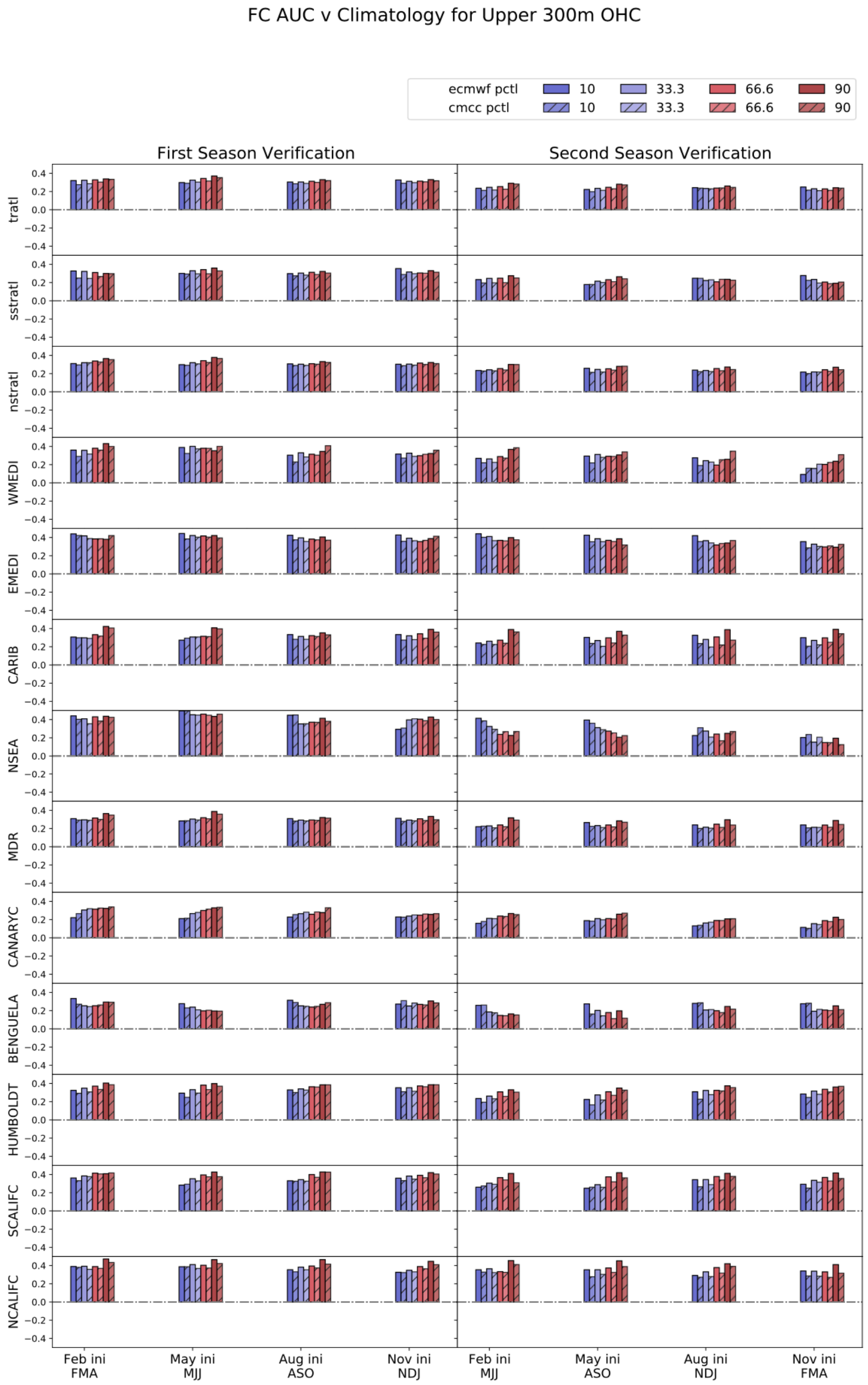


Figure A1. AUC (area under ROC curve) skill in predicting a subset of indictors by ECMWF (plain) and CMCC (stapled) seasonal forecasts of SST, compared with the climatology. Shown are the values for the difference percentiles (as indicated in legend), verifying in the 1st (left) and 2nd (right) seasons after initialization. Positive values indicate better skill than climatology. A perfect forecast would score 0.5.


FC AUC v Climatology for Upper 300m OHC
ecmwf pctl 10 33.3 66.6 90
cmcc pctl 10 33.3 66.6 90
First Season Verification
Second Season Verification
tratl
sstratl
nstratl
WMEDI
EMEDI
CARIB
NSEA
MDR
CANARYC
BENGUELA
HUMBOLDT
SCALIFC
NCALIFC
0.4
0.2
0.0
−0.2
−0.4
Feb ini FMA
May ini MJJ
Aug ini ASO
Nov ini NDJ
Feb ini MJJ
May ini ASO
Aug ini NDJ
Nov ini FMA

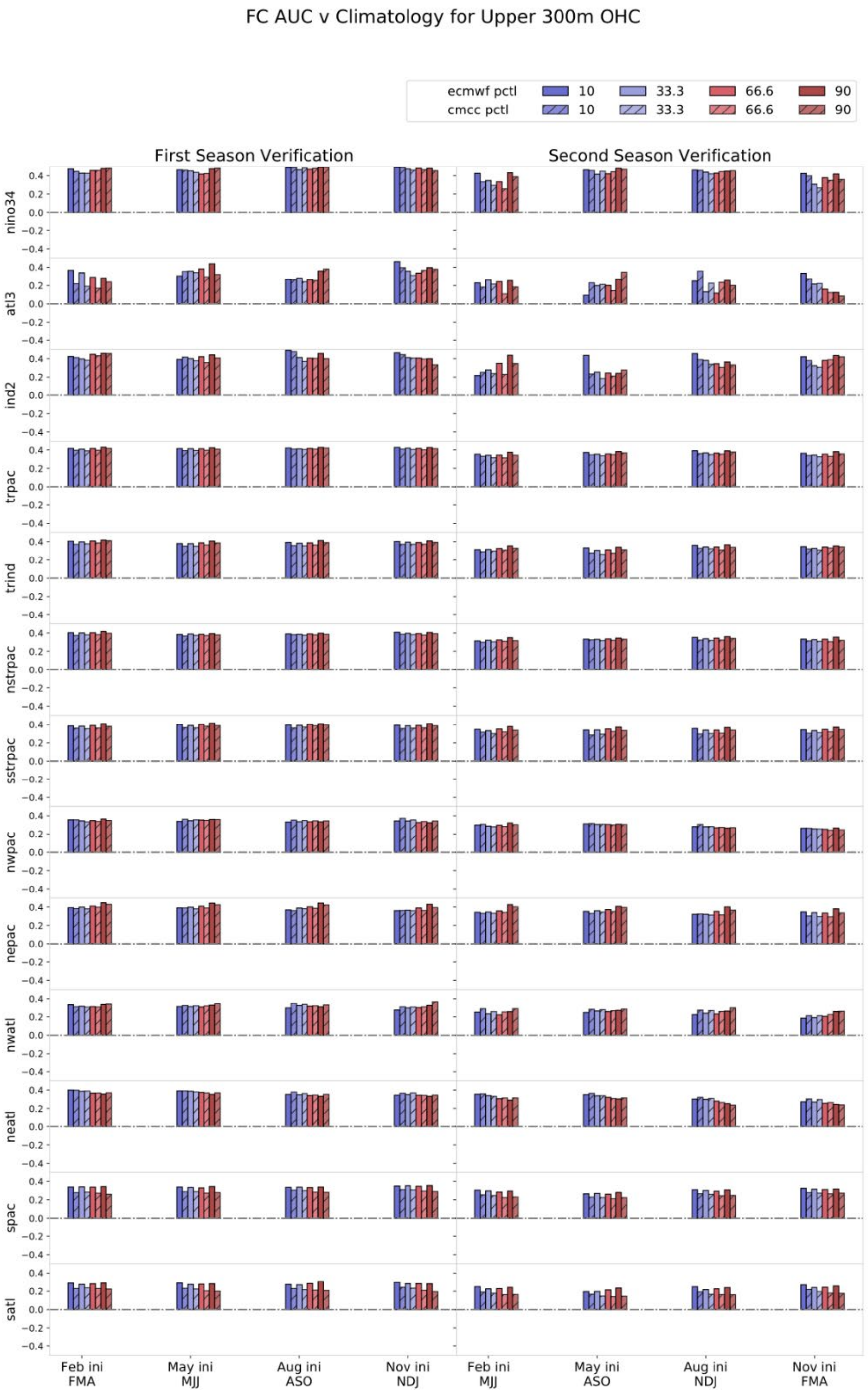
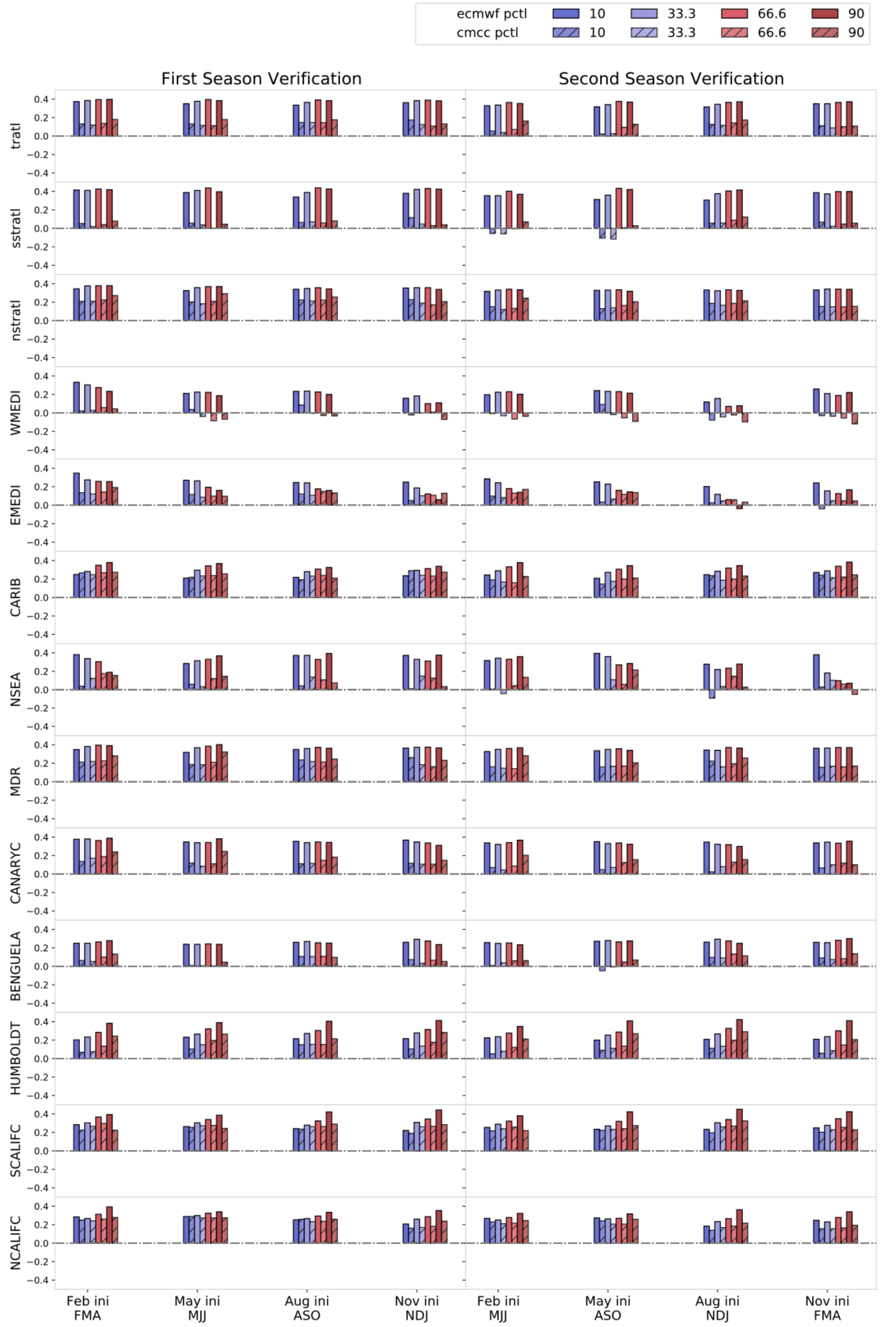


Figure A2. As in Figure A1 but for seasonal forecasts of Ocean Heat Content 0-300 m.

FC AUC v Climatology for Sea Level Anomaly



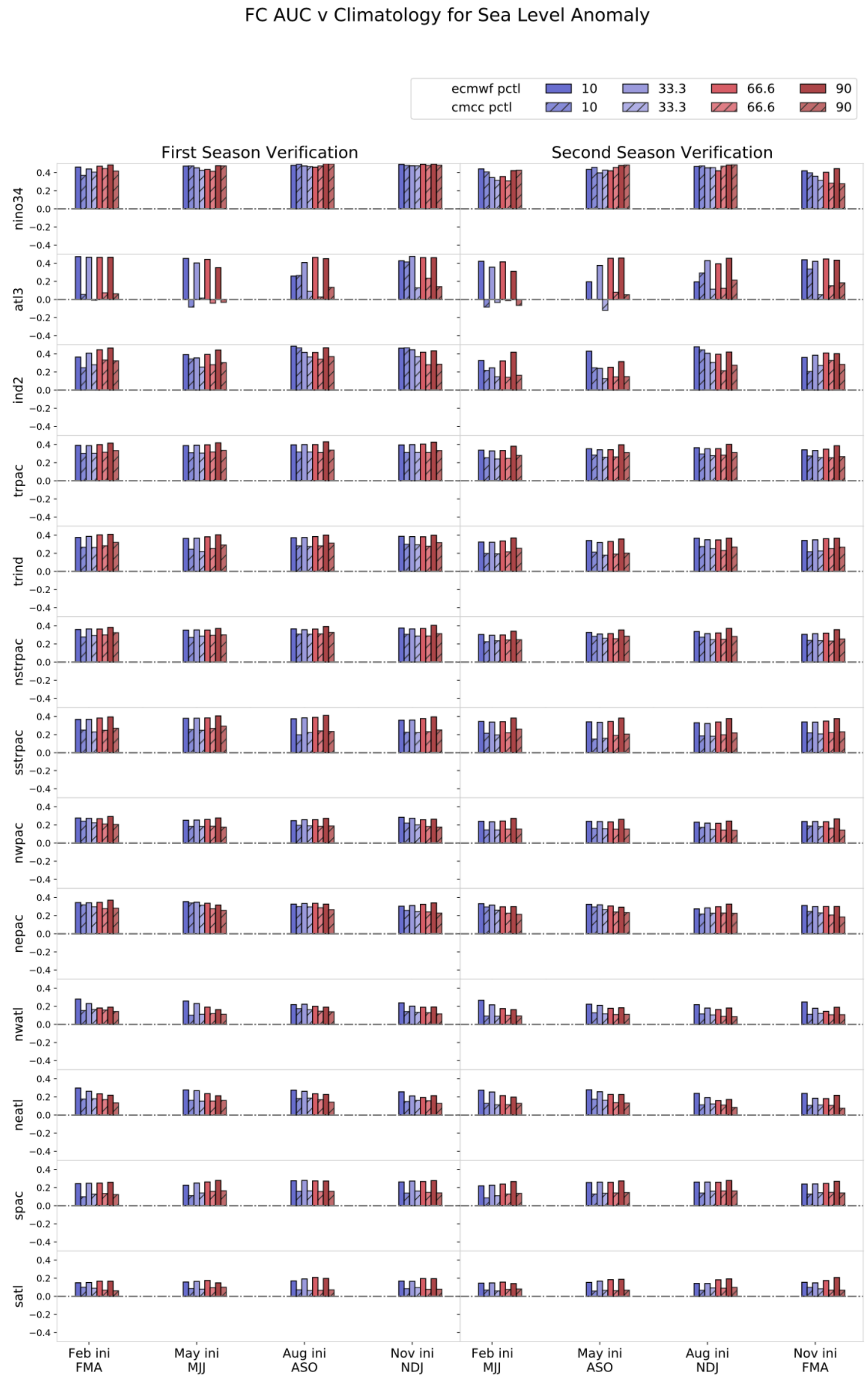


Figure A3. As in Figure A1 but for seasonal forecasts of SSH.