Intelligent Fish feeding through Integration of ENabling technologies and Circular principle

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1.0	28/04/2020	N. Goris	First final version submitted
2.0	28/06/2020	N. Goris	Modified version for resubmission
3.0	22/09/2020	N. Goris	The introduction is extended to include why (i) wind-speed was not analyzed and (ii) the report focusses on marine aquaculture. Further, the conclusion is amended to include (i) that salinity is not a main stressor and is not prioritized when measuring and (ii) possible weather related climate risks for freshwater aquaculture. Additionally, S. Prescott performed a language and content editing for the whole report.

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1 Introduction

Aquaculture is expected to provide an important contribution to future food security. By the year 2030, global aquaculture production of fish is predicted to reach approximately 109 million tonnes (live weight) by 2030, an increase of 37% relative to production in 2016 (FAO, 2018). However, this growth may be influenced by potential threats from climate change. Significant alterations of oceanic environments are predicted to occur over the next 50 years. With ongoing climate change, the ocean's physical and biogeochemical properties are very likely to undergo fundamental changes (Pörtner et al., 2014). This will affect organisms living in the ocean, including farmed fish (Nilsson et al., 2009 & 2012). At the same time, modelling tools that can accurately predict farmed fish production under climate change scenarios are currently lacking. In view of these challenges, this report (Deliverable 4.3 of iFishIENCi) is intended to deliver insights into **climate changed induced threats that have the potential to influence growth rates of European aquaculture species**. Given the technological focus of the iFishIENCi project, this report presents only a first order estimate and is by no means a complete overview. Nevertheless, it gives an indication of the potential future threats to European aquaculture. Additionally, it discusses the potential benefits of the technological accomplishments of iFishIENCi with regards to some of the projected climate conditions.

This focus of this report is on analyzing climate induced changes in environmental variables and their effects on fish growth in aquaculture. We note that climate induced changes in marine and freshwater environments will also affect a range of other species important to aquaculture such as those which are part of the value chain (i.e. pelagic fish that are reduced to fishmeal for aquafeed) and those which pose risks, including parasites and predators. Climate change may also affect the production of terrestrial crops that are used as ingredients in aquafeed. These considerations are of importance, but not part of the task-description and hence not within the scope of this report.

There are many levels of uncertainty when assessing the direct future impact of climate change on the growth of fish in aquaculture. Firstly, the quantity of greenhouse gases that will be emitted by future human activity is unclear. Different future greenhouse gas evolutions will impose different levels of climate change and hence pose differing threats. Secondly, even under a given future greenhouse gas trend, the reaction of different components of the Earth system (e.g., warming rate of the oceans) can only be estimated by climate models that contain various levels of uncertainty. Thirdly, the response of aquaculture species to climate induced stress is uncertain due to the varying, combined effects of multiple stressors to fish of different life stages and genetics, grown within different systems. However, given that the additive stress of multiple stressors can be devastating, it is likely that even non-extreme but quasi-realistic future conditions may influence the growth of fish in aquaculture.

Given the range of uncertainties, it is not possible within this deliverable, or within the scope of the iFishIENCi project, to give a precise and accurate picture of the direct impacts of various future conditions upon the growth of fish in cultivation. Nevertheless, this report tries to give insights into the uncertainties of 1) future greenhouse gas emissions by considering two possible greenhouse gas emission pathways, 2) climate models by analyzing the response of a variety of models, 3) direct response of aquaculture species by considering environmental ranges required for optimal growth and by additionally considering a model that relates warming rate to metabolic processes for selected species.

There is significant aquaculture production in both freshwater and marine waters. When it comes to the selection of suitable models to identify future environmental conditions for these aquatic ecosystems, we note that both global Earth system models and regional climate models are state-of-the-art tools for predicting the effects of future climate change (Babatunde and Adedoyin, 2016). As both types of models are simplified versions of reality, it is important to assess not only the outcome of their future projections but also their associated uncertainty. As a means of their uncertainty, it is common practice to not only compare the model output against present-day observation but also to evaluate the accuracy of the projected future trend by looking at the level of agreement between the trends of a multitude of models. For an uncertainty-analysis, it is hence of importance to have the output of several climate models available. There exists a multitude of Earth system models and their output of climate simulations covers all areas of the globe and can be publicly accessed. Earth system models consider terrestrial, atmospheric and oceanic processes and their interactions. They are computationally expensive and so can only be run on a relatively coarse grid resolution. Regional climate models reveal smaller-scale processes, but they are usually not coupled and focus on either atmospheric or oceanic processes. Due to the high computation costs of regional modelling, there is often only one regional marine climate model available for a certain ocean area. Hence, an analysis of model uncertainty under future conditions is extremely difficult when considering regional marine climate models. **For the marine environment, we have therefore chosen to consider a suite of Earth system models to analyze the impacts of climate change and their associated model uncertainty**.

Due to the high public and political interest in the future evolution of meteorological parameters, there are several regional atmospheric climate models available for Europe. Despite having a higher resolution than Earth system models, regional atmospheric climate models usually do not incorporate adequate representations of rivers or ponds. To study climate-driven change in local-regional freshwater systems, the regional atmospheric climate model results are subsequently processed through hydrological modeling. Here, the adequate assessment of freshwater changes require account of both atmospheric climate change and changes in the landscape (Asokan et al., 2016), which leads to highly inaccurate and uncertain results. Therefore, it is our choice to leave the focus of this report on the output of Earth system models as stated in the task-description and not to include an analysis of the impact of climate change on the freshwater environment.

Within the atmospheric science community, the output of regional atmospheric climate models over Europe has been analyzed with respect to extreme meteorological conditions like droughts, floods and storms. In the conclusions of this report, we include a short summary of these results in terms of general statements and their potential implications for European aquaculture. For the marine environment, analysis with Earth system models focusing on extremes are rare. **Within our analysis, we have gone beyond the current state-of-the-art and have analyzed bias-corrected seasonal envelopes and their expected maximum changes with climate change**. As the seasonal scale is of high importance for fish growth, the new results are important progress when it comes to elucidating the full impact of climate change. The results will be utilized for a subsequent publication, promoting the EU H2020 iFishIENCi project.

When considering fish growth, this report focuses on the aquaculture species Atlantic salmon, European seabass and gilthead seabream, as these species are present in the marine open-cages sites featuring in iFishIENCi. Additionally, we also include meagre as species of interest in our analysis. Although climate change will alter many marine ecosystem variables that are important for the growth of these species, it is not possible to consider them all within this report. To find the most important variables for fish growth in aquaculture, a questionnaire was sent to the iFishIENCi partners and advisors, listing all variables that are commonly simulated by Earth system models. With this expert knowledge, sea surface temperature, sea surface salinity, surface dissolved oxygen and ocean net primary productivity (as an indicator for algal blooms) have been selected as the most important variables affecting fish growth in European aquaculture. It was stated in the task-description that wind-speed will be among the variables to be considered, but instead we analyzed dissolved oxygen. This decision was based on the importance of dissolved oxygen in aquaculture production. Dissolved oxygen has a direct impact on fish growth and is predicted to be a notable stressor under future climate conditions. Wind speed, on the other hand, has no direct effect on fish growth in marine aquaculture but only has a direct effect on current speed, which subsequently has an impact on supplying water parcels that carry potentially varying levels of nutrients and oxygen. It is, however, not straightforward to infer current speed from wind-speed or other environmental conditions, and the considered Earth system models are unable to resolve realistic coastal current speeds. Hence, we conclude that an analysis of dissolved oxygen is of higher interest within the context of this study.

Based on these considerations, Section 2 of this report presents future conditions of sea surface temperature, sea surface salinity, surface dissolved oxygen and ocean net primary productivity in European waters, including potentially induced risks for selected aquaculture species. In Section 3, we present a model that relates future warming rate to metabolic processes for selected species in the Mediterranean Sea. Finally, in section 4, we summarize and discuss our results.

2 Climatic trends in European marine waters

Within this section, future conditions of sea surface temperature, sea surface salinity, surface dissolved oxygen and ocean net primary productivity in European waters will be presented, including optimal ranges of these variables for selected aquaculture species.

2.1 Future greenhouse gas emissions

In order to give insights into the uncertainties of future greenhouse gas emissions, we consider two possible future greenhouse gas emission pathways. Both pathways belong to the so-called Representative Concentration Pathways (RCP) adopted for the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5) in 2014. The RCPs are labelled according to their range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m^2, respectively). Figure 1 displays the global CO_2-emissions for all four RCPs until the year 2050. While the development of these RCPs is based on assumptions of future CO_2-emissions, the climate models considered here are driven by their implicated atmospheric CO_2-concentrations. **Within this report, we mainly focus on the climate implications of RCP8.5 (a high CO_2-scenario), while giving a few implications also for RCP4.5 (a moderate CO_2-**

scenario). We note, that this choice is mainly motivated by the fact that RCP8.5 is the only RCP-scenario that is in line with our historical emissions, while the emissions of all other RCPs pathways underestimate our actual emissions of the last decade (see Figure 1). Hence, selecting a lower RCP would neglect the climate change of the last 10 years. Nevertheless, RCP8.5 includes no emission reduction policies and hence a drastic increase in greenhouse gas emissions for the future. Its results are therefore the worst-case scenario.

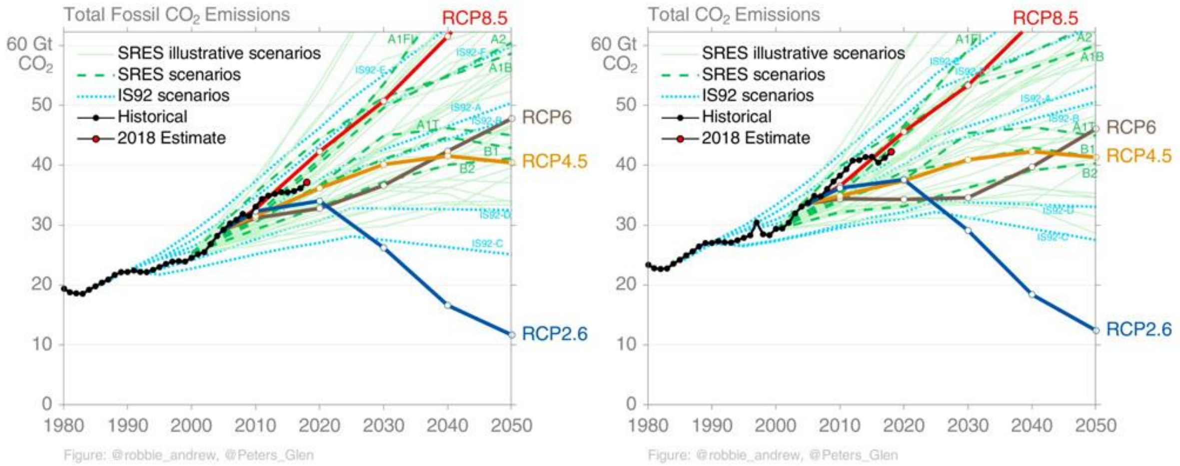

Figure 1: Global fossil fuel CO_2 emissions (left) and total CO_2 emissions from fossil fuels and land use (right) for historical observations and RCP, SRES, and IS92 scenarios. Credit: Glen Peters.

At this point in time, new and more up-to-date future pathways have been developed to assist the climate change assessment for the IPCC Sixth Assessment Report, due in 2021. While these pathways and some associated calculations with climate models are partly available right now, these results came too late in time to be considered within this report.

2.2 Climate models and their analysis

The current state-of-the art tools to predict the effects of future climate change are Earth System Models (Flato et al., 2013). These models are computationally expensive and can therefore only be run on a relatively coarse grid resolution with a current oceanic grid resolution of around 1 degree (Flato et al., 2013), i.e. a surface-size of approximately 111 x 111 km per grid cell at the equator with decreasing size towards the poles. Despite progress towards a higher resolution, the current resolution of Earth System Models does not suffice to reveal regional detail.

To gain regional detail or small-scale information, it is possible to combine results of Earth System Modelling with downscaling methods. Downscaling is a procedure that takes information that is known at large scales – e.g. the output of an Earth System Model - to make predictions at local scales. Downscaling has added value in areas with marked regional climate contrasts due to local features such as complex bathymetry, topography or coastlines (Flato et al., 2013). As open ocean cages of European aquaculture are mainly situated along the coast, the usage of downscaled physio-biogeochemical model output would be highly beneficial for a future estimate. However, due to the high costs of dynamical downscaling, there is often only one downscaled model available for a certain area. This is problematic as each model comes with its own uncertainties and uncertainty-estimates are often accomplished by comparing a range of models. To take advantage of both types of models, we use results of a regionally downscaled model in Section 3 and the results of a suite of Earth System Models within this section.

As the use of the regional model (Section 3) does not allow for an uncertainty estimate, we are using a suite of Earth System Models within this Section to provide an uncertainty-estimate. According to Flato and co-authors (2013), 25 Earth System Models with ocean biogeochemistry took part in the climate change assessments of the 5th IPCC report. Out of these 25 Earth system models, we have chosen 11 for our analysis (see Table 1 for a list). We note that the future simulations of these models have already been done. We acknowledge the CMIP (Coupled Model Intercomparison Project)-community for providing the climate model data, retained and globally distributed in the framework of the ESGF (Earth System Grid Federation). The CMIP-data of this report were replicated and made available by the German Climate Computing Centre DKRZ.

Acronym	Description	Reference
CESM1(BGC)	Community Earth System Model, version 1 (biogeochemistry)	Long et al. (2013)
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model (MOM), version 4 component	Dunne et al. (2012, 2013)
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component	Dunne et al. (2012, 2013)
HadGEM2-CC	Hadley Centre Global Environment Model, version 2 (Carbon Cycle)	Martin et al. (2011)
HadGEM2-ES	Hadley Centre Global Environment Model, version 2 (Earth System)	Martin et al. (2011)
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, medium resolution	Dufresne et al. (2013)
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution	Dufresne et al. (2013)
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Chemistry Coupled Earth System Model	Watanabe et al. (2011)
MIROC-ESM	Model for Interdisciplinary Research on Climate, Earth System Model	Watanabe et al. (2011)
MPI-ESM-LR	Max Planck Institute Earth System Model, low resolution	Giorgetta et al. (2013)
NorESM1-ME	Norwegian Earth System Model version 1 with carbon cycling (intermediate resolution)	Tjiputra et al. (2013)

Table 1: Earth system models employed in this analysis.

Commonly, climate modelling studies focus on annual or decadal values, while interannual or seasonal variations are not considered – even though they explain the largest amplitudes of variation. This kind of approach neglects significant variations and hence stress that might be imposed on European aquaculture. Moreover, it has been shown that the seasonal amplitude of many variables will increase in the future (e.g., Dwyer et al., 2012), indicating that critical thresholds will be exceeded on a monthly basis first. Therefore, our analysis will focus not only on decadal trends but also monthly extreme values.

Within the next Sections, we will discuss results of our analysis for Sea Surface Temperature, Sea Salinity, Surface Dissolved Oxygen and Net Ocean Primary Productivity separately, However, the considered Earth System Models have been simulating these variables together, meaning that e.g. the effect of higher Sea Surface Temperature is already included in the evolution of Surface Dissolved Oxygen.

2.3 Future estimates for Sea Surface Temperature

-Method by N. Goris (NORCE)

When estimating the future states of sea temperature, we focus on the oceanic top layer of the considered Earth System Models spanning approximately 0 to 10 m and denote this as sea surface temperature (SST). For our analysis, we first benchmark the performance of the considered 11 Earth System Models against observations. As observational estimate, we use the objectively analyzed temperature decadal fields as provided by the World Ocean Atlas 2018 (Locarnini et al., 2018). To obtain the best future estimate, we correct the bias of the 11 models. This is done by calculating the temporal mean bias per model/grid point for the period 1955-1994, i.e. a period that is early enough to have no significant climate change included and long enough to smooth out decadal variations. The mean bias is then subtracted from the model output in every time step. Figure 2 (middle panel) illustrates the bias-corrected decadal evolution of SST as projected by our 11 models for a selected region. We see that the bias-correction leads to a good agreement of the models during the historical period. For the future-evolution under the high CO_2-scenario RCP8.5, the considered models agree on the fact that the ocean surface is warming, but they disagree on the degree of decadal warming.

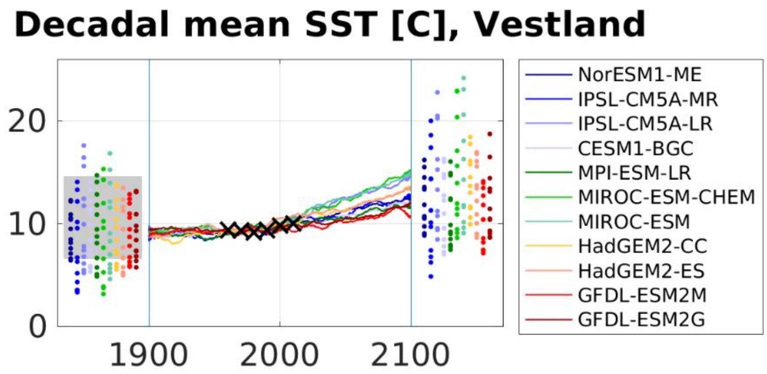

Figure 2: *Bias-corrected evolution of sea surface temperature as projected by 11 different Earth System Models for the coast along Vestland-country, western Norway. Left/right panel: Range of the mean seasonal cycle for the years 1955-1994/2085-2094 per model (color-coding in legend) and for the observational estimate (grey shading). Middle panel: decadal evolution per model (color-coding in legend) and for 6 observational estimates (black crosses).*

Figure 2 illustrates furthermore the range of a typical seasonal cycle for the years 1955-1994 (left panel) and the years 2085-2094 (right panel) for the selected region. It can be readily seen that decadal smoothing gives important information about the long-term evolution of ocean variables, yet neglects the whole range of variability as decadal variations are small in comparison to seasonal variations. Only seasonal variations are able show the whole range of temperature values that might be assumed in the future. As each surpassing of a critical threshold is important for the well-being of aquaculture species, it is of importance to focus on monthly timescales. Indeed, daily or even hourly values would even be more beneficial, but as these values are not provided, we analyze monthly values. Hence, we omit models from our impact-analysis that do not provide a good estimate of monthly variations. Based on the observational estimate in several regions, we identify the models IPSL-CM5A-MR, IPSL-CM5A-LR, MIROC-ESM-CHEM and MIROC-ESM to not be suitable for delivering monthly values within observational estimates (in Figure 2, the observational range of monthly variations is marked with a grey shading).

The remaining 7 models are deemed to be suitable and are utilized to give an estimate of monthly variations for all considered years. Figure 3 illustrates the evolution of the annual monthly maximum values for 2 out of the remaining 7 models for a chosen location. It illustrates that there are strong interannual variations at play, i.e. within two consecutive years, there can be a difference of up to 4 degrees in maximum ocean surface temperature. A sudden jump from ~15 ºC to ~19 ºC degree (as depictured in Figure 3) means**, that SST is within the optimal range for Atlantic Salmon in one year and a stressor in the next year** (see Table 2 for SST-ranges of Atlantic Salmon). Therefore, we will focus not only on mean decadal summer and winter SST values but also on their decadal maximum/ minimum. We note that climate models can project the range of interannual variation, but are not able to project the timing accurately, i.e. when a new extreme value is to be expected.

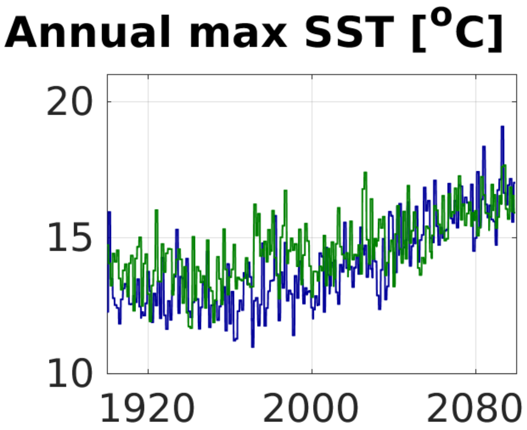

Figure 3: *Bias-corrected evolution of annual monthly maximum sea surface temperature as projected by 2 different Earth System Models for the coast along Vestland-country, western Norway (color-coding of the models is displayed in the legend of Figure 2).*

Figure 4 illustrates the seasonal range for SST as projected by our 7 well-performing models for 4 different locations under a high-CO_2 future (scenario RCP8.5). Values per location are calculated by spatially averaging over all marine grid-cells that are deemed to belong to a specific location. **We see an increase in SST in all four locations of around 3-6ºC for both winter and summer months.** The location Vestland shows the least increase in temperature, whereas Finnmark, Peloponnes and the North Aegean Sea show a more rapid increase. We note that the same increase-pattern is visible for a moderate CO_2-future (scenario RCP4.5), yet SST rises here only around 2-4 ºC (not depicted). The warming trend itself has a relatively small uncertainty (about 1ºC) in all four locations (see Figure 4). Most of model uncertainty is associated with their seasonal range and is visible already in the disagreement in contemporary summer and winter values (see Figure 4).

The selected locations in Figure 4 are of importance for the iFishIENCi project partners. The locations Vestland and Peloponnese mark regions with high aquaculture productivity for Norway and Greece, where the species Atlantic salmon (Norway) and gilthead seabream, European seabass and meagre (Greece) are farmed, among others. We also selected a second location for Norway (Finnmark) and Greece (north Aegean Sea), which are the northern most locations for each country and hence among the coldest locations. These locations are included to see if they offer potential for re-location if sea temperatures in Vestland or Peloponnese reach life-threatening conditions for the selected aquaculture species.

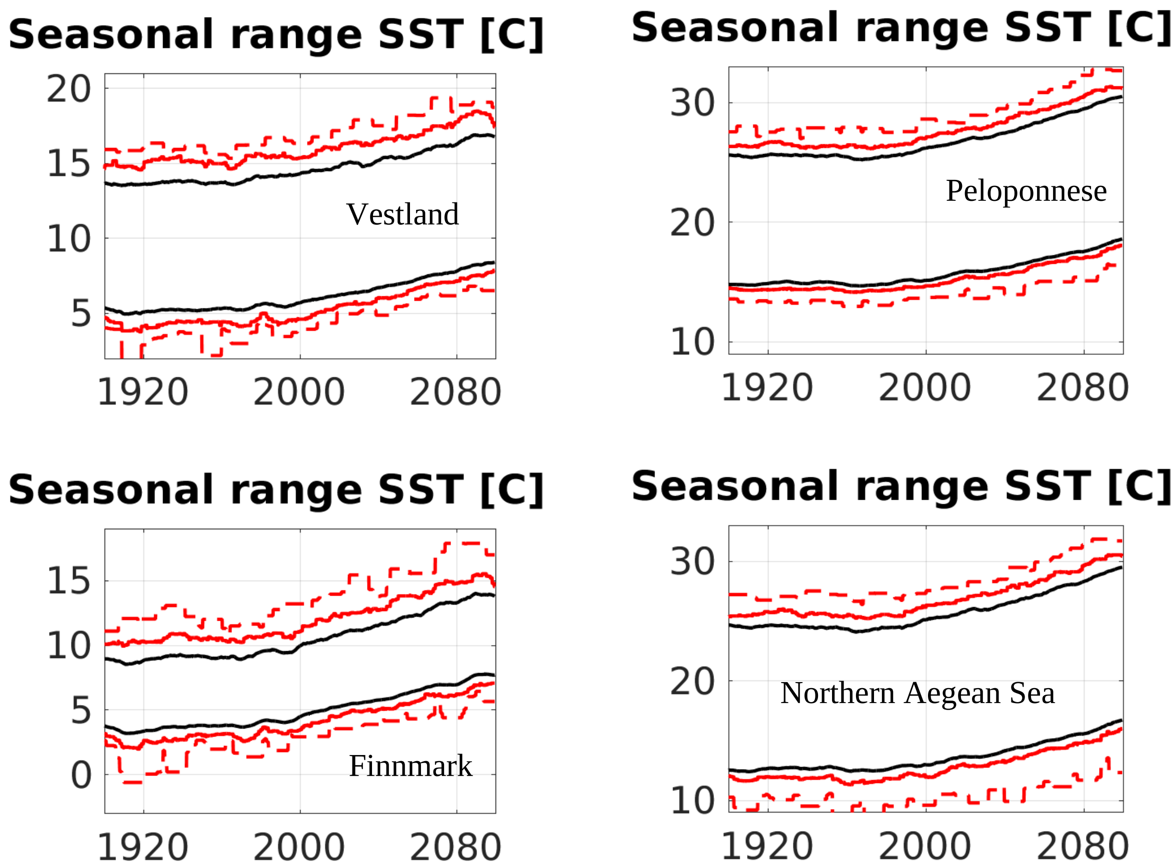

Figure 4: *Bias-corrected evolution of seasonal ranges of sea surface temperature as projected by 7 well-performing Earth System Models for 4 different locations for a high CO_2-scenario (RCP8.5). Black lines mark the decadal average of the seasonal range, red solid lines the model-average of decadal minimum and maximum-temperature and red-dashed lines the results for decadal minimum and maximum for the most-extreme model. Represented are SST-evolutions for the coast along a) Vestland country, western Norway (upper left panel), b) Finnmark country, northern Norway (lower left panel), c) Peloponnese, southern Greece (upper right panel), Norway and d) northern Aegean Sea, northern Greece (lower right panel).*

	Minimum temperature [C]	Optimal temperature [C]	Maximum Temperature [C]
Atlantic Salmon	2	10-16	22
Meagre	12	17-30	>30
Gilthead Seabream	6	14-26	33
European Seabass	2	13-27	32

Table 2: Thresholds for sea temperature for selected aquaculture species. Thresholds are provided by https://longline.co.uk/meta/list, optimal ranges are corrected for meagre according to Kir and co-authors (2017), for gilthead seabream according to Person-Le Ruyet and co-authors (2004) and for European seabass according to Polo and co-authors (1991).

Based on thresholds for Atlantic salmon (Norway) and gilthead seabream, European seabass and meagre (Greece), provided in Table 2 and the time-series of SST in Figure 4, we note that:

- For Vestland, the SST range will likely become too warm for optimal growth of Atlantic Salmon in summer around the year 2020 in the mean (uncertain model results translate to an uncertainty of ±15 years around this value), i.e. non-optimal conditions might already be present today and slightly affect Norway´s aquaculture performance. Summer conditions are expected to get worse with time, but life-threatening conditions will not be reached within the time-frame of our analysis. At the same time, winter-temperatures will become more optimal for Atlantic Salmon. **More optimal winter and less optimal summer conditions may affect stocking patterns and production cycles, potentially influencing supply chain management.**
- For Finnmark, the present SST-range is only optimal in summer month while SST is close to life-threatening in winter. **Here, future SST-ranges are more optimal for Atlantic Salmon than present conditions and present the chance to expand the cultivation northwards.**
- For Peloponnese, winter temperature will become more optimal for meagre. However, **summer conditons are worsening and will likely become too warm for optimal growth of gilthead seabream and European seabass** around the year 2030 and 2040 in the mean and might become lethal at the end of the century (uncertain model results translate to an uncertainty of ±15 years around all values). Though the North Aegean Sea offers slightly cooler temperatures, the same thresholds for gilthead seabream and European seabass will be crossed only approximately 5 years later.

In order to show a general overview over the evolution of SST for the next decades, Figure 5 illustrates the maximum SST as maps over European waters for different decades. We note that the values in the right panel of Figure 5 are representing the model mean (i.e. the maximum monthly values when averaged over all models; corresponding to the upper red solid line in Figure 4), though single models might show higher monthly values (as shown in Figure 4). Therefore, the left panel of Figure 5 shows the uncertainty of the maximum values, i.e. how much a single model might deviate from this maximum-value.

We summarize for SST under a high emission scenario (RCP8.5), that our best estimate yields that SST will increase around 3-6 ^{o}C within the next 80 years, depending on the location (higher latitudes and less ventilated locations have a faster SST increase). For a moderate emission scenario (RCP4.5), SST will increase around 2-4 ^{o}C (not depicted). **Summer temperature (monthly maximum temperature) is the most imminent threat for European aquaculture, while winter temperatures will become more optimal for several species.** More optimal winter and less optimal summer conditions may affect stocking patterns and production cycles, potentially influencing supply chain management. **SST should be continuously monitored to ensure that warming trends are identified and approaching critical values are recognised in time.** Here, iFishIENCi will provide valuable input with its online measuring system of environmental parameters.

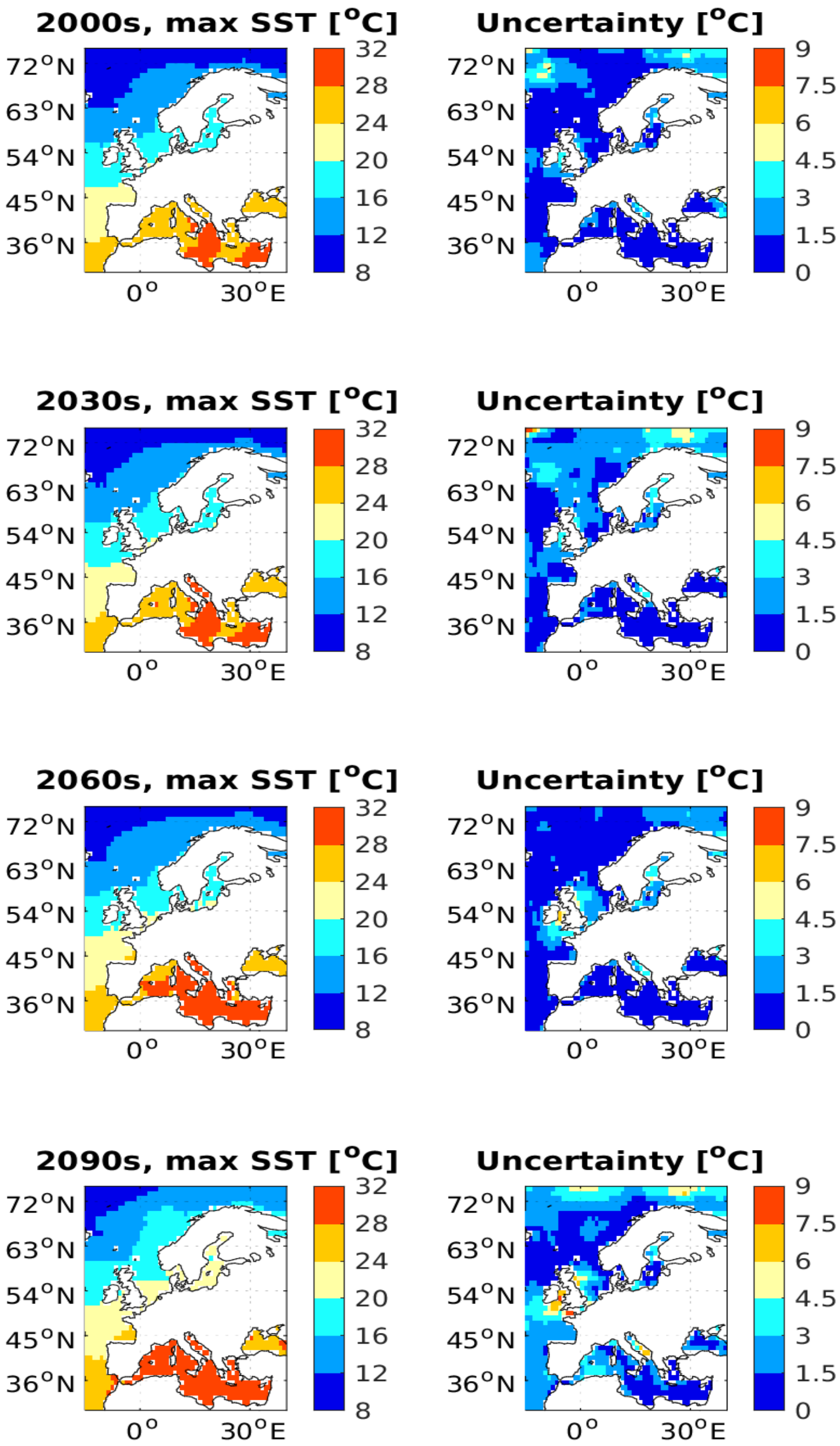

Figure 5: *Bias-corrected evolution of decadal monthly maximum sea surface temperature as projected by 7 well-performing Earth System Models for a high CO_2-scenario (RCP8.5). Left panel: mean values over all considered models; right panel: maximum deviation of single models from the values in the left panel.*

2.3.1 Risk analysis for Aquaculture in Norway and Greece associated with future sea surface summer temperature

-Method by L. Schenke (ABT), K. Hoevenaars (ABT) and N. Goris (NORCE)

As sea surface temperature belongs to the variables that Earth System Models can project relatively accurately and its thresholds for aquaculture species are relatively well known, we extend our analysis for this case and provide a risk analysis for aquaculture in selected locations in Norway and Greece associated with future maximal surface summer temperature. This approach does not consider potential benefits of warmer winter temperatures.

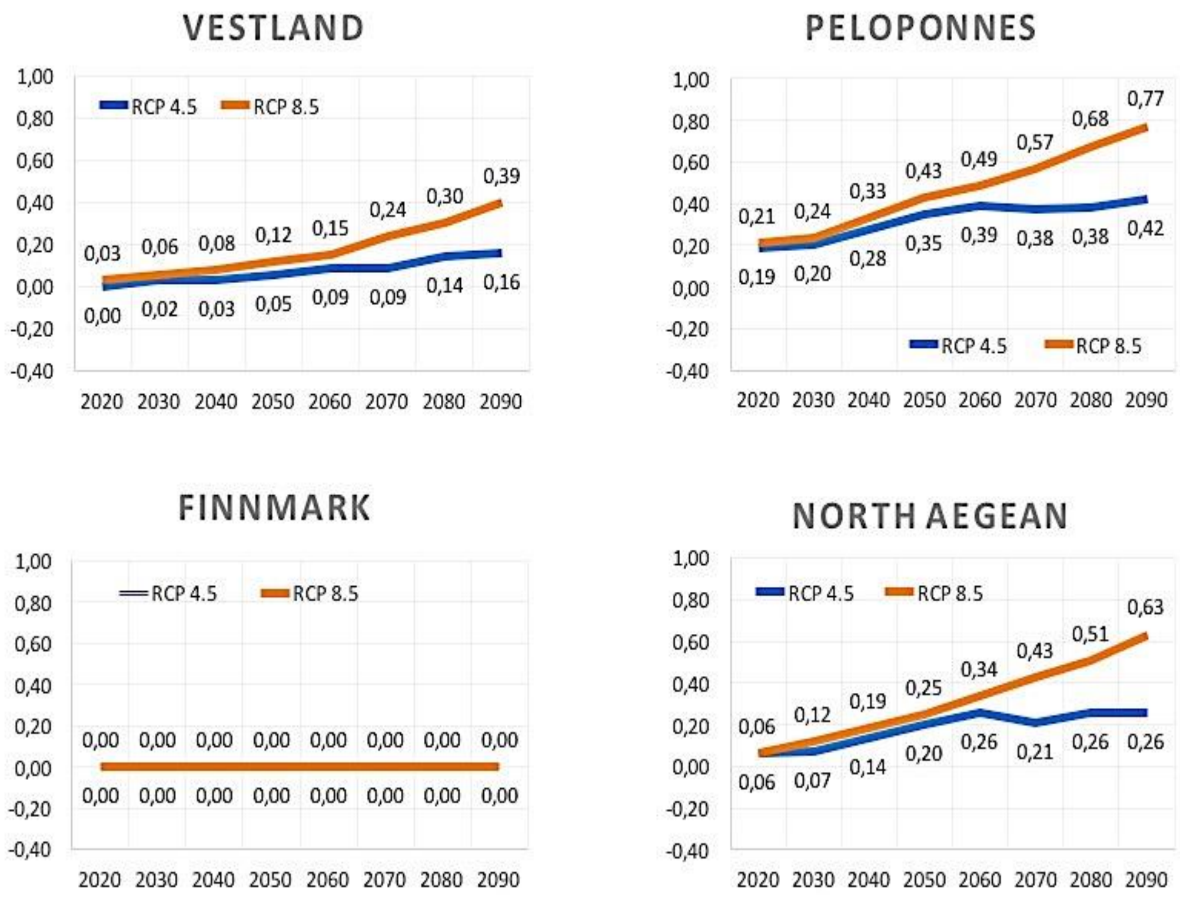

Figure 6: Risk-values for aquaculture of Atlantic salmon in Vestland and Finnmark as well as for gilthead seabream and European seabass in Peloponnes and the North Aegean Sea. Risk-values are associated with decadal monthly maximum sea surface temperature for a moderate and a high CO2-scenario (RCP4.5 and RCP8.5). A value of 0 implies zero risk, while a value of 1 implies a risk of 100%, i.e. that the mortality threshold is reached for all regionally considered species.

We linearly scale the decadal monthly maximum sea surface temperature as projected by 7 well-performing Earth System Models for a moderate and a high CO_2-scenario (RCP4.5 and RCP8.5). In detail, the scaling is first done per considered species (Atlantic salmon, European seabass and gilthead seabream) and is set to 0 (equaling a risk of zero) when the temperature is within a species optimal range (see Table 2) and is set to 1 (equaling a risk of 100%) when the temperature is exceeding the upper lethal limit (see Table 2). Temperature values between these two values are then linearly scaled so that a risk-value for each temperature and considered species is created. A risk above 0 indicates that temperature is not optimal and hence does not yield maximum species growth. We note, however, that due to large seasonal temperature ranges, it is partly to be expected that the farmed species are not continuously situated within their optimal temperature range and we deem low risk-values to be temporarily acceptable.

For risk to marine aquaculture in Norway (Finnmark and Vestland), we consider only the risk for Atlantic salmon as 1) Atlantic salmon accounts for 80% of total Norwegian aquaculture production (http://www.fao.org/fishery/countrysector/naso_norway/en) and 2) other Norwegian aquaculture species are not the focus of marine production in iFishIENCi. For the risk to marine aquaculture in Greece, we focus on gilthead seabream and European seabass, as they are the main species being produced, representing 55% and 42%, respectively (FGM, 2019). For the overall risk to marine fish farming production in Greece, we multiply the individual risks of European seabass and gilthead seabream with their normalized relative importance in Greek production (0.43 and 0.57), and add the individual results.

Figure 6 illustrates the results for our selected regions. We summarize that the risk imposed by maximal summer temperatures onto selected regions in Norway is comparatively small (Vestland) and not existing (Finnmark). In Vestland, it can be expected that Atlantic salmon aquaculture will be less productive in summer, yet also more productive in winter, so that the total risk imposed by increasing SSTs is minimal. However, the risk imposed by maximal summer temperatures in selected regions in Greece is becoming substantial over time. We note that this risk assessment is dependent on the temperature thresholds given for each of the considered species, which vary within literature. Moreover, it does not consider any adaptation (natural or induced) of the species reared.

2.4 Future estimates for Sea Surface Salinity

-Method by N. Goris (NORCE)

In order to retrieve the best estimate for future values of Sea Surface Salinity (SSS), we follow the same principles as already described for SST: We first bias-correct the models based on observational estimates and then omit those models that do not show a reasonable seasonal range when compared to observations. As observational estimate, we use the objectively analyzed salinity decadal fields as provided by the World Ocean Atlas 2018 (Zweng et al., 2018) for the period 1955-1994. We note that the climate models show less agreement with observations for SSS (when compared to SST), this is due to problems in accurately projecting rainfall and ice-melt. Based on their seasonal ranges, we identify 6 models to not be suitable for delivering monthly values within observational estimates and hence proceed with 5 models for our best future estimate.

Figure 7 illustrates the seasonal range for SSS as projected by our 5 well-performing models for 4 different locations under a high-CO_2 future (scenario RCP8.5). **We see a decrease in SSS along Norway´s coast of around 1-1.5 PSU and an increase in SSS of around 1.5-2 PSU in the Mediterranean Sea.** This contrasting behavior might be due to more freshwater in higher latitude (more rain and ice-melt) and less freshwater in lower latitudes (less rain, more heat). Figure 7 also illustrates that the models do not agree well along the Norwegian coast, one model projects a very strong decrease in salinity of about 3PSU, while another model projects no significant changes in SSS. We note that the same pattern is visible for a moderate CO_2-future (scenario RCP4.5), yet SSS increases/decreases here even less (not depicted).

Based on SSS-thresholds for Atlantic salmon (Norway) and gilthead seabream, European seabass and meagre (Greece), provided in Table 3 and the time-series of SSS in Figure 7, we note that:

- For Vestland, the contemporary conditions for SSS are up to 1PSU below optimal in winter and up to 1PSU above optimal in summer. **The future decrease in salinity will lead to SSS being a larger challenge in winter but to SSS being more optimal in summer**. However, this trend is very uncertain.
- For Finnmark, the contemporary conditions for SSS are above the optimal range all year long. Here, t**he future decrease in SSS will be of advantage for Atlantic Salmon, leading to the conditions being within optimal range in winter.** We note that this results is very uncertain.
- **For Peloponnese and the North Aegean Sea, SSS-values of gilthead seabream and European seabass remain within their optimal range.** SSS is leaving the optimal range for Meagre. However, we note that while future SSS-values might not be optimal, Meagre can tolerate a wide range of SSS-values and will not be substiancially affected by the projected SSS-values.

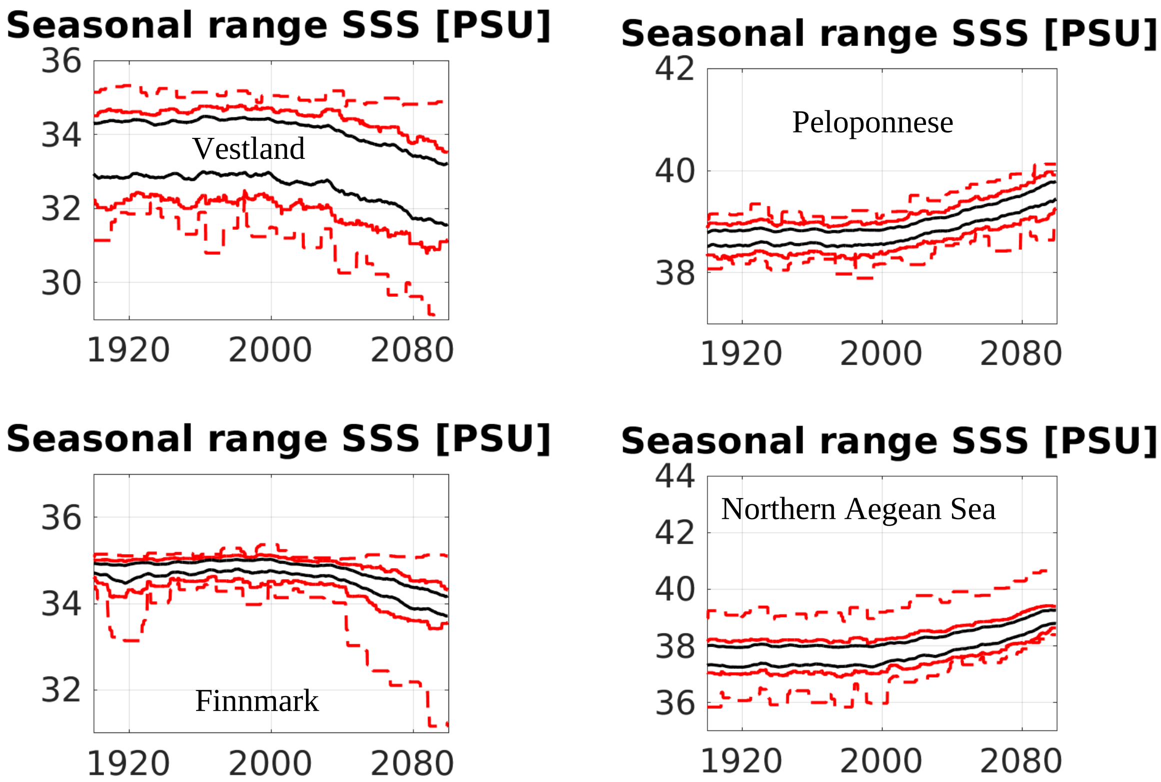

Figure 7: *Bias-corrected evolution of seasonal ranges of sea surface salinity as projected by 5 well-performing Earth System Models for 4 different locations for a high CO_2-scenario (RCP8.5). Black lines mark the decadal average of the seasonal range, red solid lines the model-average of decadal minimum and maximum-temperature and red-dashed lines the results for decadal minimum and maximum for the most-extreme model.*

	Minimum Salinity [PSU]	Optimal Salinity [PSU]	Maximum Salinity [PSU]
Atlantic Salmon	-	33-34	-
Meagre	5	15-38	50
Gilthead Seabream	5	15-40	44
European Seabass	-	30-40	-

Table 3: Thresholds for sea salinity for selected Aquaculture species. Thresholds are provided by http://www.fao.org/fishery/culturedspecies/Salmo_salar/en#tcNA0089 (Atlantic Salmon), https://longline.co.uk/meta/list, (meagre and gilthead seabream) and by http://www.fao.org/fishery/culturedspecies/Dicentrarchus_labrax/en#tcNA0078 (European seabass). Upper optimal ranges of salinity have been corrected for meagre, gilthead seabream and European seabass by HMCR based on their extensive experience with these species.

For a general overview over the evolution of SSS for the next decades, Figure 8 illustrates maximum SSS as maps over European waters for different decades. We note that the values in the right panel of Figure 8 are representing the model mean (i.e. the maximum monthly values when averaged over all models; corresponding to the upper red solid line in Figure 7), though single models might show higher monthly values (as shown in Figure 7). Therefore, the left panel of Figure 8 shows the uncertainty of the maximum values, i.e. how much a single model might deviate from this maximum-value.

We summarize for SSS under a high emission scenario (RCP8.5), that our best estimate yields that the SSS-evolution along the coastline of the Northern Atlantic is **highly uncertain**, but that SSS is likely to slightly decrease due to ice-melt. For the Mediterranean Sea, our best estimate yields an increase around 1-1.5PSU. For a moderate emission scenario (RCP4.5), these trends remain, but the total changes are less (not depicted). **Salinity changes will be beneficial for European aquaculture along the northern Norwegian coast, while it will be a stressor in winter months for lower latitudes of the Norwegian coast. For European aquaculture in the Mediterranean Sea, higher salinity values will not affect the considered species substantially. In summary, our analysis yields that SSS will not become a major stressor for the considered fish species and areas.**

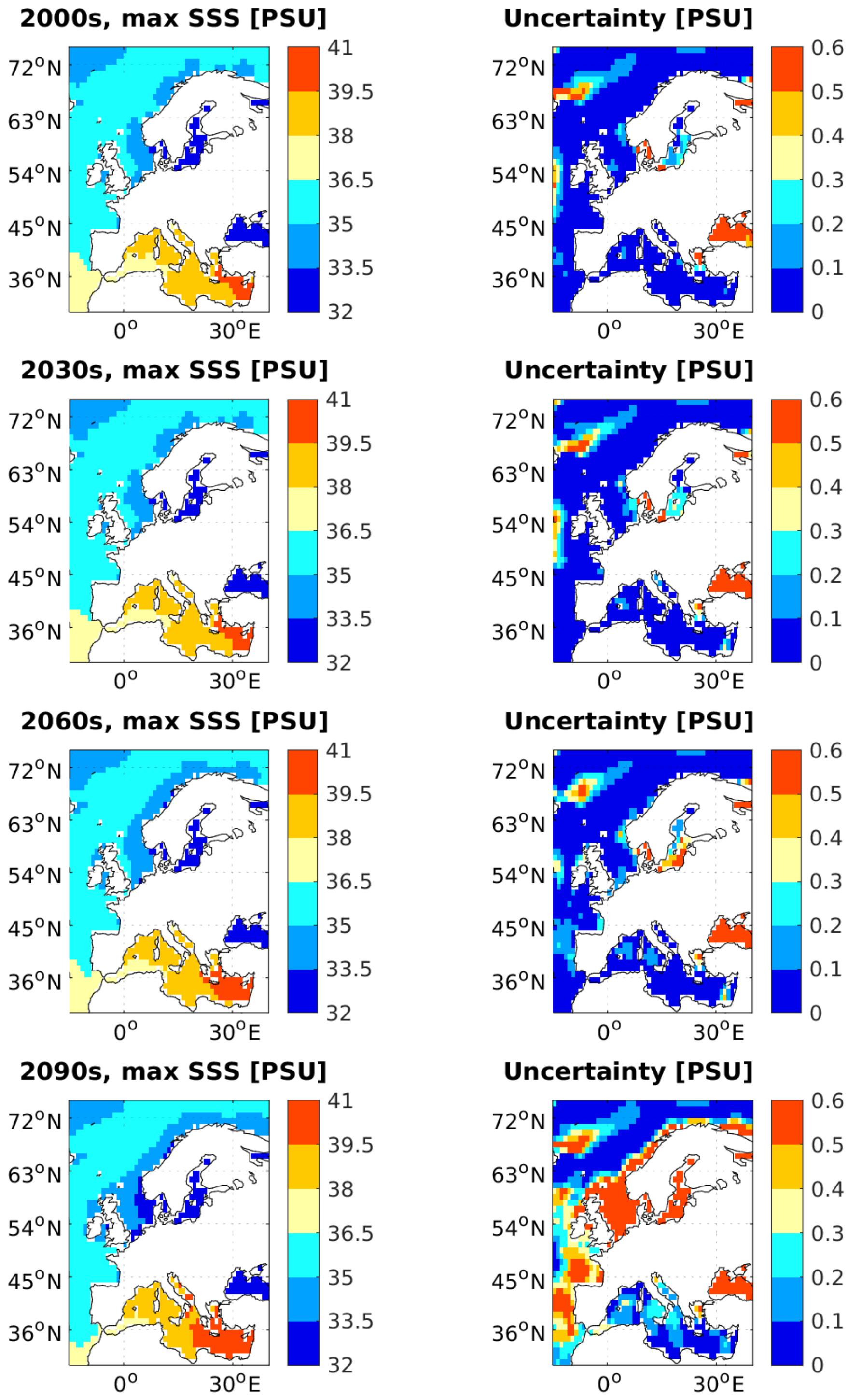

Figure 8: *Bias-corrected evolution of decadal monthly maximum SSS as projected by 5 well-performing Earth System Models for a high CO_2-scenario (RCP8.5). Left panel: mean values over all considered models; right panel: maximum deviation of single models from the values in the left panel.*

2.5 Future estimates for Sea Surface Dissolved Oxygen

-Method by N. Goris (NORCE)

For a best estimate of future values of Sea Surface Dissolved Oxygen (DO_2), we follow the same principles as already described for SST and SSS: we first bias-correct the models based on observational estimates and then omit those models that do not show a reasonable seasonal range when compared to observations. As observational estimate, we use the objectively analyzed dissolved oxygen climatological fields as provided by the World Ocean Atlas 2018 (Garcia et al., 2018) for the period 1880-2017. Based on their seasonal ranges, we identify 6 models to not be suitable for delivering monthly values within observational estimates and hence proceed with 5 models for our best future estimate.

Figure 9 illustrates the seasonal range for DO_2 as projected by our 5 well-performing models for 4 different locations under a high-CO_2 future (scenario RCP8.5). **We see a relative uniform behavior for all 4 locations with a decrease in DO_2 of around 1 mg/L**. We note that the same pattern is visible for a moderate CO_2-future (scenario RCP4.5) with a decrease in DO_2 of around 0.5 mg/L (not depicted).

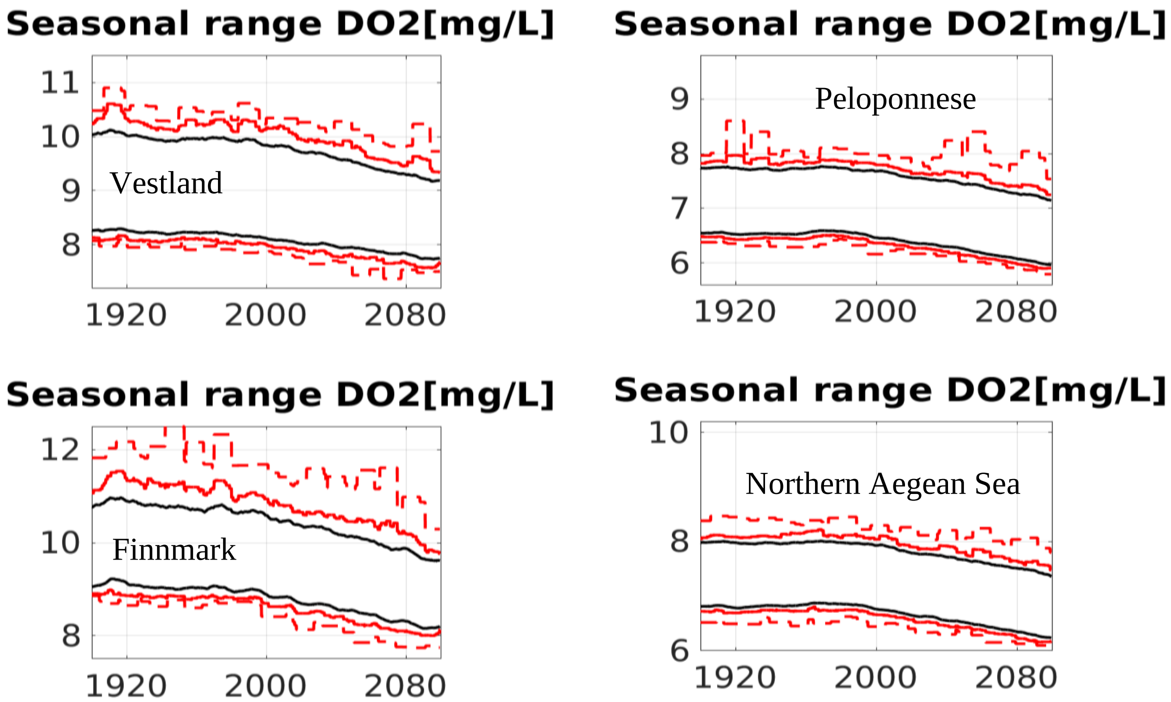

Figure 9: *Bias-corrected evolution of seasonal ranges of sea surface dissolved oxygen as projected by 5 well-performing Earth System Models for 4 different locations for a high CO_2-scenario (RCP8.5). Black lines mark the decadal average of the seasonal range, red solid lines the model-average of decadal minimum and maximum-temperature and red-dashed lines the results for decadal minimum and maximum for the most-extreme model.*

	Minimum Oxygen [mg/L]	Optimal Oxygen [mg/L]	Maximum Oxygen [mg/L]
Atlantic Salmon	5	9-11	13
Meagre	3.4	6-8.2	21.4
Gilthead Seabream	2.7	6-9	10
European Seabass	4	6-8	20

Table 4: Thresholds for dissolved oxygen for selected Aquaculture species. Thresholds are provided by https://longline.co.uk/meta/list. Lower optimal ranges of oxygen have been corrected for meagre, gilthead seabream and European seabass by HMCR based on their extensive experience with these species.

Based on DO_2-thresholds for Atlantic salmon (Norway) and gilthead seabream, European seabass and meagre (Greece), provided in Table 4 and the time-series of DO_2 in Figure 9, we provide a list of risks below. In the case of DO_2, we want to note that the thresholds in Table 4 might not be accurate under warmer conditions as increased temperature will increase oxygen consumption needs (Thorarensen and Farrell, 2011).

- For Vestland, **the present summer conditions (i.e. the minimum values) for DO_2 are already sub-optimal and they are worsening with climate change**. Though they do not reach the minimum threshold of 5mg/L, a value of 7.5mg/L in 2080 will induce additional stress for Atlantic Salmon. **This stress will appear at the same time as maximum temperature values and might lead to Atlantic salmon being substantially stressed during summer.**
- For Finnmark, **the present summer conditions for DO_2 are still optimal. Though they are worsening with climate change**, they do not go below 8mg/L. As future temperature conditions in summer are close to optimal, we foresee that the induced stress is minor.
- For Peloponnese and the Northern Aegean Sea, **optimal DO_2 conditions for European seabass, gilthead seabream and meagre are maintained under climate change**.

In order to show a general overview over the evolution of DO_2 for the next decades, Figure 10 shows the minimum DO_2 as maps over European waters for different decades. We note that the values in the right panel of Figure 10 are representing the model mean (i.e. the minimum monthly values when averaged over all models; corresponding to the lower red solid line in Figure 9), though single models might show lower monthly values (as shown in Figure 9). Therefore, the left panel of Figure 10 shows the uncertainty of the maximum values, i.e. how much a single model might deviate from this maximum-value.

We summarize for DO_2 under a high emission scenario (RCP8.5), that our best estimate yields that DO_2 will decrease around 1 mg/L in European Waters. For a moderate emission scenario (RCP4.5), these trends remain, but the total changes are less (not depicted). **Dissolved oxygen will become an additional stressor for Norwegian aquaculture in summer months, where future minimal DO_2 values will coincide with maximal temperature values.**

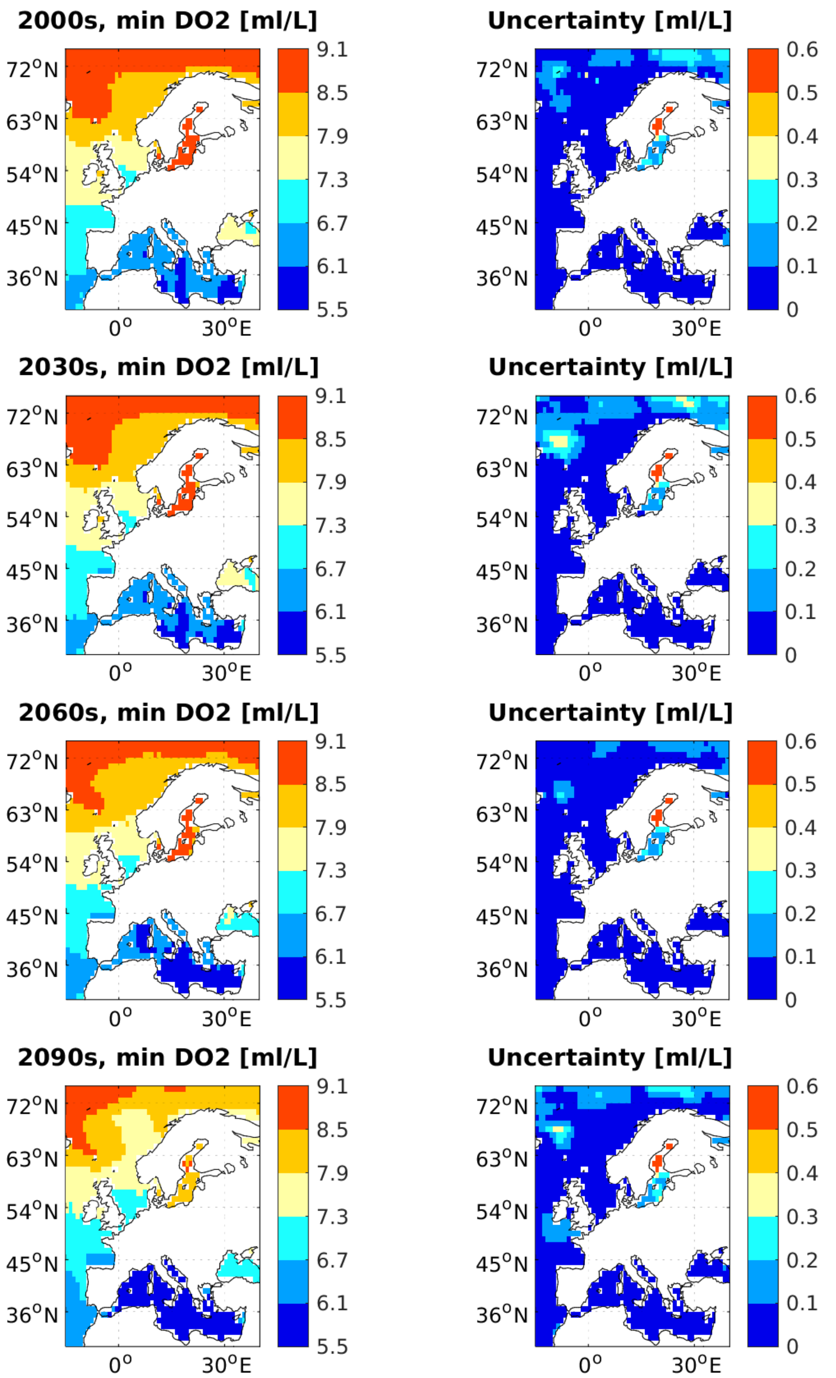

Figure 10: *Bias-corrected evolution of decadal monthly minimum sea surface dissolved oxygen as projected by 5 well-performing Earth System Models for a high CO_2-scenario (RCP8.5). Left panel: mean values over all considered models; right panel: maximum deviation of single models from the values in the left panel.*

2.6 Future estimates for Ocean Net Primary Productivity

-Method by N. Goris (NORCE)

In order to retrieve the best estimate for future values of Ocean Net Primary Productivity (NPP), we first benchmark the modelled estimate against observations. NPP is a measure of biological productivity of the oceans. The majority of primary producers in the oceans are algae. Here, we use the observational estimate derived by applying the standard Vertically Generalized

Production Mode (Behrenfeld and Falkowski, 1997) to chlorophyll concentration from satellite-borne sensor SeaWIFS as provided by the ocean productivity webpage (http://sites.science.oregonstate.edu/ocean.productivity/index.php).

However, when comparing the modelled NPP-values with the observational estimates (Figure 11 provides an example), it became apparent that the model-bias along the coast is very high. The models underestimate the productivity along the coast by 50%-80%. Moreover, even after bias-correction, none of the models provides an accurate seasonal range (Figure 11 provides an example). Bonan and Doney (2018) confirm that global climate models are not able to accurately capture coastal NPP. They state that "the spatial resolution of global models is too coarse to capture regional dynamics of highly productive coastal ecosystems and coral reefs, and models are just beginning to incorporate adequate land-ocean connectivity to assess nutrient eutrophication, water quality, and harmful algal blooms". Based on this, we do not proceed with giving a future estimate for NPP as the estimate would be too erroneous.

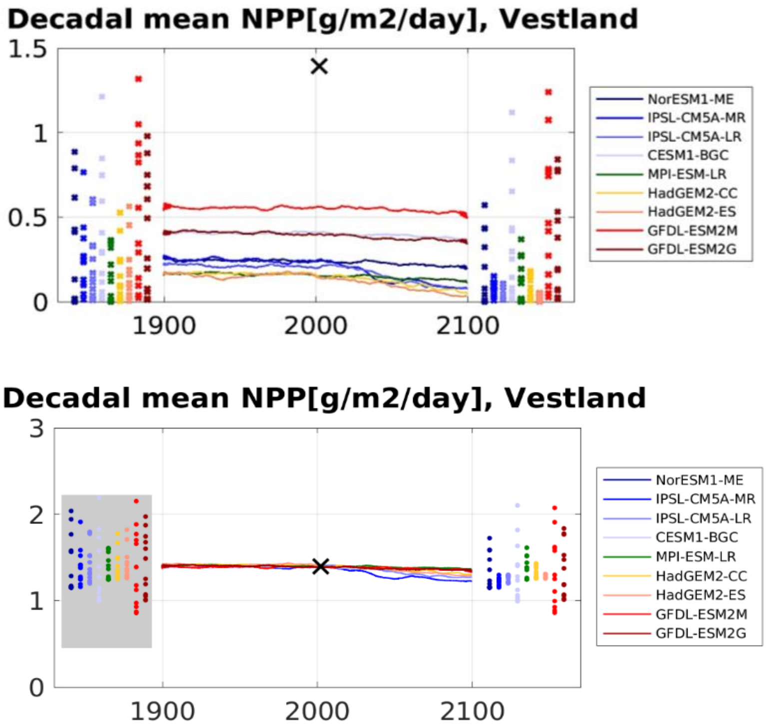

Figure 11: *Evolution of net primary productivity [g/m/day] as projected by 11 different Earth System Models for the coast along Vestland-country, western Norway for the high CO_2-scenario RCP8.5 (Upper panel: without bias-correction; lower panel: with bias correction). Each panel contains the range of the mean seasonal cycle for the years 1997-2007 (left) and 2085-2094 (right) per model (color-coding in legend) and for the observational estimate (grey shading) as well as the decadal evolution per model (middle, color-coding in legend) and for the observational estimate (black cross).*

We will try to give an indication of possible risks through quoting results of current literature. NPP is dependent on temperature, light and nutrient availability. Here, light availability can be indicated through SST (more light in warmer temperatures) and nutrient availability through stratification (more nutrients in less stratified waters). Climate change warms the oceans, which is fueling NPP, but also enhances stratification, which leads to a decrease in nutrient supply and NPP. These contradicting mechanisms will likely lead to an increase in NPP in higher latitudes (as there is ample nutrient supply) and to a decrease in NPP in lower latitudes (nutrient limitation will overpower the effect of the warming), as stated by Bopp and co-authors (2013). Moreover, in a warmer ocean, the seasonal window for algae blooms will be extended and peak-production will occur earlier (Hallegraeff, 2010).

The effect of NPP on marine finfish aquaculture is probably most significant when Harmful Algae Blooms (HAB) occur. The term HAB describes algae blooms that can cause a range of deleterious physiological and environmental effect via (i) production of toxins that pass through trophic levels and may cause stress, illness or death in some species including humans, or (ii) serious reductions in dissolved oxygen concentrations (Moore et al., 2008). Oxygen depletion may produce anoxic conditions in sheltered bays, leading to deadly conditions for fish and invertebrates (Hallegraeff, 2010).

HAB is to a large extend determined by polluting chemicals and it is unclear how this pollution will change in the future and as it is not yet well understood how different environmental and anthropogenic factors come together to create HAB. Therefore, it is not possible to give an estimate of future HAB. However, it is possible to determine future trends of the climate conditions needed for algae blooms, i.e. the future "window of opportunity" for HAB. For this, we utilize the cited research on future NPP (Bopp et al., 2013; see above) and come to the following conclusions:

- For Vestland and Finnland, **the combination of future warming and ample nutrient supply is assumed to lead to earlier, denser and extended algae bloom and hence a longer "window of opportunity" for harmful algae blooms.** These conditions will occur in spring and summer and hence partly at the same time as maximum temperature values and minimum oxygen values and might lead to Atlantic salmon being substantially stressed during summer.
- For Peloponnese and the Northern Aegean Sea, **the combination of future warming and more stratification is assumed to lead to less natural nutrient supply and hence to less algae blooms**. However, we note that in coastal regions, polluting chemicals might provide enough nutrients to allow for (harmful) algal blooms. If this is the case, then gilthead seabream, European seabass and meagre will suffer the consequences of earlier, denser and extended (harmful) algae bloom in spring and summer.

We note that these estimates are highly uncertain.

3 Case study: seabass, seabream and meagre in Mediterranean Sea

-Method by N. Papandroulakis (HCMR), O. Stavrakidis-Zachou (HCMR)

This Section discusses future growth projections for three Mediterranean aquaculture species in the context of a warming ocean. This work is predominantly based on outputs from the C12A ClimeFish case study (https://climefish.eu/2019/04/10/greek-aquaculture/), such as projections for European seabass (*Dicentrarchus labrax*) and meagre (*Argyrosomus regius*) complemented by additional work regarding gilthead seabream (*Sparus aurata*).

3.1 Representativeness

Growth projections of European seabass, gilthead seabream and meagre, have been produced for a number of regions spanning across the latitudinal boarders of Greece. Nevertheless, to a large extent, the observed trends can be considered representative for the whole Mediterranean.

The justification lies in the leading role of Greece in Mediterranean aquaculture and the type of production systems implemented across the region. Specifically, Mediterranean aquaculture is dominated by finfish. European seabass and gilthead seabream in particular, are the most important species and make up for 95% of the total production while some others such as meagre and greater amberjack have started to emerge as well. The main producer country for these species in Europe is Greece, accounting for over 60% of the European production and 24% of the global production. Turkey is another major producer country, accounting for over a third of the world production while other Mediterranean countries such as Tunisia, Italy, and Spain amount for smaller, yet significant, production (FGM, 2019). Given that the main farmed species, the production systems and the practices (marine cage farming) are similar among these countries and that Greece is a leading producer, extrapolations for the whole region can be made.

Moreover, the temperature profile of the Mediterranean Sea is rather similar across its entirety with generally mild winters and hot summers (Sea Surface Temperature of 16-20^{o}C and 24-28^{o}C respectively) typically occurring. Slight differences may occur between the eastern and western basins with the most prominent being that the eastern basin typically exhibits temperatures of up to 2^{o}C higher (Maras *et al.*, 2015). Therefore, analysis on future trends at the eastern basin in countries such as Greece and Turkey may be highly relevant in the context of climate change by providing timely insight for effects which may later manifest across the western basin.

3.2 Modelling

Growth predictions were obtained by forcing climate data onto biological models developed for the three species and simulating a typical production cycle at a theoretical farm level.

For this, projections of environmental variables such as daily Sea Surface Temperature (SST) and wind velocity were obtained for two IPCC scenarios, RCP4.5 and RCP8.5. These data were produced by the Global Climate Model ICHEC-EC-EARTH via the coupled POLCOM-ERSEM ecosystem model (Proudman Oceanographic Laboratory Coastal Ocean Modelling System and the Plymouth Marine Laboratory European Regional Seas Ecosystem Model) and the downscaled 10 x 10 km projections were used for our analysis.

The climate data were then forced on the biological models developed for the three fish species. These models are based on Dynamic Energy Budget (DEB) theory and were parametrized and validated against production data from farms. The detailed procedure is described in Marques *et al*. (2019) while the parametrization and validation of the European seabass model is given in Stavrakidis-Zachou *et al.* (2019a). For the two climate scenarios, simulations were performed at three time periods representing the short, mid, and long future (2015-25, 2025-35, and 2045-55) and for a total of 9 Greek regions (Figure 12). In each region, typical production cycles were simulated at a theoretical farm level for two types of farms, one located inshore and one offshore. Furthermore, in order to assess the effect of seasonality on growth we included adapted stocking planning as a management option in our analysis by simulating three stocking months (March, June, September) for each farm.

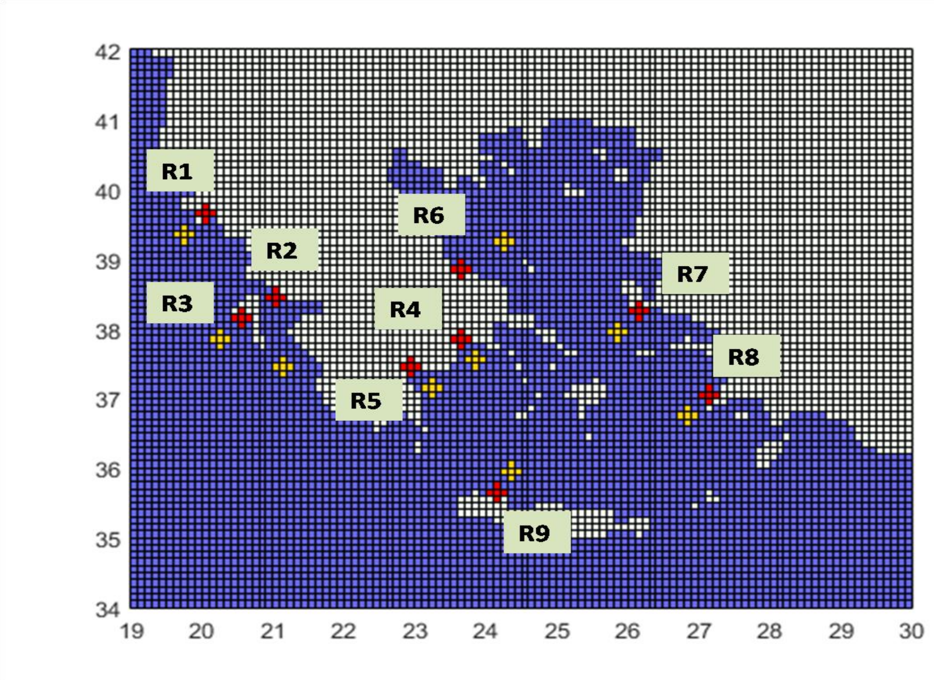

Figure 12: Case study area, map of the simulated regions (R1-R9). Red denotes inshore and yellow offshore locations.

As a proxy for detecting future trends in growth, we here use the production time that is required to reach one of the common market sizes (800g) under the various environmental and management scenarios.

3.3 Growth projections

Changes in growth for the three species over time are shown in Figures 13-15. In order to visualize differences in the time to market size between now and the future, the change in mid (2025-2035) and long (2045-2055) term periods is given as relative to the short (2015-2025)-term period which represents the current state.

Overall, relative changes in time to market size are expected to be small for all species, rarely exceeding 10%. Generally, the simulations show that compared to now, fish may exhibit negligible or even negative effects on growth in the mid-term while a small growth benefit may be observed in the long-term future. This trend relates to the RCP8.5 projections (Figures 13-15) which is currently the most likely climate scenario given the status of global carbon emissions (Teske, 2019), yet the same general but less pronounced trend was observed for RCP4.5.

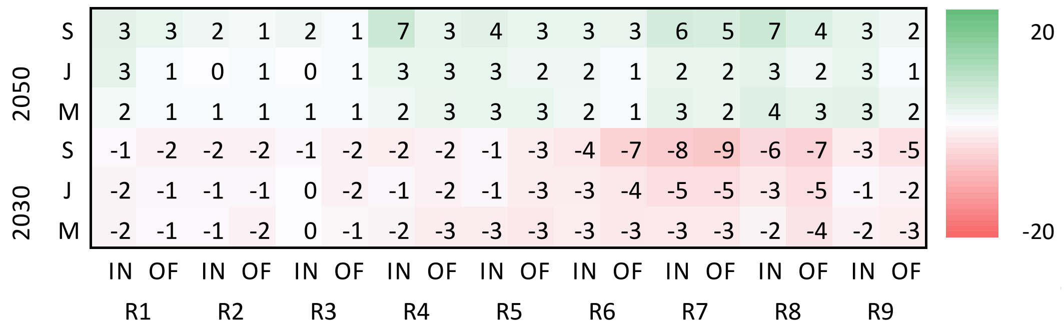

Figure 13: European seabass, relative change (%) in growth between current period (2015-2025) and mid (2025-2035) and long (2045-2055) term future for RCP8.5 using the time to market size (800g) as proxy. S: September; J: June; M: March; IN: Inshore; OF: offshore.

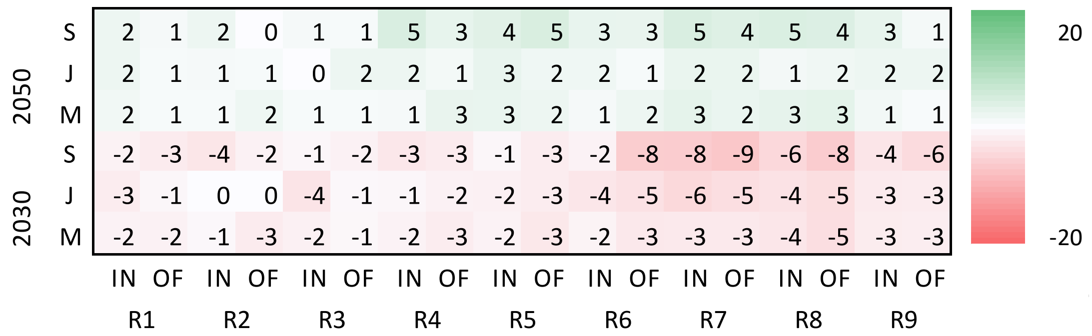

Figure 14: Gilthead seabream, relative change (%) in growth between current period (2015-2025) and mid (2025-2035) and long (2045-2055) term future for RCP8.5 using the time to market size (800g) as proxy. S: September; J: June; M: March; IN: Inshore; OF: offshore.

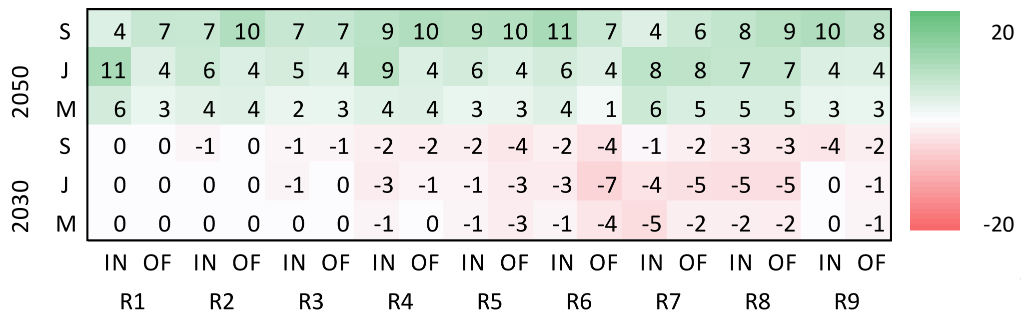

Figure 15: Meagre, relative change (%) in growth between current period (2015-2025) and mid (2025-2035) and long (2045-2055) term future for RCP8.5 using the time to market size (800g) as proxy. S: September; J: June; M: March; IN: Inshore; OF: offshore.

For the mid-term projections, growth may be up to 9% slower for European seabass and gilthead seabream while meagre will be less affected at a maximum of 7%. Despite the reduction in growth mid-term appearing counter-intuitive, this is predominantly attributed to the relatively low temperatures forecasted by the climate model for the region during that period. On the contrary, the higher temperatures projected for the long-term may result in faster growth by 2050. Meagre will see the largest relative benefit by reaching the selected market size up to 11% faster in some regions, followed by European seabass and gilthead seabream whose growth may speed up to 7 and 5% respectively. In the case of meagre, such growth benefit translates to a decrease in the production time by roughly 20-40 days, depending on the stocking period. For European seabass and gilthead seabream this reduction will be in the range of 60-80 days. Moreover, the growth benefit will be higher for the September stocking when compared to the March, and June stockings, and this appears to be consistent across the species. Finally, with respect to farm location (inshore/offshore) the effect seems to be highly region-specific with some of the regions exhibiting better growth inshore compared to their offshore counterparts and vice versa.

3.4 Uncertainties/caveats

Evaluating the effects of climate change on aquaculture stocks may be a challenging task due to the multitude of climate drivers involved as well as the significant number of existing knowledge gaps which can hinder our capacity to predict the future.

It is important to highlight that the only climate driver that was explicitly modelled in this analysis was temperature. Consequently, the results may provide incomplete or even misleading insights regarding the future and should be interpreted with caution. The lack of robust understanding of the species-specific effects of other drivers such as acidification, diseases, extreme events, hypoxia and Harmful Algal Blooms (HABs) as well as that of supporting data on environmental projections at relevant spatial-temporal resolutions poses difficulties in modelling these drivers. However, their effect can be of grave biological or economic consequences. Therefore, they should be taken into account and where explicit modelling is not possible, an assessment of the risks and opportunities should be conducted.

In the framework of ClimeFish a freely available Decision Support Software (DSS) for Greek aquaculture stakeholders was developed (http://136.144.228.39:8080/climefish/case12) which incorporates such elements that are relevant for decision-making. This tool includes the biological forecasting for European seabass and meagre shown here and allows potential users to explore changes in the biological performance of the fish and the profitability of a farm under a range of climate, management, and economic scenarios (Stavrakidis *et al.*, 2019b). The DSS also includes, as stand-alone supporting information, a risk and opportunity assessment for drivers that could not be modelled. Moreover, it incorporates to some extent, extreme events such as thunderstorms and heatwaves that are included as effects on feeding and mortality. These events may have considerable effects on farm profitability depending on their magnitude which is user defined. For instance, experimentation with the software has shown that even for mild extreme event scenarios, the biomass production and therefore farm profitability could exhibit substantial losses while more pessimistic scenarios could render farming financial unsustainable for certain regions. This appears irrespective of the positive effect on growth for the long-term future presented in the previous paragraph, which further highlights the necessity to incorporate multiple elements when interpreting the effects of climate change on aquaculture.

4 Conclusions and outlook: Climate induced risks for European Aquaculture

As stated in the introduction, there are many levels of uncertainty when assessing the direct future impacts of climate change upon marine aquaculture. Within this report, we have tried to give insights into the uncertainties of 1) future greenhouse gas emissions by considering two possible greenhouse gas emission pathways, 2) climate models by analyzing the oceanic response of 11 different Earth system models, 3) response of aquaculture species by considering environmental ranges for aquaculture species and by additionally considering a model that relates warming rate to the metabolic processes of selected species. Values for environmental thresholds and optimal ranges for growth of aquaculture species vary within the literature, and our results will be influenced by their accuracy.

Our results, based on the worst case scenario (RCP 8.5), indicate that increasing winter ocean temperatures will, to first order, be beneficial for the selected location and species (Atlantic salmon for Norway and European seabass, gilthead seabream and meagre for Greece), potentially increasing aquaculture productivity by increasing fish growth. In contrast, the trend of increasing summer temperatures suggests that summer temperatures will eventually become sub-optimal. However, in western Norway, the threat is small and productivity levels can likely be kept due to better winter conditions. Moreover, warming in northern Norway may lead to good conditions for Atlantic salmon and a chance for expanding salmon aquaculture further north. In the Mediterranean Sea, higher summer temperatures will at some point overpower the benefit of warmer winter ocean temperatures and become lethal for gilthead seabream and European seabass towards the end of the century.

For Norway, future higher than optimal summer ocean temperatures will coincide with lower than optimal oxygen values, leading to additional stress. Our analysis concludes that future oxygen values will not be a stressor for aquaculture in Greece. However, we note that given oxygen thresholds in this report are based on today´s temperature, yet oxygen demands to support aerobic processes increases with temperature (Fry and Hart, 1948). There is some understanding from experiments as to how oxygen thresholds change with increasing temperature (e.g., Remen et al., 2015, 2016). Based on this, it is likely, that future oxygen values will also be a stressor for aquaculture in Greece.

Our results suggest that future salinity values will not be a stressor for aquaculture in Greece. Salinity conditions will be more optimal in northern Norway, but salinity will be a stressor in western Norway. However, this stress occurs in winter when other stressors are absent and the stress induced by salinity alone is low. Therefore, we infer that a monitoring of salinity and its impacts is not a priority.

Research furthermore suggests that algal blooms will increase in Norway and that the likelihood of their occurrence decreases in Greece (Bopp et al, 2013). However, these results are based on future climatic conditions for algal blooms, e.g. natural nutrient and light supply as well as ocean warming. While this gives a “window of opportunity” for the occurrence of Harmful Algal Blooms (HAB), HAB is to a large extend also determined by polluting chemicals. As it is unclear how this pollution will change in the future and as it is not yet well understood how different environmental and anthropogenic factors come together to create HAB, we do not include the occurrence of HAB into our vulnerability results.

Based on the results of ocean temperature and dissolved oxygen, we conclude that marine European aquaculture in its present form is vulnerable to climate change, especially within summer months where there is an increased chance of a combination of higher temperatures and lower oxygen concentrations. This combination will increase the likelihood of stress and mortality, especially if the oxygen requirements of fish increases due an increased metabolism at warmer temperatures. We note that even minor risk might have consequences for marine aquaculture. More optimal winter and less optimal summer conditions may affect stocking patterns and production cycles, potentially influencing values-chain management.

There are other aquaculture threats associated with climate change that we could not analyze within this report. These include the effects of climate change on parasites and invasive species. Research has suggested that salmon lice thrive under warmer conditions (Hurford et al., 2019), which would hence increase the vulnerability of Norwegian aquaculture to climate change. Moreover, changes in the frequencies of extreme weather events pose a risk to aquaculture. The incidence of severe thunderstorms is predicted to increase over Europe and European coastal waters due to climate change (Rädler et al., 2019). High winds and associated waves can damage the integrity or destroy infrastructure of an aquaculture operation. This may permit the escape of large numbers of fish or cause disruption to normal farming operations such as feeding (Reid et al., 2019, Jensen et al., 2010). An increase in frequency and severity of storm events may require that aquaculture operations move to less exposed areas. Infrastructure and equipment designed for use in high energy sites may be required in areas where less energy resilient structures currently suffice.

Climate change is also likely to increase mean and heavy precipitation events in northern Europe and to decrease heavy and mean precipitation events in southern Europe (IPCC, 2013). As a result, flood peaks are expected to increase in northern Europe, mainly because of a higher projected winter precipitation (Schneider et al., 2013). Freshwater flooding is a potential stressor for aquaculture as floods can damage land-based infrastructure associated with marine aquaculture. The occurrence of floods will also threaten freshwater aquaculture. Flooding of ponds and raceways may permit cultivated fish to escape into natural water courses, and may introduce diseases, parasites and predators. As with marine aquaculture, freshwater aquaculture could be influenced by increasing water temperatures. Though details about warming in freshwaters are difficult to project, they can be inferred from projected atmospheric warming. Regional climate models agree that there will be significant warming all over Europe reaching values between 2.5 °C to 5.5 °C at the end of the 21st century (Jacob et al., 2014), with Southern Europe experiencing the strongest warming in summer and Northern Europe in winter (Goodess et al., 2009; Kjellström et al., 2011). The projections agree that there will be a future increase in the number of warm days and nights and heat waves over Europe (Jacob et al., 2014). As consequence, freshwater systems are likely to warm. Higher water temperature may lead to increased fish metabolism, feed intake and growth rates, if stressors such as low oxygen are absent. However, dissolved oxygen levels are lower in warmer waters and warming-induced increase in NPP might lead to an additional decrease in oxygen levels. Low oxygen levels lead to increased risk of stress and mortality during summer months, requiring mitigation via aeration, or reduced stocking and feeding rates. Atmospheric warming might also lead to water stress, hampering the normal functioning of flow-through aquaculture systems that require a continuous supply of flowing water.

Given all these potential risks, our results about future risks due to sea surface temperature and dissolved oxygen changes are only first indications of the climate change vulnerability of European aquaculture. We note that even for the analyzed variables, improved models with higher accuracy and at higher resolution may provide a better insight and additional information towards the climate change effect on the aquaculture industry. Furthermore, all reared species do not only offer adaptation capacity but are also subject to genetic improvements which may mitigate some of the adverse effects presented here. Hence, continuous monitoring and specific research actions are needed to follow up closely how aquaculture species respond to combined stressors like reduced dissolved oxygen and warming temperatures. Here, the suggested monitoring by iBOSS technology being produced in the iFishIENCi project can bring valuable new insights. Moreover, it is essential to closely monitor the evolution of SST and dissolved oxygen so that trends can be identified and new extreme values can be discovered in due time. The developed online water quality monitoring system (physical and chemical parameters) of iFishIENCi will be of great benefit to provide these early warnings. Lastly, for regions whose aquaculture will be threatened by climate change soon, adaptations in the technology used together with a better understanding of the species biology are of major importance. Here, the progress of iFishIENCi with SMART-RAS may prove invaluable.

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