**Projecting climate change impacts on Mediterranean finfish production: A case study in Greece.**

**Electronic Supplemental Material**

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## DEB model

This section of the Electronic Supplemental Material describes the model and gives the equations that govern the individual dynamics (Tab S1). Model parameters are described in Tab S2. Individual growth and reproduction are modeled based on the Dynamic Energy Budget (DEB) theory for metabolic organization; a theory that provides the conceptual and quantitative framework to study the whole life cycle of an individual while making explicit use of energy and mass balances (Kooijman, 2010). A fundamental concept of this framework is that biomass is divided into structural and that bound in one or more reserves with an additional reproductive buffer found in reproducing adults. The standard DEB model considers only one type of structure and one of reserve. Each of these biomass components consists of a mixture of polymers such as proteins, lipids and carbohydrates which form generalized compounds of constant composition. Structure (*V*), reserve (*E*), reproduction buffer (*ER*) and maturity (*EH*) as the cumulative investment to maturation, comprise the state variables defined by the DEB theory. Based on physiological rules for the uptake of food by organisms and its use for maintenance, growth and maturation or reproduction the theory allows for modeling of the processes of feeding, digestion, maintenance, maturation, growth, reproduction and aging. Food uptake is assumed to follow a functional response relationship with food density and to be proportional to an organism’s surface area. The scaled functional response *f* , *i.e*., the feeding rate as a fraction of the maximum feeding rate of an individual of a given size, is used as a quantifier of food availability and takes values between 0 and 1. Energy from food is extracted by the organism and added to the reserve via the process of assimilation (). Subsequent mobilization () of the reserve allows for growth (), which is the increase in structural biomass, maintenance (), and development or reproduction (). A constant fraction κ of the mobilized reserve is allocated to somatic functions, which include somatic maintenance and growth, while the remaining fraction is used for development and reproduction, after subtraction of costs related to maturity maintenance ().

The extended DEB model used to model fish assumes five life stages (embryo, prelarvae, larvae, production and adult), with stage transitions occurring when the cumulative investment into maturation exceeds certain thresholds. Important stage transitions include birth, which in the DEB context marks the start of exogenous feeding, metamorphosis as the completeness of metamorphosis, and finally puberty which is defined as the time when development ceases and allocation to reproduction commences. The stage of interest for aquaculture is the production stage which covers parts of the juvenile and adult stages and relates to the on-growing phase of the species culture. Most species, and in particular fish species, with a larval phase which show metabolic acceleration between birth (start of exogenous feeding) and metamorphosis are modeled with the abj-model (Marques *et al*., 2018). This means that during that stage (V1-morphic stage) surface area grows in proportion to structural volume. For all other stages, growth was considered isomorphic; surface area is proportional to structural volume to the power 2/3. From DEB theory follows that changes in shape affect the surface-specific maximum assimilation rate, , and the energy conductance , via the acceleration factor ; the acceleration factor multiplies the aforementioned parameters. The acceleration factor, , equals one for embryos and pre-larvae stage, during acceleration, and after acceleration, where and are the structural lengths at birth and metamorphosis, respectively. Consequently, the dynamics (Tab S1) will change via the fluxes and .

Tab S1 State variables, energy fluxes and dynamics of the standard DEB. Brackets [] indicate quantities expressed per unit of structural volume and braces {} per unit of structural surface area. Parameter interpretation is given in Tab S2.

|  |  |
| --- | --- |
| *State variables* |  |
| , *L* | Structural body volume, Volumetric structural length:  *1/3* |
| *E*, [*E*] | Energy in reserve, Reserve density: / |
|  | Energy investment into maturation |
|  | Energy investment to reproduction |
|  |  |
| *Fluxes* |  |
|  | Assimilation rate:  |
|  | Reserve mobilization rate: with  |
|  | Somatic maintenance rate: +  |
|  | Maturity maintenance rate:  |
|  | Growth rate:  |
|  | Energy flux to maturation/reproduction:  |
|  |  |
| *Dynamics* |  |
|  = |  |
| [E] =  |  |
|  |  |
|  |  |

Reserve and structure are abstract state variables that can be linked to commonly measured quantities such as length or body mass. A measurable length for a fish , e.g., fork length, is related to the structural length () by the shape factor : . Size-scaling was found to differ between the larvae and larger life stages of a fish, implying a change in shape during ontogeny. We here assume that the shape coefficients for embryos and pre-larvae, , and for juveniles and adults, , are constant and for larvae is described by the relationship with and , for , with and the volumetric structural length at birth and metamorphosis, respectively. Wet weight has contributions from structure *V*, energy reserves *E*, and energy reserves allocated to reproduction . If reproduction buffer is excluded (= 0), wet weight is given by: . The feeding rate (in g/d) is given by , where is the molecular weight of dry food (g/mol), the chemical potential of food (J/mol), and the conversion efficiency of food into assimilated energy. The formulas for other measurable quantities, such as O2 consumption, NH3 production, are given in Stavrakidis-Zachou *et al.* (2019a).

Physiological rates depend on temperature. For a species-specific range of temperatures, the temperature effect is quantified by the Arrhenius relationship (Kooijman, 2010). For *TA* the species-specific Arrhenius temperature, the rate of a physiological process *k̇* at temperature T is given by: where  the rate at a chosen reference temperature, here T1=293K. According to the extended formulation of the Arrhenius relationship, the reduction of rates at low and high temperatures, outside the temperature tolerance range is quantified by multiplication of the rate with the fraction of the enzyme catalyzing the reaction that is in active state at temperature T:

 with

where and are the Arrhenius temperatures for the rate of decrease at the lower () and upper () boundaries of the tolerance range. Estimation of , , requires data at the edges of the temperature tolerance range. While estimation of these parameters was possible for European seabass, for meagre only the *TA* was used.

## Meagre DEB model, data, parameter estimation, and validation.

This section of the ESM gives the parameter estimates for the meagre model and demonstrates the goodness of fit. The parameter estimates are given in Tab S2. The parameter estimation resulted in an acceptable goodness of fit, quantified by the mean relative error (MRE) of 0.188 and the Symmetric Mean Squared Error (SMSE) of 0.166, giving an overall good match between predictions and observations (Fig S1 and Tab S3). Furthermore, the model was validated against production datasets from farms of three different regions in terms of growth and feed consumption (Fig S2), yielding a reasonably good fit between model predictions and observations in all cases.

Tab S2 DEB parameter values of Argyrosomus regius, corrected for the reference temperature of T=20oC.

|  |  |  |  |
| --- | --- | --- | --- |
| **Symbol** | **Unit** | **Interpretation** | **Value** |
|   | J cm-2 d-1 | Specific maximum assimilation rate | 65.92/444.42a |
|   | cmd-1 | Energy conductance | 0.0633/0.4267a |
|   | - | Allocation fraction to soma | 0.843 |
|   | J cm-3 d-1 | Volume-specific somatic maintenance rate | 8.452 |
|   | d-1 | Maturity maintenance rate coefficient | 0.002 |
|  | J cm-3 | Specific costs for structure | 5543 |
|   | - | Digestion efficiency of food to reserve | 0.68 |
|   | - | Reproduction efficiency for females/males | 0.95/0.4 |
|   | J | Maturity threshold at hatching | 0.02598 |
|   | J | Maturity threshold at birth | 0.3044 |
|   | J | Maturity threshold at metamorphosis | 93.16 |
|   | J | Maturity threshold at puberty | 2.124 106 |
|   | d-2 | Weibull aging acceleration | 4.31 10-9 |
|   | - | Zoom factor | 6.575 |
|   | - | Shape coefficient for juveniles and adults | 0.1983 |
|   | - | Shape coefficient for embryos | 0.1378 |
|   | - | Shape coefficient for egg diameter | 0.1378 |
|   | K | Arrhenius temperature | 7612 |

aValues before/after acceleration.

Tab S3 Comparison of model predictions with observed age, length and weight (where available) at hatch, birth, metamorphosis and puberty for A. regius. Last column gives the relative error (RE) for each data-point.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable** | **Temp (**oC) | **Interpretation** | **Observations** | **Predictions** | **RE** |
| (d)  | 22 | Age at hatch | 1 | 1.184 | 0.185 |
| (d)  | 22 | time since hatch at birth | 4 | 2.96 | 0.260 |
| (d) | 22 | time since hatch at metamorphosis | 35 | 40.28 | 0.156 |
| (d) | 17.5 | Age at puberty | 1278 | 1028 | 0.196 |
| (cm) |  | Length at hatch | 0.295 | 0.212 | 0.281 |
| (cm)  |  | Length at birth | 0.362 | 0.483 | 0.335 |
| (cm) |  | Length at puberty | 57.2 | 65.88 | 0.068 |
| (cm) |  | Ultimate length | 230 | 223.6 | 0.028 |
| (g)  |  | Wet weight of egg | 71.8 10-5 | 49 10-5 | 0.318 |
| (g)  |  | Wet weight at birth | 37 10-5 | 36.2 10-5 | 0.022 |
| (g) |  | Wet weight at puberty | 1892 | 2735 | 0.445 |
| (g) |  | Ultimate wet weight | 103 103 | 106.8 103 | 0.037 |

|  |  |
| --- | --- |
| tL.jpg | tL2.jpg |
| tW1.jpg | tW2.jpg |
| WL.jpg | WR.jpg |
| O2.jpg | Fig S1 Comparison of model predictions (solid lines) to observations (points) for meagre. (a) Length-at-age at constant temperature (Lika et al. 2014), (b) Length-at-age at variable temperature (Vargas et al., 2014), (c) Weight-at-age at variable temperature (Vargas et al., 2014), (d) Weight-at-age at variable temperature (HCMR), (e) Length-Weight (Vargas et al., 2014), (f) Reproduction rate as function of weight (Mylonas et al., 2013), (g) O2 consumption rate as function of weight (Kir et al., 2017). |
|  |

|  |  |  |
| --- | --- | --- |
|  | Wet weight | Feeding rate |
| Farm 1 |  |  |
| Farm 2 |  |  |
| Farm 3 |  |  |
|  | Fig S2 Comparison of model predictions (solid lines) to observations (points) for validation datasets for meagre. Wet weight (g), feeding rate (g/d), and temperature (oC) are given as a function of time (d) for three farms (farm 1, farm 2, farm 3). Shaded areas indicate uncertainty (500 Monte Carlo simulations) in terms of the inter-individual variability described in methods introduced via variation of the zoom factor and broken lines the temperature at the farm site. For all simulations .  |
|  |  |

**The economic model**

The economic model has been presented in Stavrakdis-Zachou *et al.* (2019b) and its use lies in estimating the business economics of a single (model) farm. To accomplish that, it uses the predictions of the biological DEB model and a number of economic input variables to derive the main costs and the profit for the farm under various scenarios. The input variables and the list of equations are given in Tab S4 along with the default values for prices and costs. The default values are typical values for farms in Greece and have been compiled in collaboration with the Federation of Greek Maricultures (FGM) during the ClimeFish project. They do not, however, represent official statistics for the industry and the values may vary considerably depending on farm characteristics and location.

For the analysis performed in this paper, a production scenario was simulated using the default economic values, a stocking population of 200,000 and a market size of 800g. The remaining inputs for the economic model (*Feed consumption, Production time, Production*) were derived from the biological model across the various regions and climate scenarios and the equations in Tab S4 were used to calculate the farm profit.

Tab S4 Description of the input variables and the equations of the economic model. Default values according to FGM cost analysis for Greece.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Input variable*** | **Unit** | **Description** |  | **Default value**  |
| *Pricefeed* | €/kg | Feed price |  | 1.15  |
| *Pricejuveniles* | € | Price per individual juvenile |  | 0.23 |
| *Pricelabour* | €/day | Cost for total labour |  | 149.64\* |
| *Costsother* | €/day | Maintenance and other operational costs |  | 47.5 |
| *Costsdepreciation* | €/day | Cost of depreciations for equipment, buildings, storage, and vessels |  | 8.72 |
| *Priceinterest rate* | % | The daily interest rate imposed by banks |  | 2 |
| *Pricesales* | €/kg | Ex Works (sellers price before transport costs) sales price |  | 6.44 |
| *Market size* | g | Desired fish size for harvesting |  | - |
| *Stocking population* | # | Number of juveniles purchased |  | - |
| *Feed consumption* | Kg | Total feed consumed during the production cycle |  | - |
| *Production time* | days | Time required for fish to reach Market size |  | - |
| *Production* | Kg | Total biomass of fish harvested |  | - |
| ***Equations*** | *Feed Costs = Feed consumption* x *Pricefeed* |
|  | *Juveniles Costs = Stocking population* x *Pricejuveniles* |
|  | *Labour Costs = Production days* x *Pricelabour* |
|  | *Other Costs = Production days* x *Costsother* |
|  | *Depreciations Costs = Production days* x *Costsdepreciation*  |
|  | *Accumulated debtt = Accumulated debtt-1 + Feed Costst + Juveniles Costst + Labour Costst + Other Costst + Priceinterest rate* x *Accumulated debtt-1* |
|  | *Total Costs = Feed costs + Juveniles Costs + Labour Costs + Other Costs + Depreciations Costs + Priceinterest rate* x *Accumulated debtt*  |
|  | *Income = Production* x *Pricesales* |
|  | *Profit = Income – Total Costs* |
| \* Value for 4 persons involved in the production |  |  |

**Climate projections**

This section provides details on the climate data that were used for the simulations, the ``bias correction’’ that was implemented as well as visualization of the temperature projections.

Regarding simulation inputs, downscaled projections of two environmental variables, namely Sea Surface Temperature (SST) and wind velocity, were used. These projections covered the period 2006-2055 with daily temporal resolution and 10x10km2 spatial resolution. The datasets were generated by the CERES project (https://ceresproject.eu/) by using the coupled POLCOM-ERSEM ecosystem model (Proudman Oceanographic Laboratory Coastal Ocean Modelling System and the Plymouth Marine Laboratory European Regional Seas Ecosystem Model) to downscale projections of the Global Climate Model (GCM) ICHEC-EC-EARTH.

Prior to performing the simulations, temperature projections from the first ten years of the dataset (years 2006-2016) were used to evaluate the model predictions. Comparisons with measurements collected from farms and the Poseidon System (http://poseidon.hcmr.gr) showed tendency of the model to overestimate the winter minima and underestimate the summer maxima at inshore sites (Fig S3, left). However, this was not the case for offshore sites where comparison of model projections with measurements obtained by the Poseidon System resulted in a good match (Fig S3, right).

|  |  |
| --- | --- |
|  | C:\Users\orestias\Desktop\dfgff.png |
| Fig S3 Ten-year average SST of downscaled model projections (red) and measurements from the Poseidon System (blue) for an inshore and an offshore location during years 2006-2016. |

Therefore, the climate model performed well in the open sea but was unable to capture the overall higher temperature fluctuations exhibited at coastal sites. Consequently, a ``bias correction’’ technique was applied to inshore sites as described in Hawking *et al.* (2013) and Falconer *et al*. (2019). According to this, model predictions were calibrated using the daily difference between observed data from farms and modelled temperatures for a recent (2006-2016) reference period as:

where is the corrected, the modelled and the observed temperature while the subscripts and denote the future and reference periods, respectively. The bars indicate the mean over the reference period.

Subsequent visualization of the temperature projections after the bias correction was implemented allowed for observation of regional differences as well as differences between inshore and offshore locations. The temperature data are here presented as differences between the mid- and short-term as well as the long- and short-term periods in the form of heatmaps (Fig S4). Negative values (blue) indicate decrease in future temperature and positive values (red) indicate increase in future temperature.

|  |  |  |
| --- | --- | --- |
|  | RCP4.5 | RCP8.5 |
|  | Inshore | Offshore | Inshore | Offshore |
| Mid-short term | **C:\Users\Orestis\Documents\MATLAB\CC_paper\temp_heatmaps\2.jpg** | **C:\Users\Orestis\Documents\MATLAB\CC_paper\temp_heatmaps\1.jpg** | **C:\Users\Orestis\AppData\Local\Microsoft\Windows\INetCache\Content.Word\5.jpg** | **C:\Users\Orestis\AppData\Local\Microsoft\Windows\INetCache\Content.Word\7.jpg** |
| Long-short term | **C:\Users\Orestis\AppData\Local\Microsoft\Windows\INetCache\Content.Word\6.jpg** | **C:\Users\Orestis\AppData\Local\Microsoft\Windows\INetCache\Content.Word\8.jpg** | **C:\Users\Orestis\Documents\MATLAB\CC_paper\temp_heatmaps\4.jpg** | **C:\Users\Orestis\Documents\MATLAB\CC_paper\temp_heatmaps\3.jpg** |
| Fig S4 Heat maps of the temperature difference between the mid-and short term (top) and long-and short term (bottom) climate projections for the nine regions (R1-R9) and the two IPCC scenarios. |

In line with the ``bias correction’’, changes in temperature generally appear to be higher in the future for inshore farms than it is for the respective offshore, and this holds for both IPPC scenarios. The difference can be as high as 2-3oC during winter and spring. One exception is region R9 in the south where temperature differences are about the same (±0.5oC) all year round, but the summer is cooler offshore by about 1-2oC. This pattern was also observed for region R6 with the summer offshore being 2-3oC cooler than inshore.

When considering temporal shifts, there are differences between the RCP4.5 and RCP8.5 scenarios especially in the long term. Generally, differences between the mid-term and short-term are small for both RCPs. With the exception of some summer months where temperature in the next 15 years may increase up to 2oC, changes in temperature for the rest of the year are marginal. Interestingly, the decadal average appears to be particularly low for RCP4.5 and in several cases the mid-term projections exhibit colder temperatures than the short-term. However, this pattern is not conserved for the long-term projections that predict a considerable temperature increase throughout the year, with the changes in RCP8.5 being pronounced compared to RCP4.5. Overall, winters will be warmer by 0 to 1oC in the long-term and for RCP4.5 the summer months will also see an increase of up to 2oC. For RCP8.5, the increase in the summer months will be up to 2.5oC and this will be extended for the autumn months as well. The above observations apply to both inshore and offshore locations.

Finally, regarding the wind velocity data, analysis showed that the number of days per year with wind velocities greater than the no feeding threshold (45 km/h), is smaller in the inshore farms compared with the offshore ones, for both IPCC scenarios. Specifically, inshore sites averaged only two such days per year while for the offshore sites the annual range was 2-25 days.

**Extreme events and effects at farm level**

Considering the production scenario described in the methods (200,000 individuals, 800g market size), the effects of the extreme weather events (``heatwaves’’ when temperature exceeds 28oC for more than four days in a given week, and ``storms’’ when wind velocity exceeds 45km/h for four consecutive days) at the farm level are shown in Fig S5 in terms of biomass production and profitability). This includes the simulation of the three extreme event scenarios, namely the ``mild extreme events’’ (1% mortality for heatwaves and storms), the ``intense heatwaves’’ (5% and 1% mortality for heatwaves and storms), and the ``intense storminess’’ (1% and 5% mortality for heatwaves and storms) scenarios. The frequency of the extreme events is given in Tab S5.

|  |  |  |  |
| --- | --- | --- | --- |
| **a)** |  | Relative biomass production | Relative profit |
| European seabass | mild |  |  |
| heatwaves |  |  |
| storm |  |  |
| **b)** |  | Relative biomass production | Relative profit |
| meagre | mild |  |  |
| heatwaves |  |  |
| storm |  |  |
|  | Fig S5 Relative differences (%) in E seabass (a) and meagre (b) biomass production (left column) and profit (right column) between short- and mid-, and short- and long- term projections for a model farm under RCP8.5 and for three extreme event scenarios (mild, increased heatwaves, increased storminess). The scenarios consider a farm that stocks 200,000 juveniles at three stocking months March, June, and September (M, J, S) and harvests them once they reach the market size of 800g. R1-R9 denote the regions, and IN-OF the location of the farm inshore or offshore |

Tab S5 Annual frequency of extreme events by type (heatwaves and storms) and location (inshore and offshore) for each time-period and IPCC scenario. Values represent means among regions and the range (min-max) is given in parenthesis.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | heatwaves | storms |
|  | Time -period | Inshore | Offshore | Inshore | Offshore |
| RCP4.5 | Short-term | 0 (0-0) | 0 (0-0) | 0 (0-0) | 0.6 (0-1) |
| Mid-term | 0.8 (0-2) | 0.5 (0-1) | 0 (0-0) | 0.5 (0-1) |
| Long-term | 2.1 (1-3) | 1.6 (1-3) | 0 (0-0) | 0.6 (0-1) |
| RCP8.5 | Short-term | 1.8 (0-2) | 0.9 (0-1) | 0 (0-0) | 0.6 (0-1) |
| Mid-term | 2.3 (1-4) | 1.6 (0-2) | 0 (0-0) | 0.7 (0-2) |
| Long-term | 3.9 (2-6) | 2.8 (2-3) | 0 (0-0) | 0.9 (0-2) |

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