Project information

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UndersTanding and PRedicting the acidification of northern waters and its iMpacts on marine ecosystems and biogeochemistry (TRUMP)

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2018

Project leader

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Geographical localization of the research project in decimal degrees (max 5 per project, ex. 70,662°N and 23,707°E)

pan-Arctic

Participants

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Flagship

Ocean Acidification

Funding Source

KLD

Summary of Results

**D1.1: Report on model validation and OA drivers in Barents/Nordic seas (M12)**

Modelling ocean acidification in the Arctic: effects of going regional (Skogen, Hjollø, IMR)

Global coupled climate models (GCM) are generally capable of reproducing the observed trends in, e.g. the globally averaged atmospheric temperature. However, the global models do not have the horizontal resolution, which is needed in order to properly resolve the relevant features on regional scales, and the GCM outputs will contain biases relative to the observational data, which preclude its direct use. Therefore, dynamical downscaling using so-called Regional Climate Models (RCM) is necessary to translate coarse global scale information into fine regional and local grids in order to obtain climate information on scales that are relevant to society. We have performed a study to quantify whether an ocean RCM produce different projections than its driving GCM, based on climate change projections for the Barents and adjacent Seas (Skogen et al., 2018). The study should both be regarded as a direct comparison between a regional and its driving global model to investigate at what extent a global climate model can be used for regional studies, and a study of the future climate change in the Barents and adjacent Seas (defined in figure 1).

The biogeochemistry from the global climate model (Norwegian Earth System Model) has been compared with results from the regional model (NORWECOM.E2E), where the regional model is forced by downscaled physics from the global model. In the regional model, ocean acidification is modelled using an implementation of the Haltafall speciation code, as described under D.1.2, with the exception that TA=66.96*S – 36.803 have been used for the calculation of TA.

The global and regional model compare well on trends, but many details are lost when a coarse resolution global model is used to assess climate impact on regional scale. The global model has a cold (in summer) and saline bias compared with climatology (figure 2). It is clear that the temperature increases from the first to the last10 year periods. Comparing the global and regional models, the spring warming starts earlier in the regional model than in the global one. Summer maximum occurs in both models in August, and the summer maximum is higher in the regional model. The figure also show that the seasonal amplitude is larger in the regional model than in the global one, and that this amplitude is higher in the last decade than in the first. This increase in amplitude is up to 0.87°C for the regional model in the Greenland Sea.

**Figure 1.** Model domain and area used for Barents Sea, Greenland Sea and Norwegian Sea, respectively.

**Figure 2.** Upper panels: Annual mean sea surface temperature (SST, left) and salinity (SSS, right) for Barents Sea (black), the Greenland Sea (red), and the Norwegian Sea (green), for NorESM1-ME (solid line) and ROMS/NORWECOM.E2E (dashed line). X is observed values from literature. Lower panels: Annual cycle of sea surface temperature (SST) for the first (thin line) and last decades (thick line) for Barents Sea (black—left panel), the Greenland Sea (red—mid panel), and the Norwegian Sea (green—right panel), for NorESM1-ME (solid line) and ROMS/NORWECOM.E2E (dashed line). The X-es are the monthly means from the World Ocean Atlas for the period 2005–2012.

The main difference between the two models is the timing of the spring bloom, and a non-exhaustive nutrient consumption in the global model in summer (figure 3). Through the downscaling the regional model is to some extent able to alleviate the bias in the physical fields, and the timing of the spring bloom is close to observations. The summer nutrient minimum is one month early. There is no trend in future primary production in any of the models. The largest discrepancy in the future projection is in the development of the $CO_2$ uptake, where the regional suggests a slightly reduced uptake in the future.

**Figure 3.** Annual cycle (0–10 m) of inorganic nitrogen for the first 10 years (thin line) and last 10 years (thick line) for Barents Sea (black— left panel), the Greenland Sea (red—mid panel), and the Norwegian Sea (green—right panel), for NorESM1-ME (solid line) and NORWECOM (dashed line). The X-es are the monthly means from World Ocean Atlas.

Maps of annual mean pH in the upper 10m for observations and both models and averaged over the first decade of the simulation (2006–2015) are given in figure 4. The magnitude is generally higher in NorESM1-ME (mean value 8.13 compared with 8.08), and thus closer to observations (mean value 8.16) while the regional differences is more pronounced for NORWECOM.E2E, especially with lower pH levels along the Norwegian and the Greenland coast. From figure 5, right panel, there is a steady decline in pH in both models, with a negative trend between -0.0021 and -0.0025 $year^{-1}$ for both models and all three seas. The pH is slightly higher in the global model than in the regional one by a mean of 0.03 in Barents and Greenland seas and 0.05 in the Norwegian Sea. The results are similar for the saturation level of aragonite, $\Omega_{Ar}$ (not shown). Over the last 25 years pH has been observed to be decrease by a rate of ~0.0018 $yr^{-1}$ at several open-ocean time-series sites, and the IPCC reports the global mean surface pH to have declined by 0.14–0.15 compared with the level in 1986–2005. The modelled future change in pH over the 65 year long period is ~0.12/0.13, with higher regional variability seen from the regional model (figure 5 left panels). Using the modelled rate over a 75 year period (1995–2070) the models suggest a decrease in surface pH of 0.18. As the increase in atmospheric $CO_2$ is low after 2070 under RCP4.5, and the decline in pH is believed to be even stronger in the Arctic, the modelled rate of future change in surface pH is in accordance with the IPCC prediction.

**Figure 4.** Left panel: present day pH from GLODAPv2 (Lauvset et al, 2017, Olsen et al 2016) and right panels: annual

mean pH for the period 2006-2015 in the upper 10m for NorESM1-ME (left) and NORWECOM (right) model.

**Figure 5.** Annual mean change in pH (last decade – first decade of simulation) for the NorESM1-ME (left panel) and NORWECOM (middle panel) model. Right panel: Annual mean (0–10 m) pH for Barents Sea (black), the Greenland Sea (red), and the NorwegianSea (green), for NorESM1-ME (solid line) and NORWECOM (dashed line).

Validating a new, spectrally-resolved biogeochemical model for simulating Arctic Ocean acidification and multi-stressors (Wallhead, Staalstrom, Kristensen, Bellerby, NIVA)

We have developed a new physical-biogeochemical model for the Arctic Ocean by combining a ROMS model (Shchepetkin and McWilliams, 2005; pan-Arctic configuration originally developed by Met. No.) with the European Seas Regional Ecosystem Model

(ERSEM, Butenschon et al., 2016) using the FABM coupling framework (Bruggeman and Bolding, 2014). The “A20” model domain covers the Arctic Ocean and Nordic Seas at 20-km horizontal resolution (Figure 6) and uses 40 terrain-following vertical levels (s-levels). Forcings and initial/boundary conditions for a 35-year hindcast (1980-2014) were derived from: SODA 3.0 (Carton et al., 2000; Carton and Giese, 2008) for physical initial/boundary conditions, ERA-INTERIM (Uppala et al., 2005; Reigstad et al., 2011) for atmospheric physical forcing, the NOAA Greenhouse Gas Marine Boundary Layer Reference (Dlugokency et al., 2015) for atmospheric dry air molar fraction ($xCO_2$), and from NorESM-OC1.2 (Schwinger et al., 2016) for biogeochemical initial/boundary conditions.

**Figure 6.** A20 model domain and bathymetry. Pink dots show locations of daily data time series stored for comparison with observational time series.

During 2018, the NorESM-OC1.2 initial/boundary conditions for nutrients, oxygen, and carbonate chemistry were bias corrected using data collated from: the World Ocean Database (Boyer et al., 2013), the International Council for the Exploration of the Sea Dataset on Ocean Hydrography (ICES, Copenhagen, 2013), the Global Ocean Data Analysis Project, version 2 (GLODAPv2, Key et al., 2015; Olsen et al., 2016), the CARINA Iceland and Irminger Sea Time Series version 2 (Olafsson et al., 2009a, 2009b), and various cruise datasets provided by the Shirshov Institute on Oceanology and the Norwegian Environment Agency. The resulting 4D bias-corrections, resolved on the A20 horizontal grid at NorESM depth levels and for each month of the year, have been shared with IMR. We also adapted the optical and biogeochemical model components for high northern latitudes as follows: 1) the ROMS Jerlov water type was increased; 2) dissolved organic matter was split into coloured and non-coloured classes; 3) a spectral treatment of light propagation was implemented; 4) the light/temperature response parameters for phytoplankton growth were refitted to experimental incubation data for northern species; 5) the zooplankton grazing/ingestion parameters were adjusted based on experimental data meta-analysis. We call the adapted biogeochemical model "Artic ERSEM" (AERSEM) to distinguish from the default "global" ERSEM configuration and parameters set (Butenschon et al., 2016) that was used in 2017.

Figures 7 and 8 compare the 0-50 m average output from the previous model version (A20v1, left columns, blue lines) with the output from the present model version (A20v2, right columns, blue lines) and the observational data at the Irminger Sea time series station (black dots). As of 16/11/2018 the revised model has only been run through 1987 due to limited supercomputing hours allocations, but it is expected that a full 35-year run will be completed by M12 (skill scores in blue have therefore been limited to years 1983-1987 to allow a fair comparison and avoid transient variability). We see that the observed surface heat and salt content is quite well reproduced by both model versions (Fig. 7, top two rows) and that both versions show a small (~10%) negative bias in surface oxygen (Fig. 7, third row). Both versions have approximately correct seasonal drawdown for phosphate, nitrate, and silicate (Fig. 7, bottom row and Fig. 8 top two rows). However, the previous version shows a seasonal drawdown of dissolved inorganic carbon (and associated decrease in partial pressure of $CO_2$) that is roughly twice as large as in the observational data, while this error appears to be largely fixed in the new version (Fig. 8, bottom two rows). These initial analyses are encouraging with respect the applicability of AERSEM because they suggest that that an adjustment of model parameters based on experimental incubation data has led to improved agreement with independent data from in situ field measurements.

**Figure 7.** A20 model 0-50 m average output (blue lines) vs. observational data from the Irminger Sea time series station (black dots) for the previous model version (A20v1, left columns) and the present revised version (A20v2, right columns). Rows show comparisons for temperature (T), salinity (S), dissolved oxygen (O2), and phosphate (PO4).

**Figure 8.** A20 model 0-50 m average output (blue lines) vs. observational data from the Irminger Sea time series station (black dots) for the previous model version (A20v1, left columns) and the present revised version (A20v2, right columns). Rows show comparisons for nitrate (NO3), silicate (Si), dissolved inorganic carbon (DIC), and partial pressure of carbon dioxide (pCO2).

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**<u>D1.2: Validation of a high resolution OA model for Kongsfjorden (M24) (Skogen, Hjollø, IMR)</u>**

A high-resolution (160m) numerical ocean circulation model has earlier been set up for the Kongsfjorden area (Sundfjord, et al., 2017). Physical fields (currents, salinity, temperature, water level and ice) has been used as forcing for the NORWECOM.E2E ecosystem model (Hjøllo et al., 2012; Skogen et al., 2014), where an ocean acidification (OA) module has been coupled to an NPZD biogeochemical model. The model system is using a submodule (Blackford and Gilbert, 2007; Skogen et al., 2014) for the carbonate system. This module is an implementation of the Haltafall speciation code (Ingri et al., 1967), and calculates the carbonate system at any given point in space and time, using constants from Mehrbach et al. (1973) refitted by Dickson and Millero (1987). The inputs are temperature, salinity, dissolved inorganic carbon (DIC), total alkalinity (TA), and depth (pressure), whereas the outputs are pH, partial pressure of $CO_2$ in seawater, carbonate and bicarbonate ion concentrations, and calcite and aragonite calcification states. In addition, the module calculates the air sea exchange of $CO_2$ taking into account wind speed and atmospheric $pCO_2$. The latter one uses the (Nightingale et al., 2000) parameterization for gas transfer velocity. TA is not a prognostic variable in the model. As TA is conservative, we have used a relationship between salinity and TA taken from Fransson et al. 2016 ($TA = 40.6*S + 890$).

The simulation period is March 1 to September 30, 2009 (see Figure 9). The time step used is 1 minute, and nutrients and DIC is initiated from observed winter values (Fransson et al., 2016), together with some small initial amounts of phytoplankton and zooplankton.

**Figure 9:** Time series of modelled flux of $CO_2$ (upper, mmol/m$^2$/day) and the aragonite calcification state ($\Omega_{arag}$ lower) at the station KB3 in the central part of the Kongsfjorden, 2009.

**Task 2: *Projecting ecosystem response and feedbacks to OA***

**D2.1**: Comparative analyses of projected changes in primary productivity and acidification in Barents/Nordic seas models (M12) (Mousing, Skogen, IMR; Wallhead, NIVA)

Inflow of warm and saline water into the Barents Sea and fluxes between the ocean and the atmosphere are of significant importance to the regional climate and ecosystem productivity. Regionally downscaled physical models with high spatial resolution and a good representation of the heat flux are thus essential to predict future changes in productivity and ecosystem structure. Here we compare future changes in productivity following climate change as predicted by three ecosystem models (NORWECOM, NORWECOM.E2E and SINMOD) driven by three regionally downscaled ocean circulation models (see Figure 10). The predicted production differs between the models and ranges from a modest decrease to a large increase. In order to explain these differences, we apply structural equation modeling to deduce direct and indirect effects of the environment. Despite large differences between the underlying forcing, we found that the direction of impacts of the environment variables were relatively consistent for all models. Overall, we found that future changes in productivity in all models are primarily correlated to changes in temperature, ice-cover and light which works directly or indirectly by modifying nutrient and mixed layer dynamics. Thus, the discrepancy between model predictions are to a large extent caused by the choice of the underlying physical forcing. In addition, we compare changes in pH and discuss implications for the secondary production. By comparing the outcome of these models under a common framework, we can draw general conclusions regarding the circumstances under which these contrasting outcomes may apply.

Figure 10: Comparison of Gross Primary Production (top row, GPP, gC/m2/yr) and 50-year climatic changes (bottom row, gC/m2/yr) for three downscaling ocean biogeochemical models.

**D2.2:** Parameterization of feedbacks from higher trophic levels on biogeochemistry (M24) (Hansen, IMR; Wallhead, NIVA)

Diet of cod and whales are updated together with numerous other parameters, new version of NoBa model has produced the output on zooplankton rates/values that will be sent to NIVA by late November. Ina Nilsen will continue to work on this over the next weeks. She has run the NoBa model for the period 1981-2030 and printed biomass and production on a daily basis, while mortality rates are printed on a yearly basis (Figure 11). There will be more cooperation between IMR and NIVA on this matter for the months to come, before the M24 deadline.

**Figure 11:** NoBa model domain and topography (left) and daily normalized mesozooplankton biomass for the period 1981-2030. The biomass output will be used to calcluate the mortality from higher trophic levels on the mesozooplankton component in NoBa.

**D2.3:** Report on projected ecosystem impacts of OA in combination with other climatic stressors (M36).

Ina Nilsen is currently going through literature (AMAP reports, papers), with the aim of finding components where we might have enough information to add functional responses to pH and test these within various modelling frameworks.

**D3.1**: Report on local OA impact of supply of carbon/nutrient supply from thawing permafrost and CO2/methane seeps (M12) (Protsenko, Yakushev, NIVA)

The main purpose of the work is to better understand the consequences of methane seepage caused by permafrost thawing for Arctic marine environments, to estimate the fraction of the methane dissolving on the way to the atmosphere and to study the biogeochemical changes in the water column resulting from methane seepage. The outer shelf of Laptev sea, Figure 12 is a part of Eastern Siberian Arctic Shelf suggested as the area of active methane seepage with a lot of single vents spread throughout the area. The chosen region represents an area where methane fluxes are very high, and could indicate the potential for methane flux increase if the permafrost thawing progresses.

To reproduce the high latitude environment of East Siberian Arctic Shelf, Figure 12 we implemented a 1-dimensional transport-reaction modelling set consisting of Sympagic - Pelagic - Benthic transport model (SPBM) (Yakubov et al., 2017) coupled with BROM_biogeochemistry (Yakushev et al., 2017).

For the model forcing we used modelling predictions from the Regional Ocean Modeling System – ROMS (Shchepetkin and McWilliams, 2005) applied to "pan-Arctic" domain with 20 km horizontal resolution (A20 version 1, see Task 1).

Estimations of methane inflow from the bubbles were provided by the Single Bubble Model, written for this study based on the published concepts (Leifer et al., 2002; McGinnis et al., 2006). It simulates the evolution of dynamic features of methane bubbles by solving the ideal gas equation of state, that is suitable for the shallow areas (depth < 600 m).

The results of simulations for the Single Bubble Model showed that for the Laptev sea with the release depth 80 m, the bubbles with initial radii 2 mm and more reach water surface, smaller bubbles dissolve entirely at different depths in the water column, Figure 13.

This approach allows us to simulate the transport and biogeochemical processes in the ice, water, sediments and reproduce the Arctic marine environment. Parameterizing the model and understating the influence of methane seepage on the local scale gives an opportunity to apply the result of this work on a bigger scale.

The field data for nutrients for this region of Laptev Sea is available from the World Ocean Database (Boyer et al., 2013), but almost only for September, which is usually the month with open water. The new field data from this region was collected in 2018 for both sediment and water and planned to be analysed during 2018/2019.

The model baseline run was validated by confirming the reproducibility of the vertical structure and temporal dynamics of the ecosystem through a comparison between the field data and the model output. The September values from the baseline run were extracted the and compared to the available field data, Figure 14 and demonstrated reasonable behaviour.

BROM coupled with 2-dimensional vertical model 2DBP was used in 2018 for test calculations of spreading of a substance without formation of bubbles.

In 2019 we plan to continue analyzing in more detail the biogeochemical transformations near methane seeps, using 1D and 2D versions of the Transport block of the modeling set.

Figure 12: East Siberian Arctic Shelf, red polygon - study area.

Figure 13: a) evolution of bubble radii during the uplifting, b) fraction of methane dissolved in the water and transported to the atmosphere with bubbles.

Figure 14: Comparison of field data from World Ocean Database (grey circles) with modelled data (red circles), mean modelled data (black dotted line) and data from AMK_2015 (black circles) for (a)dissolved oxygen, (b) phosphate, (c)silicate, (d) nitrate.

## <u>**Task 4:** ***Tracking and forecasting Ocean Acidification (OA) impacts on complex multi-species interactions***</u>

### <u>**D4.1**: Report on workshop (M10) to test the new methodology with provisional model output (M12) (Griffith, NPI).</u>

Due to the delay in project funding / start date, the workshop and the associated report (D4.1) has been delayed to February 2019.

During 2018, we developed and then employed two new equation free (non-parametric) approaches to investigate the effect of OA combined with other environmental factors on the complex multi-species interactions (structure & function) of Arctic marine food webs:

**1. Ecological resilience of Arctic marine food webs to climate change**

We developed a new conceptual and analytical framework (Fig. 15) to investigate the changes in ecosystem-wide and local resilience of the Kongsfjorden marine food web (2004 to 2016) to the cumulative effects of OA, temperature and loss of sea ice. Our premise has been to investigate OA with temperature as this is the most realistic scenario. That is, OA will not have an independent impact on natural marine food webs. We first developed a food web model for each year between 2004 and 2016 of up to 161 species using data from the Norwegian BarEcoRe project and the Norwegian Government Environmental Monitoring of Svalbard and Jan Mayen (MOSJ). We then applied our new analytical Bayesian approach to identify the compartments of core species (feeding) interactions in each food web. We then examined the changes in the ecosystem-wide structural resilience (Fig. 16) and the changes in the resilience within each compartment of core species interactions (Fig. 17). The following abstract of a paper submitted and in review (08/11/2018) to *Nature Climate Change* summarizes the main findings:

"Food webs tend to be organised in compartments of species that interact more frequently with each other than with other species. Compartmentalization is considered to confer ecological resilience (namely, the capacity of the ecosystem to absorb environmental stress and continue functioning). The stabilizing effect of such compartments within large marine food webs to mitigate stress induced by climate change is poorly known. Here, we apply a new complex adaptive systems approach to identify changes in resilience and potential regime shifts between 2004 and 2016 of a highly observed Arctic marine food web considered a harbinger of future Arctic change. We show that while resilience declined to year 2011 with significant environmental changes, the compartments of core ecological processes have been maintained. Despite on-going climate change effects, we demonstrate a recent emergent pattern of improving resilience that can be explained by the continuing subsidiary inputs of Atlantic species. Our findings demonstrate that Arctic marine food webs can absorb, recover and begin to adapt to on-going climate change effects rather than being subjected to deleterious regime shifts."

**Figure 15 |Conceptual framework.** Two major features from the complex adaptive systems (CAS) perspective for the resilience of the structure of food webs responding to climate change: (a) System-wide resilience. Low or incomplete connectivity between the compartments may allow the system as a whole to respond gradually to perturbations, (b) Local resilience. High connectivity of species within a compartment may contain perturbations within the compartment.

**Figure 16 | System-wide resilience.** We estimated the overall system-wide resilience of the food web as the sum of the exponential random graph modelling (ERGM) parameter estimates of the seven compartments of species interaction processes. The food webs are Arctic (Ar) Atlantic (At) and the Kongsfjorden annual food webs (04–16). The error bar indicates standard error for parameter estimate.

**Figure 17 | Local resilience.** Changes in the local resilience of core species interaction processes within each compartment of the Kongsfjorden food web (2004-16) and the representative Arctic (Ar) and Atlantic (At) food webs. The changes in local resilience represent the magnitude and significance of the ERGM parameter estimates of each compartment. A decrease in local resilience indicates a reduction in the ability of the species interactions in that compartment to make local repairs to buffer perturbations. The error bar indicates standard error for parameter estimate.

### 2. Tracking and forecasting OA effects on ecosystem interactions

Our task here has been to develop a practical method, using available time-series and modelling data to measure and forecast changing state dependant nonlinear predator-prey interactions with OA (Figure 18). The aim is to elucidate the causal relationships between changes in prey availability within a complex Arctic marine food web that has been subject to significant climate change effects. Working with statistical physicists at the International Centre for Theoretical Physics (ICTP) in Italy in May 2018, we developed a new analytical approach where we can use time series data on only a single or few variables to reconstruct, characterize and model the nonlinear dynamics of the real-world Kongsfjorden marine system. Our approach is based on the firm theoretical foundations of phase space reconstruction. The advantage of this approach is that it does not involve correlational evidence and in particular 'mirage correlations'. If we can create an unfolded manifold from real world time series data as shown in figure 19, we can then use that manifold to detect the causal effect of changes on OA and other environmental factors on the interactions (i.e. predator-prey) within the food web. Potentially this allows us to study the effect of OA on dynamically changing and interconnected species interactions. Importantly for management we should be able to forecast expected changes in interactions. To date (November 2018) we have successfully applied the approach to the phase state reconstruction (manifold) of time series data for 53 species (macro algae from Kongsfjorden (1996 – 2016) and the Arctic portion of the Barents Sea (1986-2017). We have examined data for 53 species from macro algae to seals. 41 of the species showed nonlinear dynamics that make them suitable for reconstructing real-system effects of environmental drivers including OA on a single species or multiple causally related variables (e.g. pCO2, temperature, dissolved O2). To date, we have tracked the nonlinear dynamic interactions between predator and prey for 12 higher-trophic species. We have tracked the causal nonlinear linkages for changes in temperature with ocean acidification (2004-2014) for these species. An example is shown in Figure 20 that shows the causal effect on the direct and indirect feeding interactions between a ringed seal (*Phoca hispida*-predator) and prey species. In 2019, we will extend this analysis to cover the period 1996-2016). A paper is in draft for submission (by January 15th, 2019) to the ICES Journal of Marine Science Theme Series entitled "Unravelling the ripple effect of Ocean Acidification on species interactions in Arctic marine food webs"

**Figure 18 |** Strategy to uncover real world nonlinear effects of OA and other environmental factors from observed time series data,

**Figure 19 |** Example of phase space reconstruction of polar cod abundance from one year's time series data.

**Figure 20 |** Causal interactions network of the effect of temperature with ocean acidification on the mean abundance (2004-2014) of ringed seal (*Phoca hispida*) on the west coast of Svalbard. The linkages between species are the mean of the interaction coefficients quantifying the changing effects of temperature with ocean acidification derived from the phase state reconstructions (manifolds) of species.

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Master and PhD-students involved in the project

Elizaveta Protsenko (PhD student, but not FRAM-funded)

For the Management

The project appears to have got off to a good start with excellent progress in all tasks, given the present month (7) since the beginning of funding release (May).

Published Results/Planned Publications

**Bellerby R**., Anderson L.G., Osborne E., Steiner N, Pipko I., Chierici M., Fransson A., Azetsu-Scott K., Ólafsson J. And Miller L. 2018. Arctic Ocean Acidification: an update. In: AMAP Assessment 2018: Arctic Ocean Acidification. pp. 79-90 Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

**Bellerby R**., 2018. Introduction. In: AMAP Assessment 2018: Arctic Ocean Acidification. pp. 79-90 Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway

**Wallhead, P.J.,** Chen, W., Falkenberg, L., Norling, M., **Bellerby, R.,** Dupont, S., Fagerli, C., Dale, T., Hancke, K., Christie, H., 2018. Annex 2: Urchin harvesting and kelp regrowth in northern Norway under ocean acidification and warming. In: AMAP Assessment 2018: Arctic Ocean Acidification. pp. 79-90 Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

**Morten D Skogen, Solfrid S Hjøllo**, Anne Britt Sandø, Jerry Tjiputra, Handling editor: Morgane Travers-Trolet; Future ecosystem changes in the Northeast Atlantic: a comparison between a global and a regional model system, *ICES Journal of Marine Science*, , fsy088, https://doi.org/10.1093/icesjms/fsy088

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**Griffith, G.P., Hop, H.,** Vihtakari, M., Wold, A & Kalhagen, K. Ecological Resilience of Arctic marine food webs to climate change. Nature Climate Change (2018- in review)

Communicated Results

**Wallhead, P.J.**, Chen, W., Falkenberg, L., Norling, M., **Bellerby, R**., Dupont, S., Fagerli, C., Dale, T., Hancke, K., Christie, H., 2018. Urchin harvesting and kelp regrowth in northern Norway under ocean acidification and warming. Arctic Biodiversity Congress, Rovaniemi, Finland. (talk)

**E.A. Mousing**, A.B. Sandø, **P. Wallhead, S.S. Hjøllo, M.D. Skogen**: "Primary drivers of changes in productivity in a future warmer Barents Sea - a comparison of 3 downscaled ecosystem models". Presentation at 4th International Symposium: The Effects of Climate Change in the World's Oceans (ECCWO4), Washington DC 2018.11.09 (talk)

**Solfrid Hjøllo, Morten Skogen,** Anne Britt Sandø. Jerry Tjiputra: Future ecosystem changes in the Northeast Atlantic: a comparison between a global and a regional model system. Bjerknes Days 07.11.2018 (talk)

**Elizaveta Protsenko, Trond Kristiansen, Philip Wallhead**, Øystein Varpe, **Evgeniy Yakushev**, Shamil Yakubov, Anastasia Zagovenkova. Modeling the Local Effect of Subsea Permafrost Thawing on Arctic Biogeochemistry. Polar-2018 SCAR/IASC Open Science Conference, Davos, Switzerland (talk)

**Elizaveta Protsenko, Trond Kristiansen, Philip Wallhead**, Øystein Varpe, **Evgeniy Yakushev**, Shamil Yakubov, Anastasia Zagovenkova. Modeling the local effects of sub-sea permafrost degradation on Arctic marine biogeochemistry. Geophysical Research Abstracts Vol. 20, EGU2018-19072, 2018 EGU General Assembly 2018 (poster)

Interdisciplinary Cooperation

TRUMP is generating interdisciplinary cooperation between physical, chemical, and biological modellers within the project. As part of the wider Flagship project (WP3 of OADREAM) TRUMP is also generate cooperation between modellers and field observsers (WP1), experimentalists (WP2), and social scientists (WP4).

Could results from the project be subject for any commercial utilization

No

Conclusions

TRUMP is producing good science and is stimulating fruitful collaborations between discplines and institutions. The project is on track to deliver the projected results.