Modelling plastic and evolutionary responses for marine viruses.

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Marine viruses contribute to regulating the phytoplankton community. Consequently, viruses play a key role in the most important biogeochemical cycles on earth. Therefore, a precise representation of the virus-phytoplankton interaction is crucial to predict phytoplankton community dynamics, and its effects on the rest of the marine food web and biogeochemical cycles. Viruses are parasites whose reproduction depends on the metabolic efficiency of their host (i.e. host growth rate). It has been observed that the host growth rate affects the infection time (i.e. latent period) and the virion production (i.e. burst size). However, this influence is still not well understood and has never been considered when modelling the phytoplankton population in the long term. In this talk, we fill these gaps by modelling (i) the ability of the viruses to react to environmental changes in the short term (i.e. plastic response), and (ii) how, in the long term, this plasticity affects the viral trait evolution and the phytoplankton population. We will discuss how the burst size and the Evolutionary Stable Strategy for the latent period change with the host growth rate in the plastic and no plastic cases. Then, we will compare our results with experimental data. This study can improve our understanding of viral evolution and can affect deeply predictions about the future of marine resources.

Projecting the impact of climate change on *Calanus finmarchicus*: there is no future, only possible futures

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The future impact of climate change on marine ecosystems will be the consequences of two things: human choices and the responses of the earth system to those choices. Projections of climate change impacts should therefore consider the possible range of future greenhouse gas emissions and the responses to them. However, many studies continue to take a “single future” view, and only use one emissions scenario and one physical climate model. Here we evaluate the influence of choice of climate model and emissions scenario on projections of abundance of the key zooplankton species *Calanus finmarchicus* throughout the North Atlantic. A species distribution model was first derived using a general additive model parameterized using the extensive Continuous Plankton Recorder data set. We projected changes in abundance using 33 different climate models, which were part of the CMIP5 project. For each climate model we projected changes under a climate mitigation scenario, RCP 4.5, and a high-emissions scenario, RCP 8.5. Climatological mean projected abundances and temperature were compared for a historical (1986-2005) and a future (2081-2100) period. There was a clear agreement across models that there would be significant warming and thus abundance declines in the North West Atlantic under both emissions scenarios. In contrast, there is strong disagreement between the models on whether there will be warming in the West Atlantic under RCP 4.5 and thus the direction of change of abundance. There is a strong consensus across models that the impacts of climate change will be significantly greater in the East than West Atlantic. Finally, we consider projections using multi-climate model ensembles and show their potential benefits to individual models.

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Management implications of using different modelling strategies (GAM and INLA) to assess the distribution of harbour porpoise

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Understanding species distributions is important so that appropriate management strategies can be developed for species of conservation value, such as cetaceans. Recent public consultations in the UK have concerned the potential designation Special Areas of Conservation for harbour porpoise as they are listed in Annex II of the EU Habitats Directive.

Habitat association models are commonly used to predict cetacean distributions and identify potential protected areas. Generalized Additive Modelling (GAMs; Hastie and Tibshirani, 1990) is an established method that is commonly used for species distribution modelling because it is easy to implement and the models can assess non-linear relationships. However, policy makers are often faced with an alternative of using newer, or more complicated, methods to do the same thing. Here we investigate the differences between using GAMs or using the recently developed technique of Integrated Nested Laplace Approximation (INLA; Rue *et al.* 2009) to determine if the benefits of the newer technique outweigh the additional complexity and computation costs.

One of the differences between GAMs and INLA is that GAMs are limited in their ability to account for spatial and temporal autocorrelation, a feature commonly inherent in many ecological datasets and which can bias estimates. Alternatively, INLA explicitly models this autocorrelation and is therefore well suited to analysing spatial data.

The study used sightings of harbour porpoises collected during aerial video strip transect surveys along the east coast of Scotland. Video surveys were performed in August and September 2010 and 2014. These surveys covered 5,762 km and resulted in a total of 303 harbour porpoise sightings. Environmental covariates included depth, sediment type and physical and biological parameters from a hydrodynamic model and satellite data.

These data were then modelled using GAM and INLA and the resulting maps of relative density were compared to determine whether increasing model complexity results in different inferences from a management perspective.

We present maps showing the predicted relative densities of harbour porpoise and discuss the utility and benefits of each modelling framework in informing the management process. The results obtained from the two modelling frameworks differ in some ways which could influence interpretation and actions at policy level. The choice of modelling strategy is therefore of vital importance when using the results to inform management.

By asking questions such as 'which method gives more confidence in results?' or 'which is easier to implement' or 'which is less costly to use' we aim to investigate if one method is more useful to inform conservation and management.

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Copepod populations and communities in changing oceans: Testing a new model across latitude, time, and the size spectrum

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Copepods play a crucial role in temperate and high-latitude food webs, but predicting future change in their abundance, productivity, and community characteristics requires that we differentiate a number of statistically confounded climate impacts on their environments: increasing surface and deep temperatures, loss of sea ice, and changing phytoplankton production, timing, and composition. A new model (“Coltrane”: Copepod Life-history Traits and Adaptation to Novel Environments) provides a unified framework for describing environmental controls on copepod populations via both 1) phenology and life history and 2) temperature and energy budgets. A set of complementary model experiments are used to determine what copepod community responses can be predicted from a few key constraints on the individual energy budget: the total energy available in a given environment per year; the energy and time required to build an adult body; the metabolic and predation penalties for taking too long to reproduce; and the size and temperature dependence of the vital rates involved.

In an idealized global-scale testbed, the model correctly predicts life strategies in large *Calanus* spp. ranging from multiple generations per year to multiple years per generation. In a Bering Sea testbed, the model replicates the dramatic variability in the abundance of *C. glacialis/marshallae* observed between warm and cold years of the 2000s, and indicates that prey phenology linked to sea ice is a more important driver than temperature per se. In a Disko Bay, West Greenland testbed, the model predicts the viability of a spectrum of large-copepod strategies from income breeders with a adult size ~ 100 μgC reproducing once per year through capital breeders with an adult size >1000 μgC with a multiple-year life cycle. This spectrum corresponds closely to the observed life histories and physiology of local populations of *C. finmarchicus*, *C. glacialis*, and *C. hyperboreus*.

The exercise of harmonizing these test cases highlights that real limit on our ability to predict the fate of copepods in changing oceans may not be our incomplete knowledge of their biology, but rather our incomplete knowledge of how their changing environments appear from their point of view. Data-driven regional studies in the Northeast Pacific and the high Arctic are helping define the behavioural and life-history response of key *Calanus* spp. to prey and light fields, as a bridge from the simple model experiments discussed here to pan-Arctic, multi-decadal projections to come.

Connecting the Northeast Pacific coastal productivity through satellite ocean colour

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Primary production in the Northeast Pacific (NEP) is responsible for setting the pace for life of a wide range of species. In many parts of the world's oceans, marine primary production displays a distinct seasonality, especially during the spring bloom, and the NEP is no different. This region spans the subtropical California Current System, the Gulf of Alaska, and the Arctic, ice-influenced waters, including the Eastern Bering Sea.

In this study, we look at correlations of phytoplankton phenology metrics using 18 years of chlorophyll concentration, as a proxy for primary production. We use the most common phenology metrics found in the literature: timing of maximum chlorophyll concentration, timing of bloom initiation, bloom duration, and total chlorophyll concentration produced during the bloom. These are used to investigate the patterns of seasonality in the NEP, and to assess whether these patterns (if any) are transferred to higher trophic levels, such as *Calanus marshallae* and other subarctic-adapted, lipid-rich zooplankton.

We hypothesize that the crucial *C. marshallae* and other copepod species used in this study are most sensitive to productive season length, as opposed to bloom timing or mean chlorophyll levels (although all these metrics are correlated to some degree). Experiments with the Coltrane copepod life-history model suggest that season length affects copepod population dynamics mainly through overwintering success in the northern NEP, and through number of generations per year in the south.

Winter vertical migration of Arctic zooplankton

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Diel Vertical Migration (DVM) is a solar mediated behavioural response observed globally in zooplankton in marine and freshwater environments. Our general understanding of the proximate causes of DVM was recently challenged by the discovery of active vertical migration during the Arctic polar night, a time of year characterized by an extended period of continuous darkness. A novel dataset comprising 58 deployments of moored Acoustic Doppler Current Profilers is used in this study to observe the vertical migratory behaviour of zooplankton on a pan-Arctic scale. Methods of circadian rhythm analysis are applied to detect synchronous activity. South of 75°N, DVM continues throughout winter (albeit with reduced vertical amplitude when compared to other times of the year). DVM is seen to cease for a short period of time (up to 50 days) at latitudes between 75° and 82°N. The duration for which DVM ceases is controlled primarily by latitude (and therefore the altitude of the sun), but is modified by sea-ice presence and other environmental parameters. No DVM pattern is detected at 90°N, but annual periodicity is detected in the surface backscatter levels at this latitude. During the Polar Night and the absence of solar illumination, zooplankton are seen to respond to lunar illumination on a pan-Arctic scale. Aggregations at depth coincide with an avoidance of the surface for several (<6) days over the full moon. The deepest aggregation is seen at 110 m, indicating a depth limit of moonlight perception. A new type of migratory behaviour is described: Lunar Vertical Migration (LVM) which exists as LVM-day (24.8 hour periodicity) and LVM-month (29.5 day periodicity). Following this, a new understanding has been gained on mid-winter zooplankton behaviours on a pan-Arctic scale. The seasonal cycles detected in this dataset will now be integrated into an existing copepod model (Banas et al., 2016) to further understand the optimal strategy of zooplankton in a variety of Arctic environments, and how these species might adapt to future change.

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