Modelling the Changing Structure of Marine Ecosystems in Response to Changes in the Physical Climate

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Changes in Fish Assemblage at Fixed Locations


Assessed “trends in 172 cells from records of >100 million individuals sampled over 1.2 million km$^2$ from 1980–2008. We demonstrate responses to warming in 72% of common species.”
Are Our Standard Compartment Ecosystem Models Adequate?

• Current planktonic food web models have a 'fixed' structure, and few parameter values vary over time in response to a changing environment (exception – “optimality” or “adaptive” models of Markus Pahlow, S. Lan Smith, A. Merico, ...)

• Try a model where adaptation is formulated in terms of the distribution of species or phenotypes as a function of traits (e.g., intrinsic growth rate) which in turn are functions of environmental variables: Temp, pH, O\textsubscript{2}, pCO\textsubscript{2}, etc.

e.g. maybe a simple 'Complex Adaptive System' model
Ecological Adaptation to a Changing Climate

Relative Growth Rate = \( f(\text{environmental variables: } T, \text{pH}, O_2, \text{etc}) \)

Change in Biomass $P(x_i, t)$

of species or phenotype $i$ as a function of environmental variable $x_i$ for a step change in environmental 'fitness', i.e. a regime shift in the environment

$$\frac{dP(x_i, t)}{dt} = P(x_i, t)\left[(v(x_i)H(x_i - x_m) - m_i)\right]$$

where:

- $v(x_i)$ is the intrinsic growth rate (a 'trait') for phenotype $i$,
  as a function of the environmental variable $x_i$ (e.g. pH, O$_2$, SST, etc)
- $H(x_i)$, the 'fitness function' is maximum at $x_m$
  $$H(x_i) = \frac{1}{2} \left[ 1 + \cos \left( \frac{2\pi(x_i - x_m)}{w} \right) \right]$$ over $[-\pi, \pi]$, $w =$ width of 'cos' at $H = 0.5$
- $m_i$ is the linear mortality coefficient for phenotype $i$, and
- total biomass $B(t) = \int P(x_i, t)dx_i$ is currently controlled by a 'logistic' equation

So far, ignores diffusion, immigration, emigration, plasticity, genetic adaptation (evolution), etc.
Response to a Shift in T

\[ T_{\text{old}}(H_{\text{max}}) = 12.5^\circ C \]
\[ T_{\text{new}}(H_{\text{max}}) = 20^\circ C \]

Success & rate of adaptation depend on the degree of overlap of the initial distribution \( P(x_i, 0) \) of species or phenotypes and the new fitness function \( H(x_i, t) \)
Response to Decreasing pH (1)

Smoothly decreasing pH

Fitness function

$H(t=0)$

$P_i(pH, t=0)$
Time-Varying Environmental Forcing

1. At each time $t$, vary forcing by adding random forcing $R_t$ to the slowly-increasing $T_t$ (or decreasing $pH_t$)

But this is “too random”

2. So create first order autoregressive variable “AR1”:
   
   \[ Z_t = a_1 Z_{t-1} + a_2 R_t \]

   where ‘$a_2$’ can be calculated from ‘$a_1$’ such that the new distribution $Z_t$ has the same variance about its centre as the original distribution $R_t$
Response to Decreasing pH (2)

Decreasing pH with short term variability
Effect of Variable Forcing in pH
(1 generation = 5 timesteps)

Smoothly decreasing pH

Decreasing pH with short term variability

Demonstrates how an extreme in variability imposed on a smooth decrease in pH over several generations could cause local extinction
Consider \( a_1 = 0.8 \) and \( a_1 = 0.95 \)

Larger AR1 coefficient \( a_1 \) has a longer ‘memory’
Uniform Warming + Variable Forcing

'Slow' trend in $T$

Plus random forcing $Z_t$

Peak biomass

95% cpdf

75% cpdf

25% cpdf

5% cpdf

$a_1 = 0.8$
AR1 Forcing Starting at $t = 0, 500, 1000, 1500, 2000$

Time Series of Forcing for AR1 coeff $a_1 = 0.95$
Effect of ‘Slower’ Variability

![Graph showing time series of forcing for AR1 coeff a1 with a1 = 0.80 and a1 = 0.95.](image)

- Forcing Max at Phenotype # vs. Timestep
- Temperature at Phenotype # (°C)

**a_1 = 0.80**

**a_1 = 0.95**
Constant Max Growth Rate vs $Q_{10} = 2$ Increase with $T$

Run 917, Temperature at Pheno# (°C), at $t = 200$

Run 922, Temperature at Pheno# (°C)

$t = 200$

$\nu_{max}(T)$
Effect of $Q_{10}$ Dependence on Total and Peak Biomass

![Graph showing the effect of $Q_{10}$ on temperature dependence on growth rate. The graph plots total biomass and peak biomass against time, with lines for $Q_{10}=2$ and constant growth.]
Adding Realism? i.e. Complexity

So far we have started to explore only the effect of change in 1 environmental variable (T or pH) on 1 physiological trait (maximum intrinsic growth rate), of 1 group.

What is next?

1. Add size dependence of phytoplankton as a function of T
2. Develop zooplankton whose size is a function of the size of their prey, via an allometric relationship
3. Start to build a foodweb with these adaptive groups
4. Add multiple stressors, e.g. changing T, pH, O₂, etc., possibly using Hans Pörtner’s ‘Optimum Thermal Window’ concept.
Thanks

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