Physical processes mediating climate impacts in regional sea ecosystems

Jason Holt, Icarus Allen, Yuri Artioli, Laurent Bopp, Momme Butenschon, Heather Cannaby, Ute Daewel, Bettina Fach, James Harle, Dhanya Pushpadas, Baris Salihoglu, Corinna Schrum, Sarah Wakelin

National Oceanography Centre, Liverpool, UK
University of Bergen, Norway
IMS-METU, Turkey
Plymouth Marine Laboratory, UK
LSCE, IPSL, France
The Big questions....

How can we make future climate projections of regional sea ecosystems that are reliable enough to inform decisions or opinions?

How do we begin to understand the uncertainty in the projections?
Downscaling global change

Projected changes

netPP  \( \Delta \) netPP

Global Fish Catch

Focus PP as the engine of the ecosystem
Multi model ensemble (AR4):
Decrease in mid- low- latitude basins
  • Increased stratification, slowed circulation
Increase (variable) in high latitudes
  • Relaxation of light limitation

Big mismatch in scales

Streinacher et al 2010

Watson and Pauly, 2001

Streinacher et al 2010
MEECE: Models and downscaling approaches

- Three models in five (out of ten) regions

- **NPZD module**
  - Nitrification
  - O2
  - SiO2
  - $2H2O$
  - N2
  - NH4
  - PO4
  - NO3
  - $P_f$
  - $Z_s$
  - $Z_l$
  - $P_d$
  - DOM
  - Denitrification

- **ECOSMO**: Barents, Baltic, North Sea

- **POM-BIMS_ECO**: Black Sea

- **POLCOMS-ERSEM**: Atlantic Margin

- **IPSLCM4 + other AR4/5 models**
  - A1B Timeslice experiments:
    - 2080-2099 v’s 1981-2000

- [Website](http://www.meeceatlas.eu/Menu/)
The common forcing: IPSL CM4

Air temp

Wind Stress

SWR

Air temp

Summer - Spring

Wind Stress

Spring

Oceanic nutrient boundary conditions

A single ‘sensitivity’ experiment
No assessment of likelihood at this stage
Change in netPP: Five regions and Global

- Heterogeneous change, positive and negative regions – not seen in global model
- Suggests added value from downscaling
How to address uncertainty for a multiply coupled system?

- Each model has
  - internal variability,
  - structural uncertainty
  - parameter uncertainty
- a 9D space: too big to build a PDF from ensembles

Instead

- Need a deeper understanding of systems response and drivers
- Here confidence in the sign of change would be a good start
- Guide ensemble design

Hawkins and Sutton BMS, 2009
Physics process controlling phytoplankton growth

Three key general mechanisms

OA-GCMs

Biogeochemical composition

Phytoplankton blooms/Meso-scale processes

Physiological response

Winter mixing
Seasonal upwelling
Ocean-shelf exchange

Sverdrup (1953)

Turbulence-stratification-light Interplay

Eppley (1972)

Growth rate response to temperature: autotrophic and heterotrophic
A key difference between open ocean and shelf seas

- Shelf seas are in (dynamic) thermal equilibriums,
- Deep ocean/regional seas are not

- Permanent stratification necessarily increases
- Inhibits winter mixing
- Seasonal stratification doesn’t necessarily increase
Nutrient Resupply: Deep-Ocean or -Sea

Available N for spring bloom

\[ N_2 h_x = N_o (1 - h_1/h_2) h_x \]

i.e. decreases with decreasing \( h_2 \)

\[ h_x = h_L \ldots h_1 \]

How much N is available before onset of strong strat.?

Depends on heating, mixing and growth rates
Nutrient Resupply: Shallow-Sea

\[ N_1 = N_0 \left(1 - \frac{h_1}{h_2}\right) \]

\[ N_2 = N_0 \]

\[ N_{\text{mix}} \]

\[ N_{\text{recyc}} \]

\[ h_1 \]

\[ h_2 \]

\[ h_L \]

\[ h_x \]

\[ t_b \]

\[ h_1 \]

\[ h_2 \]

Available N

\[ N_1 h_x = N_0 \left(1 - \frac{h_1}{h_2}\right) h_x \]

\[ h_x = h_L \ldots h_1 \]

\( h_2 \) is here fixed, so this big driver is absent

Variations in \( t_b \), \( h_x \), \( N_{\text{mix}} \) all still present
Regional seas are more sensitive to changes in total budget (c.f. big reservoir in open ocean)

Changes in external N will change internal, relative to other inputs

Care needed with this approach: seas are rarely horizontally ‘well-mixed’

Budget in region LOICZ type approach:

\[ N_s = \frac{Q_o N_o + Q_r N_r + F_a}{Q_o + Q_r} \]

Holt et al 2012 *Biogeosciences*
Wind Effects: Mixing

Possible mixing effects of changing wind stress:
Idealised phytoplankton profile: dashed line is with increased wind

- Entrains N on deepening, lower light, more tidal pumping
- Later bloom, and/or later stratification
- Earlier autumn bloom, maybe in higher light

Very difficult to guess what overall effect would be: very dependent on details of mixing conditions
Wind effects: Circulation

Very regionally specific
Enclosed basin susceptible to large changes
• Taylor-Proudman theorem: follow topography in direction of Coastal Trapped Waves (same for thermal wind circulation, if stratification decreases shorewards)
• Not case for Black Sea

Up/downwelling according to Ekman theory
• Directly dependent on changes in wind stress

Attributed to changes in wind stress curl
Illustrations from NW European shelf

Regional Model

Global

netPP

ΔnetPP
Phytoplankton growth (1): Ocean-shelf Exchange
Regional winter N v’s N uptake following year

ER40 Reference

Winter N

A1B - CNTRL

Δf N uptake

Δf Winter N

Holt et al BGS 2012
Phytoplankton require nutrients and light

• Nutrient re-supply controlled by
  • Horizontal and vertical cross-gradient transport
  • Often diffusive on sub-seasonal timescale
• Light controlled by
  • season/latitude
  • atmospheric and in-water composition
• In Early bloom:
  • Phytoplankton respond to reduced mixing but full depth nutrient flux still active.

A simple heuristic approach:
Average properties over three stages, defined by thresholds:
• \text{netPP}>0.2\times\text{netPPmax}
• \text{N}<0.2\times\text{Nwint}
• \text{Netpp}<0.2\times\text{netPPmax}
Phytoplankton growth(2): Mixing-light response

- Earlier/longer spring bloom means more efficient silicate usage
- Increased stratification impacts mid-water production in summer
- Different to what suggested in ocean ocean: shift to smaller groups
Phytoplankton growth (3): Temperature effects

- Experiments with T dependence removed
- Temperature dependence is much more apparent on plankton biomass than netPP
- Heterotrophs and autotrophs have same q10 parameterisation
Driver – Response experiments

- B: Boundary nutrients
- W: Wind
- L: SWR
- A: Air temp
- P: Precip

Random present day year is swapped in to future forcing

\[ \Delta V_p = \Delta V - \Delta V_p' \]
How linear is the system?

- System is close to linear but tendencies to a damping
- Combined effect less than sum of drivers
- Ecosystem feedback e.g. grazing?

- The system has multiple competing drivers acting in positive and negative sense
- General driver response wrt net PP:
  - Reduced ocean nutrients: -ve
  - Increased wind: +ve mixing, -ve growing season
  - Increased SWR: +ve
  - Increased air temp: -ve stratification +ve growth rates.
The MEECE Experiments: Common analysis

netPP Fractional change

Divided by +ve and –ve region, scaled by total

Potential Energy Anomaly (200m)
## Qualitative summary of Driver - Responses

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Black Sea</th>
<th>Barents Sea</th>
<th>Baltic Sea</th>
<th>North Sea</th>
<th>NW Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temp.</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
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<tr>
<td>Wind</td>
<td>curl(w) -ve</td>
<td>+ve</td>
<td>+ve (Winter)</td>
<td>-ve (Summer)</td>
<td>-ve</td>
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<td>Precip</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
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<tr>
<td>SWR</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
<td>-ve</td>
<td>+ve</td>
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<tr>
<td>Nut. BC</td>
<td></td>
<td></td>
<td></td>
<td>-ve</td>
<td>-ve</td>
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<table>
<thead>
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<th>Response</th>
<th>Black Sea</th>
<th>Barents Sea</th>
<th>Baltic Sea</th>
<th>North Sea</th>
<th>NW Shelf</th>
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</thead>
<tbody>
<tr>
<td>netPP</td>
<td>-ve East</td>
<td>+ve</td>
<td>+ve</td>
<td>-ve Open shelf</td>
<td>-ve Open shelf (NS)</td>
</tr>
<tr>
<td></td>
<td>+ve west</td>
<td></td>
<td>+ve Coastal</td>
<td>+ve Coastal/Celtic Seas</td>
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<tr>
<td>Phyto Biomass</td>
<td>-ve East</td>
<td>+ve North</td>
<td>+ve</td>
<td>-ve Open shelf</td>
<td>-ve Open Shelf/coast</td>
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<tr>
<td></td>
<td>+ve west</td>
<td>-ve South</td>
<td></td>
<td>+ve Coastal</td>
<td>+ve Celtic Sea</td>
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<tr>
<td>Diatom Fraction</td>
<td>-ve East</td>
<td>+ve west</td>
<td></td>
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<td>+ve</td>
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<tr>
<td></td>
<td>+ve west</td>
<td></td>
<td></td>
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<tr>
<td>Growing season timing</td>
<td></td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
</tr>
</tbody>
</table>

Driver-Response is not unique. Changes to mixing-light (+ice) appears to be important in many cases.
Conclusions

• Climate change impacts in regional seas are highly nuanced, with multiple competing drivers and interactions
  – Highly dependent on regional conditions
  – Drivers of different sign can mitigate - locally or across gradients of response
  – Isolated seas vulnerable to single drivers
  – Enhance uncertainty: Often dependent on uncertain aspects of forcing
• Shallow seas are not susceptible to changes in permanent stratification
  – A major vector of change for open-ocean systems is absent
  – Instead vulnerable to changes in ocean-shelf exchange (again more nuanced)
• Deep basin, regional seas are subject to changes in permanent stratification
  – But here wind effects (circulation and mixing) dominate
• Provides a guide for forcing ensemble selection to aid understanding of uncertainty