Biological controls of the CO_2 air-sea flux in a high-latitude shelf sea

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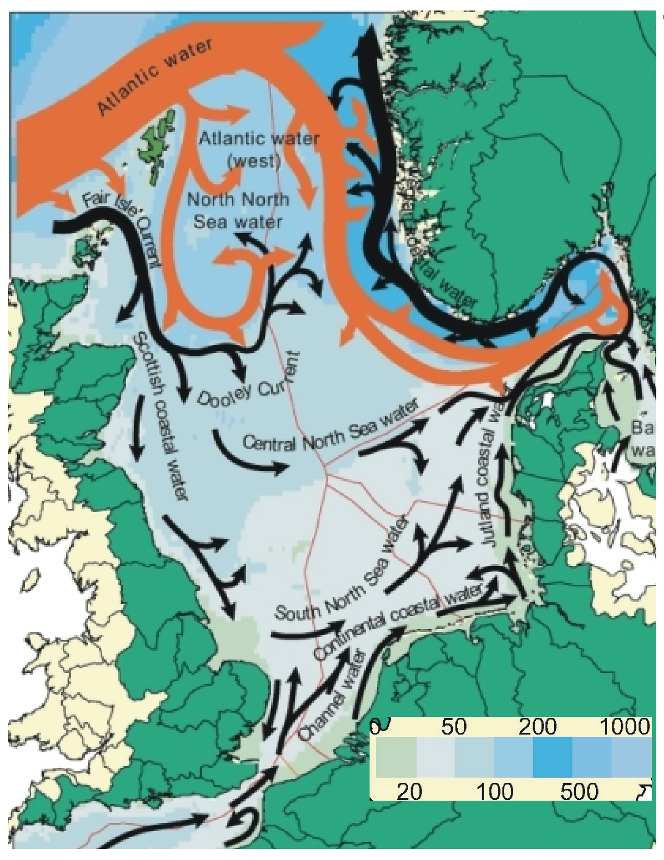


Fig. 1: General circulation and depth [m] of the North Sea [2]. Red arrows indicate water masses with dominant Atlantic signature.

The North Sea is a highly productive shelf sea receiving significant terrestrial nutrient and carbon input from Northwest Europe. Nonetheless, it takes up 1.38 mol C m^{-2} yr^{-1} ($8\cdot10^{-3}$ Pg C yr^{-1}) atmospheric CO_2 per year [1]. Observational studies [1] suggest that this uptake is linked to an oceanic export of carbon into the North Atlantic following the prevailing circulation (Fig. 1). They characterize two different hydrographic regimes in the southern and northern North Sea, respectively, enabling carbon export via the continental shelf pump mechanism. Here, a 3d coupled ecosystem model is used to investigate the controls of the CO_2 air-sea flux in the different regions.

The continental shelf pump (Fig. 2)

southern North Sea:
shallow, mixed water column: biological processes in a single compartment
- primary production: CO_2 uptake by phytoplankton
  => net CO_2 drawdown from atmosphere
- respiration: CO_2 release by heterotrophic food web
  => net CO_2 release to atmosphere

primary production and respiration occur in the same compartment of the water column, minor net CO_2 air-sea flux

northern North Sea: deep, seasonally stratified: surface mixed layer (SML) and deeper layer
- primary production: CO_2 uptake in SML, organic matter sinks down into deeper layer
- respiration of organic matter in deeper layer, i.e. not in contact with atmosphere by stratification during productive season

=> DIC enriched in deeper layer, depleted in SML (Fig. 3).
Currents (Fig. 1) remove DIC enriched water into North Atlantic, while CO_2 is drawn down from the atmosphere

Model: ECOHAM3 - 3d coupled physical-biogeochemical ecosystem model (IfM Hamburg), simulating years 2001 and 2002; state variables: DIC, TA, NO_3^-, NH_4^+, 1xPhytoplankton, 1xZooplankton, 2xDetritus, Bacteria, DOM, O_2; full C-, N- and O-cycles; resolution: 20km horizontal, 5-25m vertical (about 12 z-levels); fixed C/N ratio for Phyto-, Zooplankton, Bacteria, and related processes except for primary production: C fixation is decoupled from N uptake via simple parameterization allowing C uptake and excretion as semi-labile organic matter under nutrient-limited conditions, e.g. representing photoinhibition.
Observations: Data sets for the full carbon system (DIC, TA, pCO_2) from four North Sea cruises in Aug/Sep 2001, Nov 2001, Feb 2002 and May 2002, covering 90 identical stations.

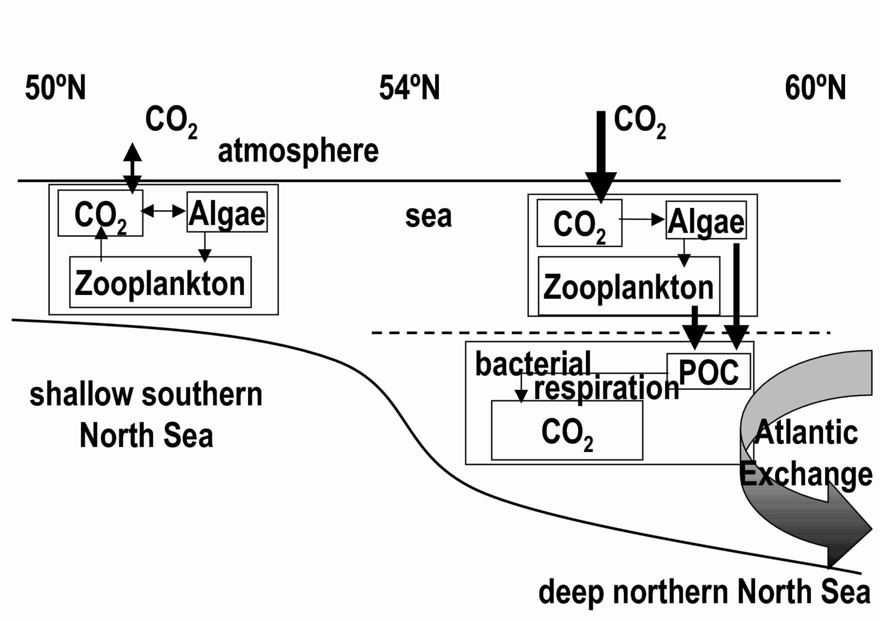


Fig. 2: The continental shelf pump mechanism [1].

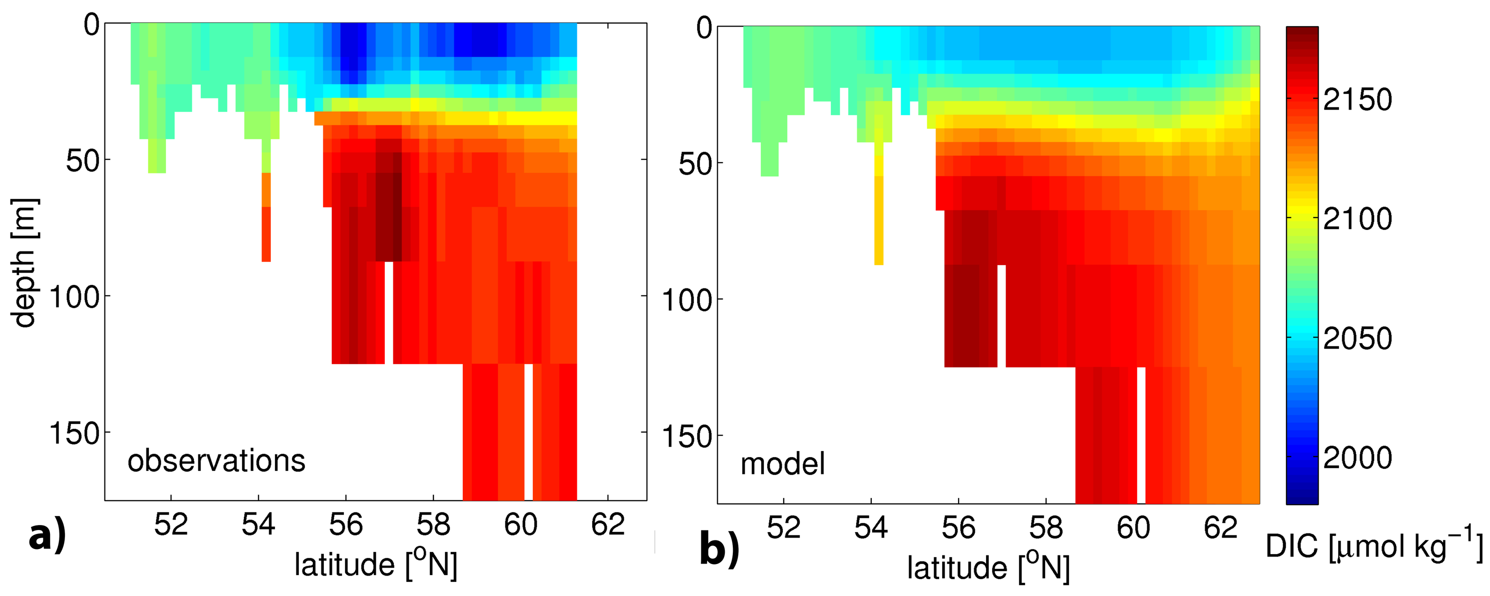


Fig. 3: (a) Observed and (b) simulated DIC [µmol kg^{-1}] along a North-South section at 2°E through the North Sea in Aug 2001.

What controls the CO_2 air-sea flux in the two regimes?

Northern North Sea (Fig. 4a):
water column: deep, seasonally stratified
Primary production: spring bloom supported by stratification (line a); bloom collapses when NO_3^- is depleted (line b); ongoing PP until decrease with mixing in fall (line c)
=> non-Redfield production!
Respiration: increases in spring/fall due to increased PP/mixing; does not balance PP in upper 30 m (SML) during productive season: organic matter sinks out of SML
=> **net community production** (NCP = GPP - R) **positive** in SML over most of the year: more CO_2 fixation than CO_2 release.
ΔpCO_2: strong decrease during spring bloom: strongly undersaturated surface pCO_2. Subsequent increase caused by increasing temperatures counteracting biological uptake. Mixing in fall brings up DIC rich waters, increasing pCO_2 to supersaturated values.
=> **net CO_2 uptake** (positive air-sea flux), CO_2 release only in winter.

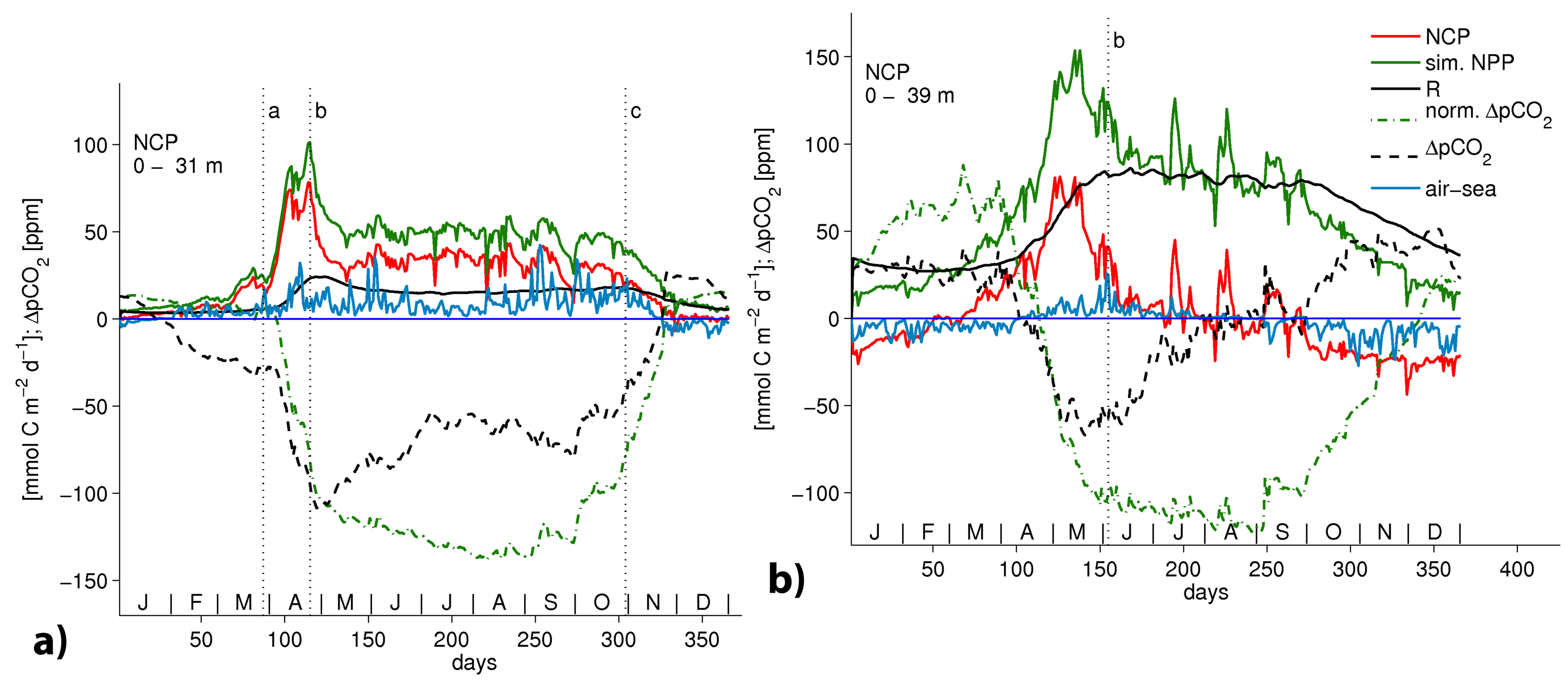
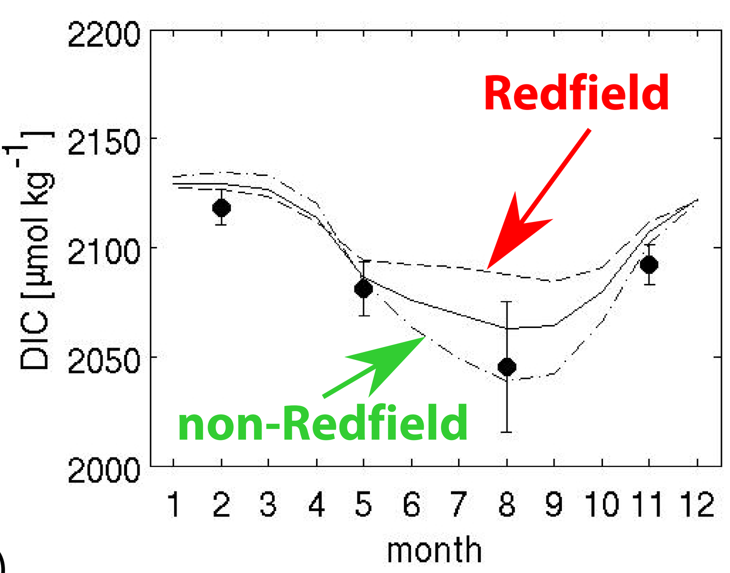


Fig. 4: Simulated net community production (NCP), primary production (PP), respiration (R), ΔpCO_2 (in situ; normalized to temperature at Jan 1, 2001), CO_2 air-sea flux. NCP, PP and R integrated over (a) the total depth at the southern location (Fig. 6a) and (b) 0-30 m at the northern location. Lines: (a) onset of stratification, (b) NO_3^- depletion, (c) onset of mixing.

Fig. 5: Average simulated DIC [µmol kg^{-1}] of the upper 30 m for the central North Sea (ICES box 4) in 2001. • observations; – – Redfield production; —, · – non-Redfield production.



non-Redfield production: C fixation under nutrient-depleted conditions!
=> sustains high PP during summer in stratified regime (Fig. 4a)
Redfield production: DIC drawdown in summer not strong enough compared to observations (Fig. 5)

Southern North Sea (Fig. 4b):
water column: shallow, predominantly mixed
Primary production: stronger spring bloom than in northern North Sea; high PP sustained by NH_4^+ after NO_3^- is depleted (line b) => regenerated production;
Respiration: builds up to high level following spring bloom; balances PP in summer
=> **NCP neutral or negative** from summer to winter, **positive only in spring**
ΔpCO_2: undersaturated during spring bloom, subsequently rising temperatures lead to neutral state; supersaturation in winter despite decreasing temperature due to negative NCP
=> positive CO_2 air-sea flux only following spring bloom, **CO_2 release dominates**

net air-sea flux (Fig. 6):
northern North Sea: net uptake => C transfer from atmosphere via sinking and export to North Atlantic: continental shelf pump!
southern North Sea: net release
model performance: captures DIC and air-sea flux characteristics in both regions; overestimates CO_2 release in

southern Bight:	missing sediment resuspension => overestimates DIC; hydrography
off British Coast:	hydrography, primary production?
off Norwegian Coast:	Alkalinity too low

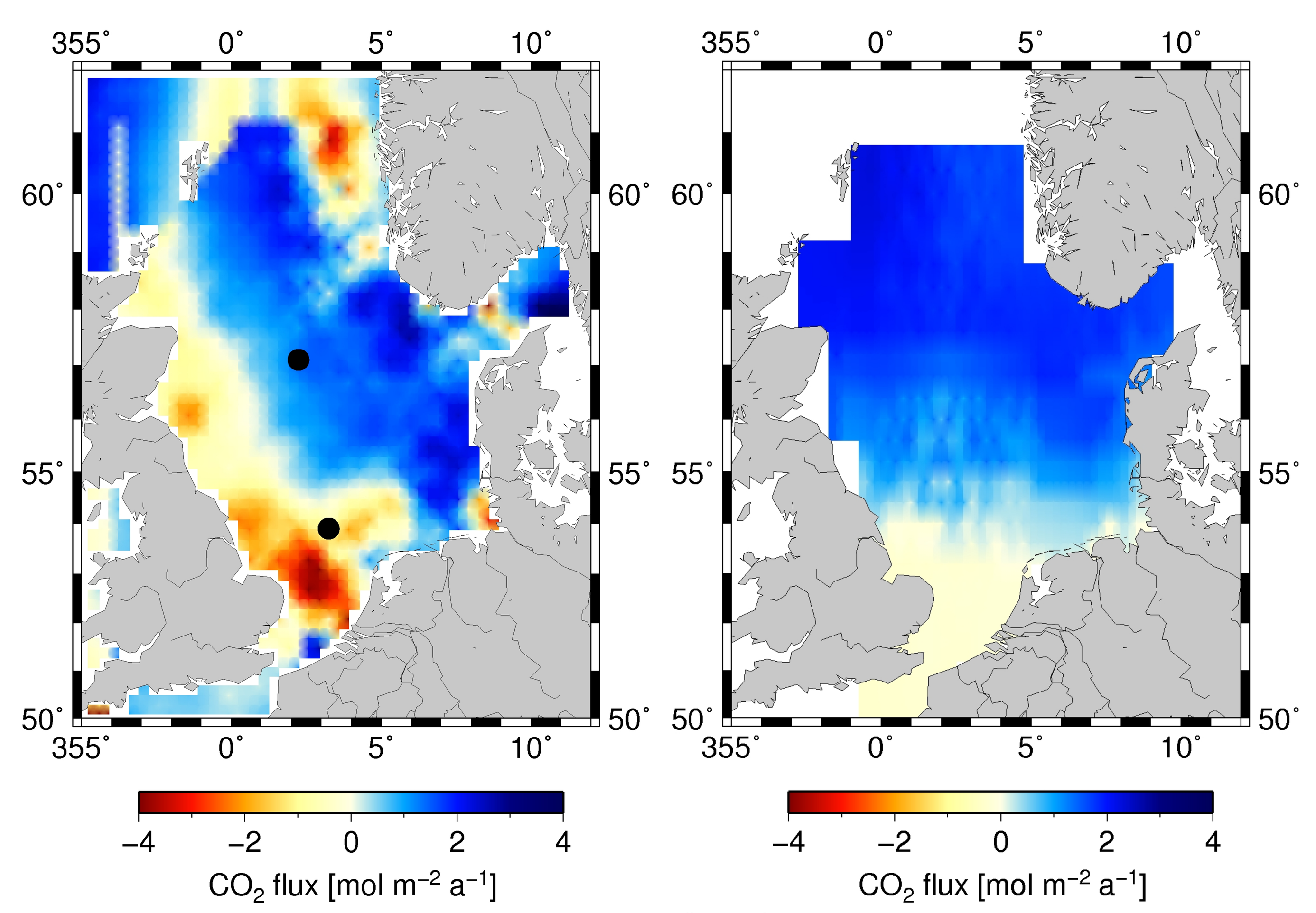


Fig. 6: Annual CO_2 air-sea flux [mol m^{-2} yr^{-1}] for 2001 (a) simulated and (b) deduced from observations [1].

Summary:
high primary production ≠ atmospheric CO_2 uptake
high primary production ≠ high NCP
NCP governs biological component of CO_2 air-sea flux
stratification, sinking and DIC export into North Atlantic enable net CO_2 uptake
effective C continental shelf pump
C overconsumption needed!

References:
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