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over the past 50 years (a. with free atmospheric CO_2, b. with prescribed atmospheric CO_2)

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SUMMARY

Ocean state estimation is applied to reconstruct the air-sea CO2 flux and anthropogenic carbon inventory of the high northern latitudes and the transports of Dissolved Inorganic Carbon (DIC) over the entrances of the Greenland-Iceland-Norwegian (GIN) Sea and the Arctic Ocean over the last 50 years. The model applied is the German contribution to the Estimating the Circulation and Climate of the Ocean (GECCO). Circulation and hydrography are optimized by constraining both the forcing and the initial conditions by assimilating the majority of available ocean observations. Two integrations are performed, covering the years 1852-2011. One is a control integration applying a fixed preindustrial atmospheric CO2 concentration of 285ppm, the second uses realistic, observed CO2 concentrations. Differences in carbon fluxes and inventories of the two integrations are termed 'anthropogenic'. Both, air-sea fluxes and DIC transports over key passages compare reasonably well with the few reported observation-based estimations. Based on our results, the temporal mean air-sea CO2 fluxes over the GIN Sea (Arctic Ocean) in the last 50 years amounts to 0.10 (0.057) Gt C yr-1 and increased by 50 (105)% when comparing the 1960s with the last ten years. Storage of anthropogenic carbon increased from 0.5Gt to 1.2Gt for the GIN Sea, and from 1.0Gt to 2.4Gt for the Arctic Ocean. Roughly 75% of the anthropogenic carbon is stored in the upper 1000m. DIC transports over key passages of the region all increased strongly. In summary, CO2 air-sea fluxes, as well anthropogenic carbon storage and transports exhibit positive, progressive trends for both the GIN Sea and the Arctic Ocean.

MONARCH-A CONSORTIUM

Participant no.	Participant organisation name	Short name	Country
1 (Coordinator)	Nansen Environmental and Remote Sensing Center	NERSC	NO
2	The University of Sheffield	USFD	UK
3	Universität Hamburg	UHAM	NO
4	Centre National de la Recherche Scientifique	CNRS	FR
5	Scientific foundation Nansen International Environmental and Remote Sensing Center	NIERSC	RU
6	Universitetet i Bergen	UiB	NO
7	Danmarks Tekniske Universitet	DTU	DK
8	Institut Francais de Recherche pour l'Exploitation de la Mer	IFREMER	FR

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1 Introduction

In this document we present an analysis of the ocean carbon cycle in the GIN Sea and the Arctic Ocean for the last 50 years. This analysis is based on an ocean state estimation applying the German contribution to the Estimating the Circulation and Climate of the Ocean (GECCO) model. The purpose of this study is to complement results in the project obtained from direct observations of components of the ocean carbon cycle and from integration of a coupled physical-biogeochemical ocean model.

Modeling the ocean carbon cycle is necessary in this context, since direct observations of the carbon cycle are sparse, especially in the high latitudes. On the other hand, a vast number of ocean observations exist. These data sets provide constraints on the ocean state, especially the circulation, which is a key component in the carbon cycle. However, it is not straight forward to use these observations (e.g. in a linear approach) to draw consequences for the carbon cycle. In ocean state estimation ocean observations can be assimilated to optimize the ocean state by applying corrections to both the forcing and initial conditions of the Ocean General Circulation Model (OGCM).The target of the optimization process is to provide the best possible consistency of observations, forcing and initial conditions, based on the errors provided with the data.

In order to obtain anthropogenic changes in the carbon cycle, two model integrations are performed. One integration uses a pre-industrial atmospheric carbon concentration, the other one is forced with realistic values. The difference in carbon content or flux of the two integrations is termed ‘anthropogenic’ in the following. We present an analysis of the air-sea flux of CO2 and the anthropogenic carbon inventory, as well as total and anthropogenic DIC fluxes over key passages of the GIN Sea and the Arctic Ocean in the last 50 years.

2 Model description

The GECCO (German part of Estimating the Circulation and Climate of the Ocean) model is based on the Massachusetts Institute of Technology general circulation model (MITgcm; (Marshall et al., 1997), which is a numerical implementation of the primitive equations formulated on z-levels on a spherical coordinate system.

The configuration used here is similar to the 50-year run (1952-2001) of the GECCO model (Köhl and Stammer, 2008a, 2008b). In the new synthesis (GECCO2, 1948-2011), the resolution was increased from uniformly 1° x 1° horizontal grid to a grid with a with a 1/3° telescopic meridional refinement at the equator and isotropic grid cells north of 25°N that were continued north of 66°N with a polar cap of roughly 40 km resolution. The vertical resolution was increased from 23 depth levels to 50 levels. As additional improvements, GECCO2 now includes the Arctic Ocean and the dynamic/thermodynamic sea ice model of Zhang and Rothrock (2000).

The synthesis uses the adjoint method to bring the model into consistency with available hydrographic and satellite data as well as prior estimates of surface fluxes. The estimation of the control parameters was changed from a direct estimation of the fluxes every 10 days to the estimation of daily atmospheric state variables, which include surface air temperature, humidity, precipitation and the 10 m wind. The prior of the atmospheric state derives as in the previous estimate from the National Centers for Environmental Prediction (NCEP).

To model the carbon content and exchange , Dissolved Inorganic Carbon (DIC), alkalinity and Dissolved Organic Phosphor (DOP) are incorporated as tracer variables, phosphate and surface silicate are prescribed as climatology (World Ocean Atlas 2009;, Garcia et al., 2010).
Carbonate chemistry is solved following Follows et al. (2006). Air-sea gas transfer is parameterized according to Wanninkhof (1992). Biological processes are assumed to occur in Redfieldian stoichiometry. A detailed description of the ocean carbon model is given in Dutkiewicz et al. (2005).

To allow for a realistic simulation of anthropogenic carbon the model integrations were started in 1852, when the ocean carbon inventory was in steady state with the atmospheric CO2 concentrations. To provide the atmospheric forcing with realistic space-time variability prior to the start of the NCEP reanalysis dataset in 1948, the NCEP reanalysis for the period 1948-1971 was repeatedly applied, together with its corrections gained from the 1948-2011 synthesis.

Two model integrations were performed. One is a preindustrial control run with the atmospheric CO2 concentration fixed to the 1952-value of 285ppm. The second run uses CMIP5 recommended CO2 concentrations (Meinshausen et al., 2011) extended with observed data for the period 2006-2011 (Conway et al., 1994). Initial conditions for DIC; DOP

and alkalinity are spatially interpolated from a coarse resolution long term setup of a coupled atmosphere-ocean model (Dutkiewicz et al., 2005).

In the following we analyze results of the last 50 years of the model integrations. Anthropogenic carbon content or flux is defined as the deviation of the realistic from the control integration.

3 Results

Our model integrations confirm that the Arctic Mediterranean is a sink for CO2 (Fig. 1). Based on the anthropogenic run, on average over the last 50 years, the GIN Seas took up 0.10 Gt C yr-1 and the Arctic Ocean 0.057 Gt C yr-1. The uptake for the whole Arctic Mediterranean is 0.16 Gt yr-1. Based on observations, Lundberg and Haugan (1996) report 0.11Gt C yr-1 +-40%, but their data basis is representative for the 1980s. For that period we find 0.14 Gt yr-1, which is within the uncertainty of Lundberg and Haugan's value. Jeanssen et al. (2011) report an air-sea flux of 0.19 Gt yr^{-1} for the GIN Sea alone, which is considerably larger than our value.

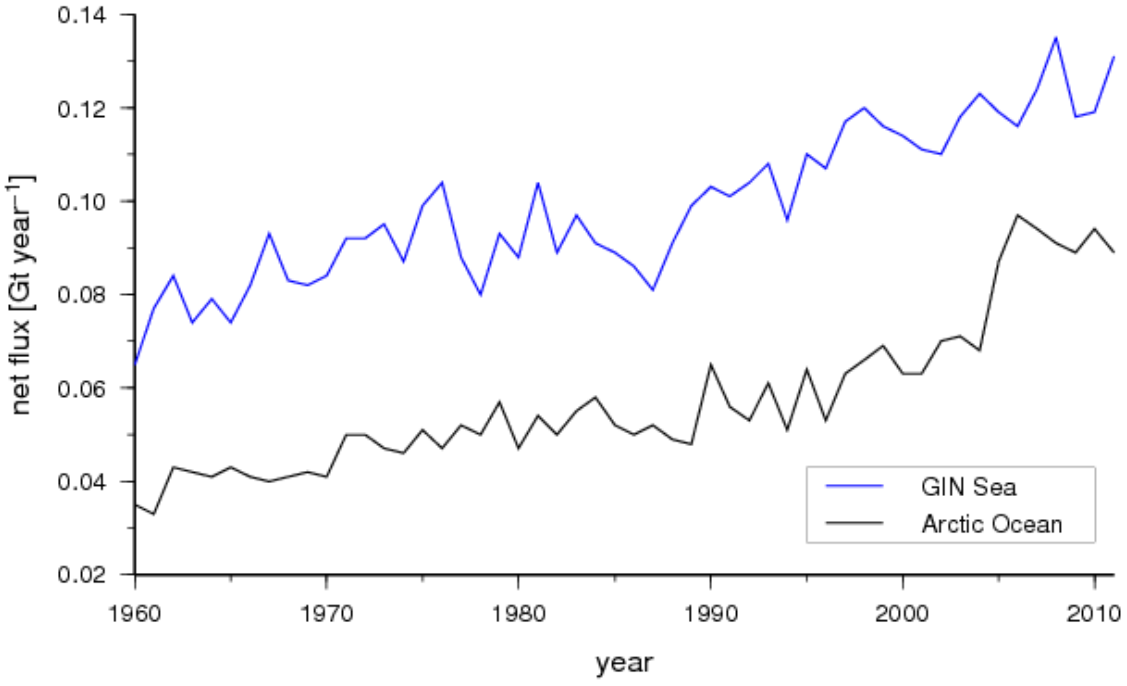

Figure 1: Net annual air-sea carbon flux from the GECCO anthropogenic run (positive, indicating oceanic uptake).

On temporal average the whole region considered (poleward of 60°N) shows a positive air-sea flux, despite those areas covered by sea ice the whole year (Fig. 2). However, a distinct spatial structure exists, with a strong uptake of around 5 moles m^{-2} per year in the GIN Sea and the Barents Sea in recent years, compared to lower values below 1 mole/m^2 in the rest of the Arctic Ocean.

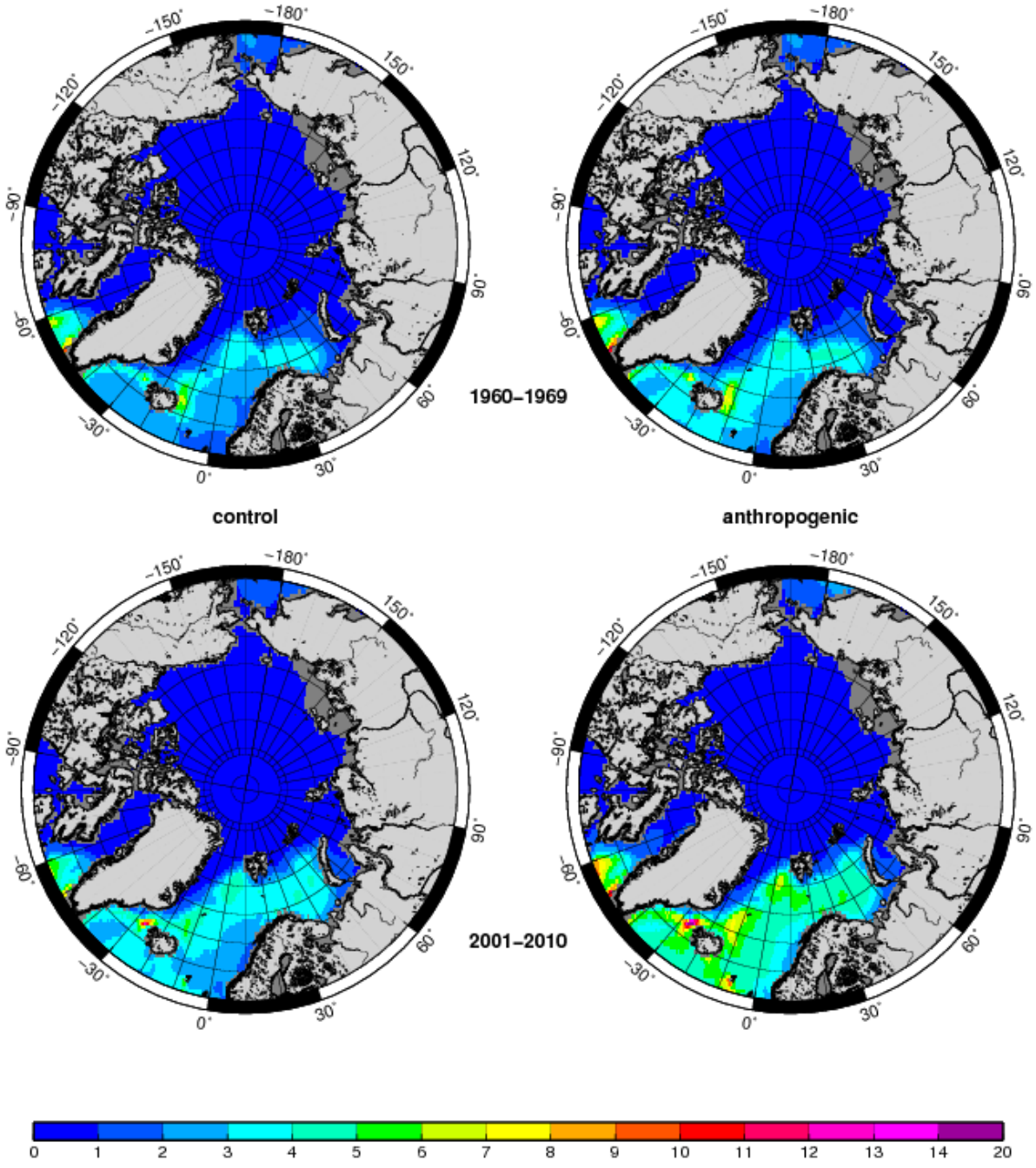

Figure 2: Net annual air-sea carbon flux (moles CO_2 m^{-2}) for pre-industrial atmospheric CO2 concentration (left) and realistic forcing (right). Two periods are considered as indicated.

From our model integrations, air-sea carbon fluxes increased 50% in the GIN Sea and 105% in the Arctic Ocean (Fig.1) during the last 50 years, when comparing the CO_2-uptake in the 1960s with those of the last ten years. These trends accelerate with time in both regions. A part of the increase is also found in the control integration (see Fig. 2) and is thus not directly caused by the increase in atmospheric CO2 concentration, but is due to changes in the physical state of the ocean in the high latitudes, specifically retreat of sea ice extend in

recent years discovering large oceanic areas that are under-saturated with respect to CO_2 concentration.

Due to the prescribed increase in atmospheric CO_2 also surface ocean pCO2 and concentration of DIC increased, causing a gain in storage of ocean anthropogenic carbon. 0.5 Gt of anthropogenic carbon is stored in the GIN Sea in the 1960s, increasing to 1.2 Gt in the average of the last ten years (Fig. 3). This is an annual average increase of approximately 0.02 Gt yr^{-1}, or about 20% of the net air-sea flux. Most of the anthropogenic CO_2 (roughly 80%) is stored in the upper 1000m, only 20% in the deep ocean.

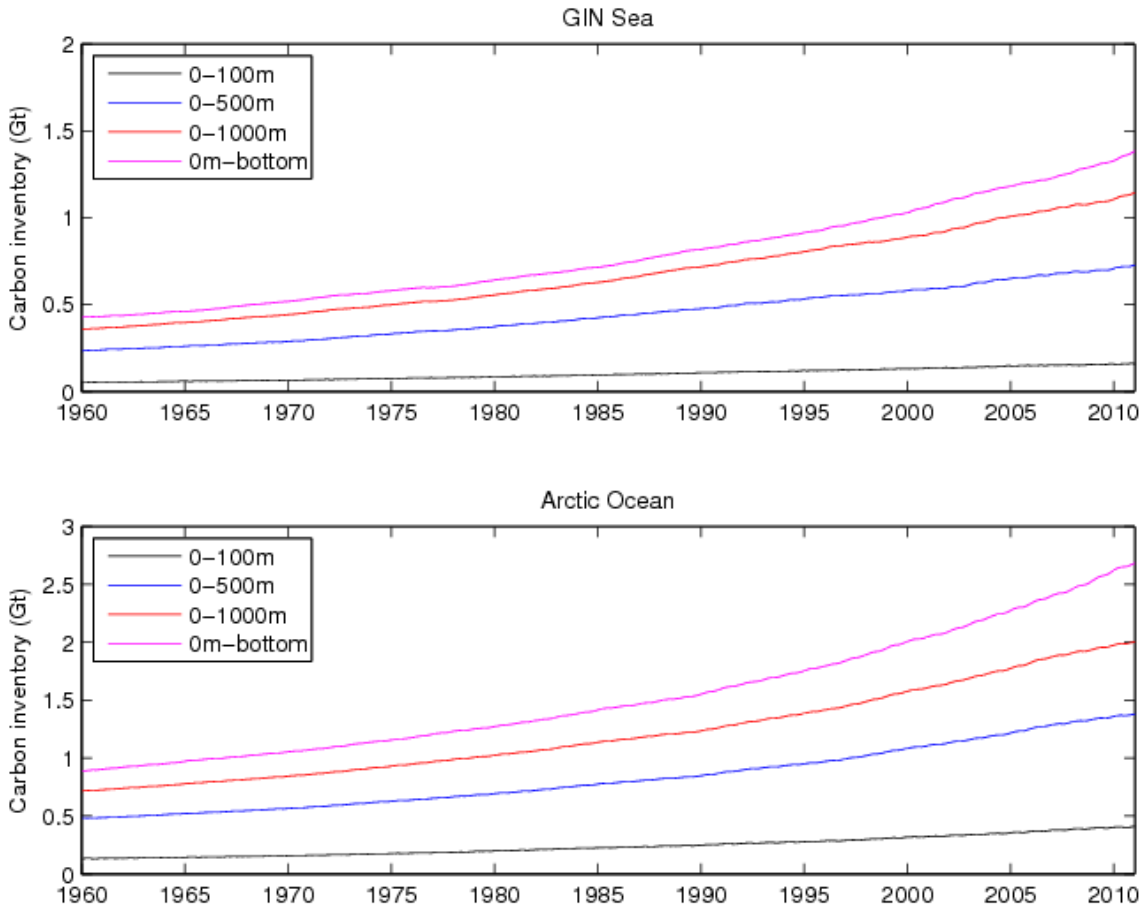

Figure 3: Storage of anthropogenic carbon (Gt) in different levels as indicated in the inset.

The relative increase in the carbon inventory of the Arctic Ocean is almost identical to that of the GIN Sea. The anthropogenic carbon storage increased from 1.0 Gt in the 1960s to 2.4 Gt in the last ten years. This is a gain of approximately 0.04 Gt yr^{-1} and in the order of the local air-sea fluxes. As in the GIN Sea most of the anthropogenic carbon is stored in the upper part of the water column, with 73% in the upper 1000m.

Beside the increased air-sea carbon flux also the carbon concentration of the Atlantic inflow to the Arctic Mediterranean is increased. As, representative, example, the anthropogenic DIC concentration in the Faroe-Shetland Channel, as average over the last ten years (2002-2011), is shown in Fig. 4. The DIC concentrations of the inflow gained 40-60 µMol kg^{-1} depending on depth and region, while the concentrations in the deep outflows are also increased, but with smaller magnitudes.

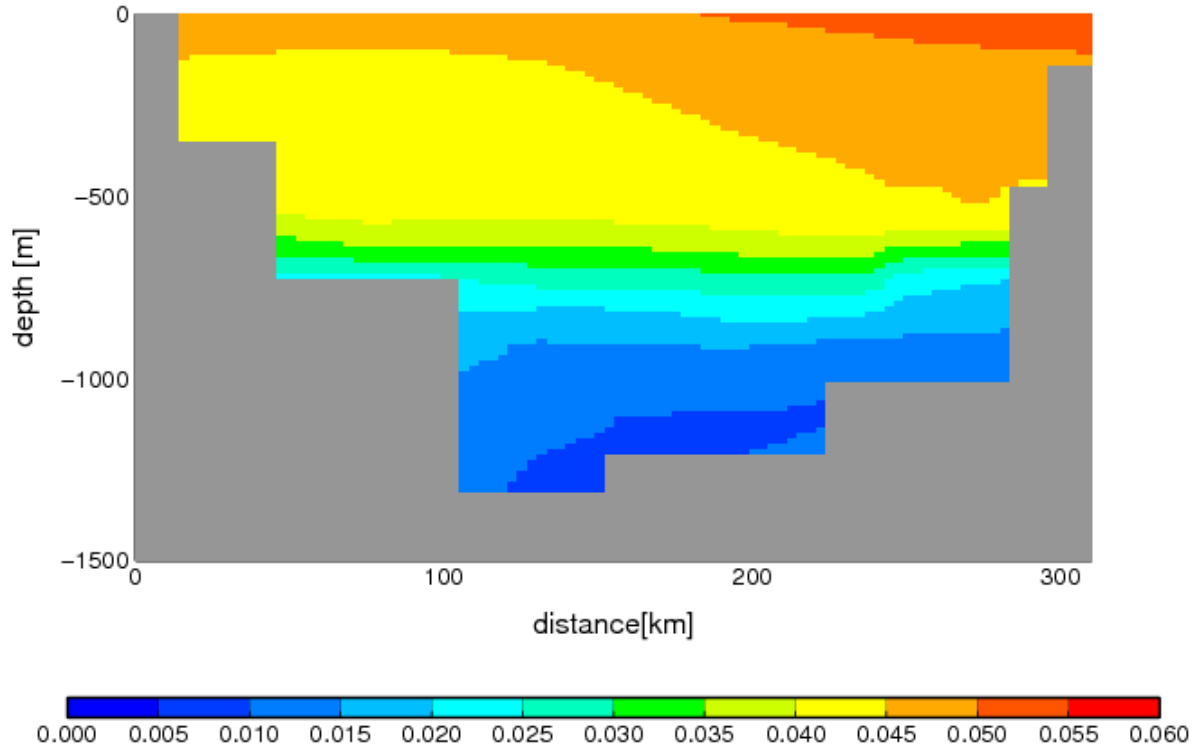

Figure 4: Carbon concentration (moles m^{-3}) in the Faroe-Shetland Channel seen from the south, averaged over the period 2002-2011.

Net carbon fluxes over the entrances of the GIN Sea are displayed in Fig. 5 and summarized in Tab. 1. The fluxes show large inter-annual and especially inter-decadal variability that is dominated by variations in the volume transports (not shown). The fluxes for the 1980s are in general close to those reported by Lundberg and Haugan (1996) and Jeansson et al. (2011), while for both the 1960s and the last decade, our modelled transports are considerably stronger.

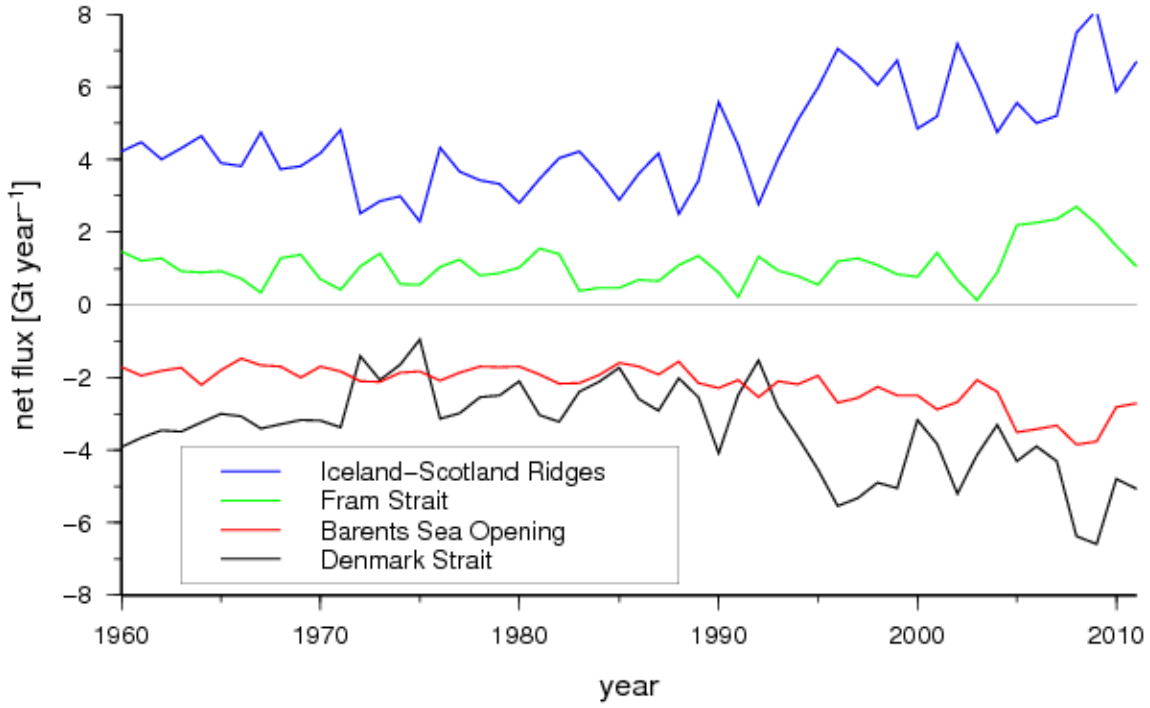

Figure 5: Net carbon fluxes (GtC yr^{-1}) over the entrances of the GIN Sea.

Due to the increased DIC concentrations the net anthropogenic carbon fluxes increased strongly in the last 50 years for all entrances of the GIN Sea and the Arctic Ocean (Fig. 6 and Tab. 1). The values reported by Jeansson et al. (2011) are between our modelled values for the 1980s and the recent decade. To some extend this might reflect the reference time of the data used by Jeansson et al.

Table 1: Total net and anthropogenic fluxes of DIC over the entrances of the GIN Sea and the Arctic Ocean. Estimated transports based on observations are obtained from Lundberg and Haugan (1996) for Bering Strait and Canadian Archipelago, all other estimates are provided by Jeansson et al. (2011).

Area	DIC flux (Gt C yr^{-1})							
	1960-1969		1980-1989		2002-2011		observed	
	total	anthrop.	total	anthrop.	total	anthrop.	total	anthrop.
Denmark Strait	-3.4	-0.025	-2.5	-0.029	-4.8	-0.092	-3.4	-0.058
Iceland-Faroe-Scotland Ridge	6.2	0.041	3.5	0.055	6.2	0.158	3.7	0.109
Barents Sea Opening	-1.8	-0.017	-1.9	-0.029	-3.1	-0.073	-1.8	-0.041
Fram Strait	1.0	0.001	0.9	0.005	1.6	0.012	0.8	
Bering Strait	0.7	0.006	0.7	0.010	0.7	0.015	0.63	
Canadian Archipelago	-1.5	-0.008	-1.7	-0.014	-2.2	-0.028	1.1	

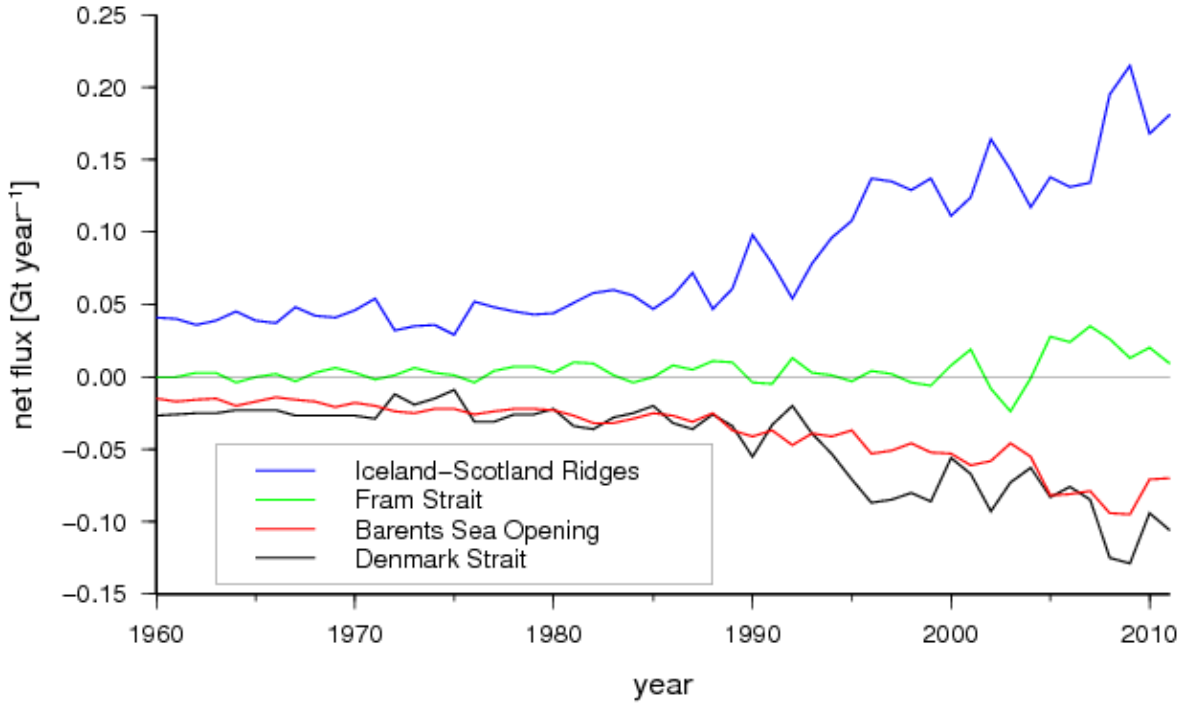

Figure 6: Net anthropogenic carbon fluxes (Gt C yr^{-1}) over the entrances of the GIN Sea.

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