Supplementary Materials

Appendix A: Nutrient inputs overview

Overview of all rivers included in the exercise and their respective reduction percentages.

Supplementary Table 1: Overview of 1900 loads (estimated percentage of current day loads) as applied in the study. Reductions based on JMP-EUNOSAT results (in black) and local studies (in red). Where rivers were estimated to have higher loads or discharges around 1900 than currently the values applied were reset to 100%, i.e. the same as current day loads or discharges. The reduction percentages were applied to the loads in the observations-based OSPAR ICG-EMO riverine database.

River name	Country	Discharge %	HS TN%	HS TP%	River name	Country	discharge%	HS TN%	HS TP%
Meuse	NL	102	38	38	**CARRADALE**	GB	101	94	182
Rhine	NL	101	43	38	**CARRON**	GB	100	146	634
North Sea Canal	NL	106	30	27	**CEFNI**	GB	98	38	67
Lake IJssel East	NL	106	22	36	**CHELMER**	GB	118	52	65
Lake IJssel West	NL	104	21	36	**CLEDDAU**	GB	99	35	59
Schelde	NL	103	46	81	**CLWYD**	GB	101	41	66
GentTerneuzenCanal	NL	100	31	33	**CLYDE**	GB	99	43	45
Brede	DK	112	32	36	**COBER**	GB	105	55	54
Brons	DK	112	32	36	**COLNE**	GB	102	38	27
Elling	DK	111	28	36	**CONDOR**	GB	98	57	78
Gera	DK	116	30	36	**CONON**	GB	100	111	419
Grona	DK	116	29	36	**CONWY**	GB	98	56	60
Gudena	DK	111	26	36	**COQUET**	GB	101	51	95
Haslevgards	DK	116	24	36	**Cormarty Firth**	GB	102	61	94
Jordbro	DK	109	28	36	**CREE**	GB	101	73	160
Karup	DK	109	28	36	**CUCKMERE**	GB	98	40	36
Kastbjerg	DK	113	37	36	**CURRYPOOL STREAM**	GB	97	30	58
Konge	DK	117	29	36	**DARENT**	GB	98	59	80
Lindenborg	DK	113	28	36	**DART**	GB	104	42	25
Liver	DK	116	34	36	**DEBEN**	GB	100	47	100
Omme	DK	110	30	36	**DEE AT ABERDEEN**	GB	101	66	152
Ribe	DK	116	30	36	**DEE AT CHESTER**	GB	99	49	57
Ry	DK	111	17	36	**DEE AT TONGLAND**	GB	101	66	122
Simested	DK	109	28	36	**DENE MOUTH**	GB	101	26	28
Skals	DK	109	28	36	**DERWENT**	GB	102	28	19
Skjern	DK	110	30	36	**DEVERON**	GB	103	45	68
Sneum	DK	116	31	36	**DIGHTY WATER**	GB	107	50	89
Stora	DK	108	32	36	**DON**	GB	103	50	74
Uggerby	DK	111	33	36	**DONIFORD STREAM**	GB	103	39	54
Varde	DK	114	32	36	**Dornach Firth**	GB	100	102	376
Vida	DK	117	30	36	**DOUGLAS**	GB	101	42	56
Voer	DK	116	30	36	**DOVER**	GB	104	59	60
Warnow	D	102	32	118	**DWYFAWR**	GB	99	97	277
Trave	D	105	29	96	**DWYRYD**	GB	99	97	277
Schwentine	D	105	31	98	**DYFI**	GB	99	65	216
Elbe	D	105	51	26	**DYSYNNI**	GB	100	84	331
Ems	D	106	26	17	**EARN**	GB	101	54	94
Weser	D	104	37	24	**EAST SOLENT**	GB	99	41	53
Eider	D	101	23	8	**EBBW FAWR**	GB	96	48	193
Miele	D	101	25	83	**EDEN AT CARLISLE**	GB	101	48	68
Pinnau	D	103	27	77	**EDEN IN SCOTLAND**	GB	107	50	89

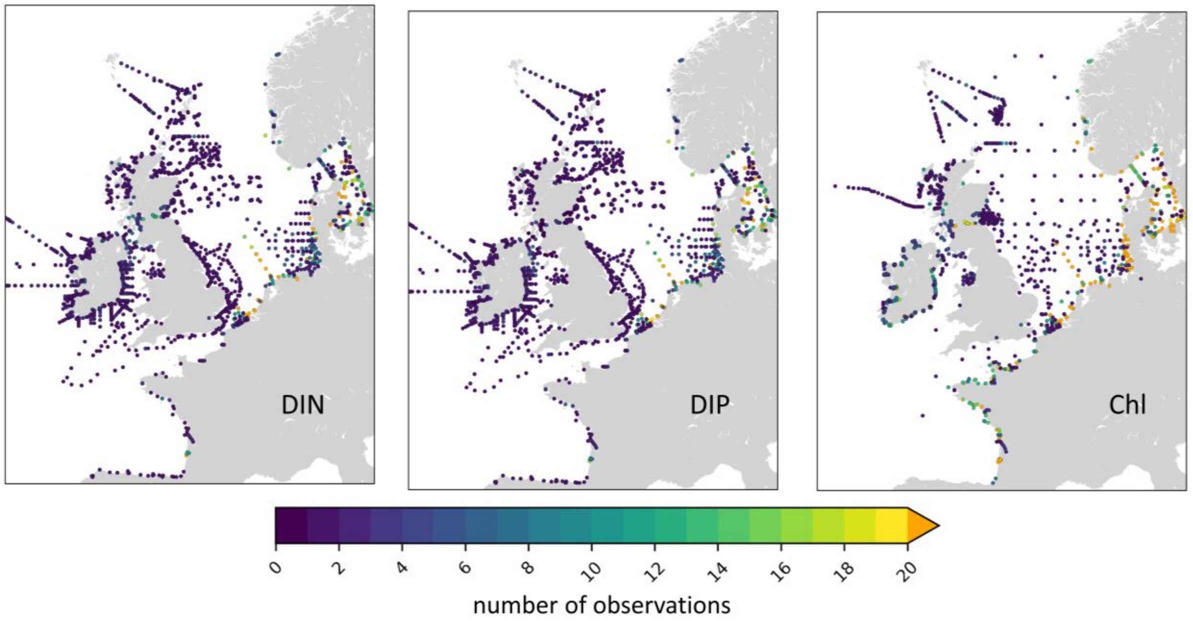
Tetenbuellspieker Kanal	D	101	23	73	**EHEN**	GB	100	16	10
Accumersiel	D	100	26	57	**ELLEN**	GB	100	58	117
Bensersiel	D	100	26	57	**ELY**	GB	97	23	15
Harlesiel	D	99	23	73	**Enler**	GB	100	29	21
Knock	D	101	23	68	**ERCH**	GB	101	42	71
Leybuchtsiel	D	100	26	57	**ERME**	GB	101	45	50
Neuharlingersiel	D	99	23	73	**ESK AT EDINBURGH**	GB	101	26	25
Dangaster Siel	D	97	30	72	**ESK AT WHITBY**	GB	106	35	45
Eckwarder Siel	D	96	20	89	**ESK INTO SOLWAY FIRTH**	GB	101	62	132
Ems-Jade Kanal	D	97	30	72	**EWE**	GB	100	138	413
Fedderwardersiel	D	95	26	95	**EXE**	GB	102	41	51
Jade-Wapeler Siel	D	96	20	89	**EYE WATER**	GB	103	56	83
Maade Siel	D	97	30	72	**FAL**	GB	105	55	54
Schleuse Hooksiel	D	95	26	95	**FINDHORN**	GB	101	94	270
Schweiburger Siel	D	96	20	89	**Finn**	IRL	101	42	69
Vareler Siel	D	96	20	89	**FIRTH OF FORTH**	GB	99	58	103
Wanger Siel	D	100	25	45	**FOWEY**	GB	105	45	55
Arlau	D	110	26	56	**Foyle**	GB	101	42	69
Bongsieler Kanal	D	110	26	56	**FROME**	GB	100	39	52
Husumer Au	D	104	25	70	**GIPPING**	GB	114	49	82
Deichsiel Suederhafen	D	101	25	83	**GIRVAN**	GB	100	60	5
Gota alv	S	102	56	62	**GLASLYN**	GB	99	97	277
Lagan	S	101	48	57	**GREAT EAU**	GB	116	33	15
Nissan	S	100	48	45	**GREAT STOUR**	GB	106	49	44
Ronnean	S	101	35	57	**GWYRFAI**	GB	98	38	67
Viskan	S	101	47	62	**GYPSEY RACE**	GB	107	34	43
Atran	S	101	48	66	**HALLADALE**	GB	100	98	400
Deba	E	99	44	34	**HASTINGS**	GB	94	58	118
Oria	E	99	39	43	**HAYLE**	GB	107	49	49
Oiartzun	E	99	31	21	**HELMSDALE**	GB	100	96	377
Urola	E	99	44	34	**HOLLAND BROOK**	GB	112	40	43
Urumea	E	99	31	21	**HUMBER**	GB	110	34	33
Scheldt	BE	103	46	81	**ILFRACOMBE**	GB	103	39	54
SchipdonkCanal	BE	100	25	49	**INVER**	GB	100	148	435
BlankebergseVaart	BE	100	17	76	**IRVINE**	GB	99	20	7
LeopoldCanal	BE	100	25	49	**ITCHEN**	GB	99	51	86
IJzer	BE	107	23	61	**KENT**	GB	98	42	48
GentOostendeCanal	BE	100	17	76	**Lagan**	GB	100	42	104
Seine	FR	104	45	71	**LEVEN**	GB	98	53	89
Authie	FR	101	35	79	**LEVEN IN SCOTLAND**	GB	104	29	24
Canche	FR	109	44	63	**LITTLE EACHAIG**	GB	101	78	164
Somme	FR	106	27	86	**LOCHY**	GB	100	102	484
Loire	FR	100	50	92	**LOSSIE**	GB	101	51	48
Vilaine	FR	103	55	76	**LOUGHOR**	GB	97	39	77
Garonne	FR	107	70	74	**LUD**	GB	116	33	15
Charente	FR	107	62	88	**LUNE**	GB	98	57	78
Dordogne	FR	103	57	82	**LYMN**	GB	125	43	45
Eyre	FR	105	72	45	**MAWDDACH**	GB	99	40	42
Orne	FR	100	46	38	**MEDWAY**	GB	102	39	39
Seudre	FR	100	35	17	**MEON**	GB	99	41	53
Sevre-Niortaise	FR	107	45	91	**MERSEY**	GB	98	37	39
Shannon	IRL	100	29	53	**Mourne**	GB	101	42	69
Corrib	IRL	100	39	75	**NAIRN**	GB	102	30	13
Erne	IRL	102	38	62	**Naver**	GB	100	122	431
Ballysadare	IRL	102	35	66	**NEATH**	GB	99	30	51
Blackwater	IRL	102	35	55	**NENE**	GB	119	37	49
Moy	IRL	102	39	72	**NESS**	GB	101	107	335
Suir	IRL	102	34	57	**NEVIS**	GB	100	102	484
Barrow	IRL	102	34	57	**Newry**	GB	100	25	29
Nore	IRL	102	34	57	**NITH**	GB	100	56	109
Boyne	IRL	102	31	50	**NORTH ESK**	GB	103	62	100
Slaney	IRL	104	34	57	**OGMORE**	GB	99	30	51

Feale	IRL	101	42	63	**OGWEN**	GB	99	50	61
Garavogue	IRL	102	42	72	**ORCHY**	GB	100	87	331
Mulkear	IRL	100	29	53	**OTTER**	GB	102	41	51
Clarin	IRL	100	41	84	**OUSE AT KINGS LYNN**	GB	119	37	49
Bandon	IRL	102	33	45	**OUSE AT NEWHAVEN**	GB	98	40	36
Maigue	IRL	100	37	65	**PARRETT**	GB	97	30	58
Fergus	IRL	101	43	62	**PENZANCE**	GB	105	55	54
Deel	IRL	101	33	56	**PIDDLE**	GB	100	39	52
Liffey	IRL	100	36	74	**PLYM**	GB	102	49	56
Dunkellin	IRL	100	41	84	**PORLOCK BAY**	GB	103	39	54
Glyde	IRL	104	29	55	**Quoile**	GB	100	40	65
Dee	IRL	104	29	55	**RED**	GB	107	49	49
Avoca	IRL	103	34	54	**RHEIDOL**	GB	98	46	91
Lee	IRL	102	33	35	**RHYMNEY**	GB	99	46	74
Fane	IRL	102	34	62	**RIBBLE**	GB	99	38	32
Inagh	IRL	101	45	66	**Roe**	GB	100	35	48
Laune	IRL	101	40	45	**ROTHER**	GB	97	56	89
Leannan	IRL	102	44	59	**SCARBOROUGH**	GB	107	34	43
Maine	IRL	100	39	55	**SEVERN**	GB	103	42	54
Nanny	IRL	102	31	50	**SHIEL**	GB	100	114	440
Owenavorragh	IRL	103	34	54	**SHIN**	GB	100	102	376
Owenboliskey	IRL	102	40	66	**SOUTH ESK**	GB	103	62	82
Owenboy	IRL	103	32	32	**SPEY**	GB	101	82	237
Owenea	IRL	101	44	61	**STOUR AT BOURNEMOUTH**	GB	102	41	50
Tolka	IRL	102	14	9	**STOUR AT HARWICH**	GB	122	53	50
Swilly	IRL	102	44	59	**TAF**	GB	99	37	58
Glomma	NO	101	44	50	**TAFF**	GB	99	46	74
Numedal	NO	100	53	64	**TAMAR**	GB	105	45	55
Skien	NO	100	47	76	**TAW**	GB	102	39	55
Drammen	NO	103	25	53	**TAWE**	GB	97	44	60
Otra	NO	100	48	91	**TAY**	GB	101	63	143
Orre	NO	102	33	46	**TEES**	GB	101	26	28
bjerkreim	NO	101	33	40	**TEIFI**	GB	98	37	69
elkelandsosen	NO	100	47	32	**TEIGN**	GB	104	47	60
kvina	NO	100	37	80	**TEST**	GB	102	36	49
lygna	NO	100	37	58	**THAMES**	GB	100	35	38
mandal	NO	101	44	59	**THAW**	GB	97	37	57
nidelva trondheim	NO	101	63	64	**THEDDLETHORPE**	GB	122	34	33
nidelva	NO	100	53	91	**THURSO**	GB	101	91	244
orkla	NO	101	63	64	**TIDDY**	GB	105	45	55
sira	NO	100	21	8	**TORRIDGE**	GB	102	39	55
suldal	NO	100	39	62	**TWEED**	**GB**	**103**	**56**	**83**
tovdal	NO	100	32	66	**TYNE**	GB	100	47	43
gaula	NO	101	63	64	**TYNE IN SCOTLAND**	GB	110	44	53
ADUR	GB	99	50	80	**TYWI**	GB	98	40	76
AFON GOCH	GB	98	38	67	**UGIE**	GB	101	40	65
ALDE	GB	100	47	100	**URR WATER**	GB	101	47	83
ALMOND	GB	100	49	55	**USK**	GB	99	46	74
ALT	GB	99	42	73	**WALLERS HAVEN**	GB	95	47	61
ANNAN	GB	101	52	86	**WALLINGTON**	GB	99	41	53
ARUN	GB	99	57	60	**WANSBECK**	GB	106	32	29
AVON AT BANTHAM	GB	104	42	25	**WATER OF LEITH**	GB	101	26	25
AVON AT BOURNEMOUTH	GB	102	41	50	**WATER OF LUCE**	GB	99	97	316
AVON AT BRISTOL	GB	100	41	71	**WAVENEY**	GB	118	36	38
AXE	GB	103	38	36	**WEAR**	GB	101	44	64
AYR	GB	100	51	100	**WEAVER**	GB	103	36	48
BABINGLEY	GB	119	37	49	**WELLAND**	GB	119	41	38
Bann	GB	100	35	48	**WEST BAY**	GB	103	39	56
BEAULY	GB	101	107	335	**WEY**	GB	103	39	56
BLYTH	GB	106	32	29	**WICK**	GB	101	71	134
BLYTH AT WALBERSWICK	GB	114	41	52	**WITHAM**	GB	124	44	53

BRIDLINGTON	GB	107	34	43	**WYE**	GB	102	48	61
BRORA	GB	101	76	172	**WYRE**	GB	98	57	78
BURE	GB	118	36	38	**YAR**	GB	101	41	48
Bush	GB	100	35	48	**YARE**	GB	118	36	38
CADOXTEN	GB	97	37	57	**YSTWYTH**	GB	99	30	54
CAMEL	GB	107	54	51	**YTHAN**	GB	105	37	72
CARNON	GB	105	55	54					

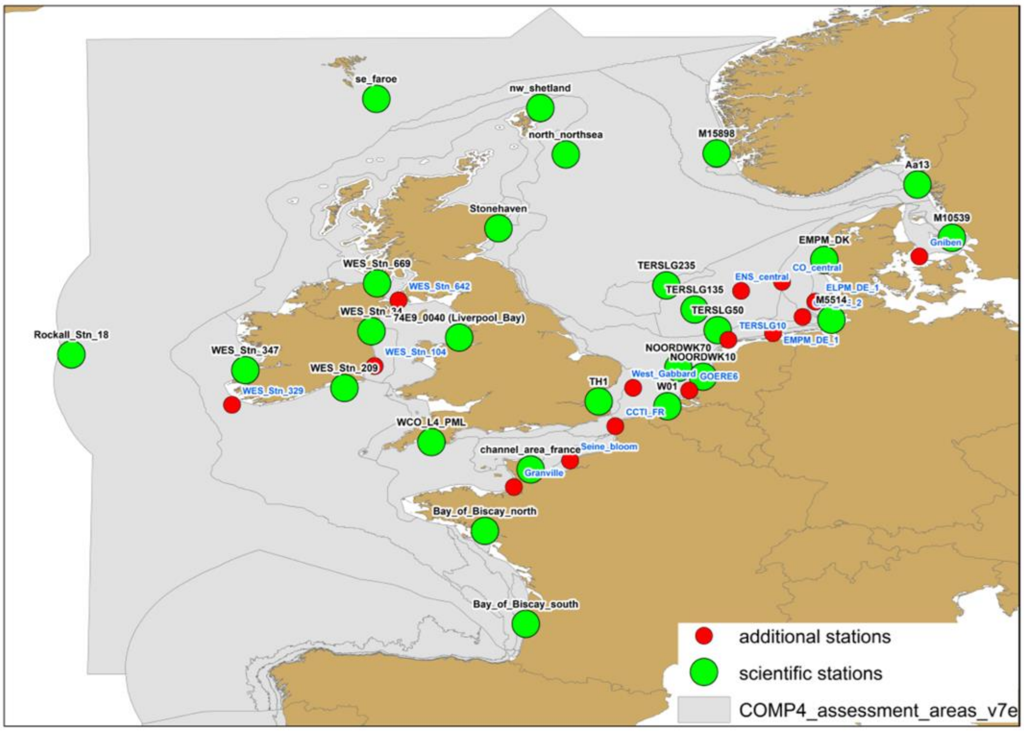
Appendix B: Observations overview

The weighting method applied in this study is based on observations. As such, the quality of the observations is of prime importance, and is considered here. First we display the spatial distribution of the observations used in the weighting method (Supplementary Figure *1*), which were extracted from the ICES data base (ICES, 2022, https://data.ices.dk/view-map) using the COMPEAT tool. The weighting method compares the averaged simulated results with the averaged observations (spatially averaged per area, temporally averaged over 2009-2014), thus the spatial and temporal distribution of observations within the areas is important. For DIN and DIP the relative variance (i.e. standard deviation/mean) is generally higher for inshore assessment areas than offshore ones. The assessment areas have been chosen to have similar oceanographic properties, but inshore areas can have steep gradients in DIN/DIP. There may also be a bias in some areas where the sampling locations do not reflect the mean concentration over the entire area, resulting in a mismatched comparison to simulated results which do cover the entire area and period. Supplementary Figure *1* shows the spatial distribution of in situ observations used for DIN, DIP and Chl. As expected, most of the effort is focused on- the coastal zones, with a sparsity of *in-situ* observations for some offshore areas. This applies particularly to the Northern North Sea, Norwegian trench, much of the Atlantic and Bay of Biscay areas.



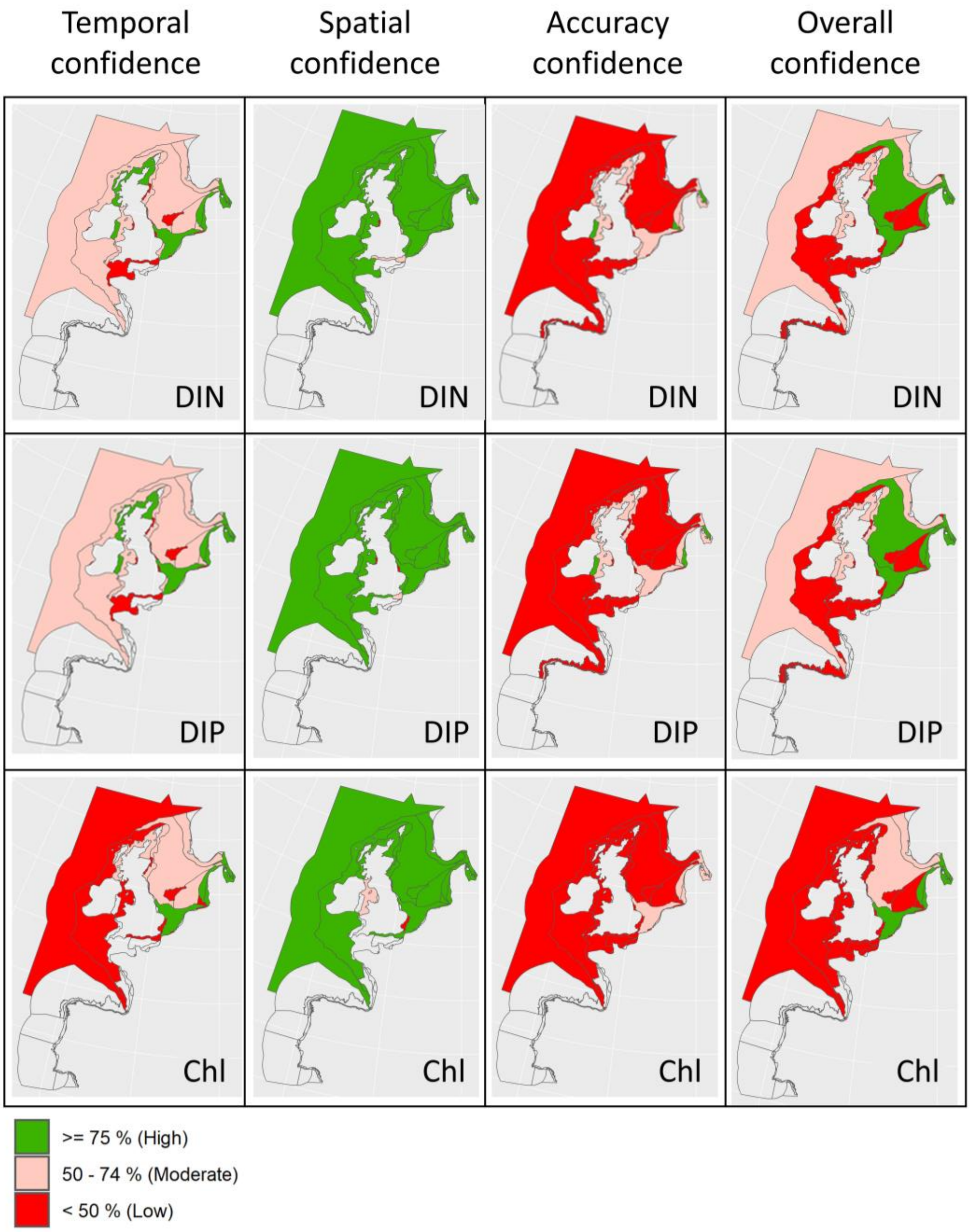
Supplementary Figure 1: Spatial distribution of the in-situ observations in COMPEAT for DIN, DIP and Chl in the period 2009-2014, as used in this study in the weighting method (Almroth & Skogen, 2010).

Secondly, we show the additional stations where observations were gathered for the model validation exercise (Supplementary Figure 2, see Figure 2 main article). For this purpose stations were selected that had continuous measurements throughout the simulated time period. Note again the coastal bias present in the stations' spatial distribution.



Supplementary Figure 2: stations used in the common validation exercise based on long-term observational time series.

The COMPEAT tool provides 3 methods of assessing observational confidence: temporal distribution, spatial distribution and accuracy (function of how close the mean results are to a threshold) for each parameter. These are then combined in an overall confidence level (Supplementary Figure 3). For DIN and DIP there is poor temporal confidence for all of the offshore regions. Spatial confidence is generally better, but overall confidence is only high for regions in the North Sea. In general there is lower confidence in the *in-situ* chlorophyll observations than in those of DIN or DIP.

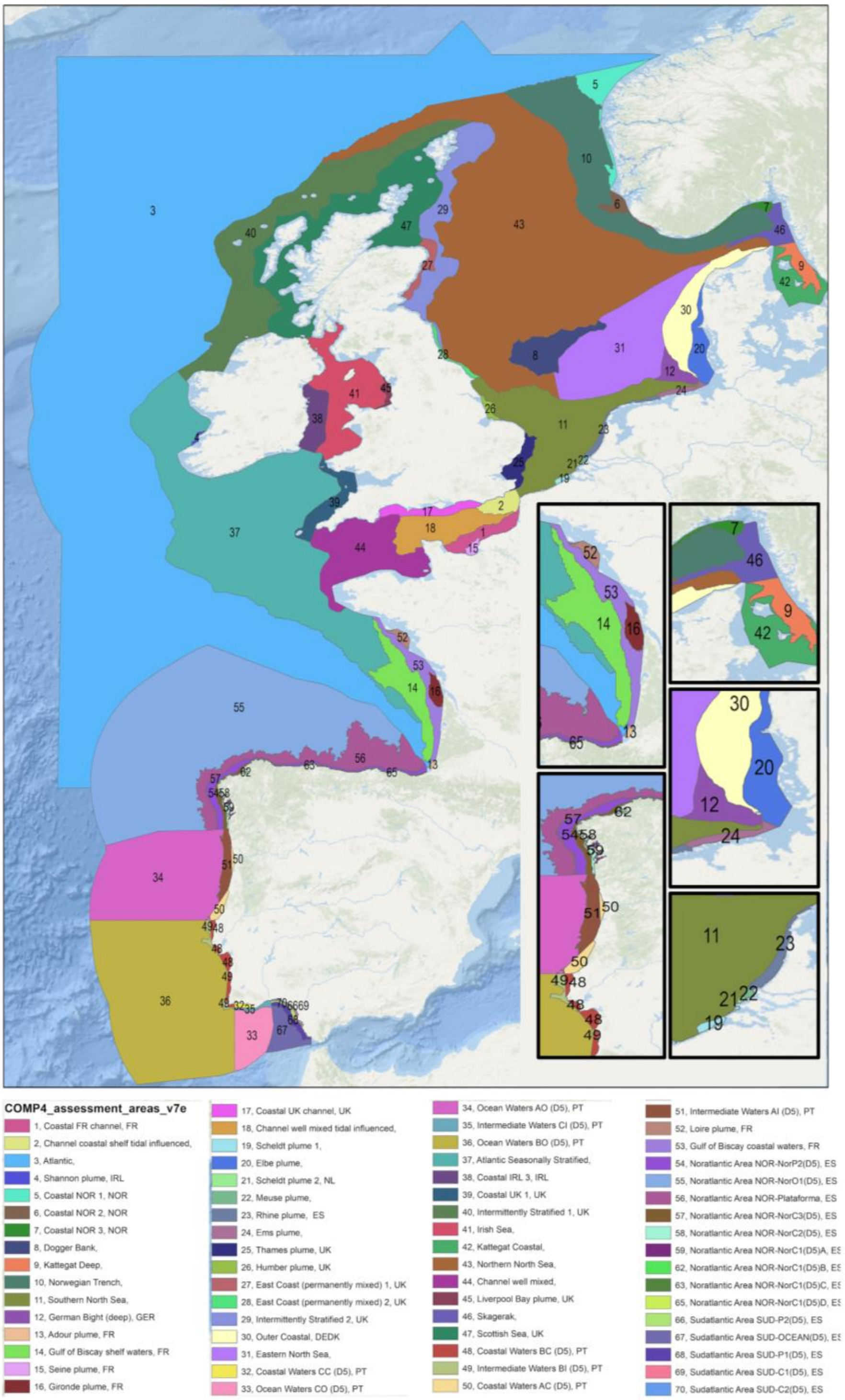


Supplementary Figure 3: From left to right: temporal distribution, spatial distribution, accuracy and overall confidence assessments of the applied in situ observations as derived by COMPEAT, for DIN, DIP and Chl.

Because of the poor confidence in *in-situ* chlorophyll measurements, satellite derived values were incorporated into the COMPEAT tool. This result of the combined satellite – in-situ product gives high confidence for temporal, spatial, accuracy and overall. It is this combined value which has been used in the weighting. The consequence of using this combined product is that the relative variance drops to around 13 % for chlorophyll, however, there is some uncertainty and potential bias in near shore chlorophyll satellite measurements.

Appendix C: COMP4 areas

Supplementary Figure 4 shows the areas as defined by OSPAR for use in the 4th application of the Common procedure (COMP4, Enserink et al, 2019), based on the work of van Leeuwen et al (2015). Note that not all areas are covered by the participating models: only 2 models include the major part of the Bay of Biscay and none cover the Portuguese coastline.



Supplementary Figure 4: Overview of the COMP4 assessment areas (version 7e, numbering by ICG-EMO).

Appendix D: Model overview

ECOHAM (University of Hamburg and HZG, Germany)

ECOHAM (ECOlogical Model-HAMburg) is defined on 31 z-levels and a 1/5°x1/3°km grid, that covers almost the entire Northwest Continental Shelf. The biogeochemical model consists of two phytoplankton (diatoms and flagellates), two zooplankton groups (micro- and mesozooplankton) and a bacteria group with fixed stoichiometry, O2, and C, N, P bound to two detritus size classes, dissolved organic material, dissolved inorganic material and 2D (plate) sediment pools. At the open ocean boundaries, biogeochemical model variables are nudged to the values extracted from the World Ocean Atlas for all scenarios. Transport of modelled biogeochemical variables are calculated based on the diffusion and convection fields estimated by the hydrodynamical model HAMSOM (HAMburg Shelf Ocean Model). Details about the model setup and biogeochemical model can be found in Große et al., 2017 and references therein.

GPM (University of Oldenburg, Germany)

GPM (Generalized Plankton Model) is defined on 20 σ-layers and a 1.5-4.5km curvilinear grid, covering only the southern North Sea. In the present implementation, the 'geochemistry' portion (O2 and C, N, P bound to dissolved inorganic and organic material, detritus and sediment pools) of the model is as in ECOHAM, but for the description of plankton growth and interactions, the variable chlorophyll content and C:N:P ratios of phytoplankton were taken into account. At the open ocean boundaries, geochemical variables are clamped to the ECOHAM results obtained for respective scenarios, whereas for plankton variables, zero-gradient conditions were assumed. The biogeochemical model is on-line coupled to the Generalized Estuarine Transport Model (GETM) as the hydrodynamical driver. A detailed description of the model setup and the biogeochemical model can be found in Kerimoglu et al. 2020 and references therein.

MIRO&CO (RBINS, Belgium)

MIRO&CO results from the coupling of the 3D hydrodynamic COHERENS model (Luyten, 2011) with the biogeochemical MIRO model (Lancelot et al., 2005). COHERENS is a three-dimensional numerical model, designed for application in coastal and shelf seas, estuaries, lakes, reservoirs. MIRO is a biogeochemical model that has been designed for *Phaeocystis*-dominated ecosystems. It describes the dynamics of phytoplankton (three functional groups), zooplankton (two functional groups), heterotrophic bacteria, organic matter degradation (dissolved and particulate) and nutrient cycles (N, P, Si) in the water column and the sediment. The current setup has been obtained by coupling MIRO with COHERENS v2 (MIRO&CO v2): details and validation are shown in Dulière et al. (2019).

GETM-FABM-ERSEM (JRC Ispra, European Union)

The JRC-NWES is largely described by Friedland et al. (2020), including a variety of validation results. For the present study, the model setup was adapted to the river inputs provided within ICG-EMO and extended with a more sophisticated sediment model, inclusion of atmospheric nitrogen deposition and an improved attenuation calculation method.

ECO-MARS3D (IFREMER, France)

The ECO-MARS3D ecological model is based on the MARS3D hydrodynamical code (Lazure & Dumas, 2008), a three-dimensional model based on Navier-Stokes equations under the classic Boussinesq and hydrostatic assumptions within a sigma framework. The originality of this model is on the coupling between barotropic and baroclinic modes especially designed for the alternate direction implicit method (ADI). The time-step is adaptative and the model is forced by a barotropic sea-level oscillation (at the oceanic boundaries) and by atmospheric conditions (throughout the domain). It provides realistic descriptions of coastal hydrodynamics for research and operational interests. The fully coupled biogeochemical module ECO-MARS3D is a NPZD model type (Nutrient–Phytoplankton–Zooplankton–Detritus), that aims to simulate the fluxes of limiting elements such as nitrogen (N), phosphorus (P) and silicon (Si). The phytoplankton compartment is described by the following variables 'diatoms', 'dinoflagellates', 'nanopicoplankton' and the haptophyte '*Phaeocystis globosa*'. The grazers are split into two groups 'micro-zooplankton' and 'meso-zooplankton' and the detritus coming from phytoplankton, zooplankton senescence and excretion are mineralized and contribute to the nutrient renewal. Moreover, variables 'dissolved oxygen' as well as 'oxygen saturation' are calculated taking into account air-water exchanges, primary production and respiration processes in the water column. The current application to the French Atlantic shelf is based on a regular grid with 4 × 4 km meshes and 30 sigma layers, which covers the Bay of Biscay, the English Channel and the southern part of the North Sea, up to the Rhine estuary. Detailed description and validation is provided in Ménesguen et al. (2018, 2019).

DFLOW-FM (Deltares, the Netherlands)

The model used by Deltares for the model comparison is a combination of the Generic Ecological Model (GEM) for the water quality and ecological processes (Blauw et al., 2009) and a newly developed hydrodynamic model for the greater North Sea. The model uses the Delft Flexible Mesh (DFM) simulation software both for the hydrodynamics and water quality and ecological processes. The hydrodynamical part of the model is originally developed for flood forecasting and transport simulation purposes (Zijl et al., 2021). In combination with the GEM model it is used to study the effects of several anthropogenic impacts to the North Sea, such as eutrophication, climate change, aquaculture and wind farms. The GEM model simulates the nutrient cycles of nitrogen, phosphorus and silicate and the dynamics of phytoplankton and oxygen. Additionally, grazing by benthic filter feeders is included based on Dynamic Energy Budget (DEB) modelling (Troost et al., 2010; 2018). Four groups of phytoplankton are modelled (diatoms, flagellates, dinoflagellates and *Phaeocystis*) and 2 groups of benthic filter feeders (*Mytilus edulis* and *Ensis*).

NEMO-SCOBI (SMHI, Sweden)

The model used by the Swedish Meteorological and Hydrological Institute (SMHI) is based on the Nucleus for European Modelling of the Ocean (NEMO) framework (Madec, 2010), version 3.6 but specifically configured for the Baltic and North Seas (NEMO-Nordic; Hordoir et al., 2019). It has 56 vertical levels with a resolution of 3 m close to the surface and decreasing up to 22 m at the bottom of the deepest part of the domain (Norwegian trench). The horizontal resolution is of approximately 2 nautical miles (~3700 m). NEMO-Nordic has two open boundaries located in the English Channel between Brittany and Cornwall and between Scotland and Norway (Hordoir et al., 2019). The biogeochemistry is simulated by the Swedish Coastal and Ocean Biogeochemical module (SCOBI; e.g., Eilola et al., 2009). It includes the nutrient cycles of nitrogen, phosphorus and silicate in both the water column and sediments, simulates the oxygen cycle and accounts for 3 phytoplankton species in the water column: diatoms, flagellates and cyanobacteria (Almroth-Rosell et al., 2011).

All 3 runs with NEMO-SCOBI were initiated in year 1961 in order to ensure a close to balance Baltic Sea at years 1992-2014. Boundary profiles for nitrate, phosphate and oxygen used to force the model are similar to those from CMEMS. Atmospheric NOx and NHx input from EMEP MSC-W 2018 data (with agreed reduction for the Historical Scenarios) was used throughout the run. The river nutrient forcing provided by the ICG-EMO group for the historic scenario was adjusted to the model domain and combined to data of E-Hype version v.5.6.2. This former version of e-hype had to be used, as it showed important improvements in the salinity of the Baltic Sea when used as a forcing for NEMO-Nordic. Because this model domain includes the Baltic Sea and ICG-EMO river data did not include a reduction of P and N for the Historical Scenarios in this region, for these scenarios we used a constant factor to reduce each nutrient load in the Baltic Sea based on the reduction factors applied to the North Sea.

GETM-ERSEM-BFM (CEFAS, UK)

GETM-ERSEM-BFM, GETM (General Estuarine Transport Model) is a public domain, three-dimensional Finite Difference hydrodynamical model (www.getm.eu). It solves the 3D partial differential equations for conservation of mass, momentum, salt and heat, and was designed to handle drying and flooding (e.g. tidal flats). The ERSEM-BFM (European Regional Seas Ecosystem Model - Biogeochemical Flux Model) version is a development of the model ERSEM III (see Baretta et al., 1995; Ruardij and van Raaphorst, 1995; Vichi et al., 2007; van der Molen et al., 2013; www.nioz.nl/en/about/cos/ecosystem-modelling), and describes the dynamics of the biogeochemical fluxes within the pelagic and benthic environment. The ERSEM-BFM model simulates the cycles of carbon, nitrogen, phosphorus, silicate and oxygen and allows for variable internal nutrient ratios inside organisms, based on external availability and physiological status. The model applies a functional group approach and contains 6 phytoplankton groups, 4 zooplankton groups and 5 benthic groups, the latter comprising 4 macrofauna and 1 meiofauna group. Pelagic and benthic aerobic and anaerobic bacteria are also included. SPM concentrations are calculated as proportional to the local wave-induced bed-shear stress, varying linearly with depth, and with an exponential relaxation mechanism that represents delayed settling. The ERSEM-BFM model includes a 3-layer benthic module comprising 53 state variables. TEP (Transparent Exopolymeric Particles) production by diatoms is included, allowing for macro-aggregate formation and rapid sinking out of the spring bloom. The ERSEM-BFM model also has enhanced pelagic-benthic coupling compared other ERSEM-III based models.

The setup includes a spherical grid covering the area 46.4°N-63°N, 17.25°W-13°E with a resolution of 0.08° in longitude and 0.05° in latitude (approximately 5.5 km), and 25 non-equidistant layers in the vertical. The model bathymetry was based on the NOOS bathymetry (www.noos.cc/index.php?id=173). The model was forced with tidal constituents derived from TOPEX-POSEIDON satellite altimetry and atmospheric forcing from ECMWF ERA-Interim.

Appendix E: Model comparison

Here a more direct comparison of the different model features is presented.

Supplementary Table 2: Direct comparison of model capabilities of all contributing marine ecosystem models

Model name	**MIRO&CO-3D** **(RBINS, Belgium)**	**ECO-MARS3D** **(IFREMER, France)**	**ECOHAM4** **(UHH-HZG, Germany)**	**GPM** **(Oldenburg, Germany)**	**Deft3D-GEM** **(Deltares, the Netherlands)**	**JRC-ERSEM** **(JRC Ispra, EU)**	**GETM-ERSEM-BFM** **(Cefas - United Kingdom)**	**NEMO -SCOBI** **(SMHI, Sweden)**
General simulation characteristics								
Hydrodynamic model	COHERENS	MARS-3D	HAMSOM	GETM	DFLOW-FM	GETM	GETM	NEMO
Biogeochemical model	MIRO&CO	ECO-MARS-3D	ECOHAM4	GPM	GEM	PML-ERSEM	ERSEM-BFM	SCOBI
Used model domain area	English Channel and Southern Bight of the North Sea	Southern North Sea, Channel, Celtic Sea, Bay of Biscay	European Shelf down to the top of the Bay of Biscay	Selected area of Southern North Sea	European Shelf including the entire Bay of Biscay	European Shelf halfway down to the Bay of Biscay	European Shelf halfway down to the Bay of Biscay	North Sea, Channel, Baltic Sea
Spatial Resolution Δh (km)	5.89 km (lon) x 4.63 km (lat)	4 km x 4km	20km x 20 km	1.5 – 4.5 curvilinear grid	1-8 km: 1 km in waters < 100 m deep, 8 km in water > 400 m deep and 4 km in between	4.04-6.13 km (x-direction) and 5.56 km (y)	5.5 x 5.5 km	~3.7 km
Vertical resolution	5 sigma layers	30 sigma layers	30 z layer	20 layers	20 layers	25 layers, dynamically adapting to density gradients	25 sigma layers	56 layers, with smaller layer width near the surface
Longitude (degree)	[-4.0,5.0]	-7.922° – 5.104°E	15.°W – 14.°E	0.15.°W – 9.15°E	-15 to + 14	17.5° W-13.1° E	17.25⍰W-13⍰E	4.15278∘ W to 30.1802∘ E

Model name	**MIRO&CO-3D**	**ECO-MARS3D**	**ECOHAM4**	**GPM**	**Deft3D-GEM**	**JRC-ERSEM**	**GETM-ERSEM-BFM**	**NEMO -SCOBI**
Latitude (degree)	[48.5,52.5]	52.769°N – 43.267°N	47.85°N – 64.°N	51.35°N – 55.6°N	44 to 62	46.4° N-63° N	46.4⍰N-63⍰N,	48.4917–65.8914◦ N
Temporal resolution Δt (sec)	Hydrodynamics: 60s, MIRO: 15 min.	200-240	60 s	2D: 5 s 3D: 360 s	Hydrodynamics 2 min (max), water quality: 10 min.	12.87	15 seconds for hydrodynamics, 450 seconds for biology	Hydrodynamics: 3-90 s Biogeochemistry: 60 s
Temporal range	2000-2014	2006-2014	2009-2014	2009-2014	2009-2014	2006-2014	2009 – 2014	1992-2014
Spin up time	5 years	2006-2008	2006-2008	2006-2008	2006-2008	1 year	20 years	1961-1991
Meteo data	RMIB 6 hourly data based on UKMO atmospheric model.	Météo France ALADIN model	ERA 5	COSMO-CLM	ERA5	ERA5	ECMWF	UERRA
Inclusion of tides	Yes (15 harmonics)	Yes, through FES2004 tidal atlas (Lyard et al., 2006)	Yes, through sea surface elevation input from large-scale model	Yes, using hourly surface elevatations estimated by TRIM-NP-2D : doi:10.1594/WDCC/coastDat-2_TRIM-NP-2d	Yes, through sea surface elevation input from CMEMS model	Yes. Using http://volkov.oce.orst.edu/tides/AO.html along the 2d boundaries	Yes, through sea surface elevation on the open boundaries from a larger scale model	Yes
Temperature & Salinity diagnostic or prognostic	Prognostic. SST from weekly sea surface gridded temperature (BSH)	prognostic	T: Prognostic S: diagnostic	T: prognostic S: prognostic	Prognostic i.e. simulated in the model	Prognostic	Prognostic	Prognostic

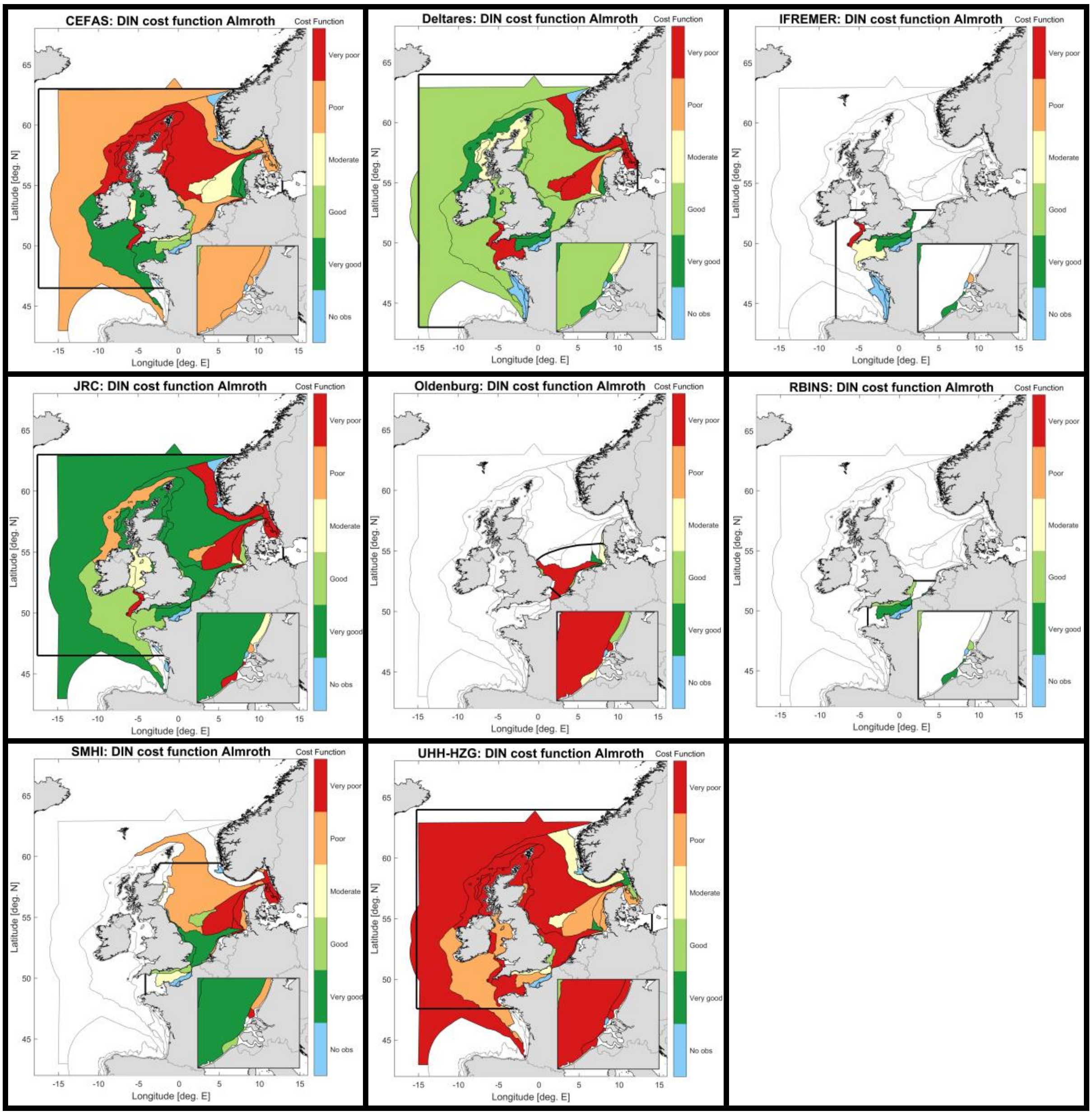
Model name	MIRO&CO-3D	ECO-MARS3D	ECOHAM4	GPM	Deft3D-GEM	JRC-ERSEM	GETM-ERSEM-BFM	NEMO -SCOBI
Light	Irradiance model modulated by 6-hourly fields of cloud cover	Astronomically calculated irradiance + cloud cover + attenuation by suspended matter and Chl a	Daily mean astronomical irradiance + cloud cover + attenuation from data	Incoming+ Astronomically calculated irradiance + cloud cover + attenuation by silt and organic material	Solar irradiance from ERA5 and extinction determined by SPM, phytoplankton, detritus and salinity (as proxy for CDOM from rivers)	Using the ERSEM light model (light_iop)	Using the ERSEM light model, which includes shading by phytoplankton, SPM and a background component including CDOM	Yes
Oxygen dynamics	NA	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPM dynamics	Forced with daily climatology of SPM derived from MODIS-Aqua images of SPM and interpolated with DINEOF methodology (Sirjacobs et al. 2011)	Yes, partly: only transport of suspended matter brought by rivers (no erosion)	External forcing based on daily data by Heath et al. (2002)	External forcing based on a parameterization of cross-shore and temporal variability derived from scanfish measurements (see Kerimoglu et al. 2020)	External forcing, based on satellite data	No	Yes, using the 3D SPM model by van der Molen et al (2017)	No
Pelagic description								
Pelagic matter cycle (C, N, P, Si)	N, P, Si	N, P, Si	C, N, P, Si	C, N, P, Si	N, P, Si	C, N, P, Si	C, N, P. Si, reduction equivalents	N, P, Si
No. of Pelagic state variables	22	21	24	25	20	50	32	13
Pelagic nutrients (bulk or explicit)	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit

Model name	MIRO&CO-3D	ECO-MARS3D	ECOHAM4	GPM	Deft3D-GEM	JRC-ERSEM	GETM-ERSEM-BFM	NEMO -SCOBI
Types of Phytoplankton	3 groups: diatoms *Phaeocystis globosa* (colonial form), autotrophic nanoflagellates	4 groups: diatoms, dinoflagellates, pico-nanophytoplankton, *Phaeocystis*	2 groups: diatoms and flagellates	2 groups: diatoms and flagellates	4 groups: diatoms, flagellates, dinoflagellates, *Phaeocystis*	4 groups : diatoms, nano-phytoplankton, pico-phytoplankton, micro-phytoplankton	6 groups: diatoms, flagellates, picophytoplankton, dinoflagellates, small diatoms, *Phaeocystis* colonies	3 groups: diatoms, flagellates + picophyto-plankton, cyanobacteria (for Baltic Sea)
Types of Zooplankton	2 groups: micro-zooplankton, copepods	2 groups: micro and meso-zooplankton	2 groups: micro- and meso-zooplankton	2 groups: micro and meso-zooplankton	None	3 groups: meso-zooplankton, micro-zooplankton, heterotrophic nanoflagellates	4 groups: carnivorous mesozooplank-ton, omnivorous mesozooplank-ton, micro-zooplankton, heterotrophic nanoflagellates	1 group: zooplankton
Types of pelagic bacteria	1 group: heterotrophic pelagic bacteria	None	1 group: heterorophic bacteria	None	None	1 group: heterotrophic pelagic bacteria	2 groups: pelagic bacteria and nitrifying archaea	None
Pelagic POM	POC (refractory and non-refractory), PON (ref. and non-ref.), POP (ref. and non-ref.)	Detrital organic N, detrital organic P	Slow (C,N and P) and fast sinking (C,N,P,Si and $CaCO_3$)	Slow (C, N, P) and Fast sinking (C, N, P, Si)	POC, PON, POP, Opal	Labile dissolved organic matter, semi-labile dissolved organic matter, small-size POM, medium-size POM, large-size POM	POC, PON, POP, TEP, faecal pellets	Nitrogen detritus, Phosphate detritus, Silica detritus
Benthic description								
Benthic matter cycle (C, N, P, Si)	N, P, Si	N, P, Si	C, N, P, Si and $CaCO_3$	C, N, P, Si	C, N, P, Si	C, N, P, Si	C, N, P, Si, DIC, S--, H+, SiO3	N, P, Si

Model name	MIRO&CO-3D	ECO-MARS3D	ECOHAM4	GPM	Deft3D-GEM	JRC-ERSEM	GETM-ERSEM-BFM	NEMO -SCOBI
No. of benthic state variables	10	3	5	4	10 (4 detritus + 6 biota)	36	53	4 (PON, POP, Opal, inorganic phosphorous)
Benthic Nutrients (bulk or explicit)	Bulk	Bulk	Bulk	Bulk	Bulk (only detritus)	Explicit	Explicit	Explicit
Types of Zoobenthos	None	None	None	None	Mussels and Ensis	3 groups: benthic deposit feeder, benthic suspension feeder, benthic meiofauna	5 groups: meiobenthos, filter feeders, infaunal predators, deposit feeders, megabenthos	None
Types of benthic bacteria	None	None	None	None	None	2 groups: aerobic and anaerobic benthic bacteri**a**	2 groups: aerobic and anaerobic benthic bacteria	None
Benthic DOM	No	No	No	No	No	Yes	Yes	No
Benthic POM	Refractory and non-refractory POC, PON, POP	Benthic organic matter in C, N, P, Si	No	No	One fraction of detritus for carbon, nitrogen, phosphorus and silicate	Benthic particulate organic matter , benthic refractory matter , benthic buried matter	Benthic POC, PON, POP	Yes, as particulate organic nitrogen (PON) and phosphorus (POP)
Participant to add further characteristics if required							TEP production by nutrient stressed diatoms included.	

Appendix F: Cost functions

Here we show the individual results for the different models in terms of the cost function (eq. 1) from Almroth & Skogen (2010). The function scores have been replaced by general goodness-of-fit statements, as follows: 0-1(very good), 1-2 (good), 2-3 (moderate), 3-4 (poor) 4-5 (very poor), with dark red areas representing cost function values > 5. Note that a bad cost function score may be due to limited observations being available. The observations used in the cost function were extracted from the COMPEAT tool, and include both *in situ* and satellite observations for Chl.



CEFAS: DIN cost function Almroth

Deltares: DIN cost function Almroth

IFREMER: DIN cost function Almroth

JRC: DIN cost function Almroth

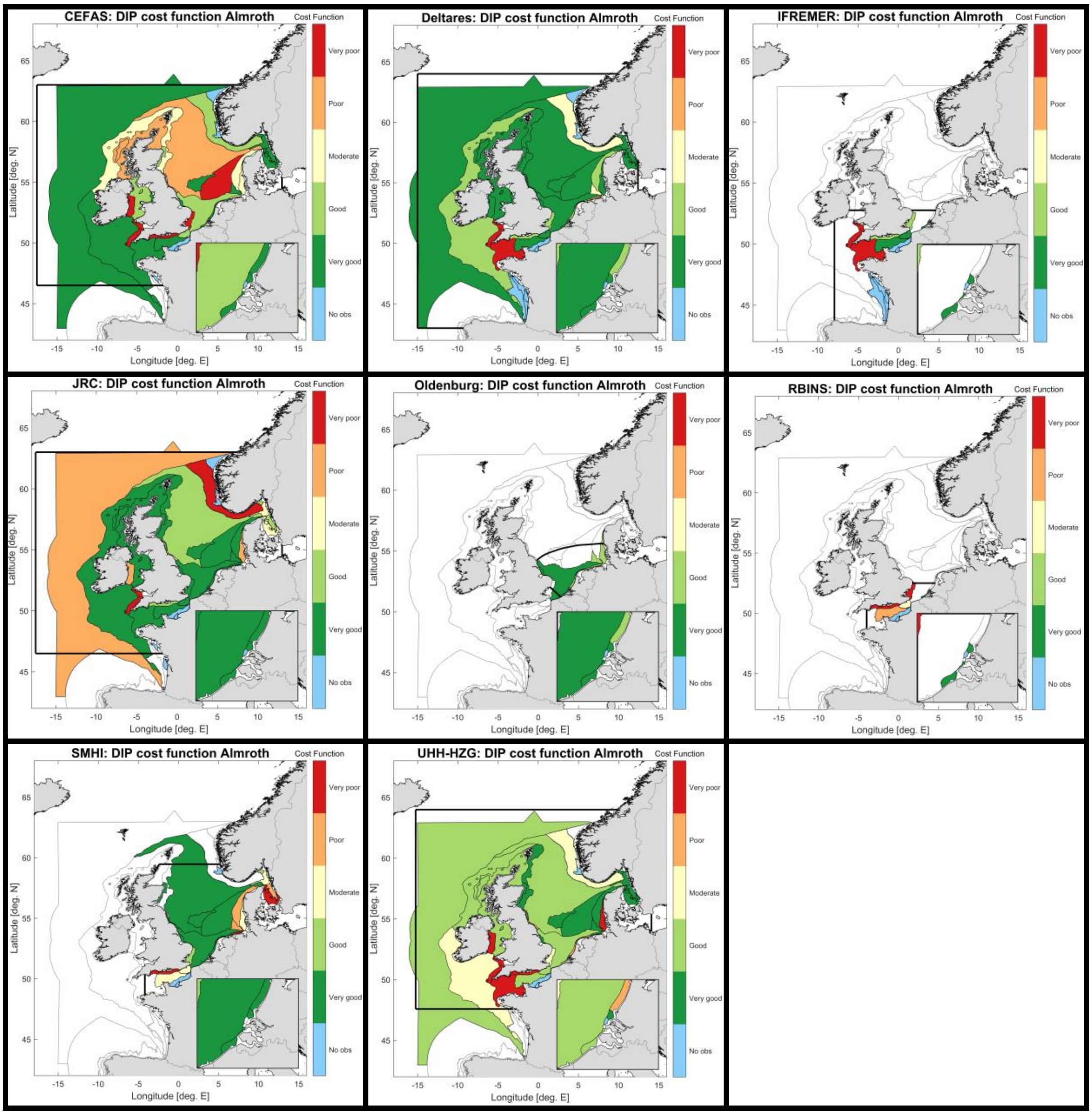
Oldenburg: DIN cost function Almroth

RBINS: DIN cost function Almroth

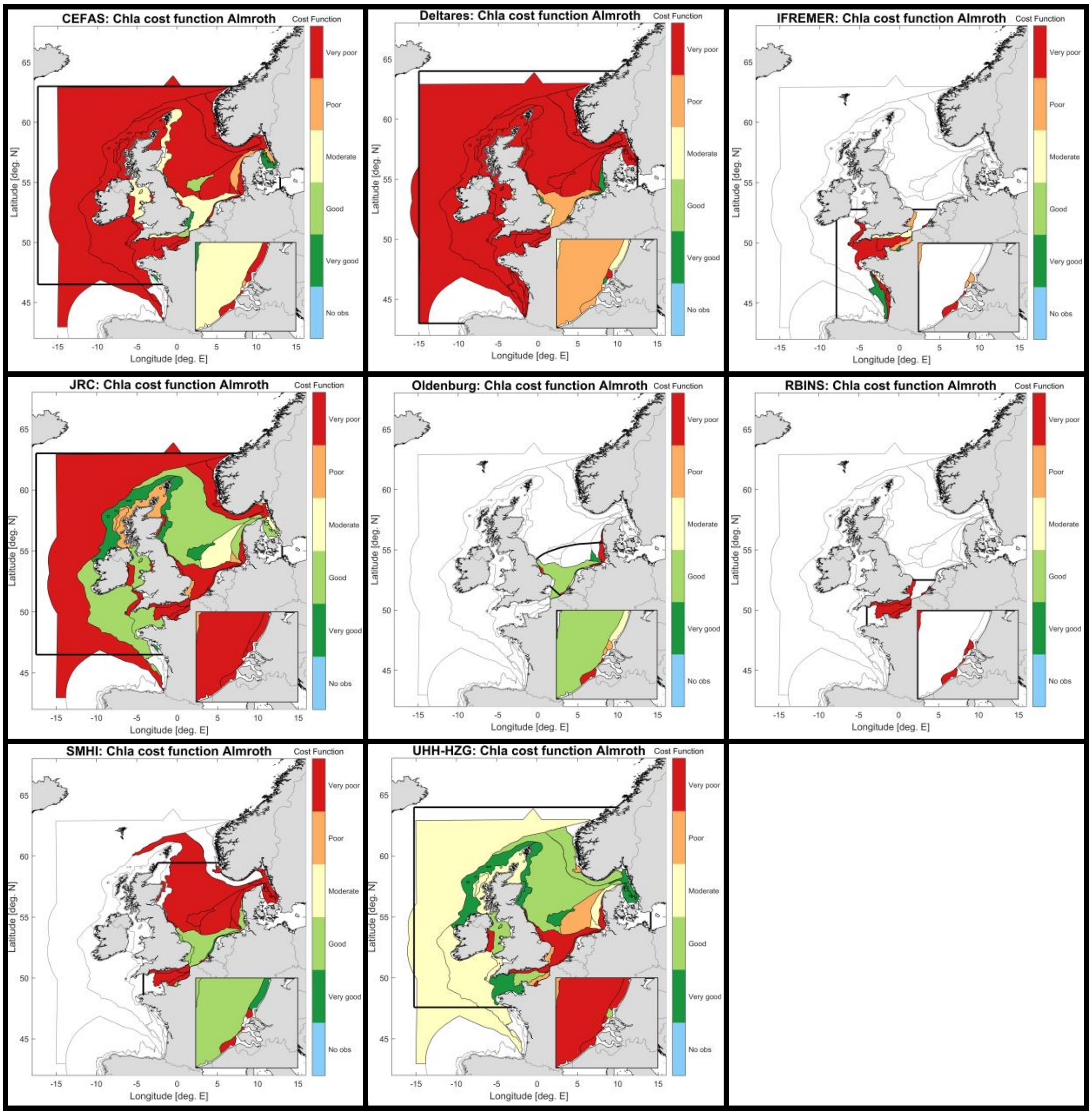
SMHI: DIN cost function Almroth

UHH-HZG: DIN cost function Almroth

Supplementary Figure 5: DIN cost function results from the Almroth & Skogen (2010) weighting method for all models. The thick lines indicate the domain boundaries for each participating model. Areas without sufficient model coverage (< 80%) are kept white, while light blue areas indicate areas with sufficient coverage for the model but without any observational evidence to allow for calculation of the cost function.



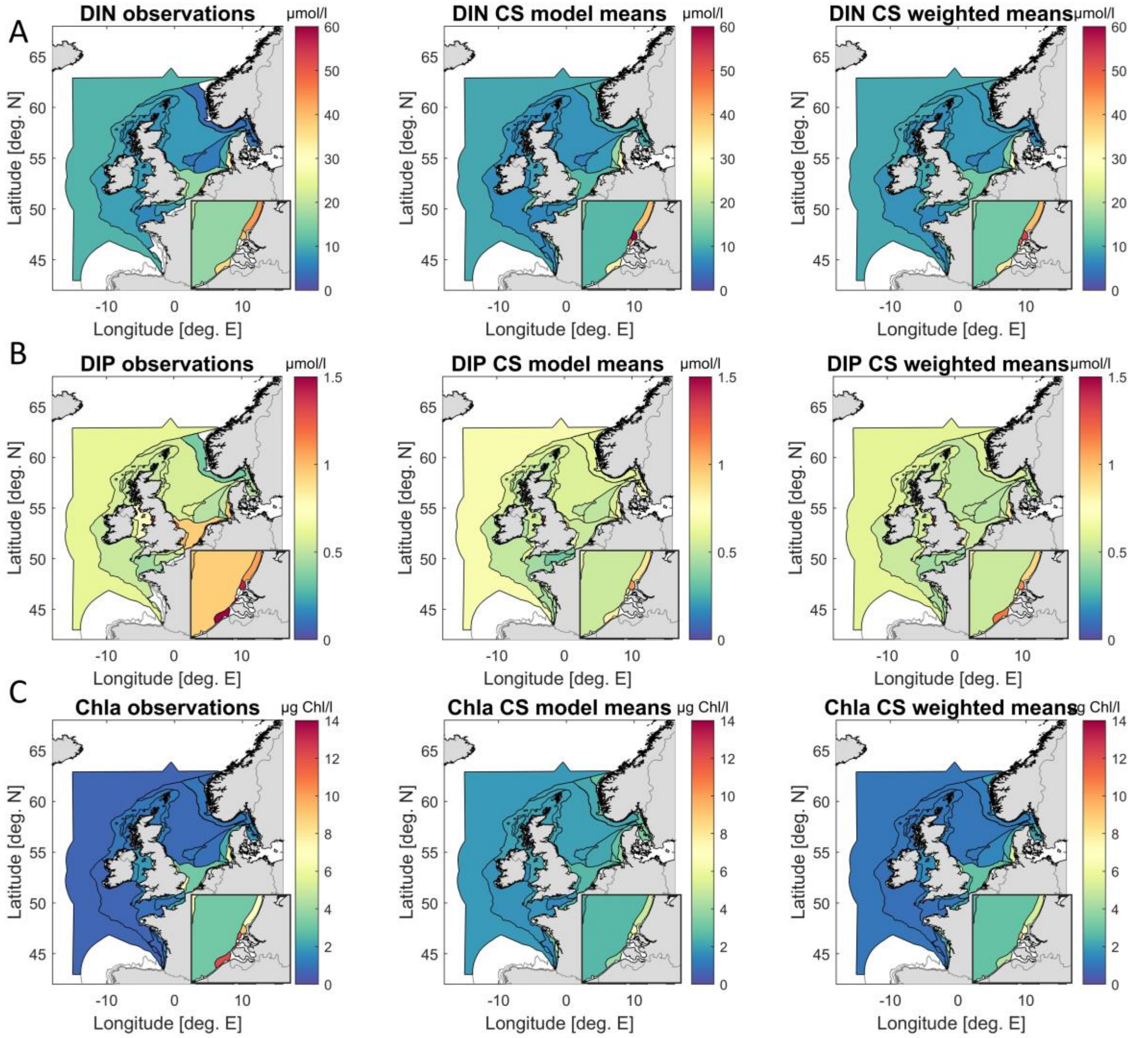
Supplementary Figure 6: DIP cost function results from the Almroth & Skogen (2010) weighting method for all models. The thick lines indicate the domain boundaries for each participating model. Areas without sufficient model coverage (< 80%) are kept white, while light blue areas indicate areas with sufficient model coverage but without any observational evidence.



Supplementary Figure 7: Chl cost function results from the Almroth & Skogen (2010) weighting method for all models. The thick lines indicate the domain boundaries for each participating model. Areas without sufficient model coverage (< 80%) are kept white, while light blue areas indicate areas with sufficient model coverage but without any observational evidence.

Appendix G: Example application of weighting method

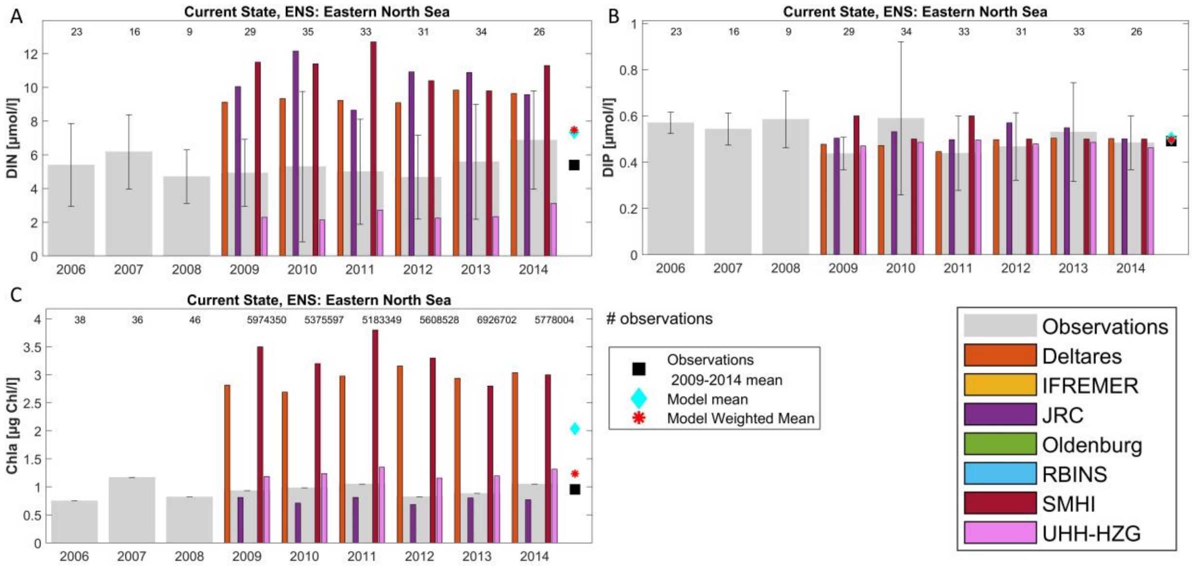
Supplementary Figure 9 shows the effect of the applied weighting method, by spatially showing the observational values (left), followed by the unweighted ensemble model mean values (center) and the weighted ensemble model mean values (right). Although the model ensemble values do not always align with the observational evidence, this may be due to the scarcity of observations in time and space in some areas.



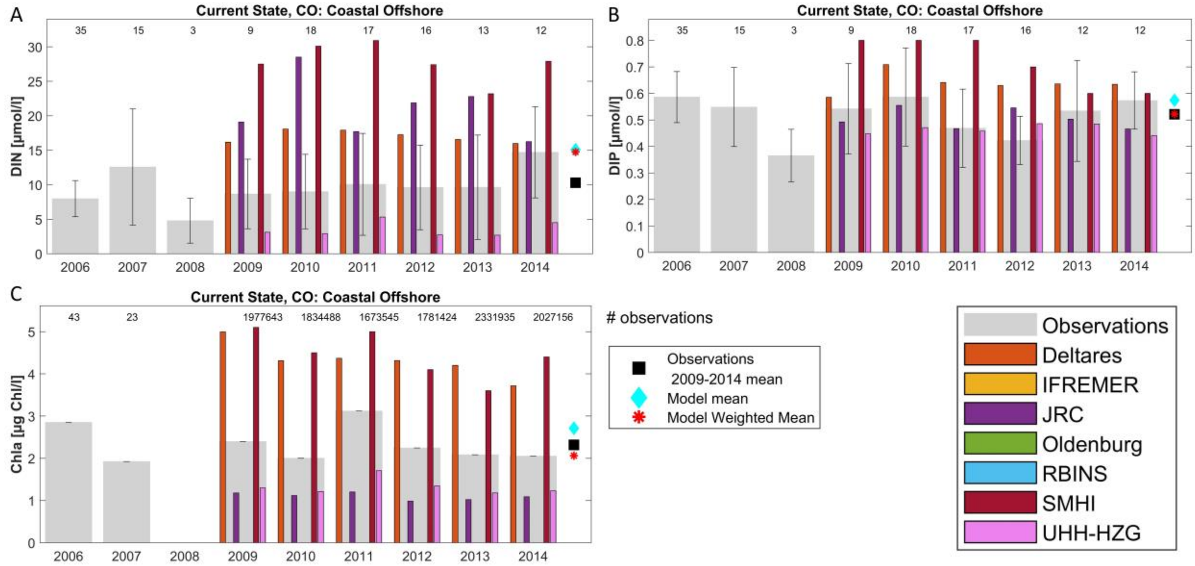
Supplementary Figure 8: spatial distributions averaged per area and over the period 2009-2014. For A) DIN, B) DIP and C) Chl showing the observational values (left), unweighted ensemble model mean (center) and weighted ensemble model mean (right).

Appendix H: Individual results for selected areas

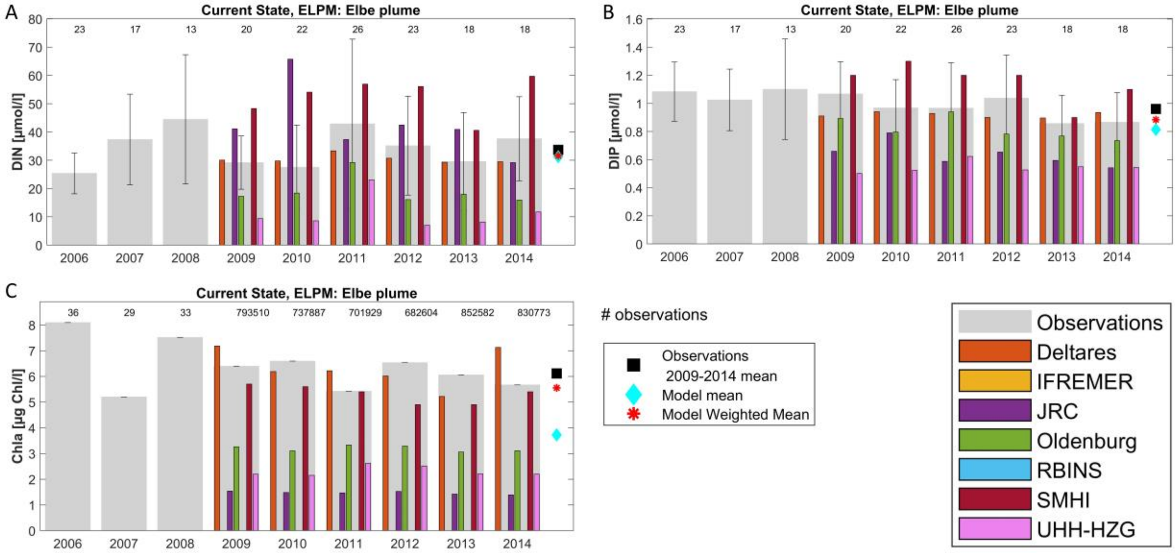
Here we show more details of the application of the weighting procedure to particular areas: the Eastern North Sea (ENS, Supplementary Figure 9), Coastal Offshore (CO, Supplementary Figure 10), Elbe plume (ELPM, Supplementary Figure 11), Rhine plume (RHPM, Supplementary Figure 12), Thames plume (THPM, Supplementary Figure 13), Irish Sea (IRS, Supplementary Figure 14) and Seine plume (SPM, Supplementary Figure 15).



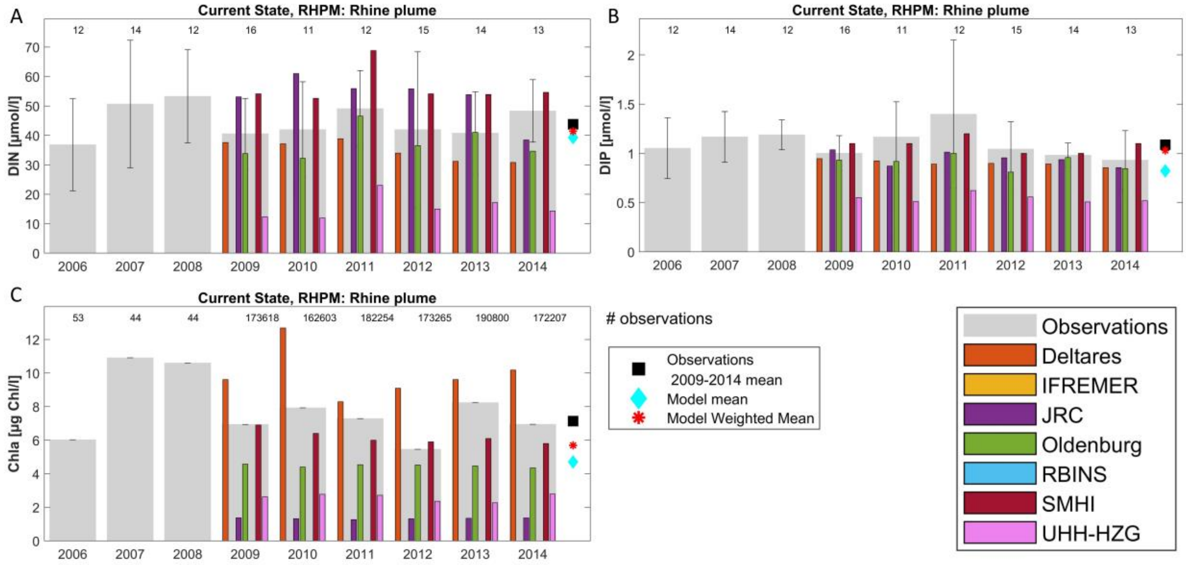
Supplementary Figure 9: annual results per model for area Eastern North Sea (ENS, 31): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year.



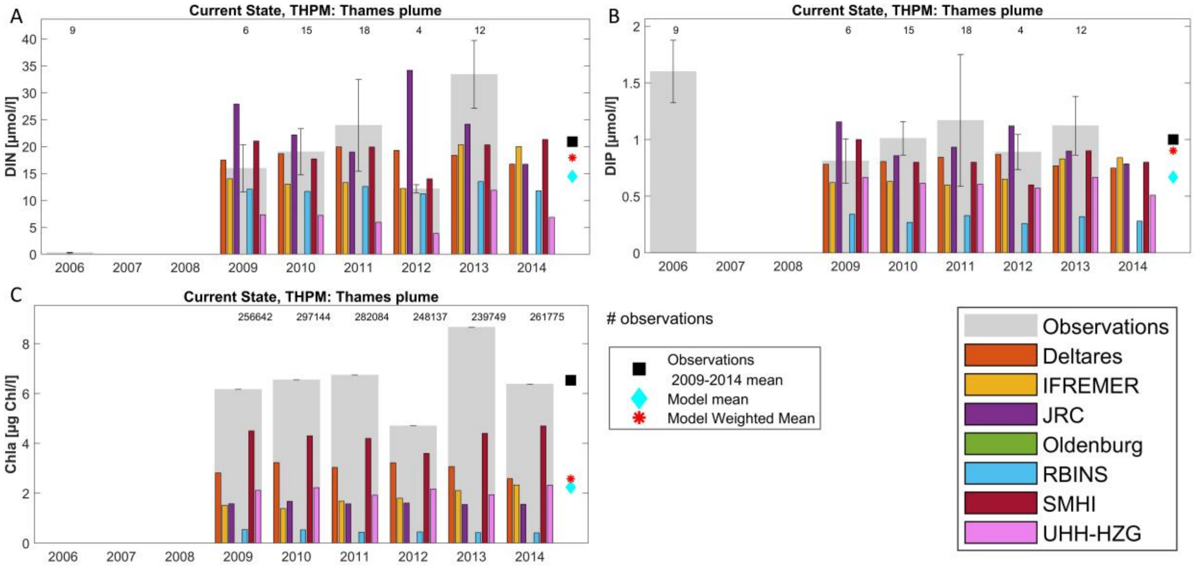
Supplementary Figure 10: annual results per model for area Coastal Offshore (CO, 30): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year.



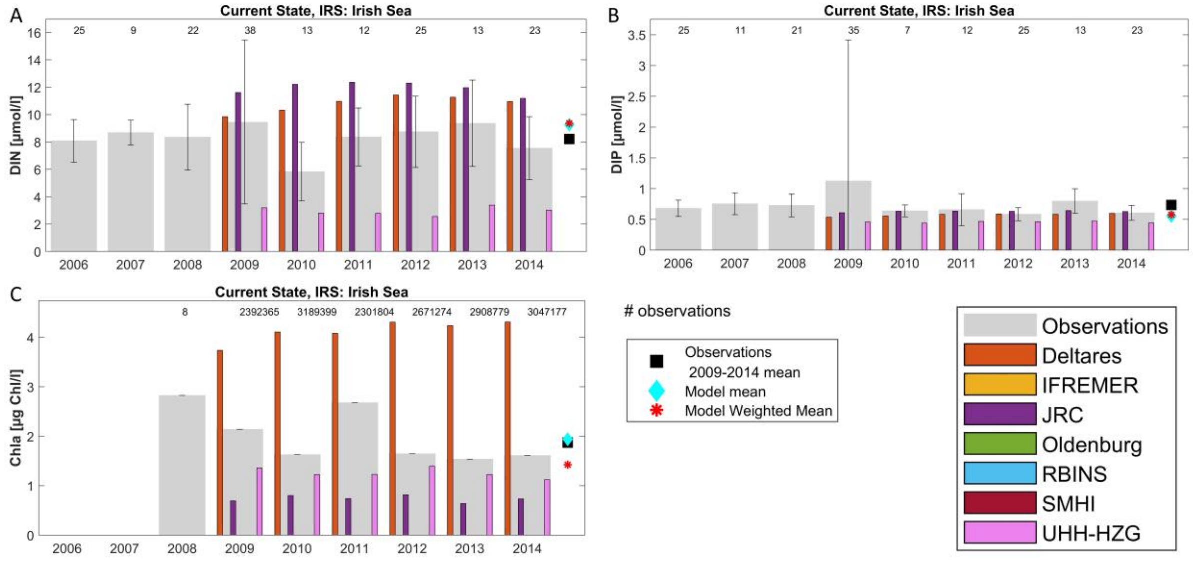
Supplementary Figure 11: annual results per model for area Elbe Plume (ELPM, 20): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year, including their standard deviation.



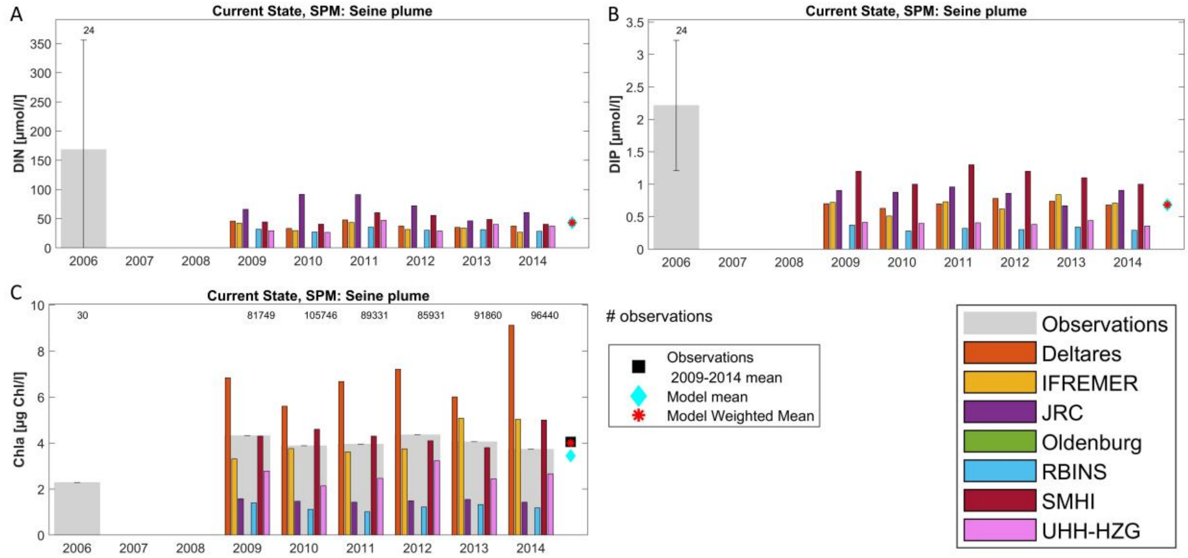
Supplementary Figure 12: annual results per model for area Rhine Plume (RHPM, 23): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year.



Supplementary Figure 13: annual results per model for area Thames Plume (THPM, 25): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year.



Supplementary Figure 14: annual results per model for area Irish Sea (IRS, 41): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year.



Supplementary Figure 15: annual results per model for area Seine Plume (SPM, 15): A) DIN, B) DIP and C) Chl. The grey bars denote the observational values per year.

Appendix I: Pre-eutrophic state ensemble values

Here we include the weighted ensemble concentrations for winter DIN, DIP, total N, total P and growing season Chl and Chl P90 for all areas for the pre-eutrophic state. These values can serve as a basis for marine management policies combatting eutrophication problems. Concentrations in red denote areas and compounds where the unweighted ensemble results is used, due to a lack of observations. As Chl *in-situ* measurements were sparse, good observational coverage for Chl was obtained by inclusion of satellite data.

Supplementary Table 3: weighted ensemble mean concentrations for each area. Concentrations in red indicate areas and compounds where no observations were available, displaying the unweighted ensemble mean.

	Pre-eutrophic state	DIN	DIP	TotalN	TotalP	Chl	Chl P90
ICG EMO ID	Area	µmol/l	µmol/l	µmol/l	µmol/l	µg Chl/l	µg Chl/l
1	**CFR**	10.53	0.40	9.80	0.41	1.88	3.00
2	**CCTI**	8.01	0.43	11.12	0.45	1.56	2.51
3	**ATL**	10.23	0.65	13.89	0.96	1.22	2.80
4	**SHPM**	7.38	0.53	8.74	0.61	1.22	2.49
5	**CNOR1**	8.34	0.58	9.00	0.64	1.83	4.25
6	**CNOR2**	6.89	0.51	7.58	0.55	1.29	2.69
7	**CNOR3**	6.10	0.45	6.83	0.57	1.57	2.96
8	**DB**	4.80	0.50	4.39	0.46	0.88	1.94
9	**KD**	4.43	0.46	5.17	0.54	1.84	3.39
10	**NT**	7.28	0.58	9.51	0.72	1.12	2.77
11	**SNS**	8.65	0.47	6.64	0.46	2.51	3.24
12	**GBC**	4.83	0.46	5.07	0.51	1.79	2.86
13	**ADPM**	5.91	0.45	6.24	0.48	1.15	2.47

14	**GBSW**	5.80	0.46	6.25	0.49	0.58	1.47
15	**SPM**	25.25	0.61	19.85	0.54	3.41	4.79
16	**GDPM**	8.49	0.45	10.42	0.62	3.61	6.64
17	**CUKC**	8.53	0.49	9.19	0.50	1.51	2.60
18	**CWMTI**	6.14	0.46	7.50	0.47	0.97	1.80
19	**SCHPM1**	17.13	0.77	18.24	0.83	3.32	4.73
20	**ELPM**	17.37	0.53	14.04	0.48	3.50	4.87
21	**SCHPM2**	22.06	0.57	23.68	0.72	5.56	9.20
22	**MPM**	27.08	0.76	24.30	0.67	4.47	7.05
23	**RHPM**	19.71	0.66	15.86	0.26	4.14	4.42
24	**EMPM**	7.20	0.45	7.36	0.58	3.53	4.63
25	**THPM**	9.69	0.60	8.32	0.67	2.11	3.16
26	**HPM**	17.42	0.77	13.23	0.68	4.92	6.72
27	**ECPM1**	7.31	0.52	7.60	0.50	1.39	3.35
28	**ECPM2**	7.25	0.57	3.23	0.50	2.35	3.80
29	**IS2**	7.51	0.58	8.14	0.63	1.16	3.09
30	**CO**	8.89	0.44	7.71	0.52	1.82	3.31
31	**ENS**	5.38	0.45	5.36	0.43	1.15	2.57
37	**ASS**	7.77	0.56	8.43	0.61	0.92	1.96
38	**CIRL**	7.57	0.51	7.82	0.54	1.20	2.59
39	**CUK1**	7.80	0.55	8.82	0.60	1.14	2.44
40	**IS1**	9.14	0.60	9.48	0.65	1.10	2.70
41	**IRS**	6.61	0.52	7.32	0.57	1.31	2.77
42	**KC**	5.03	0.43	5.07	0.47	1.58	3.14
43	**NNS**	7.64	0.59	7.86	0.41	1.05	2.39
44	**CWM**	5.50	0.44	6.12	0.48	0.87	1.87
45	**LBPM**	19.54	0.91	19.30	0.92	4.91	8.88
46	**SK**	4.47	0.47	5.97	0.55	1.15	2.45
47	**SS**	6.44	0.53	7.01	0.57	0.98	2.50
52	**LPM**	12.89	0.53	12.15	0.62	2.23	3.81
53	**GBCW**	7.86	0.50	8.65	0.56	1.78	3.75

References

Almroth-Rosell, E., Eilola, K., Hordoir, R., Meier, H.M. and Hall, P.O., 2011. Transport of fresh and resuspended particulate organic material in the Baltic Sea—a model study. *Journal of Marine Systems*, *87*(1), pp.1-12

Almroth, E. and Skogen, M.D., 2010. A North Sea and Baltic Sea model ensemble eutrophication assessment. *Ambio*, *39*(1), pp.59-69.

Baretta, J.W., Ebenhöh, W. and Ruardij, P., 1995. The European regional seas ecosystem model, a complex marine ecosystem model. *Netherlands Journal of Sea Research*, *33*(3-4), pp.233-246. Blauw, A.N., Los, H.F., Bokhorst, M. and Erftemeijer, P.L., 2009. GEM: a generic ecological model for estuaries and coastal waters. *Hydrobiologia*, *618*(1), pp.175-198.

Dulière V., Gypens N., Lancelot C., Luyten P., Lacroix G. (2019) Origin of nitrogen in the English Channel and Southern Bight of the North Sea ecosystems. *Hydrobiologia* 845: 13-33 – Doi: 10.1007/s10750-017-3419-5

Eilola, K., Meier, H.M. and Almroth, E., 2009. On the dynamics of oxygen, phosphorus and cyanobacteria in the Baltic Sea; A model study. *Journal of Marine Systems*, *75*(1-2), pp.163-184

Enserink, L., Blauw, A., van der Zande, D. and Markager, S. (2019). Summary report of the EU project 'Joint monitoring programme of the eutrophication of the North Sea with satellite data' (Ref: DG ENV/MSFD Second Cycle/2016). Belgium: REMSEM, 21

Friedland, R., Stips, A., Grizzetti, B., de Roo, A. and Lessin, G., 2020. Report on the bio-geochemical model of the North-Western European Shelf. *Publications Of-fice of the European Union, Luxembourg, ISBN*, pp.978-92.

Große, F., Kreus, M., Lenhart, H.J., Pätsch, J. and Pohlmann, T. (2017) A novel modeling approach to quantify the influence of nitrogen inputs on the oxygen dynamics of the North Sea. *Frontiers in Marine Science*, *4*, p.383

Heath, M. R., Edwards, A. C., Patsch, J., & Turrell, W. R. (2002). Modelling the behaviour of nutrients in the coastal waters of Scotland. Report. https://strathprints.strath.ac.uk/18568/6/strathprints018568.pdf

Hordoir, R., Axell, L., Höglund, A., Dieterich, C., Fransner, F., Gröger, M., Liu, Y., Pemberton, P., Schimanke, S., Andersson, H. and Ljungemyr, P. (2019) Nemo-Nordic 1.0: a NEMO-based ocean model for the Baltic and North seas–research and operational applications. *Geoscientific Model Development*, *12*(1), pp.363-386.

ICES (2022) ICES Data Portal, Dataset on Ocean HydroChemistry, Extracted April 21, 2022. ICES, Copenhagen

Kerimoglu, O., Voynova, Y.G., Chegini, F., Brix, H., Callies, U., Hofmeister, R., Klingbeil, K., Schrum, C. and van Beusekom, J.E. (2020) Interactive impacts of meteorological and hydrological conditions on the physical and biogeochemical structure of a coastal system. *Biogeosciences*, *17*(20), pp.5097-5127

Lancelot C, Spitz Y, Gypens N, Ruddick K, Becquevort S, Rousseau V, Lacroix G, Billen G. (2005) Modelling diatom and *Phaeocystis* blooms and nutrient cycles in the Southern Bight of the North Sea: the MIRO model. *Marine Ecology Progress Series* 289 : 63-78 – Doi: 10.3354/meps289063

Lazure, P. and Dumas, F. (2008) An external–internal mode coupling for a 3D hydrodynamical model for applications at regional scale (MARS). *Advances in water resources*, *31*(2), pp.233-250.

Luyten P. (2011) COHERENS – A Coupled HydrodynamicalEcological Model for Regional and Shelf Seas: User Documentation. Version 2.0. RBINS-MUMM Report, Royal Belgian Institute of Natural Sciences.

Lyard, F., Lefevre, F., Letellier, T. et al. (2006) Modelling the global ocean tides: modern insights from FES2004. *Ocean Dynamics* 56, 394–415.

Madec, G., 2010. Nemo ocean engine, v. 3.3. *IPSL Paris France*.

Menesguen, A., Lacroix, G. (2018) Modelling the marine eutrophication: A review. Science of the Total Environment 636: 339-354. https://doi.org/10.1016/j.scitotenv.2018.04.183

Ménesguen, A., Dussauze, M., Dumas, F., Thouvenin, B., Garnier, V., Lecornu, F. and Répécaud, M., (2019) Ecological model of the Bay of Biscay and English Channel shelf for environmental status assessment part 1: Nutrients, phytoplankton and oxygen. *Ocean Modelling*, *133*, pp.56-78

Ruardij, P. and Van Raaphorst, W., 1995. Benthic nutrient regeneration in the ERSEM ecosystem model of the North Sea. *Netherlands Journal of Sea Research*, *33*(3-4), pp.453-483.

Sirjacobs, Damien, et al. (2011) Cloud filling of ocean colour and sea surface temperature remote sensing products over the Southern North Sea by the Data Interpolating Empirical Orthogonal Functions methodology. *Journal of Sea Research* 65.1: 114-130.

Troost, T.A., Desclaux, T., Leslie, H.A., van der Meulen, M.D. and Vethaak, A.D. (2018) Do microplastics affect marine ecosystem productivity?. *Marine pollution bulletin*, *135*, pp.17-29.

Troost, T.A., Wijsman, J.W.M., Saraiva, S. and Freitas, V. (2010) Modelling shellfish growth with dynamic energy budget models: an application for cockles and mussels in the Oosterschelde (southwest Netherlands). *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1557), pp.3567-3577.

van der Molen, J., Aldridge, J.N., Coughlan, C., Parker, E.R., Stephens, D. and Ruardij, P. (2013) Modelling marine ecosystem response to climate change and trawling in the North Sea. *Biogeochemistry*, *113*(1), pp.213-236

van der Molen, J., Ruardij, P., Greenwood, N. (2017) A 3D SPM model for biogeochemical modelling, with application to the northwest European continental shelf, J of Sea Res., 127, 63:81, DOI: 10.1016/j.seares.2016.12.003

van Leeuwen, S., Tett, P., Mills, D. and van der Molen, J. (2015). Stratified and nonstratified areas in the North Sea: Long-term variability and biological and policy implications. *Journal of Geophysical Research: Oceans* 120: 4670-4686

Vichi, M., Pinardi, N. and Masina, S. (2007). A generalized model of pelagic biogeochemistry for the global ocean ecosystem. Part I: Theory. *Journal of Marine Systems*, *64*(1-4), pp.89-109

Zijl, F. , S.C. Laan, J. Groenenboom, (2021). Development of a 3D model for the NW European Shelf (3D DCSM-FM). Deltares report 11205259-015-ZKS-003, 61 pp. https://publications.deltares.nl/11205259_015.pdf