US CLIVAR Summit, August 2023

Model evaluation capabilities for marine ecosystem/biogeochemical variables

Nadja Steiner with input from: DFO/CCCMa carbon modelling group, SCOR-WG CIce2Clouds
Institute of Ocean Sciences, Fisheries and Oceans Canada
Canadian Center of Climate Modelling and Analysis, Environment and Climate Change Canada

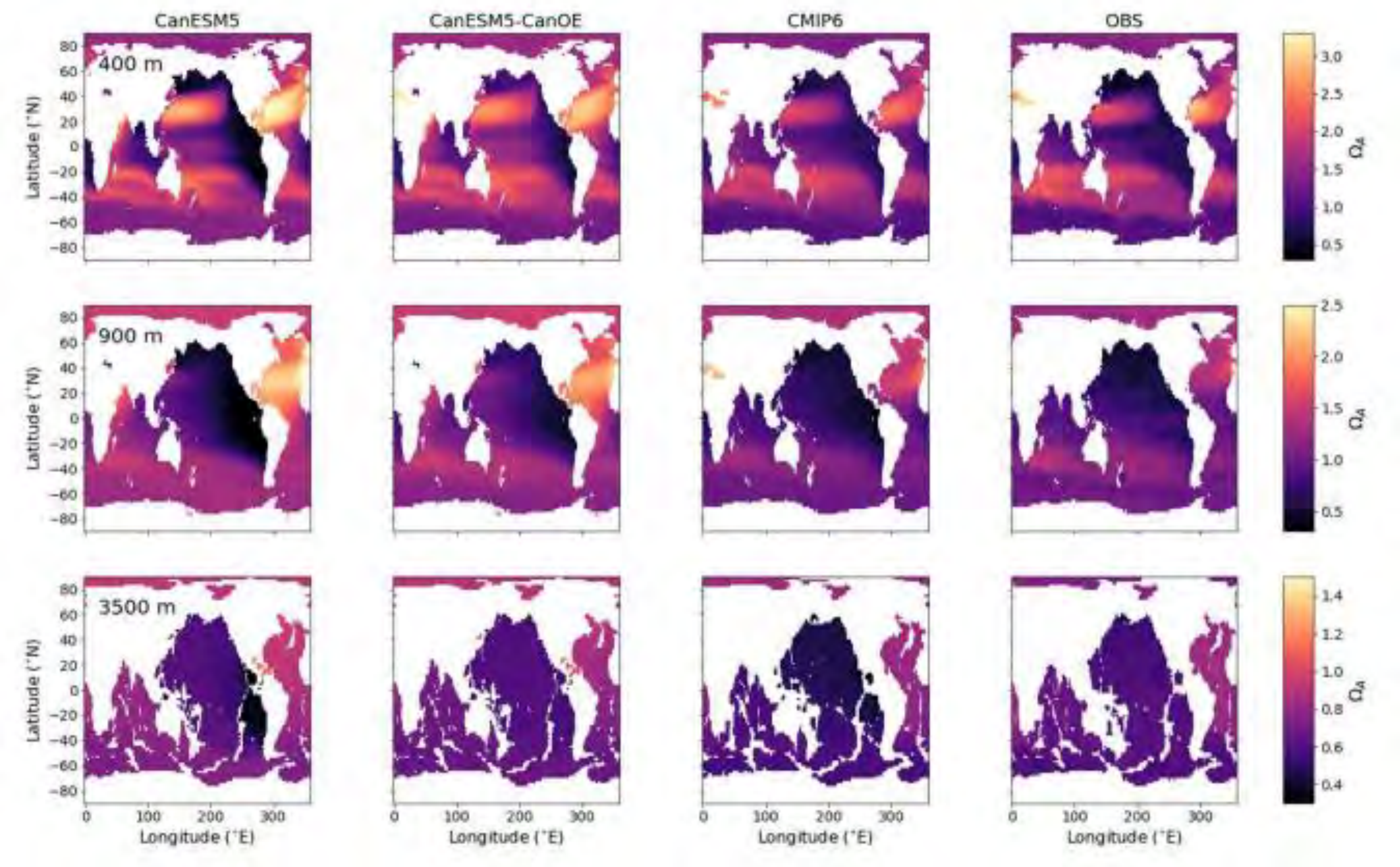
1. Climatologies
2. Multi-model intercomparisons
3. Trends
4. Patterns/Regional averages/Seasonal cycles
5. Observational data synthesis

Arctic focus

Questions asked:

- What are current developments in Earth system model evaluation capabilities?
- What are the most pressing gaps in the current multi-model validation capabilities? (e.g., capabilities for evaluating the ocean are limited)
- What are the most pressing challenges for Earth system model evaluation? (e.g., ever-increasing data volume, lack of observations, etc.)
- How can “predictability” of long-term climate projections be defined and evaluated?

Biogeochemical model evaluation for ESMs – Climatologies – Ocean Acidfication



Global distribution of aragonite saturation (Ω_A) at 400, 900, and 3500 m for CanESM5-CanOE, CanESM5, the mean for other CMIP6 models, and observations (GLODAPv2 and WOA2018). *Note different colour scales for different depths. Numbers on the lower left are the mean model bias.*

Christian et al 2022, GMD

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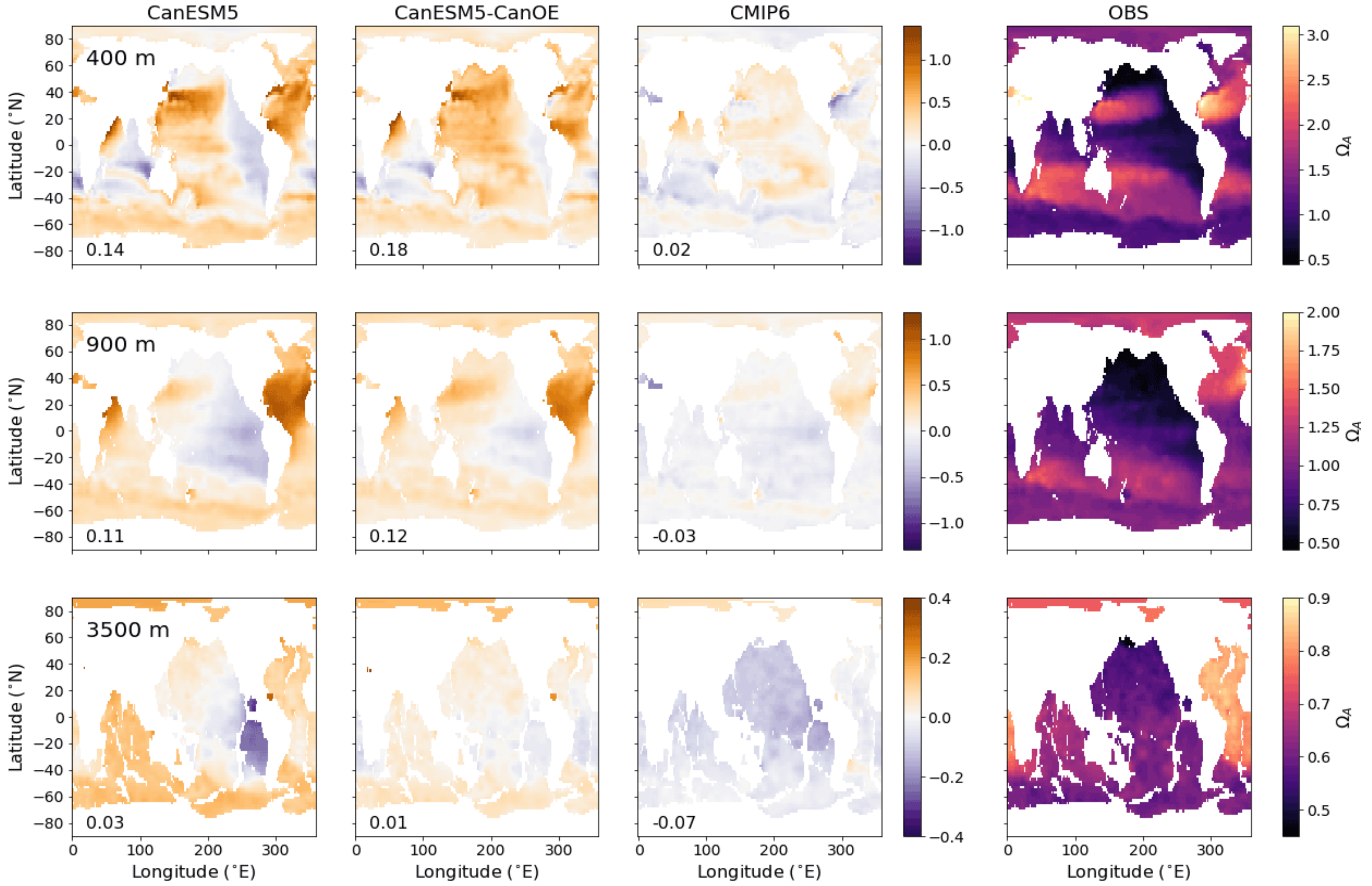
Biogeochemical model evaluation for ESMs – climatologies – ocean acidification



Differences from the observation-based fields of aragonite saturation state (Ω_A) at 400, 900 and 3500 m for CanESM5-CanOE, CanESM5, the mean for other CMIP6 models, and observations (GLODAPv2 and WOA2018). Numbers on the lower left are the mean model bias.

Climatologies cover temporal averages over a period of change, number/type/location of observations per year/decade varies

Christian et al 2022, GMD

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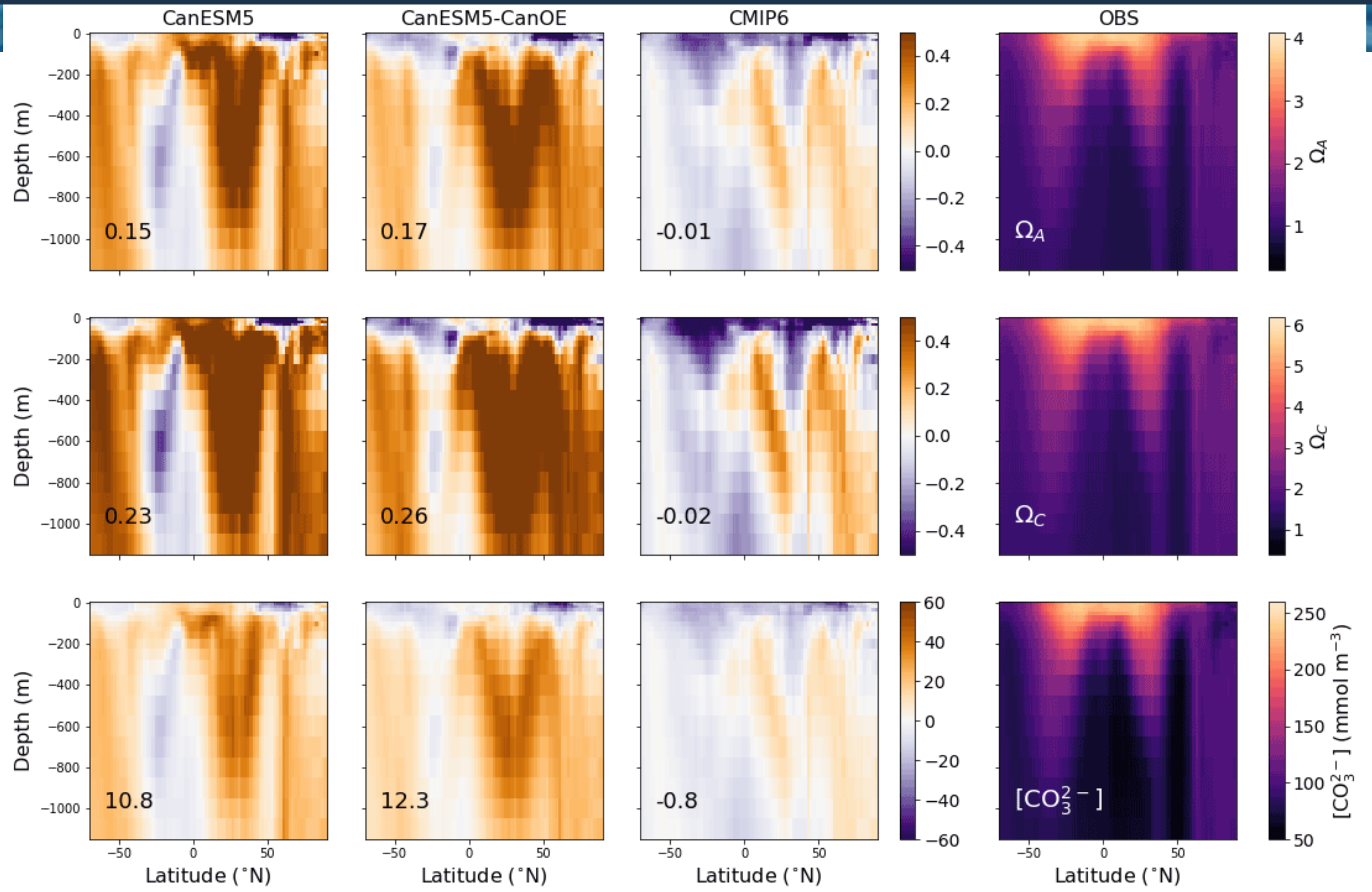
Biogeochemical model evaluation for ESMs – climatologies – 3rd dimension



Differences from the observation-based fields for latitude–depth distribution (surface to 1150 m) of zonal mean aragonite saturation state (Ω_A), calcite saturation state (Ω_C), and carbonate ion concentration ($[CO]_3^{2-}$) in mmol m^{-3} for CanESM5-CanOE, CanESM5, the mean for other CMIP6 models, and observations (GLODAPv2 and WOA2018). Numbers on the lower left are the mean model bias.

Climatologies more likely to cover the surface, limited observations below the surface (however, less change in the deep ocean)

Christian et al 2022, GMD

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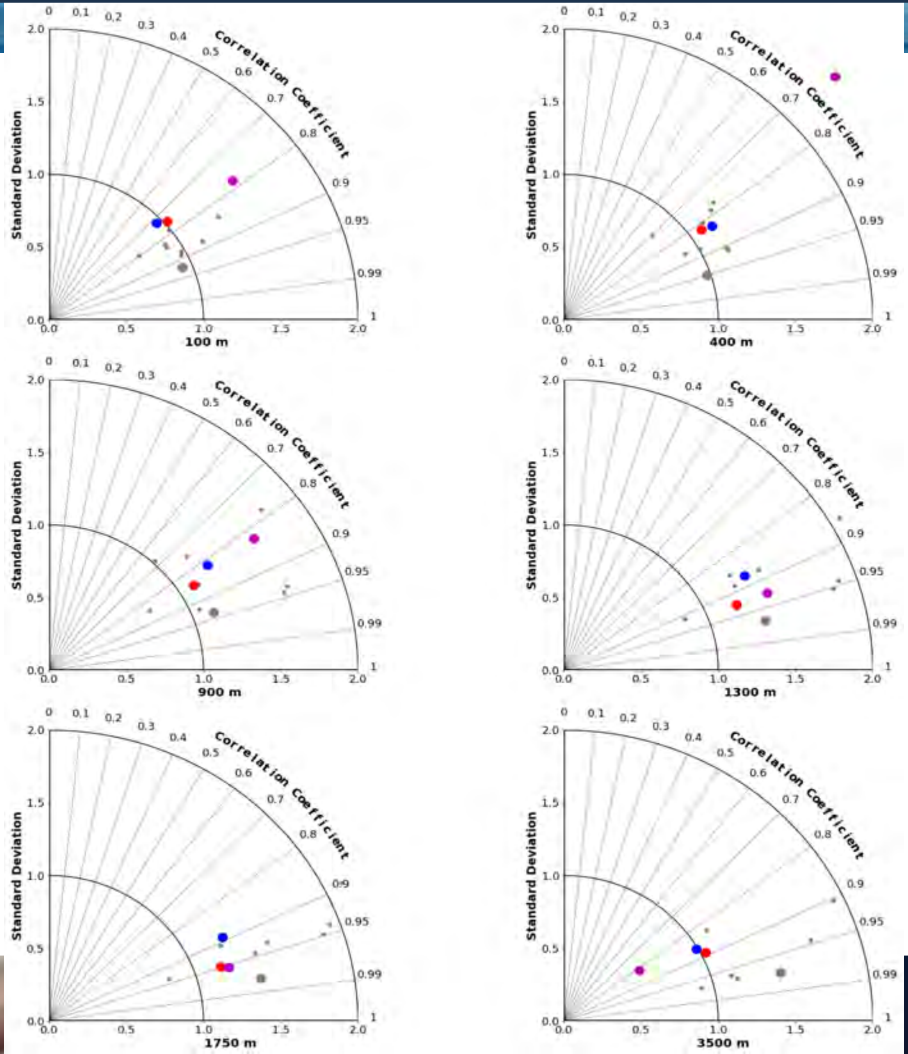
Biogeochemical model evaluation for ESMs – climatologies – Taylor diagrams - DIC

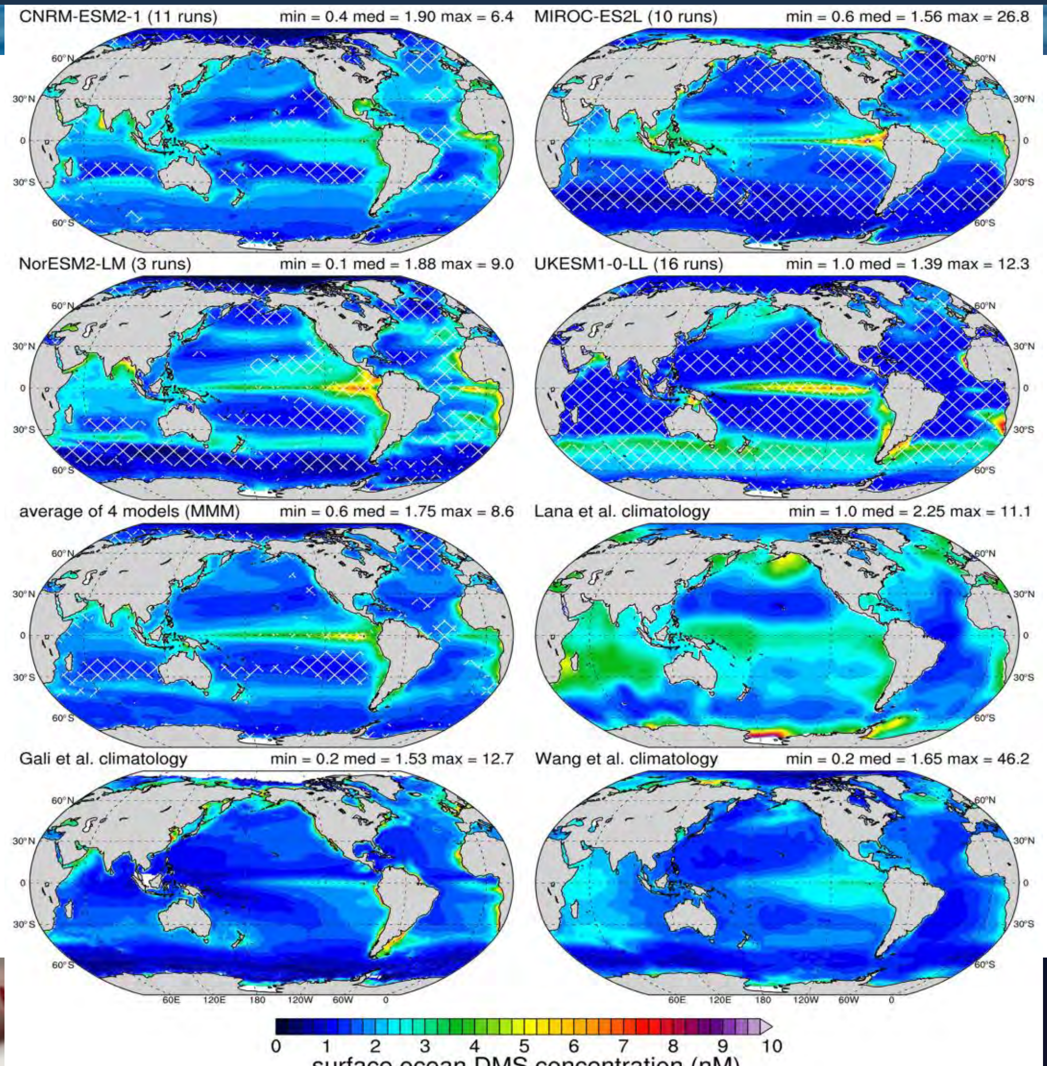


Taylor diagrams comparing modelled and observed distributions of dissolved inorganic carbon (DIC) at specific depths from 100 to 3500 m. *The angle from the vertical indicates spatial pattern correlation. Distance from the origin indicates ratio of standard deviation in modelled vs. observations* from GLODAPv2 (Lauvset et al., 2016). Red dots represent CanESM5-CanOE, blue dots CanESM5, magenta dots CanESM2, small grey dots other CMIP6 models, and large grey dots the model ensemble mean for all CMIP6 models except CanESM5 and CanESM5-CanOE.

Similar evaluations for O2, some also for nitrate and Fe – still limited bgc climatologies available

Christian et al 2022, GMD

Biogeochemical model evaluation for ESMs – climatologies - DMS



Mean (1980–2009) surface ocean DMS concentration (nM) for: CMIP6 historical experiments of the four models: CNRM-ESM2-1, MIROC-ES2L, NorESM2-LM, UKESM1-0-LL, and the MMM. And climatologies: L11, G18, and W20

Hatching on the model plots shows locations where the DMS concentration is outside the range covered by L11, G18, and W20 (see text for details).

Bock et al. 2021, DMS CMIP6

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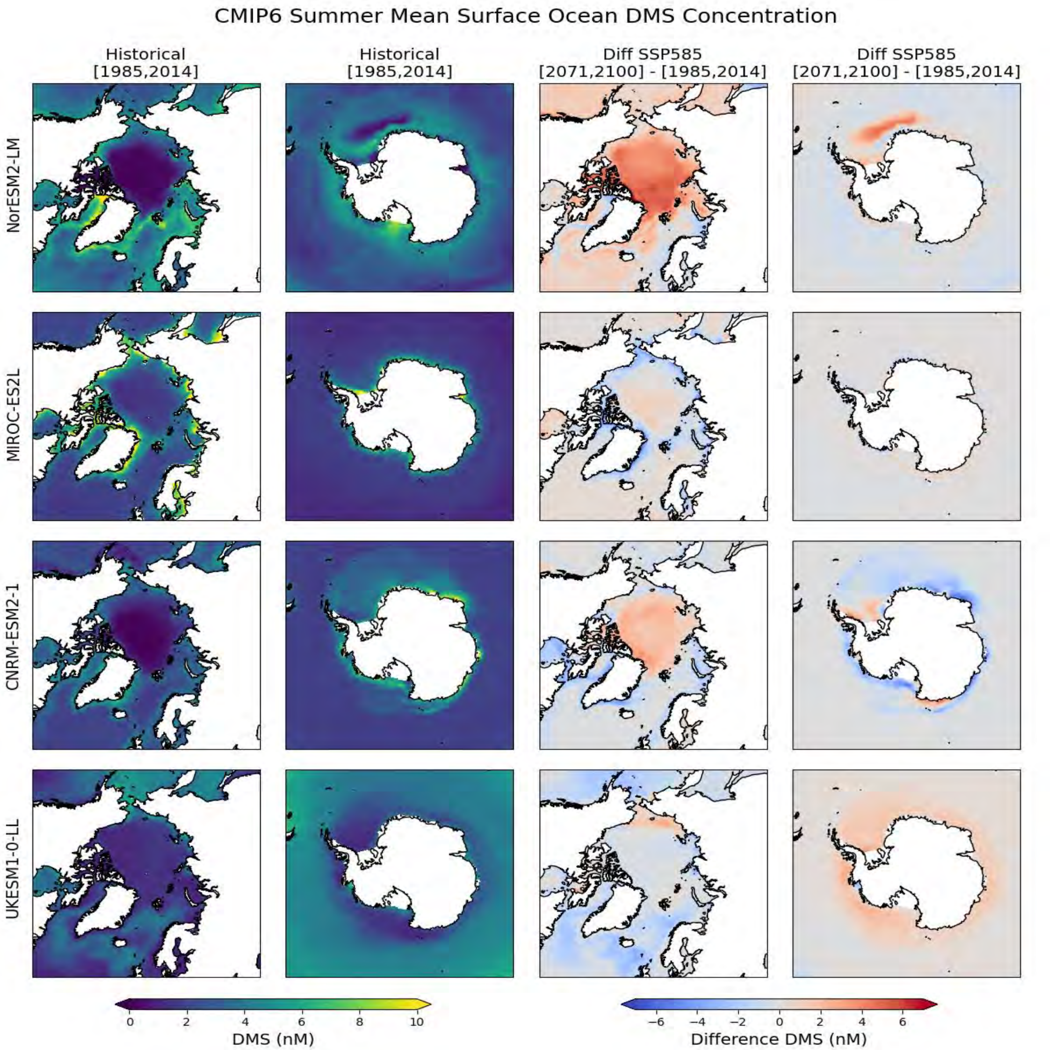
Biogeochemical model evaluation for ESMs at the Poles – climatologies - DMS



SCOR-WG #163 CICE2Clouds: S-cycle working group synthesis Ishino et al., in prep.

Ocean surface DMS concentrations from CMIP6 models for the Historical and SSP585 scenarios.

Historical: 30 year mean over 1985 to 2014
DIFF: difference between the future (2071 to 2100) and recent past (1985 to 2014).

Averages are for summer in the northern (June, July and August) and southern (December, January and February) hemispheres.

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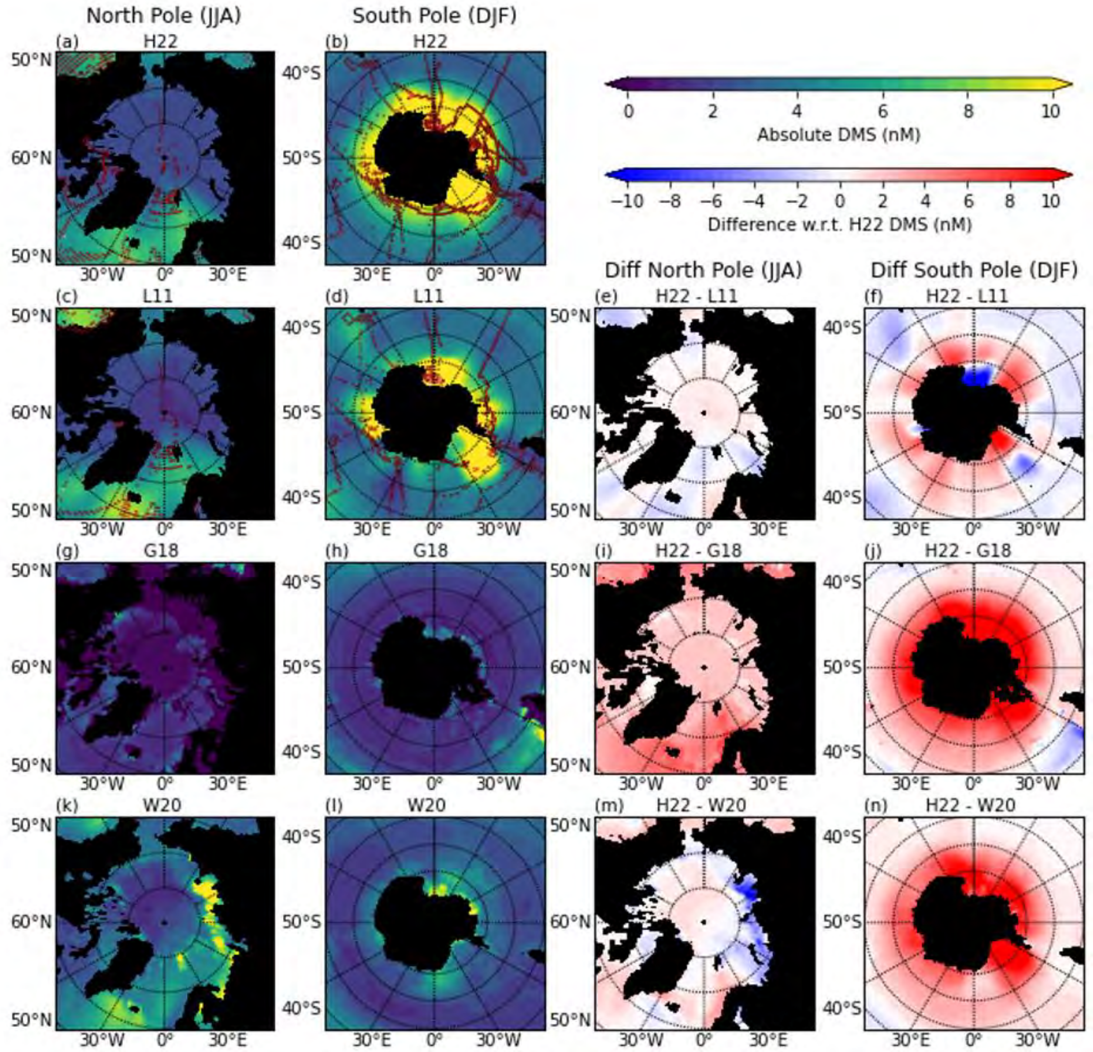
Biogeochemical model evaluation for ESMs – climatologies - DMS



SCOR-WG #163 CICE2Clouds: S-cycle working group synthesis Ishino et al., in prep.

Latest seawater DMS climatologies shown for the summer months in the northern (June, July and August) and southern (December, January and February) hemispheres.

1. Hulswar et al., 2022 climatology (H22) updated using new observations since
2. Lana et al., 2011 climatology L11. (observations included shown in red dots).
3. Gali et al., 2018 (G18): regression analysis on satellite-based proxies;
4. Wang et al., 2020 (W20) climatology predicted using an artificial neural network with satellite-based proxies as inputs.

Differences of each climatology with the H22 climatology are show on the right

New SCOR WG #167 – DMS-PRO

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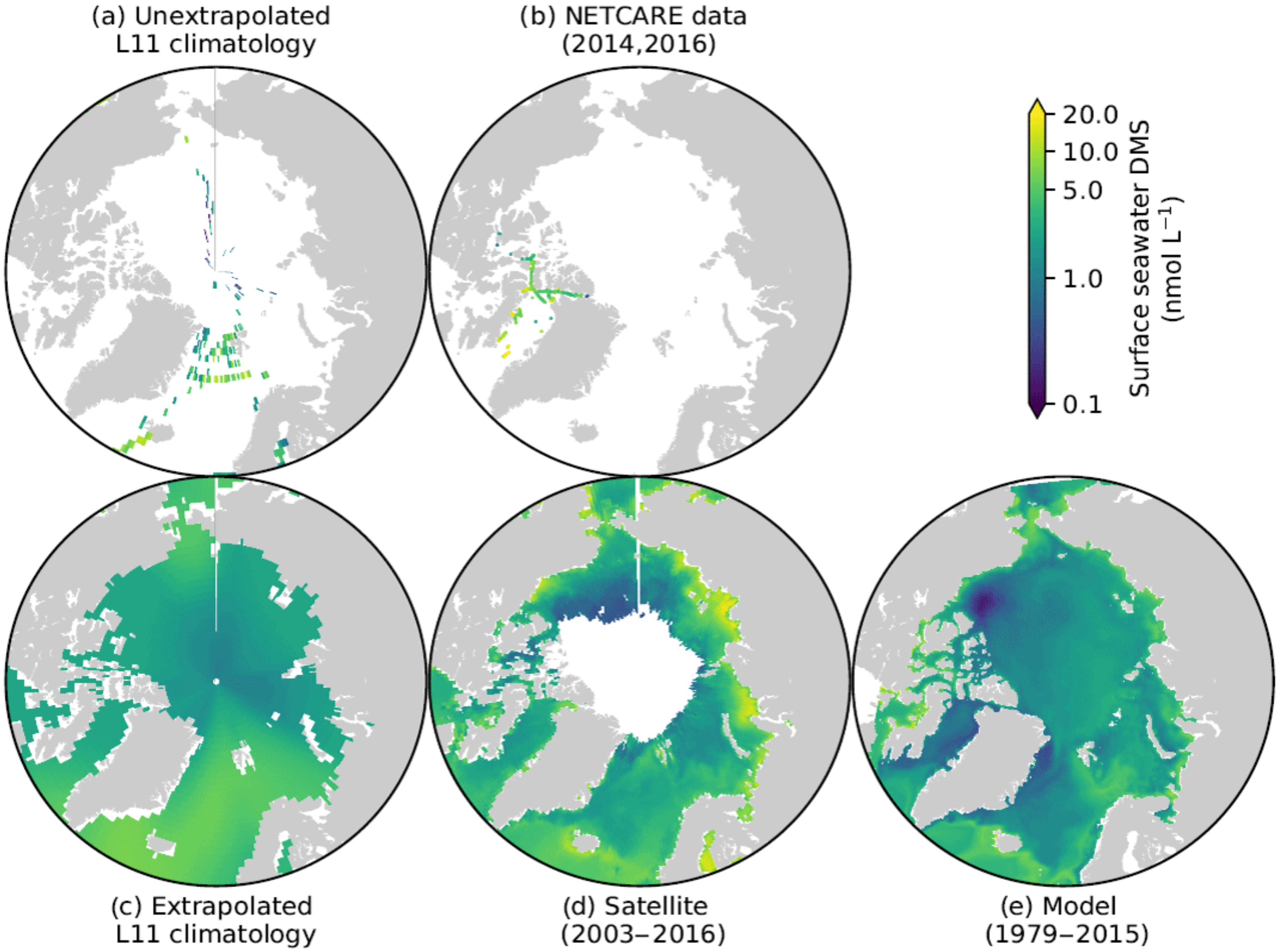
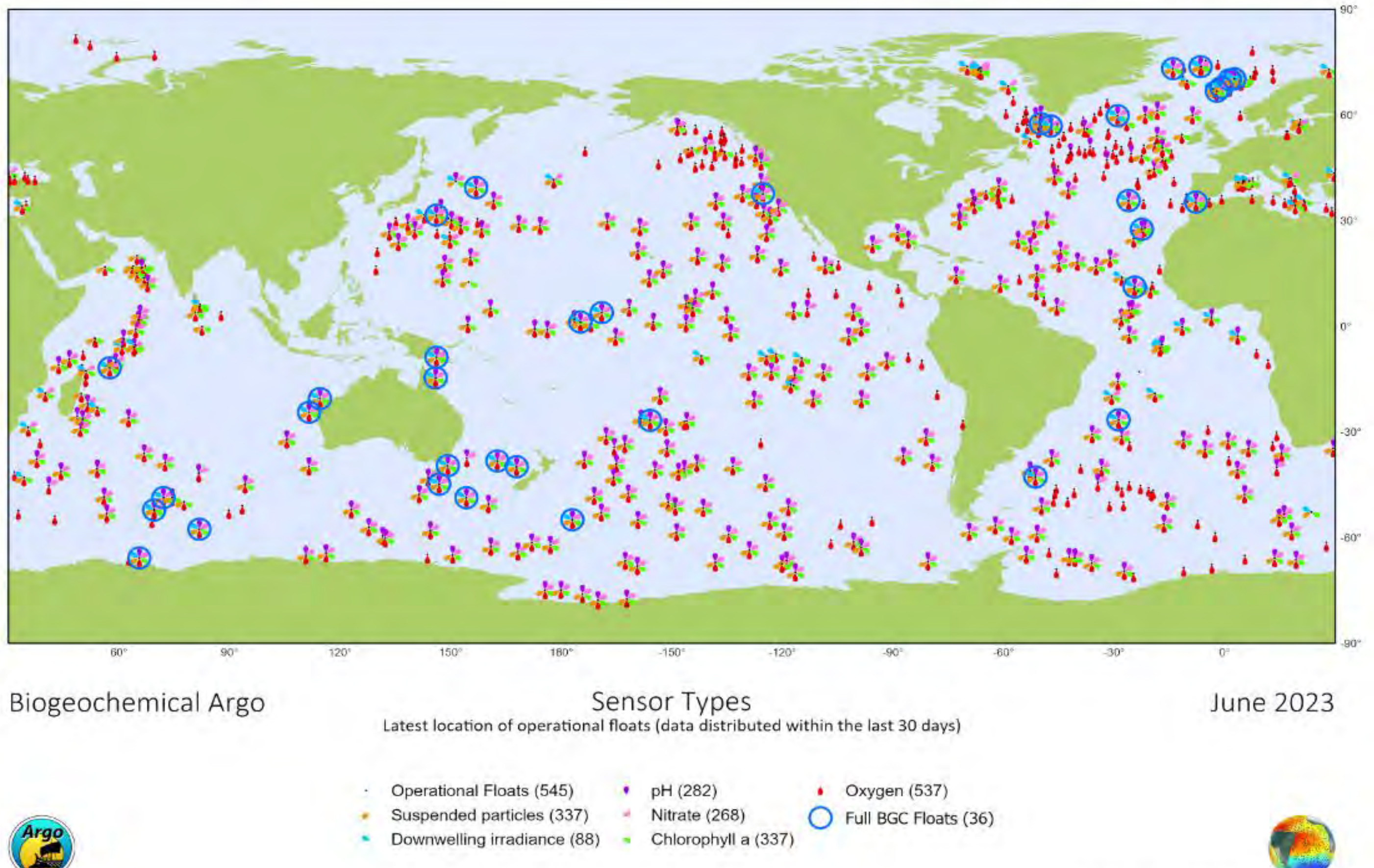
Biogeochemical model evaluation for the Arctic – climatologies - DMS



Pan-Arctic distribution of July–August concentrations of surface ocean DMS.
(a) the discrete (Lana et al., 2011) climatology
(b) the data collected during the two NETCARE field campaigns.
(c) observation- based (Lana et al., 2011)
(d) satellite-derived (Galí et al., 2018;
(e) model-based (Hayashida, 2018) climatologies

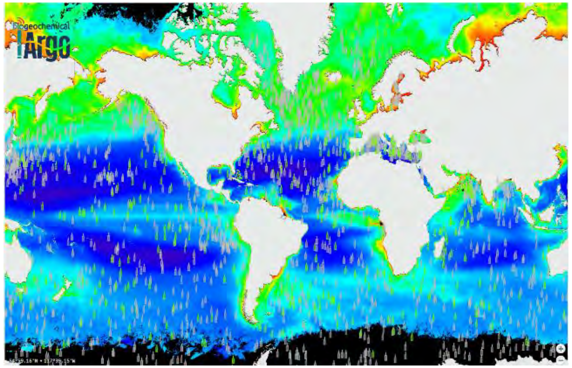
Climatologies are based on regionally limited data, particularly in polar regions

Biogeochemical model evaluation – climatologies – new developments: BGC Argo



BGC-Argo

O2
Nitrate
Chl-a
PH
Suspended particles



Proposed SCOR WG 4D-BGC => Gridded 4D data products

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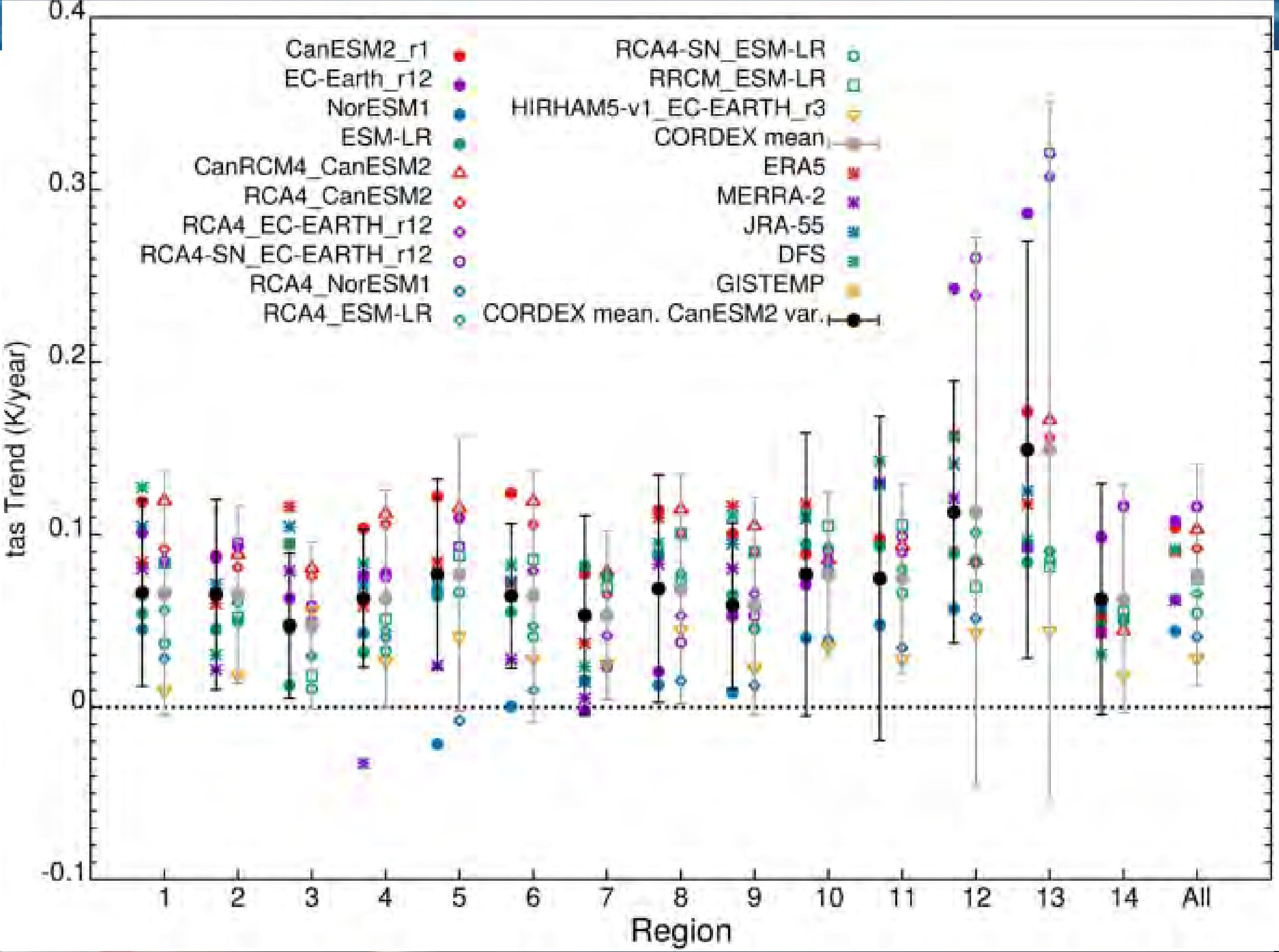
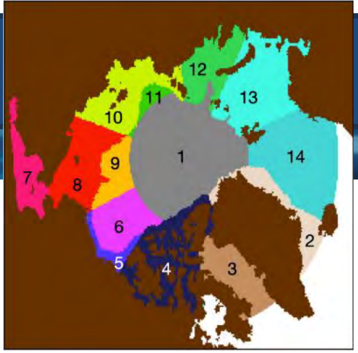
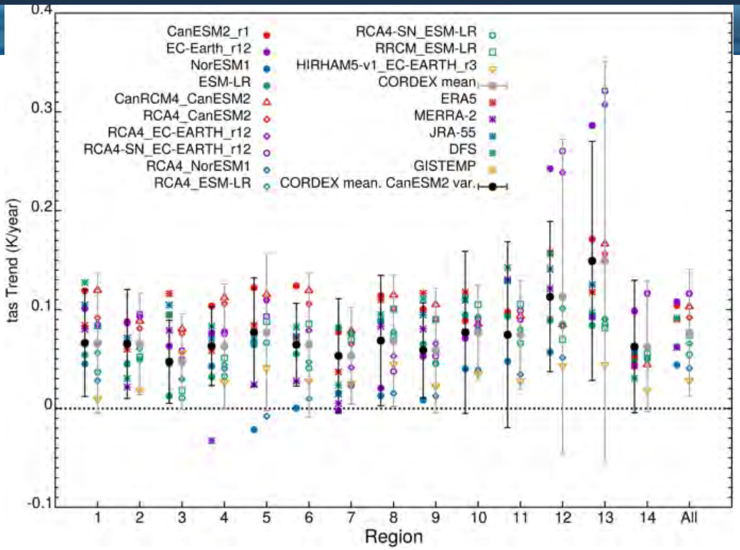
Biogeochemical model evaluation for the Arctic – Trends

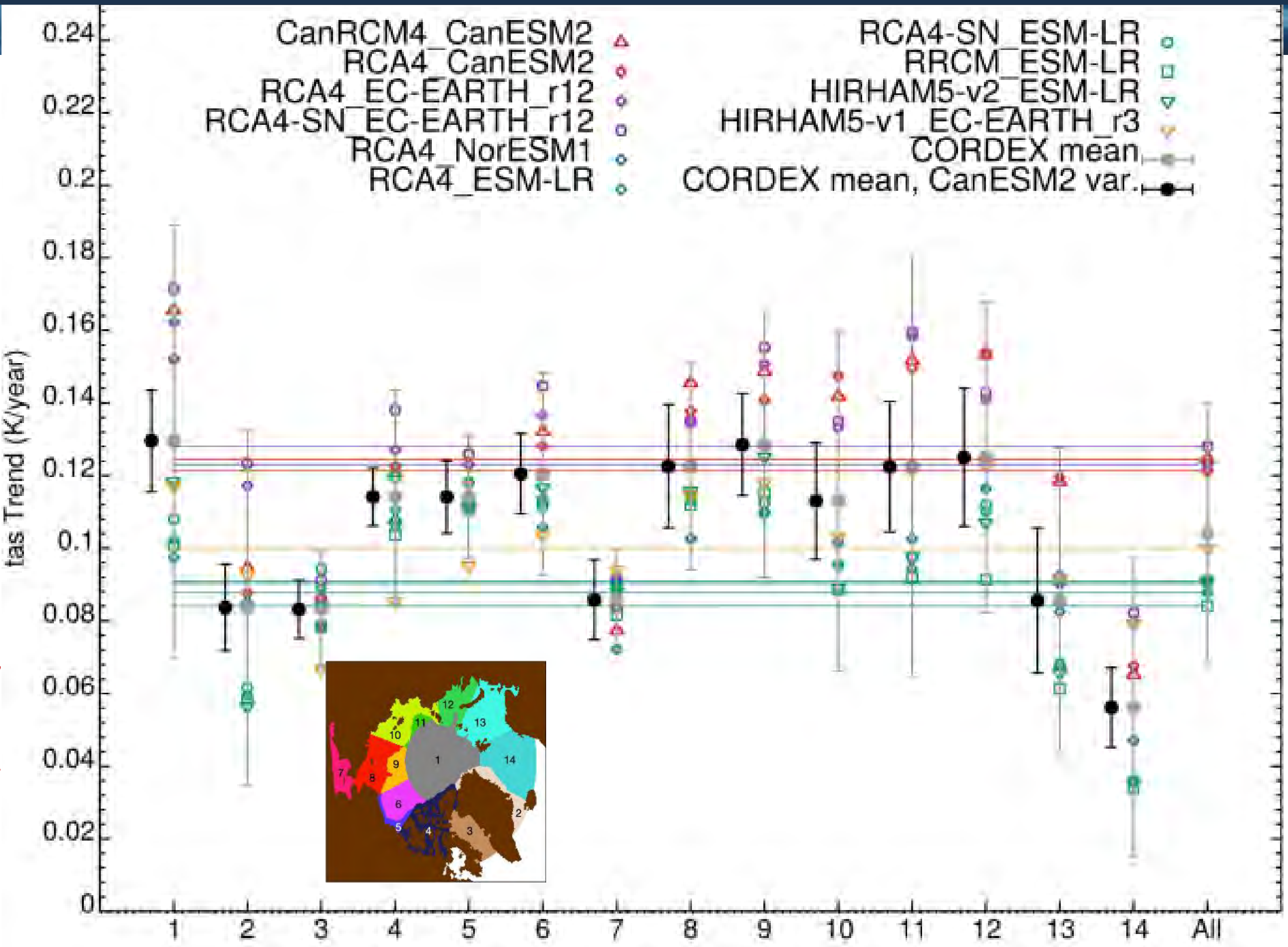




The subregional 1986–2015 annual average near-surface temperature *tas* trends (K/y) for the *CORDEX historical* (1986–2005) + RCP8.5 (2006–2015) simulations (*open shapes*) and *observation-based data sets (asterisks)* with the mean of the CORDEX models (large filled circles), the *driving GCM* ensemble members (*small filled circles*) and *2σ error bars estimated from the CanESM2 historical large ensemble (black)* and *CORDEX suite (grey)*

Biogeochemical model projections for the Arctic – Trends & Multi-Model Intercomparisons



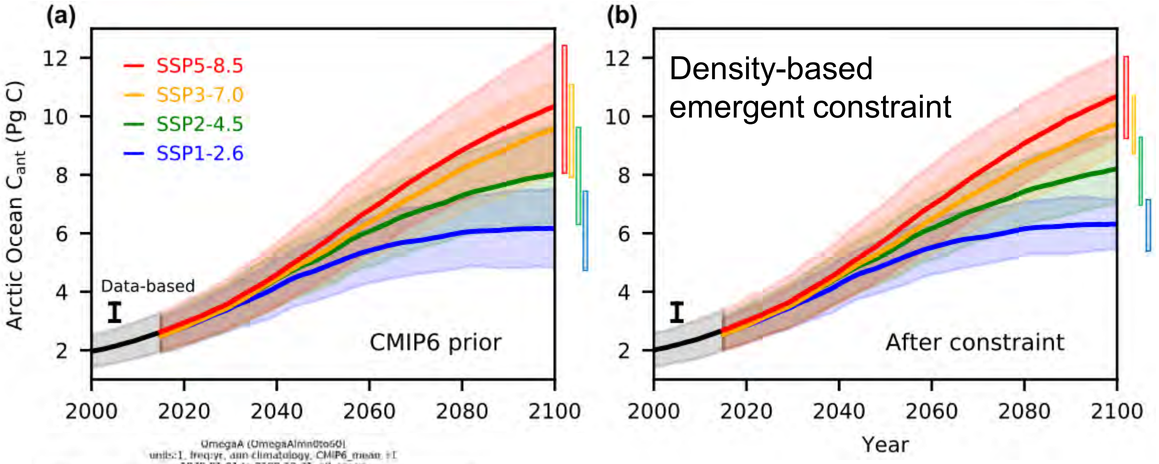


Strong regional difference in Arctic trends.

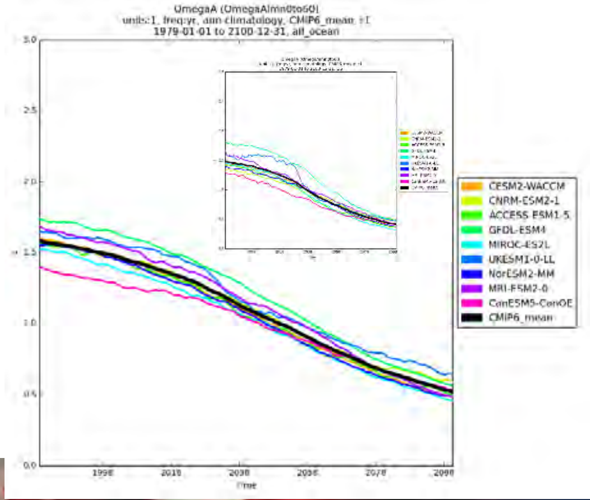
Hardly any trend information available for bgc data, examples from physical variables (ocean and atmosphere suggest to evaluate past trends to address credibility for the future. => 4D-BGC

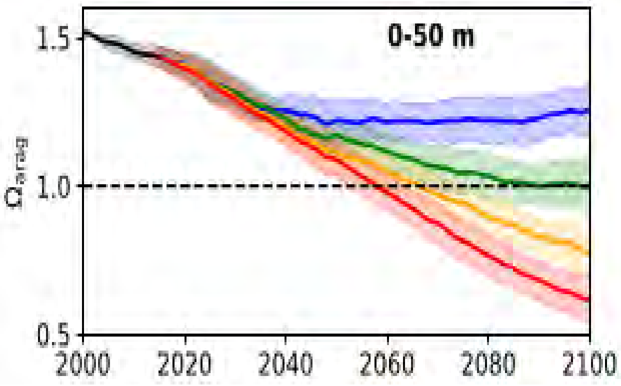
Reader & Steiner 2022, Climate Dynamics

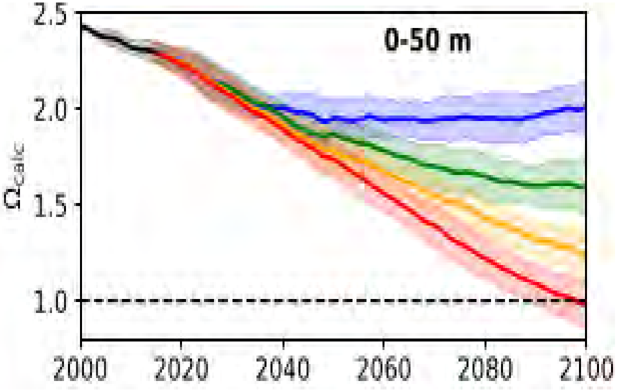
BGC model projections for the Arctic – Multi-Model – Emergent Constraints- Ocean Acidfication



- *Emergent constraints* – Selective choice of models based on performance in a “better-known” variable (here: density)
- How to deal with the *bias in initial conditions?* – Is the use of a common starting point+anomalies masking a decrease in uncertainty in some variables?







Terhaar et al. 2021

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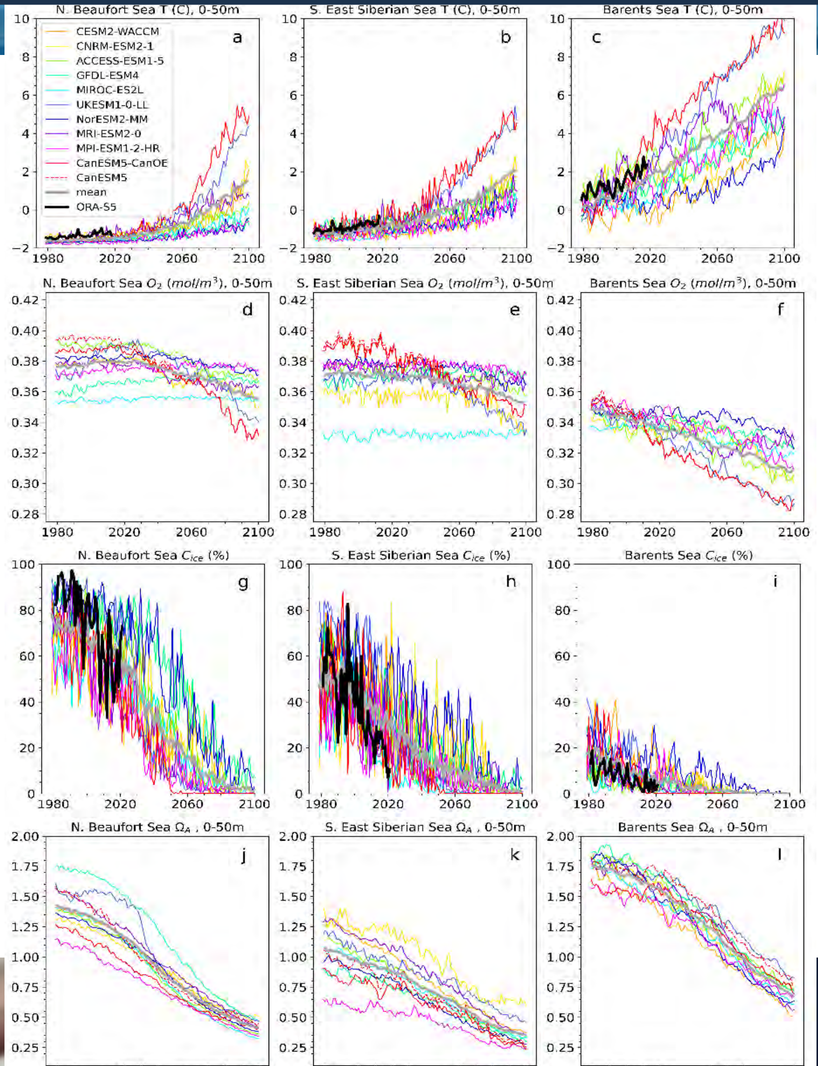
Biogeochemical model evaluation for the Arctic – Trends & Multi-Model Intercomparisons



Temperature 0-50m

O2

Summer sea ice concentration

Ωa - Aragonite 0-50m

CMIP6 trends & projections for Arctic regions (SSP595

Average trends available for physical variables such as sea-ice concentration (NOAA/NSIDC) and (ORAS5), not available for bgc variables

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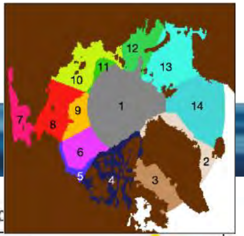
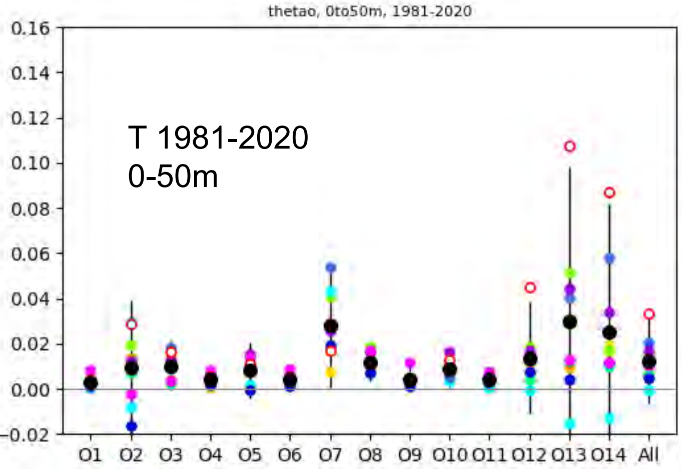
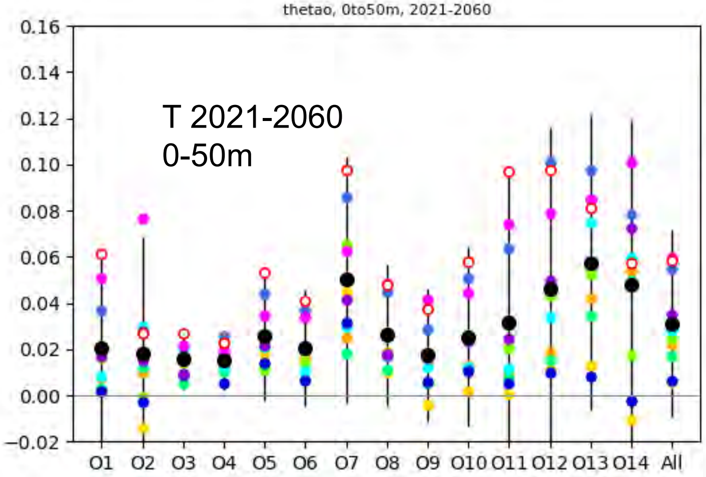
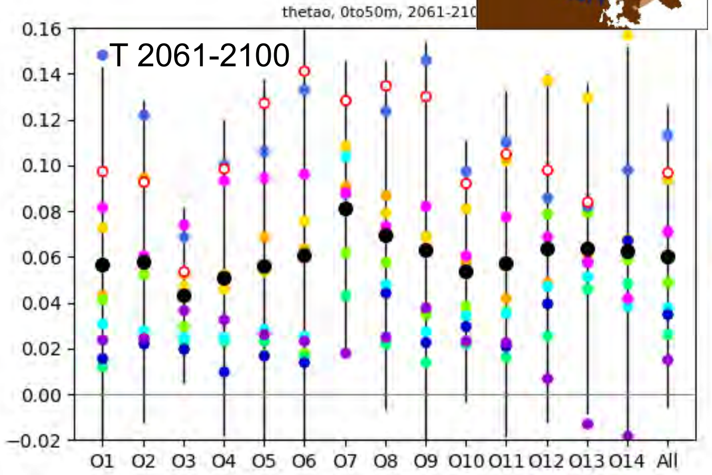
Fisheries and Oceans Canada | Pêches et Océans Canada

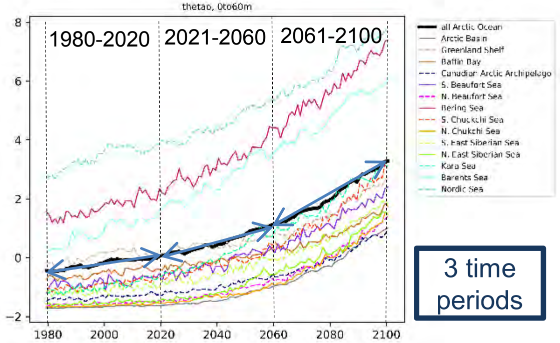
CMIP6 model trends 3 40-year timeperiods – SSP585 Temperature 0-50m



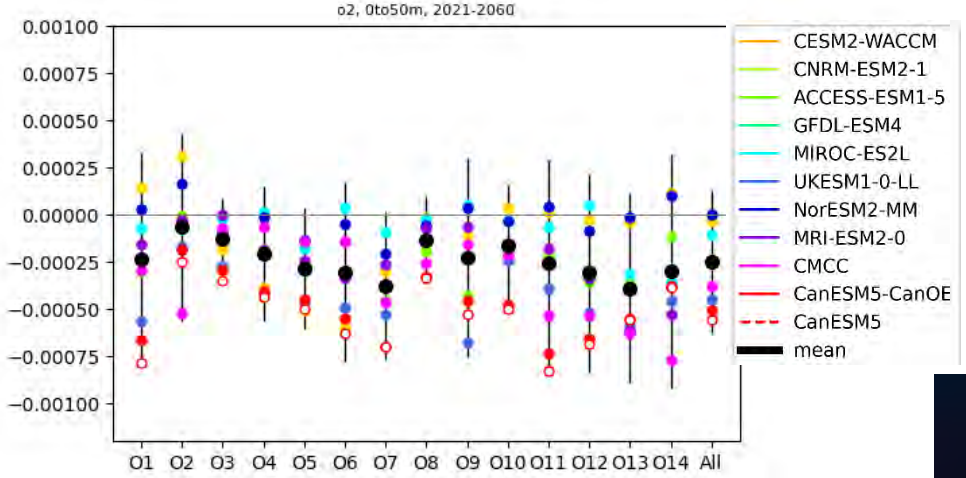








3 time periods



Models show distinct regional differences in trends and large spread among models (increasing over time). CanESM comparison indicates that despite consistent T-trends O2 trends show varying trend biases by region

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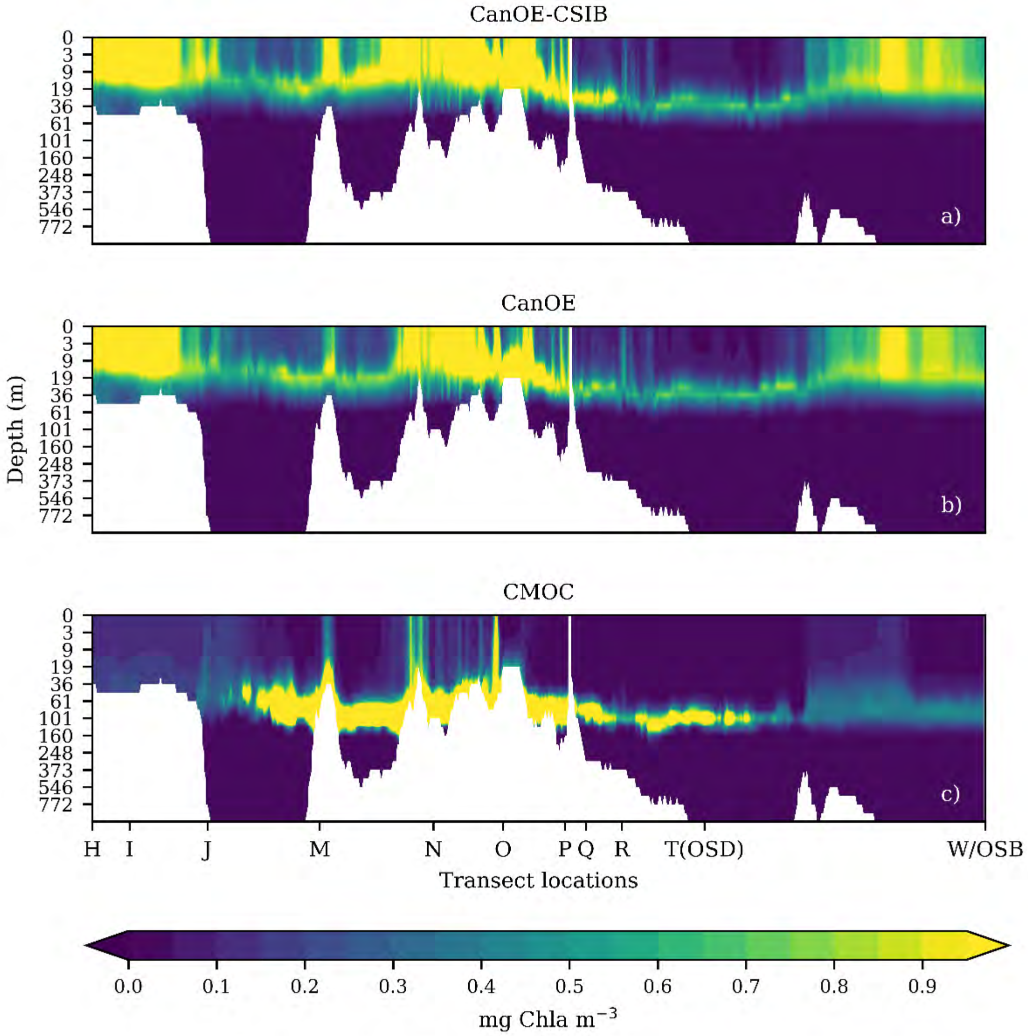
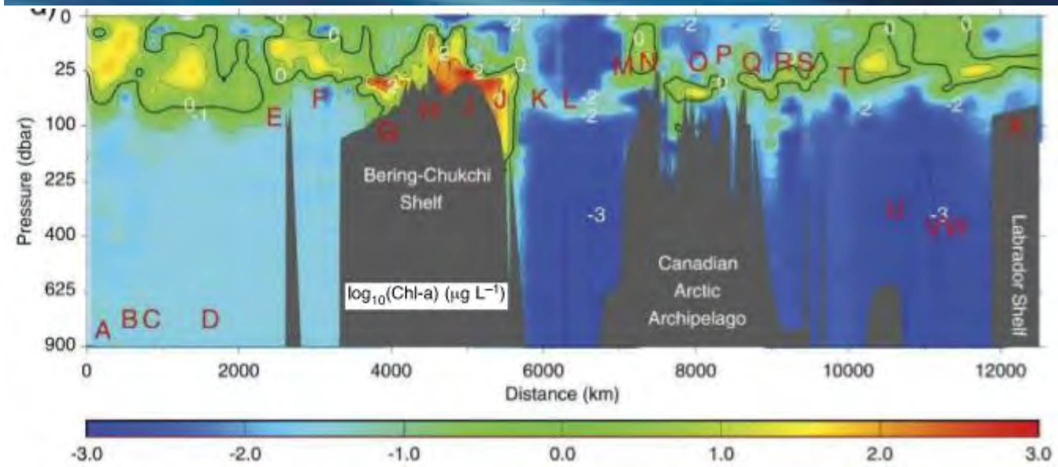
Biogeochemical model evaluation, Arctic – Characteristic Patterns – Subsurface Chl Max (SCM)





Carmack et al., 2010

The SCM is a characteristic feature in low-nutrient Arctic regions.

Reproducing characteristic patterns or features in a particular area can be used to evaluate the model performance

Steiner et al., in prep.

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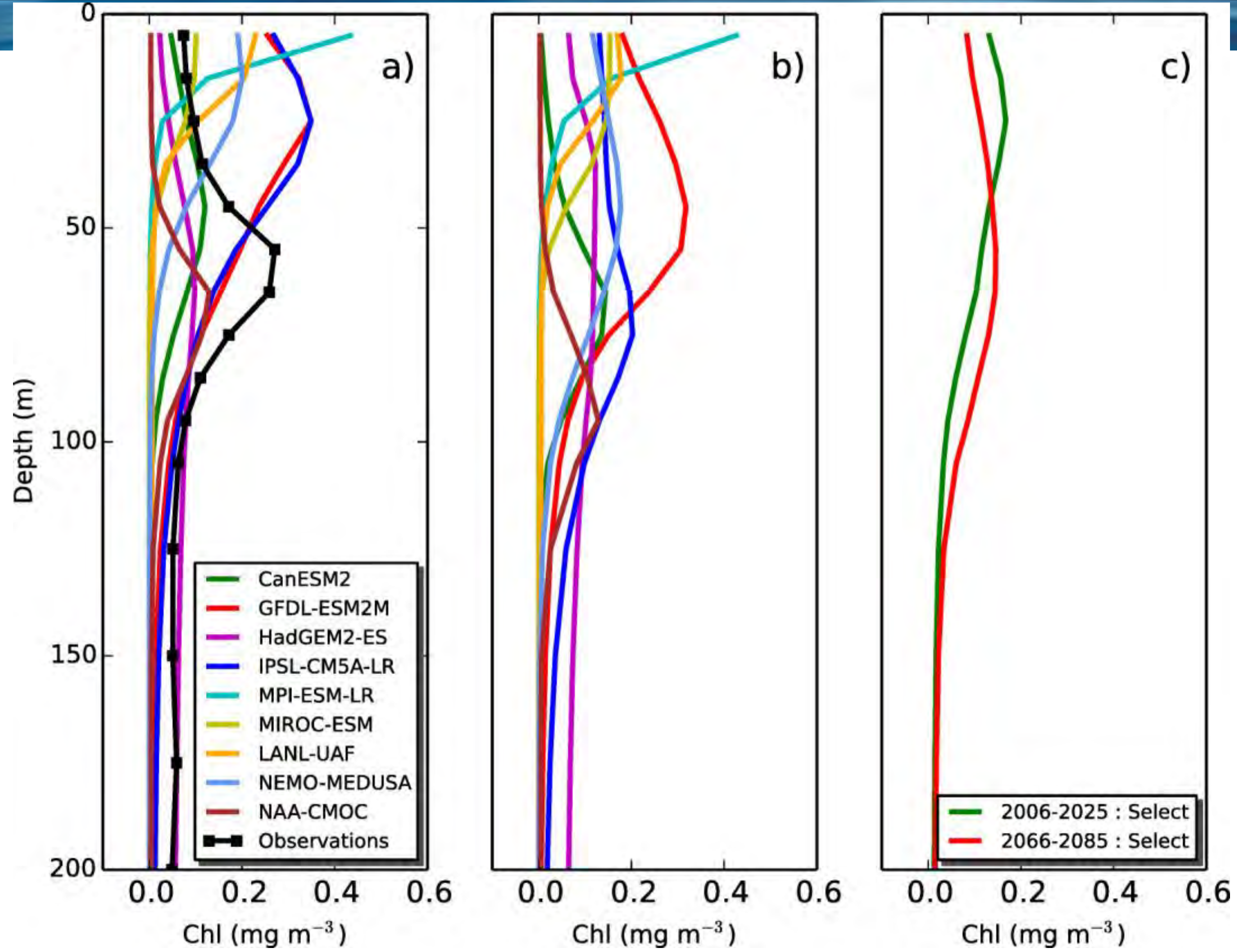
Biogeochemical model projections, Arctic – Characteristic Patterns – Subsurface Chl Max (SCM)



Simulated bidecadal averages of the annual mean vertical Chl-*a* profiles (mg m^{-3}) for the various ESMs and HROMs averaged over the area 73°N–79°N and 130°W–150°W. (a) 2006–2025, (b) 2066–2085. (c) The multimodel mean for both time periods excluding the MPI-ESM-LR, MIROC-ESM, and LANL-UAF models which do not show a SCM.

Steiner et al. , 2015, JGR Oceans

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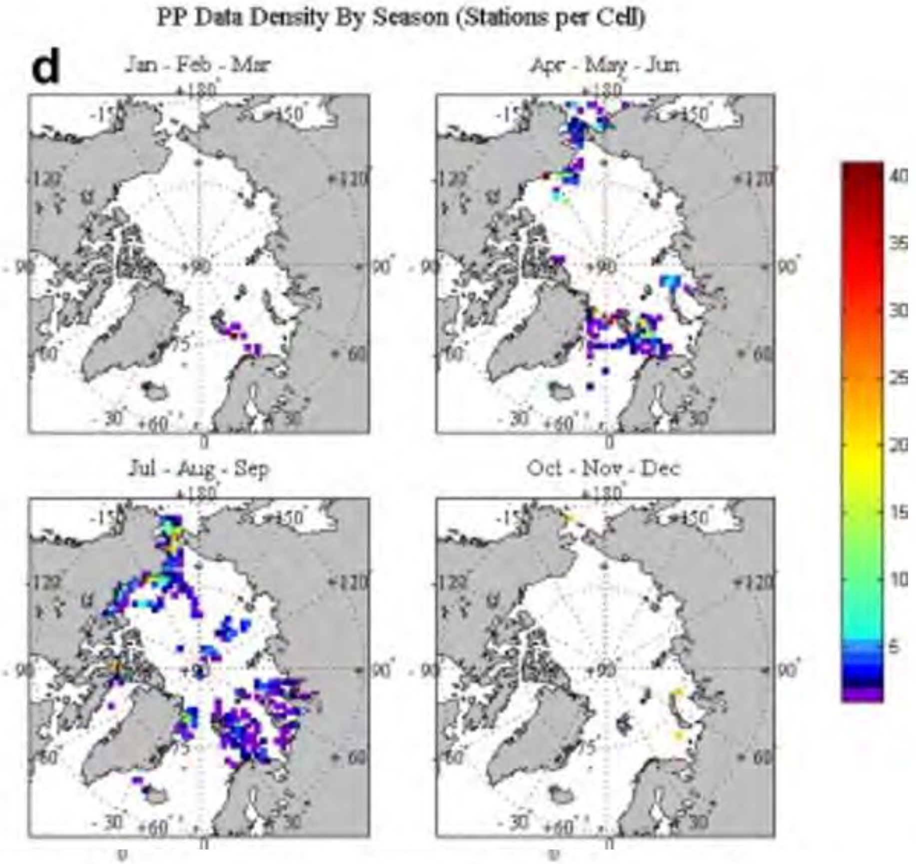
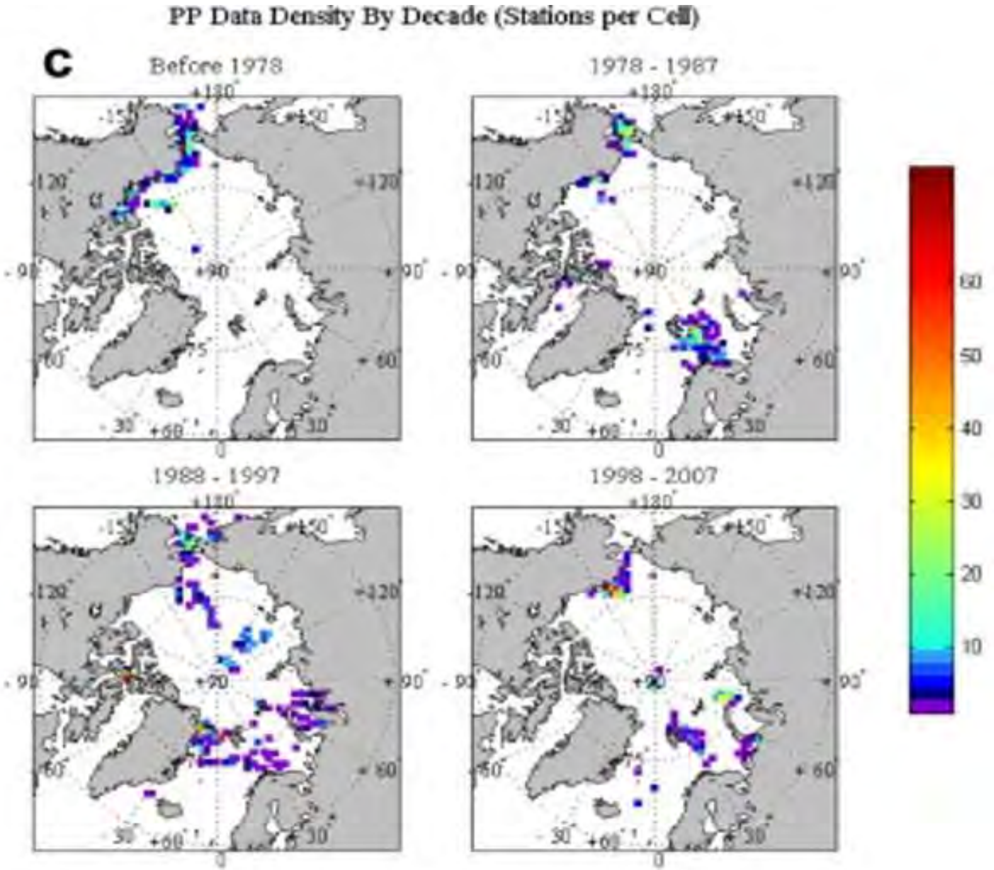
Biogeochemical model evaluations – limited data - regional averages – bias by decade/season

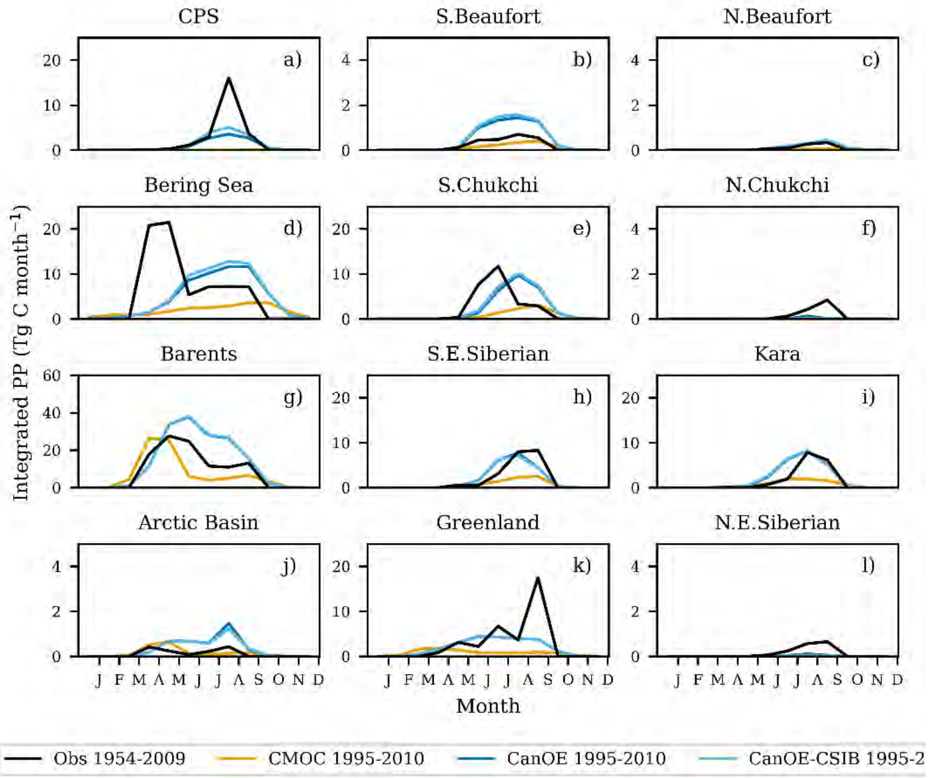


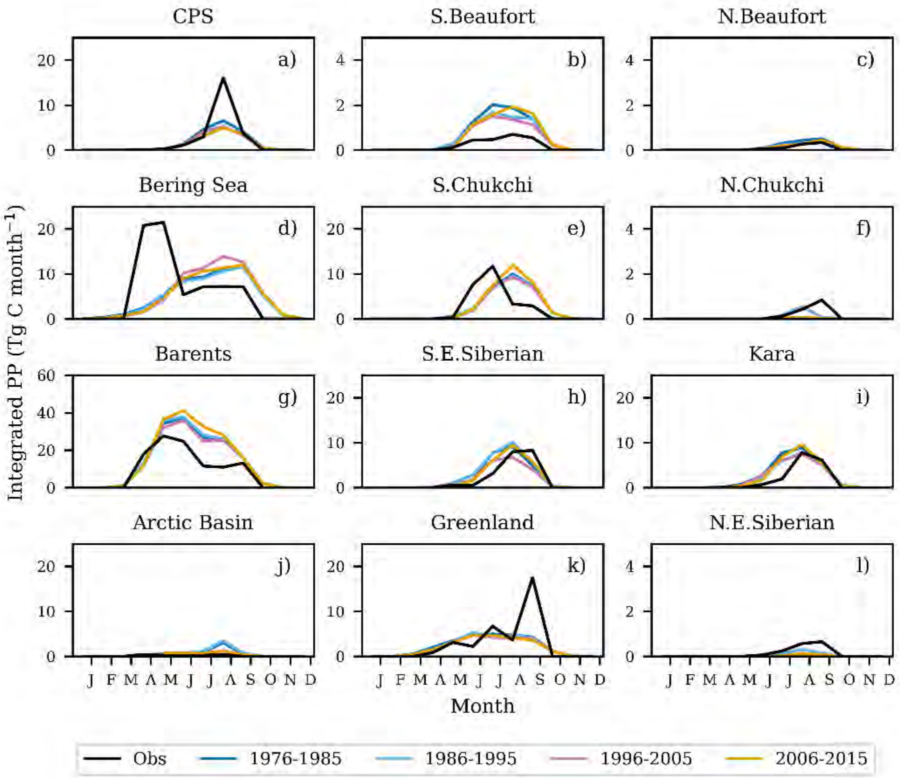


Matrai et al. 2013, Prog. Oceanography

Fisheries and Oceans Canada Pêches et Océans Canada

Biogeochemical model evaluations – limited data - regional averages – bias by decade/season





Different bgc models ***Different decades***

Steiner et al., in preparation

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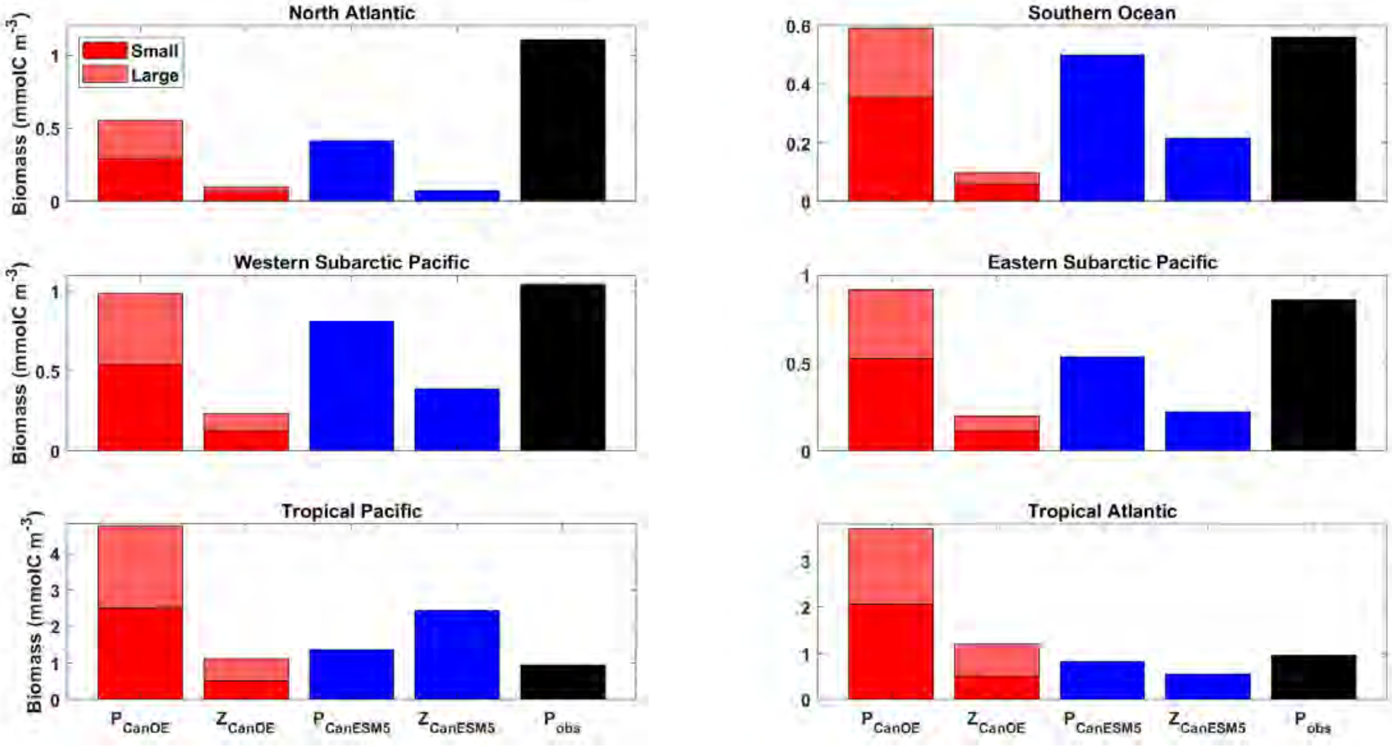
Biogeochemical model evaluation for ESMs – regional averages



Annual mean surface ocean concentration of large and small phytoplankton and zooplankton in CanESM5-CanOE (red) and of phytoplankton and zooplankton in CanESM5 (blue) for representative ocean regions. Observational estimates (black) are for phytoplankton biomass calculated from satellite ocean colour estimates of surface chlorophyll (SeaWiFS/MODIS; Tesdal et al. 2016), assuming a carbon-to-chlorophyll ratio of 50 g g^{-1}

Christian et al 2022, GMD

Biogeochemical model evaluation for ESMs – comparison with direct local data

Modeller's perspective:

a *Five star observationalist* is the one who measures the process of large interest repeatedly in several places and for long time periods, and has a good global understanding on the variability that might drive the process

Idea: K. Popova, graphics N&A Steiner

Biogeochemical model evaluation – Key points from Modeller-Observer discussions

Observers and modellers need to speak a common language;
Follow what best practices have been established by the community;
Quantities and units need to be consistently defined;
Observed data need to be assessed for representativeness of the respective model output ("scale awareness" in time and space);
Establish and maintain coordinated databases; Gridded datasets (commonly used format) with meta data facilitate usage for large scale model evaluation;
Observations need to address key uncertainties in existing parameterisations (e.g., process rates, functional dependencies) or help identify important processes that are not yet considered;
Provide the ancillary data;
Provide ranges of uncertainty and detection limits;
Express species compositions in terms of their function in the ecosystem (i.e. functional types).

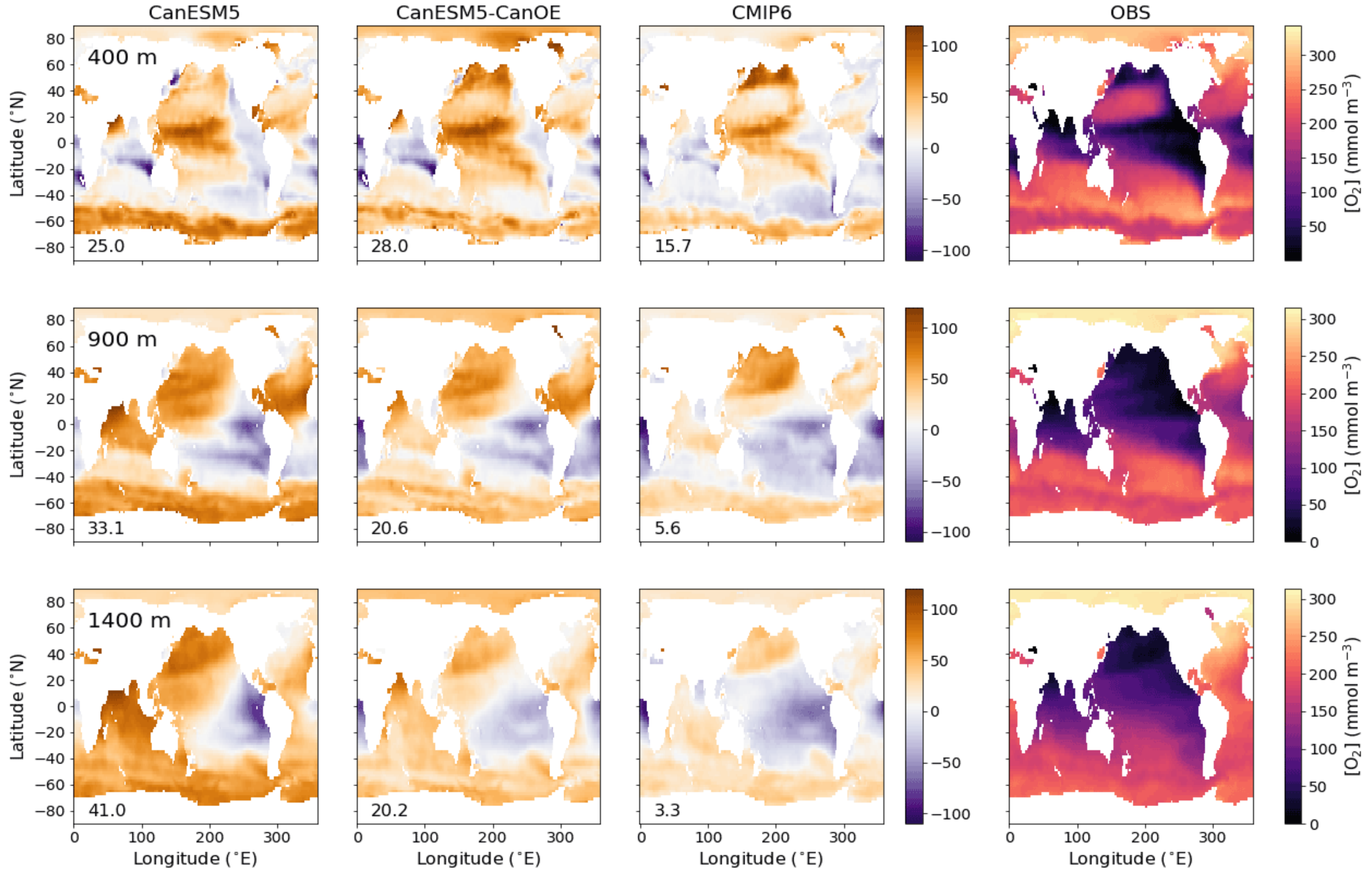
(Steiner et al, 2016 with adaptations from the Polar Climate Working Group – Living Document)

Summary – BGC Model Evaluation

- What are current developments in Earth system model evaluation capabilities? – *Improved/Updated gridded climatologies, addition of 4th dimension (time), data synthesis and improved data coordination ("Findability" + Consistency)*
- What are the most pressing gaps in the current multi-model validation capabilities & What are the most pressing challenges for Earth system model evaluation? – *climatologies remain biased to the "observational good times" (regions and seasons with good access, years/decades with good funding support), particularly for bgc variables. Temporally resolved climatologies are rare/non-existent (some progress in sight, e.g. BGC Argo). Some key regions (e.g. Arctic) under-observed.*
- How can "predictability" of long-term climate projections be defined and evaluated? *Evaluation of past trends and past pattern reproduction may provide increased confidence in future projections, multi-model ranges remain high for projections, even for the best observed variables and despite low historical biases. – continue to improve system understanding, model development and methodologies (example: AI), international collaboration and coordination (Example: SCOR-WGs).*


Questions??

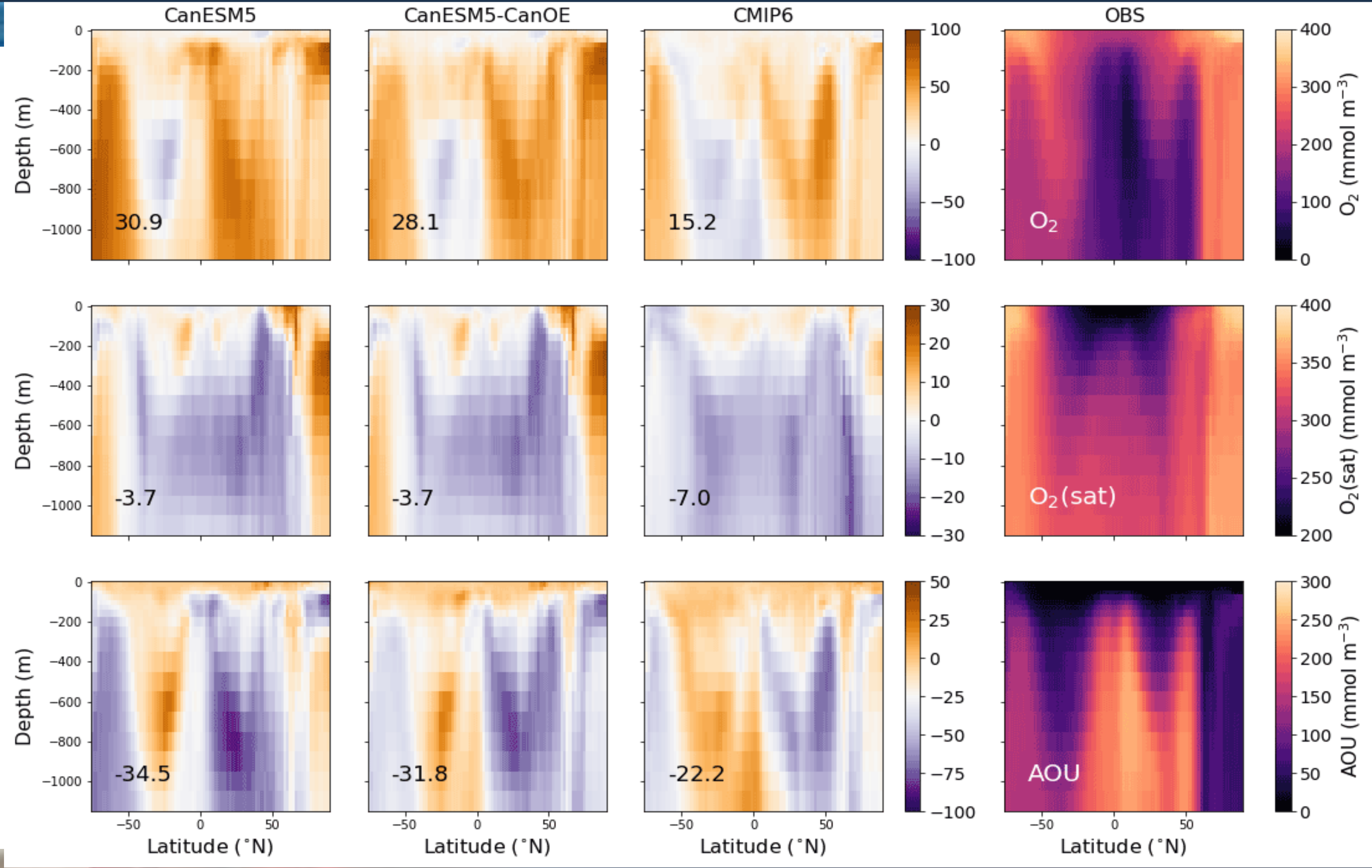
Biogeochemical model evaluation for ESMs - climatologies



Differences from the observation-based fields of oxygen (O_2), concentrations in mmol m^{-3} at 400, 900, and 1400 m (rows) for CanESM5-CanOE, CanESM5, and the mean for other (non-CanESM) CMIP6 models, and World Ocean Atlas 2018 (WOA2018) observations. Numbers on the lower left are the mean model bias.

Christian et al 2022, GMD

Biogeochemical model evaluation for ESMs - climatologies



Differences from the observation-based fields for latitude–depth distribution (surface to 1750 m) of zonal mean oxygen concentration (O_2), O2 concentration at saturation (O_2(sat)), and apparent oxygen utilization (AOU) in mmol m^{-3} for CanESM5-CanOE, CanESM5, and the mean for other CMIP6 models, and observations (WOA2018). Numbers on the lower left are the mean model bias.

Christian et al 2022, GMD

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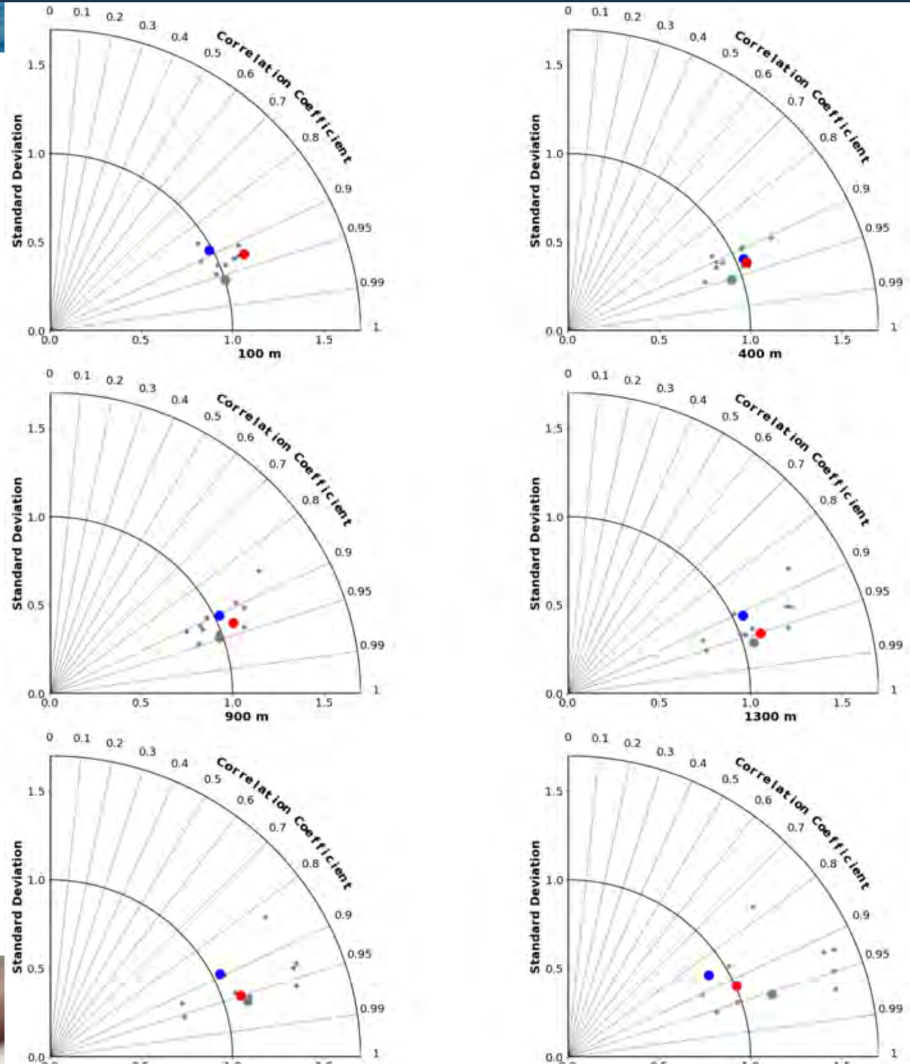
Biogeochemical model evaluation for ESMs – climatologies – Taylor diagrams



Taylor diagrams (Taylor, 2001) comparing modelled and observed distributions of oxygen at specific depths from 100 to 3500 m. The angle from the vertical indicates spatial pattern correlation. Distance from the origin indicates ratio of standard deviation in modelled vs. observed (WOA2018) fields. Red dots represent CanESM5-CanOE, blue dots CanESM5, small grey dots other CMIP6 models, and large grey dots the model ensemble mean for all CMIP6 models except CanESM5 and CanESM5-CanOE.

Christian et al 2022, GMD

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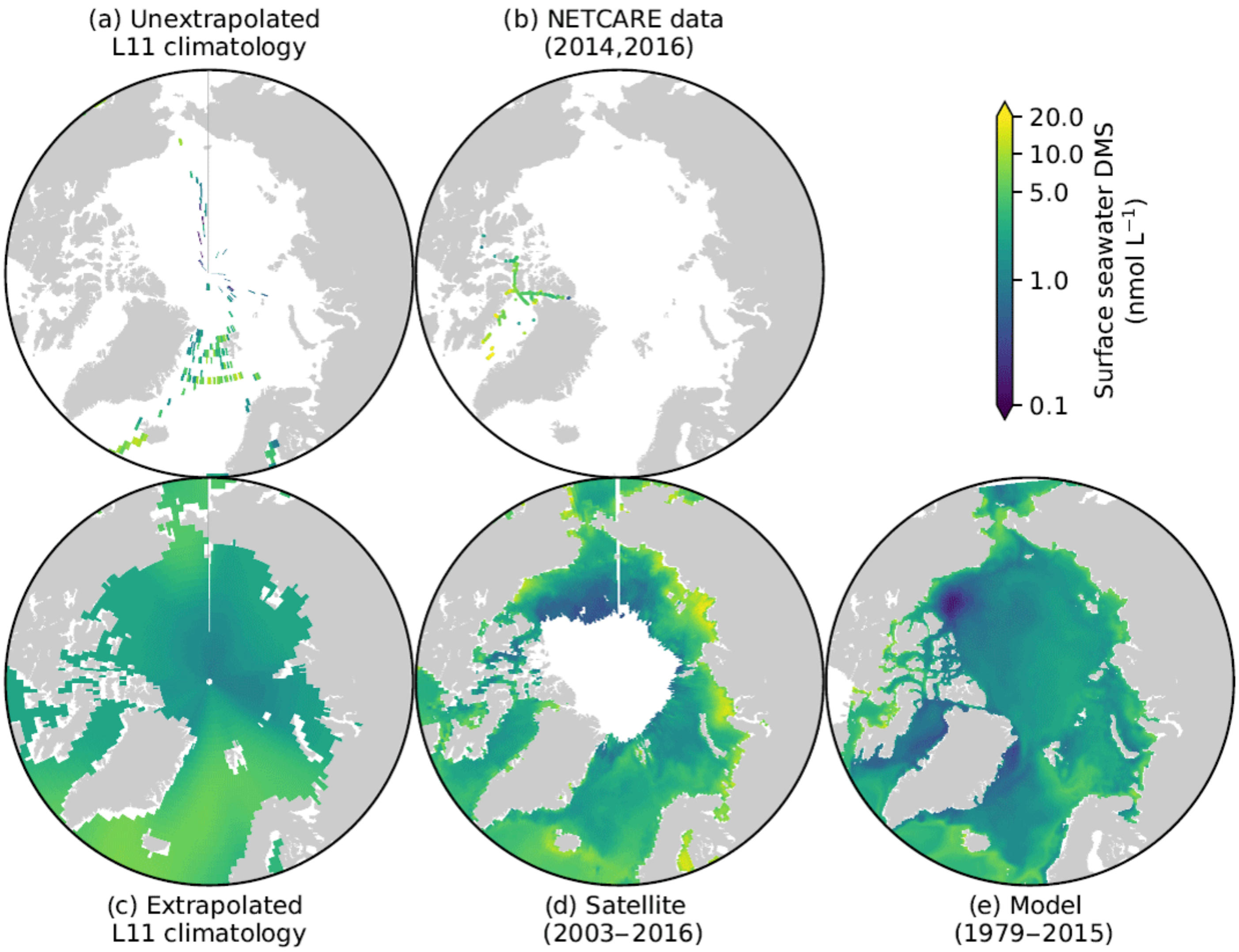


Pan-Arctic distribution of July–August concentrations of surface ocean DMS.

(a) the discrete (Lana et al., 2011) climatology

(b) the data collected during the two NETCARE field campaigns.

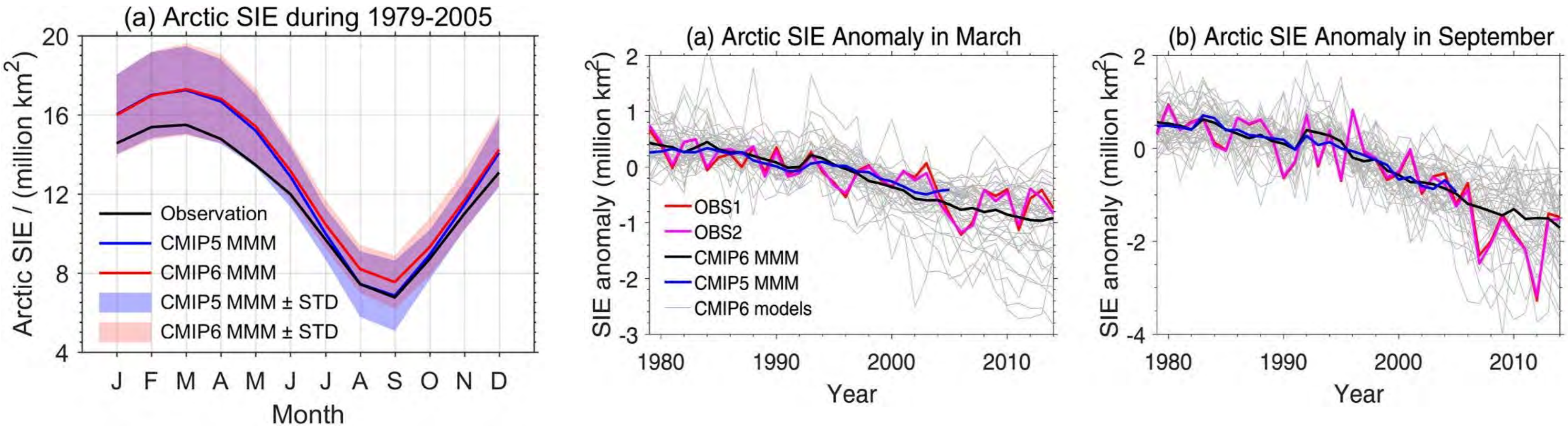
(c) observation- based (Lana et al., 2011)

(d) satellite-derived (Galí et al., 2018;

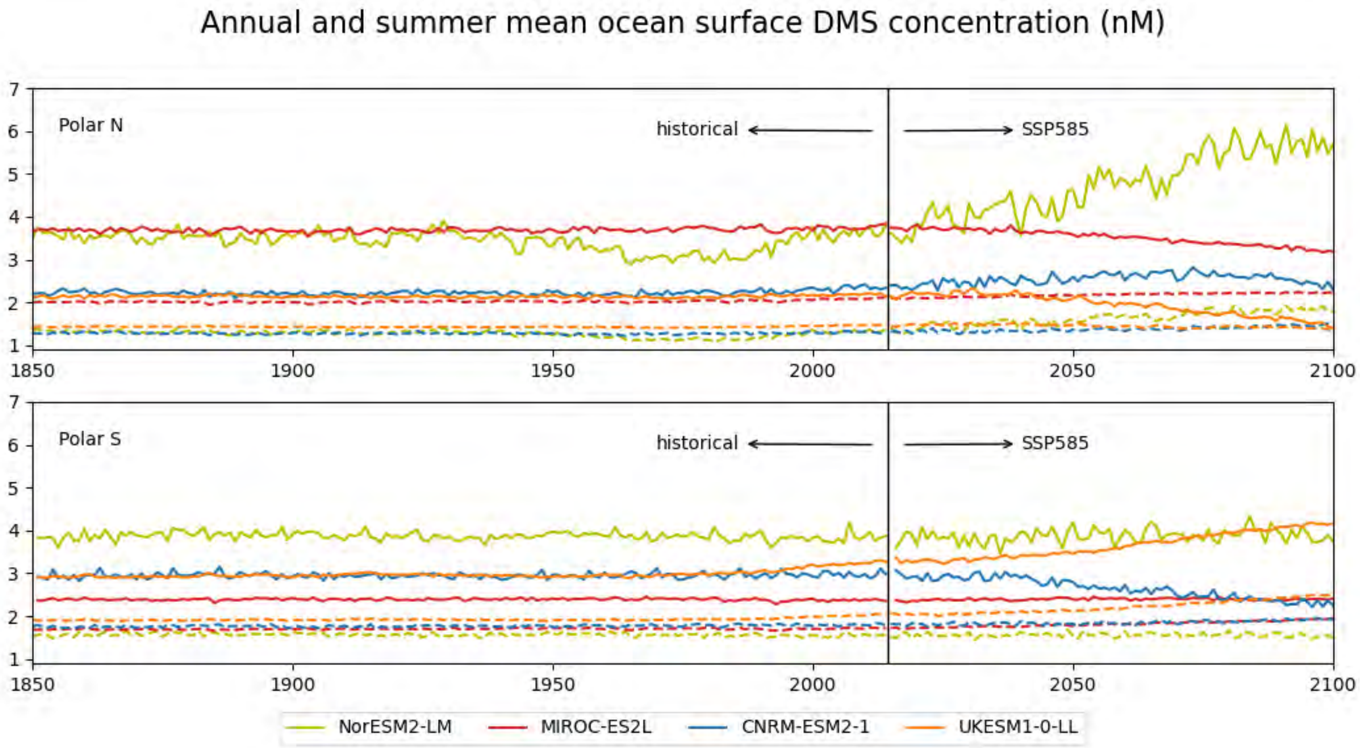
(e) model-based (Hayashida, 2018) climatologies

Abbott et al 2019, NETCARE Project, Atm Chem

CMIP6 Validation - Shu et al. 2021 – sea ice in CMIP5 & CMIP6



- Little change from CMIP5 to CMIP6 => Models reproduce seasonal cycle, CMIP6 shows slightly lower intermodal spread in SIE but larger summer bias.
- Observed Arctic September SIE decline is slightly underestimated.
- CMIP6 models did not reproduce the summer tendencies after 2000, including a faster decline in Arctic SIE – induced by spatially constrained acceleration in the pace of melt – could be internal variability



Mean ocean surface DMS concentrations from CMIP6 models for the Historical and SSP585 scenarios. Annual (dashed lines) and summer (full lines) means are shown with averages taken for the polar regions beyond 60°N and 60°S. The summer mean is computed over the summer months in the northern (June, July and August) and southern (December, January and February) hemispheres.