7th Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics - Estimating Ocean Transports: Single Sections, Box Models and Reanalysis Products

Trieste, 29 Jun – 10 Jul 2026

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Characterization of Arctic Sea Ice from satellite observations and reanalysis data

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Introducing sea ice

“Any form of ice found at sea which has originated from the freezing of seawater” (WMO, 1970).

- **Forms, grows, and melts in the ocean**, and is found primarily in Earth's polar regions.
- Sea-ice floes span a **wide range of sizes**, from centimeters to hundreds of kilometers.
- **Solid, liquid, and gaseous inclusions** determine the thermodynamic and mechanical **properties of sea ice**.
- **Seasonal sea ice** melts completely during summer, whereas **multiyear sea ice** survives one or more summer melt seasons.

Introducing sea ice

Why sea ice is important in the Earth's system?

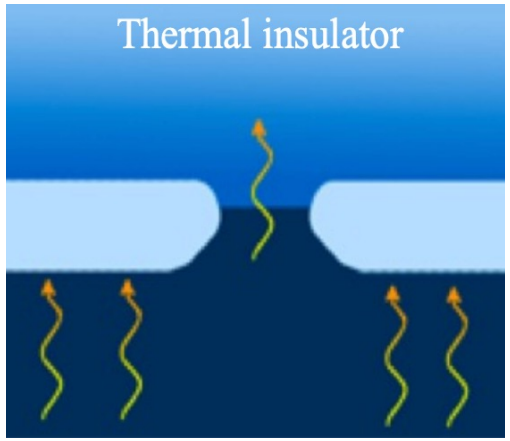
HEAT EXCHANGE – Sea ice acts as **thermal insulator**, reducing the heat exchange between the ocean and the atmosphere.

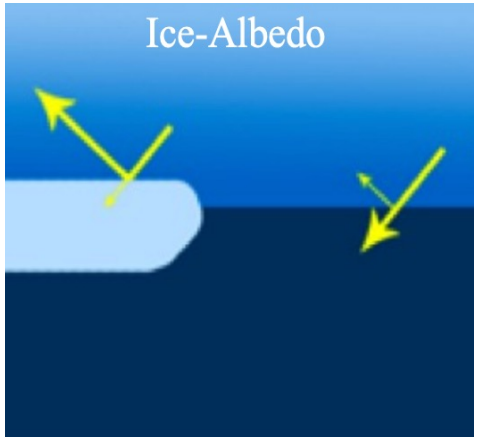
RADIATION BUDGET – Sea ice increases the ocean's **surface albedo**, limiting the absorption of incoming solar radiation.

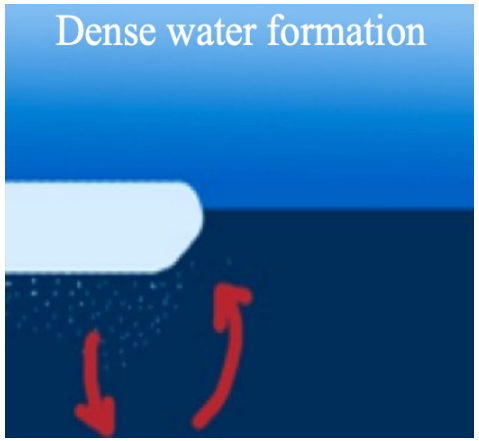
SALT/FRESHWATER BUDGET – **Brine rejection** promotes dense-water formation, influencing global ocean circulation.

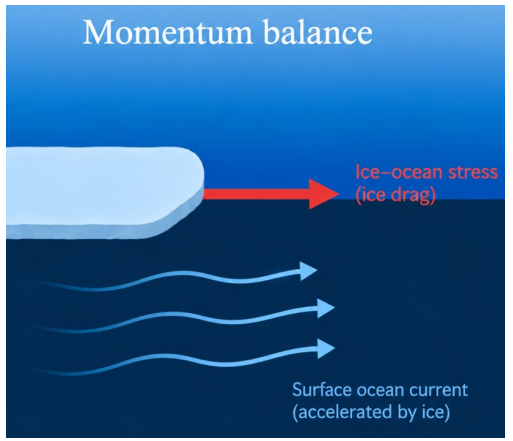
MOMENTUM BALANCE – **Ice–ocean drag** transfers momentum to the upper ocean, influencing surface currents.

ECOSYSTEM – Sea ice provides **habitat** for a wide range of species.





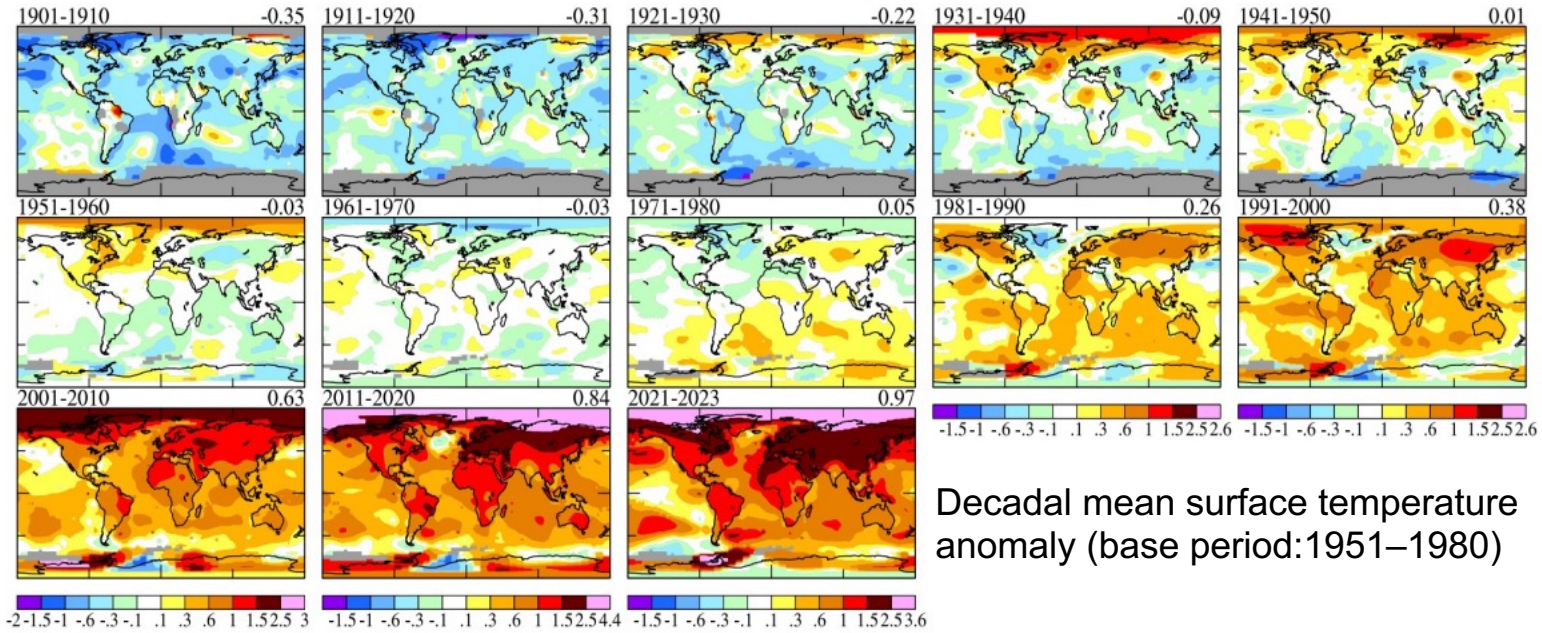




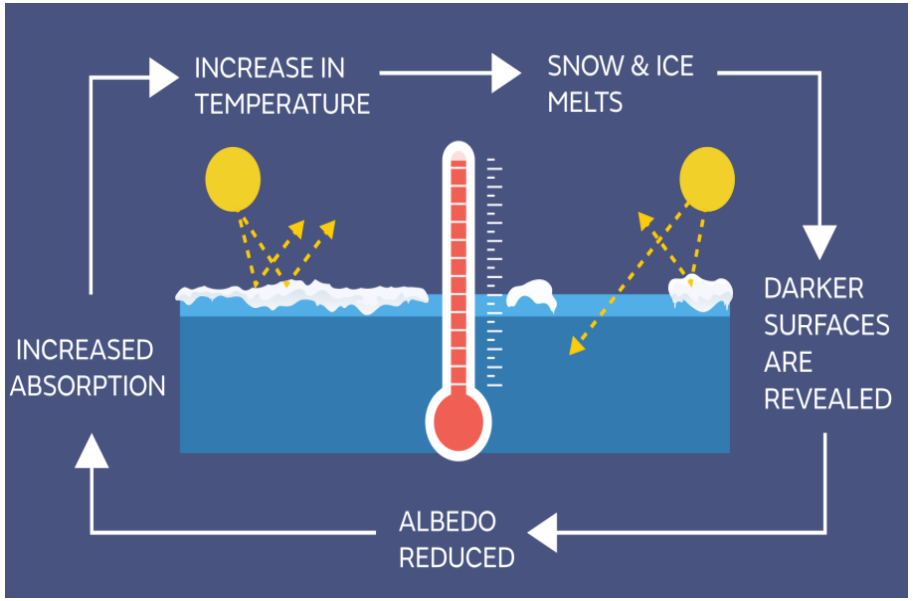
Arctic sea ice in changing climate

The Arctic sea ice is an early indicator of climate change.

- The Arctic region has warmed nearly **four times** faster than the global average.
- **Positive ice–albedo feedback** process amplifies Arctic warming.
- Small changes in the climate can produce large changes in sea ice thickness and extent.



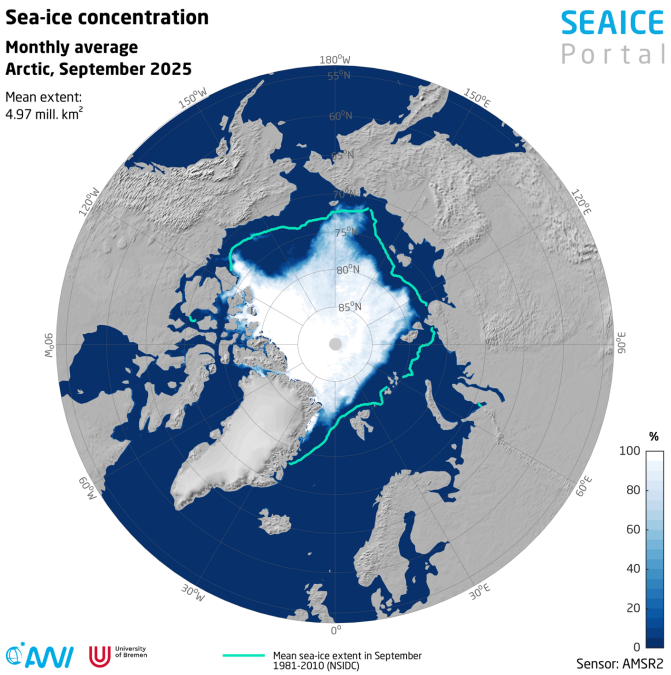
Decadal mean surface temperature anomaly (base period:1951–1980)

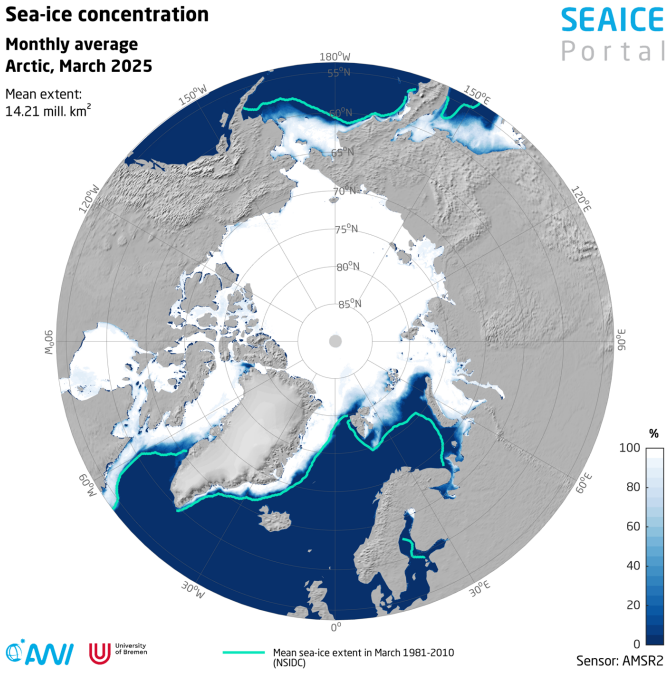


Satellite observations of Arctic sea ice

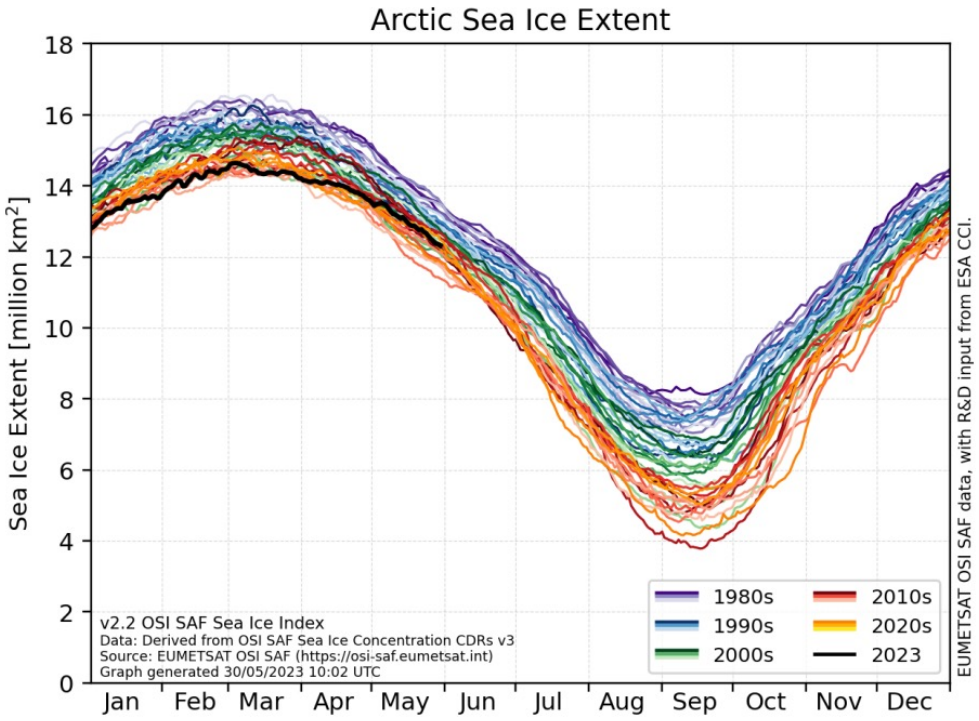
Observing arctic sea-ice cover

Arctic sea ice experiences a seasonal cycle that has its minimum in September and its maximum in March.





Sea ice concentration (C) is the relative cover of ice within a given satelite pixel (grid cell)

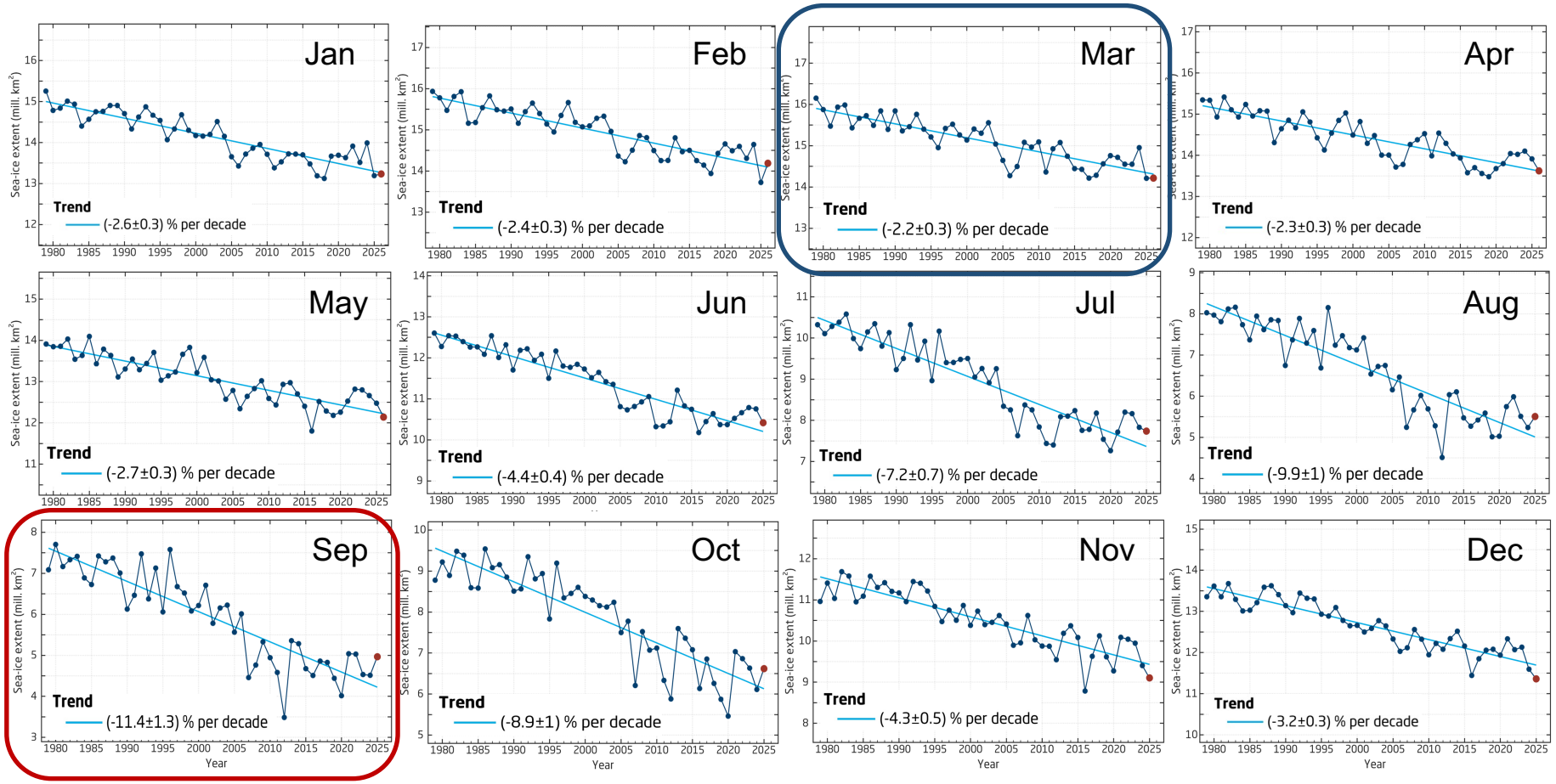


The sea-ice extent (SIE) is the sum of satellite grid pixel (grid cell) where sea ice concentration ≥15%

$$SIE = \sum_{i=1}^{N} A_i \cdot f(C_i) \qquad f(C_i) = \begin{cases} 1 & \text{if } C_i \geq 15\% \\ 0 & \text{if } C_i < 15\% \end{cases}$$

Observing arctic sea-ice cover

The monthly trends in SIE reveal heterogeneous sea-ice contraction, most pronounced in September.



Observing arctic sea-ice cover

Ice concentration-based satellite observations are highly consistent in capturing climate signal (trend and variability).

Intercomparison of passive microwave sea ice concentration retrievals over the high-concentration Arctic sea ice

Søren Andersen,[1] Rasmus Tonboe,[1] Lars Kaleschke,[2] Georg Heygster,[3] and Leif Toudal Pedersen[4]

Received 13 Februa

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Satellite passive microwave sea-ice concentration data set inter-comparison for Arctic summer conditions

Stefan Kern[1], Thomas Lavergne[2], Dirk Notz[3], Leif Toudal Pedersen[4], and Rasmus Tonboe[5]

[1]Integrated Climate Data Center (ICDC), Center for Earth Syste
University of Hamburg, Hamburg, Germany
[2]Research and Development Department, Norwegian Meteorolog
[3]Institute for Marine Research, University of Hamburg and Max
[4]Danish Technical University, Lyngby, Denmark
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Received: 27 January 2020 – Discussion started: 20 February 202
Revised: 25 May 2020 – Accepted: 14 June 2020 – Published: 28

Abstract. We report on results of a systematic inter-comparison of 10 global sea-ice concentration (SIC) data products at 12.5 to 50.0 km grid resolution from satellite passive microwave (PMW) observations for the Arctic during summer. The products are compared against SIC and net ice surface fraction (ISF) – SIC minus the per-grid-cell melt pond fraction (MPF) on sea ice – as derived from MODerate

Satellite passive microwave sea-ice concentration data set intercomparison: closed ice and ship-based observations

Stefan Kern[1], Thomas Lavergne[2], Dirk Notz[3], Leif Toudal Pedersen[4], Rasmus Tage Tonboe[5], Roberto Saldo[4], and Atle MacDonald Sørensen[2]

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Estimating the uncertainty of sea-ice area and sea-ice extent from satellite retrievals

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Revised: 2 April 2024 – Accepted: 14 April 2024 – Published: 17 May 2024

Abstract. The net Arctic sea-ice area (SIA) can be estimated from the sea-ice concentration (SIC) by passive mi-

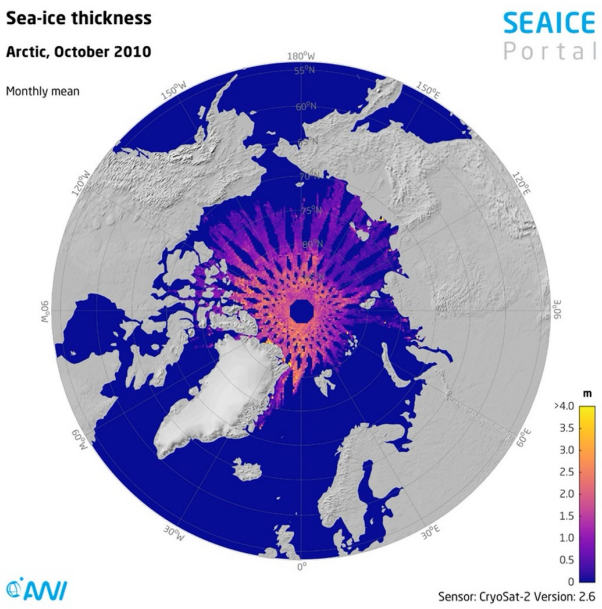
1 Introduction

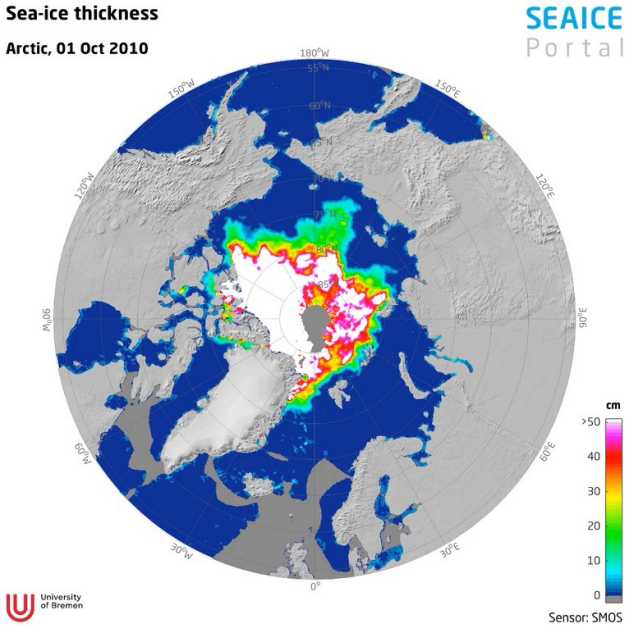
2019

l Antarctic (2.5 % to 3.1 %) than for group

Observing Arctic sea-ice thickness

Quantifying sea-ice thickness remains a major challenge in satellite remote sensing.

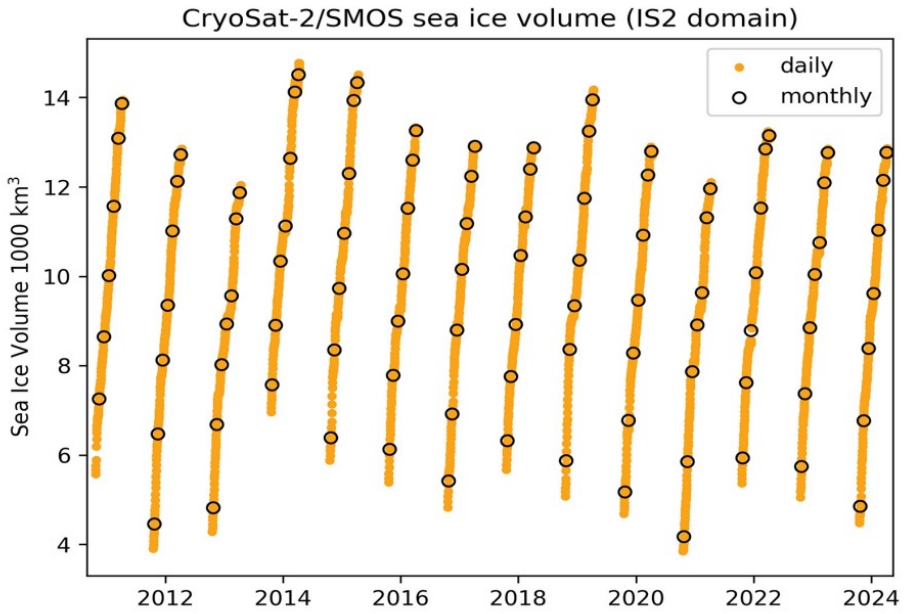




SEASONAL RESTRICTION – Observations available only **Oct–Apr** due to summer melt pond interference.

SHORT DATA RECORD – Continuous time-series are only available **from 2010 onwards**.

METHODOLOGICAL UNCERTANTIES – High sensitivity to **retrieval and post-processing techniques**.



Arctic sea ice through ocean reanalyses

Ocean reanalyses

Ocean reanalyses integrate models and observations to provide consistent 3D reconstructions of ocean and sea ice states.

- **Continuity in time and space –** Physically consistent fields without data gaps.
- **Unobserved or inadequately observed variables –** e.g. sea-ice thickness.
- **Consistent climate baseline –** More than 30 years of data for long-term trend and variability analysis.
- **Coupled physical framework –** Link sea-ice dynamics and underlying ocean properties.
- **Regional and global products –** Arctic-focused reanalyses (PIOMAS, TOPAZ)

GREP – a global ocean ensemble approach

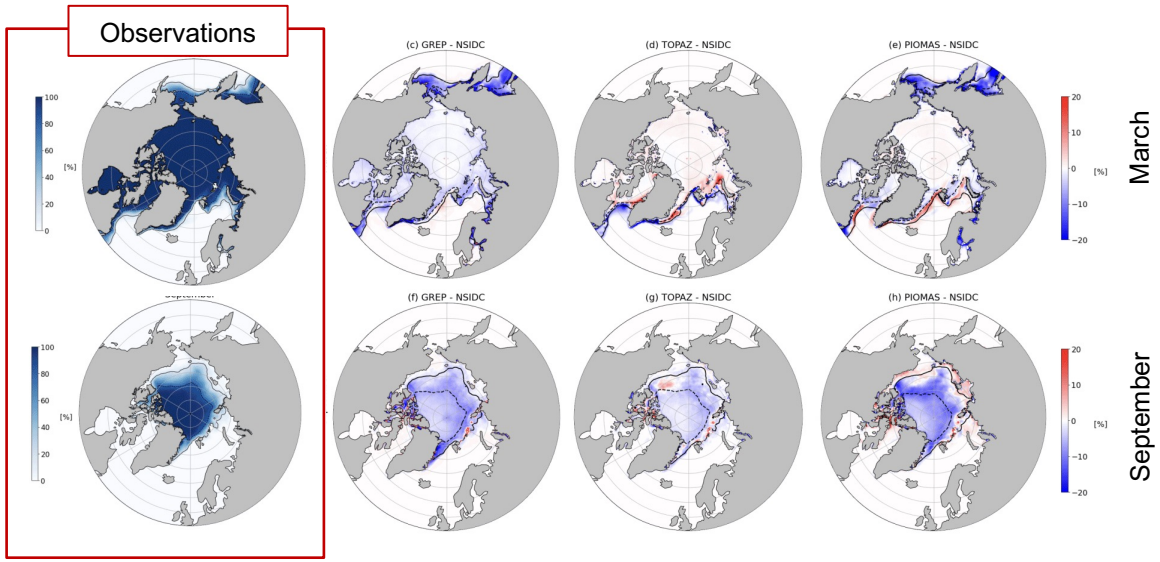
GREP (Global ocean Reanalysis Ensemble Product) is provided by Copernicus Marine Service.

- GREP is composed of **four ensemble members** and is available from 1993 onward.
- The ensemble members run on the **global tri-polar ORCA025 grid** (1/4° horizontal resolution and 75 vertical levels).
- Global ocean reanalysis are applied mainly for ocean applications; however, their outputs includes also **sea-ice concentration and thickness**.

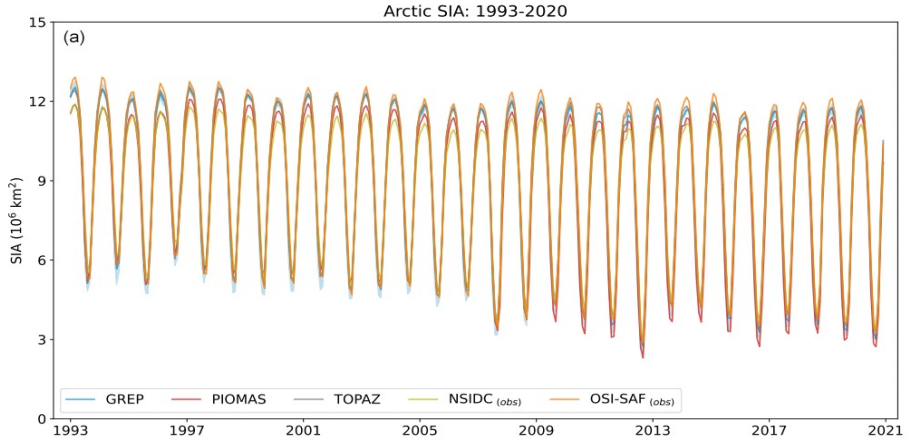
GREP member	C-GLORSv7	GLORYS2v4	ORAS5	FOAM-GloSea5v13
Institution	CMCC	Mercator Océan	ECMWF	UK Met Office
Ocean - sea ice model	NEMO 3.6 – LIM 2 (EVP rheology)	NEMO 3.1 – LIM 2 (EVP rheology)	NEMO 3.4 – LIM 2 (VP rheology)	NEMO 3.2 – CICE 4.1 (EVP rheology)
Time period	1986 - 2024	1993 - 2024	1976 - 2024	1993 - 2020
Sea ice data assimilation method	Linear nudging	Refused order KF (SEEK)	3DVAR - FGAT	3DVAR
Ocean data assimilation method	3VAR (7 days)	SAM2 (SEEK) (7 days)	3DVAR-FGAT (5 days)	3DVAR (1 days)
Sea ice product for DA	Sea ice concentration OSI SAF: OSI-450-a 25 km	Sea ice concentration CERSAT 12.5 km	Sea ice concentration OSTIA 0.05°	Sea ice concentration OSI SAF: OSI-450-a 25 km
Ice thickness categories	1	1	1	15
Reference	Storto et al. (2015)	Lellouche et al. (2013)	Zuo et al. (2019)	MacLachlan et al. (2014)

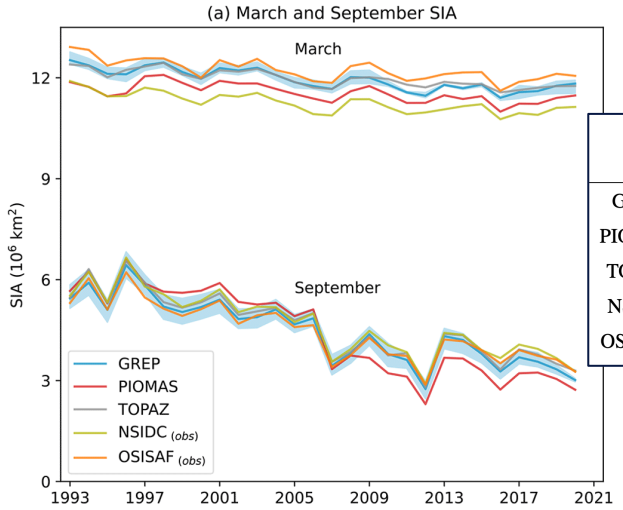
Sea-ice cover in GREP

GREP aligns well with regional reanalyses and satellite observations in capturing SIC-based metrics.



Cocetta et al. (2024)





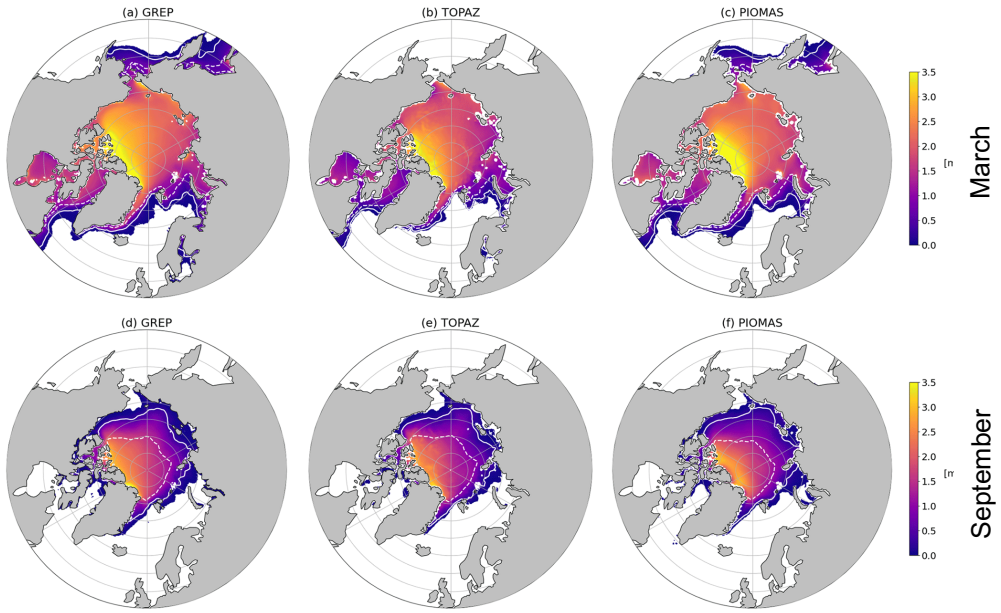
	March 10^6 km^2/decade	September 10^6 km^2/decade	Annual 10^6 km^2/decade
GREP	-0.31 ± 0.04	-1.03 ± 0.11	-0.68 ± 0.19
PIOMAS	-0.23 ± 0.05	-1.42 ± 0.13	-0.77 ± 0.18
TOPAZ	-0.26 ± 0.03	-1.03 ± 0.11	-0.63 ± 0.19
NSIDC	-0.28 ± 0.04	-0.99 ± 0.11	-0.62 ± 0.16
OSI SAF	-0.28 ± 0.05	-0.90 ± 0.10	-0.61 ± 0.19

The sea-ice area (SIA) is the sum of each grid cell's area weighted by its sea-ice concentration

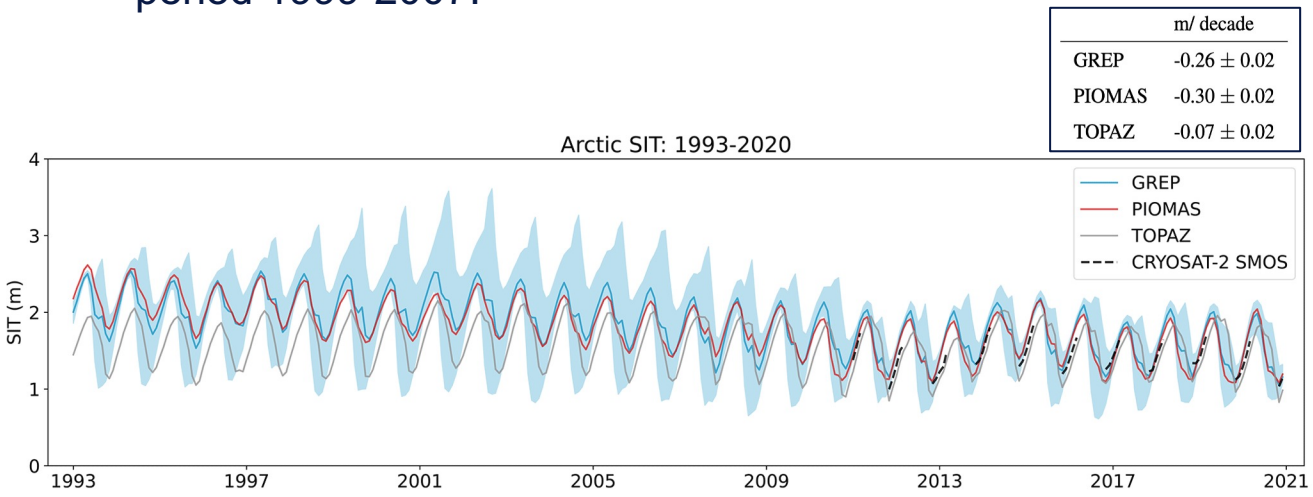
$$SIA = \sum_{i=1}^{N} A_i \cdot C_i \qquad 0 \leq C_i \leq 100$$

Sea-ice thickness in GREP

GREP effectively resolves the seasonal and multi-annual evolution of SIT, as regional reanalyses.



- The time series of total Arctic SIT displays minima in November and maxima in May; with negative interannual trend.
- Thickening phase in the reanalyses agree with available observations.
- GREP ensemble approach allows good agreement with PIOMAS despite spread among members is large in period 1999-2007.



The average Sea-Ice Thickness (SIT) is calculated as the grid-cell area-weighted mean based on effective sea-ice fractional coverage.

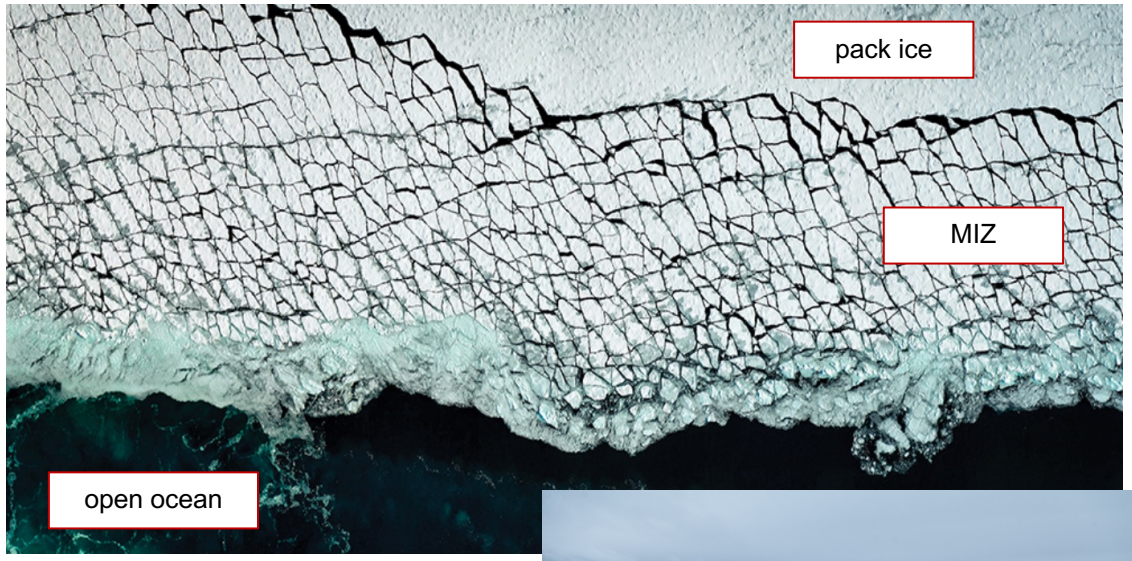
Advancing Arctic sea ice research with global ocean reanalyses

The Arctic Marginal ice Zone

The GREP framework can be leveraged for further investigations into Arctic sea ice.

The Arctic Marginal Ice Zone is the **transition region** between the consolidated ice (pack ice) and the open ocean.

- The sea ice in the MIZ is fragmented and mobile.
- **Strong dynamical interactions** of sea ice with waves, ocean currents, and storms shape the sea ice floes.
- Biologically active environment characterized by **intense ocean-atmosphere fluxes**.
- Operatively defined as the region where **sea-ice concentration is between 15% and 80%**.



Peng et al., 2008

The MIZ expansion

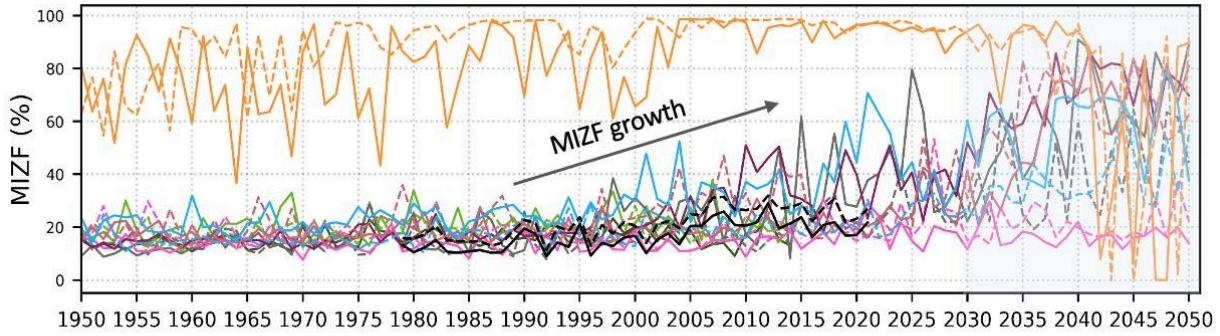
The widening of the Marginal Ice Zone shapes the evolution of the Arctic sea ice state.

Rapid MIZ Expansion – Advancing at the expense of pack ice, with projections suggesting MIZ dominance by 2050.

Arctic Ice Transformation – Shifting the properties of sea ice cover toward thinner, more seasonal, and highly heterogeneous conditions.

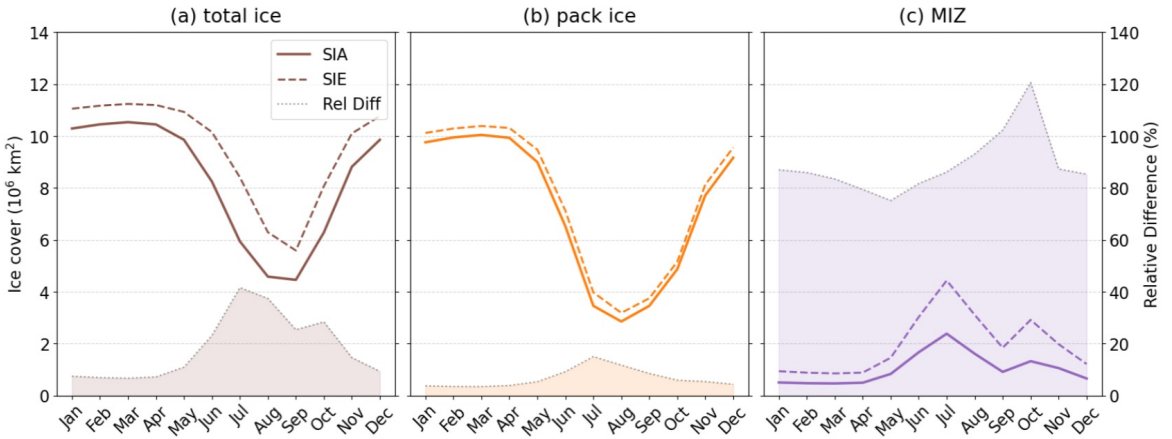
Diagnostic Limitations – Challenging the reliability of traditional metrics originally developed for thick, compact ice (cf. SIE).

Selivanova et al. (2024)



The marginal ice zone fraction (MIZF) is defined as the ratio of MIZ SIA to total SIA

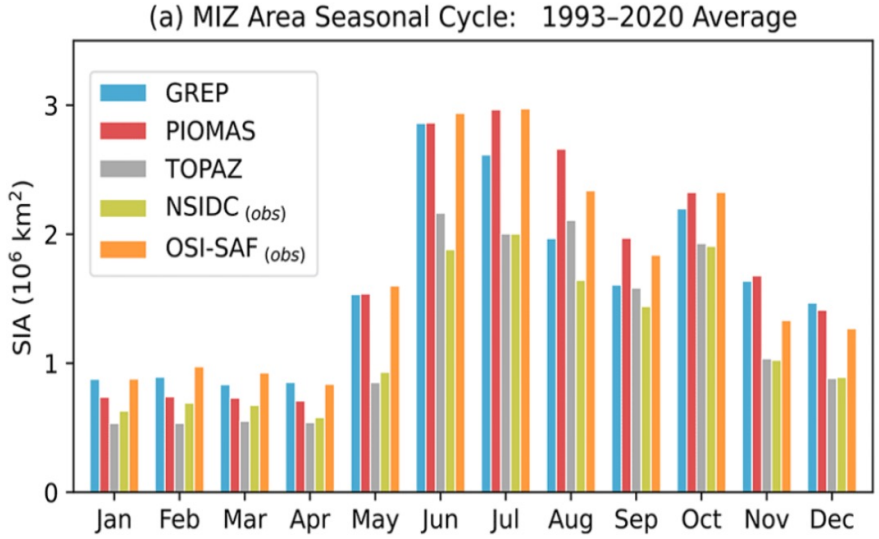
$$MIZF = \frac{SIA_{MIZ}}{SIA_{tot}}$$



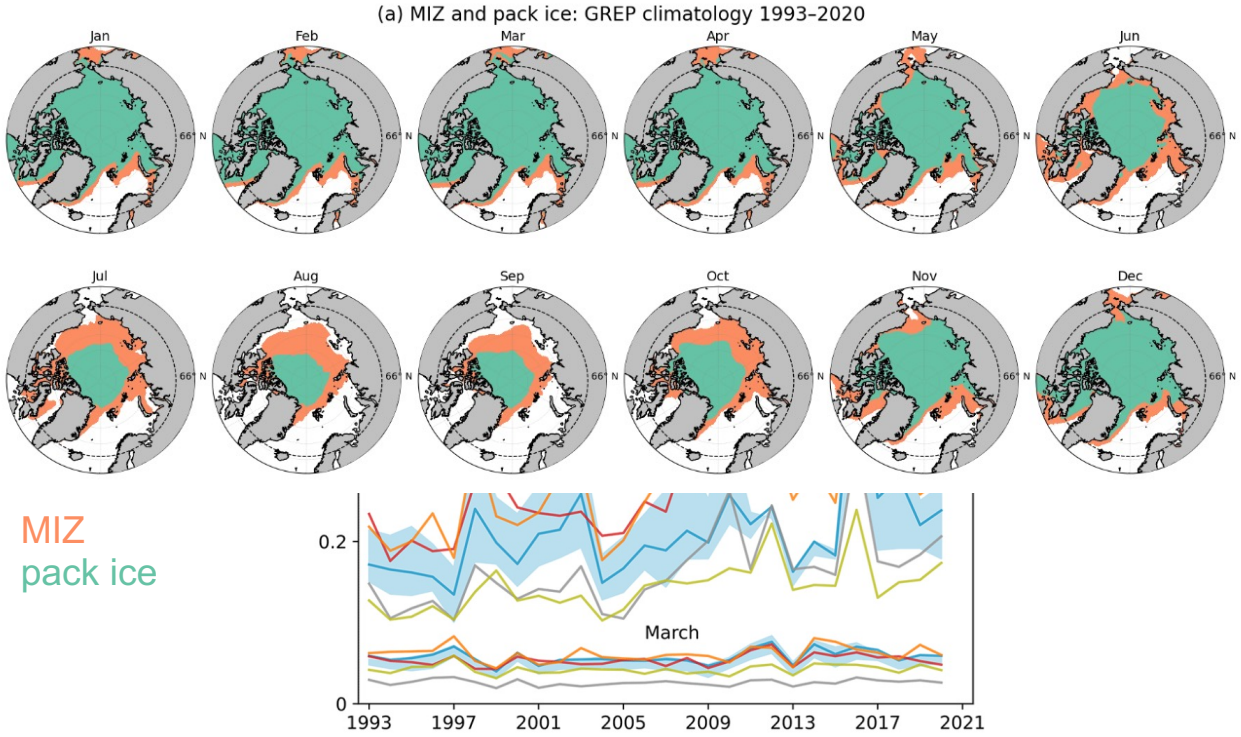
Characterizing the MIZ

The seasonal cycle and monthly trends in SIA differ between total ice and MIZ.

- **Two peaks** and an **extened minimum** characterize the SIA of the MIZ.
- **Difference among products** (observations and reanalyses) is larger compared to that of pack ice.



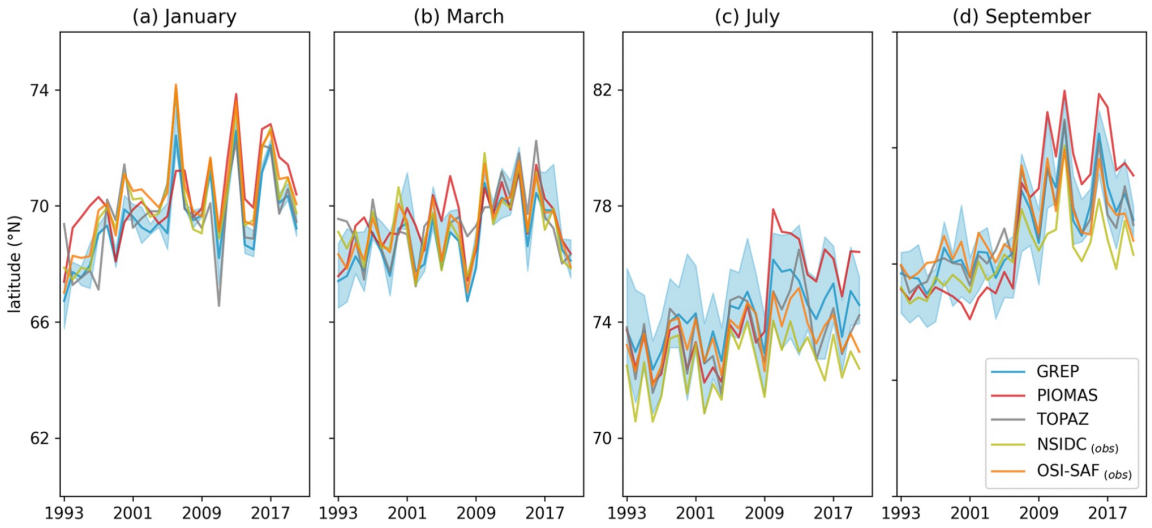
- **Positive inter-annual trend** between May and Decemberi in MIZF, in contrast with the declining total sea ice area.



MIZ location over the years

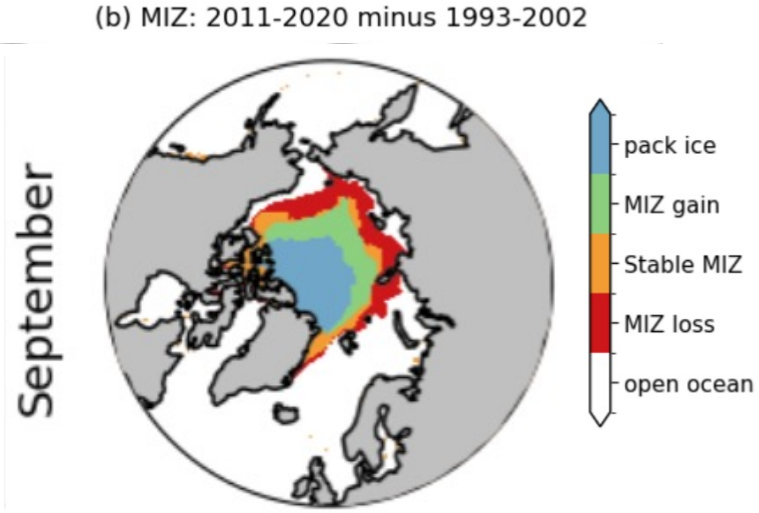
The MIZ is simultaneously expanding and moving Northward.

- The average latitude of MIZ indicated that the **fastest movement occurs in September**.



GREP	January	March	July	September
°/decade	1.00 ± 0.28	0.69 ± 0.24	0.70 ± 0.20	1.42 ± 0.25

- Northward migration occurs since **pack ice transitions to MIZ** and **simultaneous conversion of MIZ to open ocean.**
- In September, the MIZ region has migrated almost entirely northward, with stable MIZ region barely visible (orange) and large new open ocean areas (red).

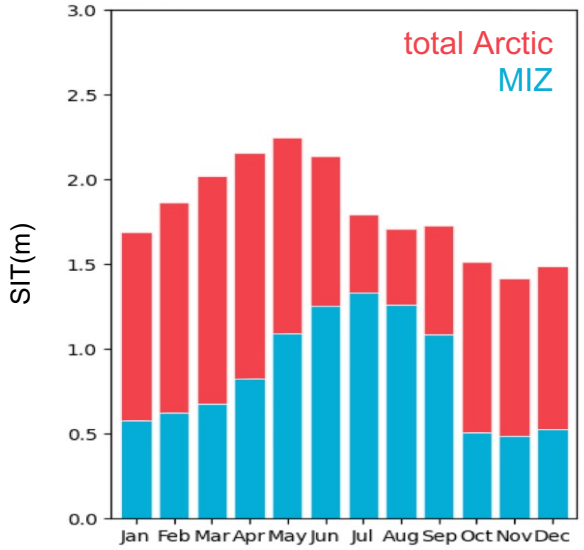


Sea ice thickness in the MIZ

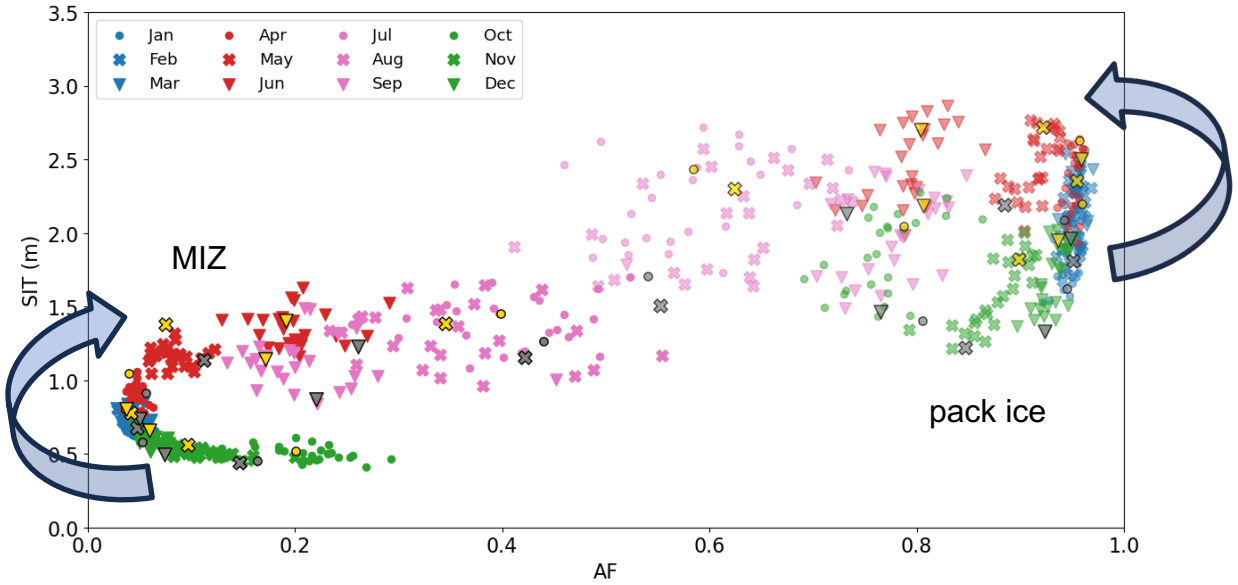
The average SIT in the MIZ has different seasonal variability compared to that of pack ice.

Seasonal Phase Shift – Maximum ice thickness occurs in May for the total Arctic, while it is delayed in summer (July) within the MIZ.

Rapid Autumn Decline – Abrupt thinning in autumn (October) results in a widespread spatial minimum across the MIZ.



- Plotting average SIT against MIZ and pack-ice significance reveals **two distinct Arctic regimes**.
- The **clockwise and counter-clockwise trajectories** distinguish the two ice types, which **converge** during the September minimum.
- Arrows connecting the start (yellow) and end (grey) years of the time series highlight the **long-term tendency of both regimes to converge** toward the center of the scatter space.

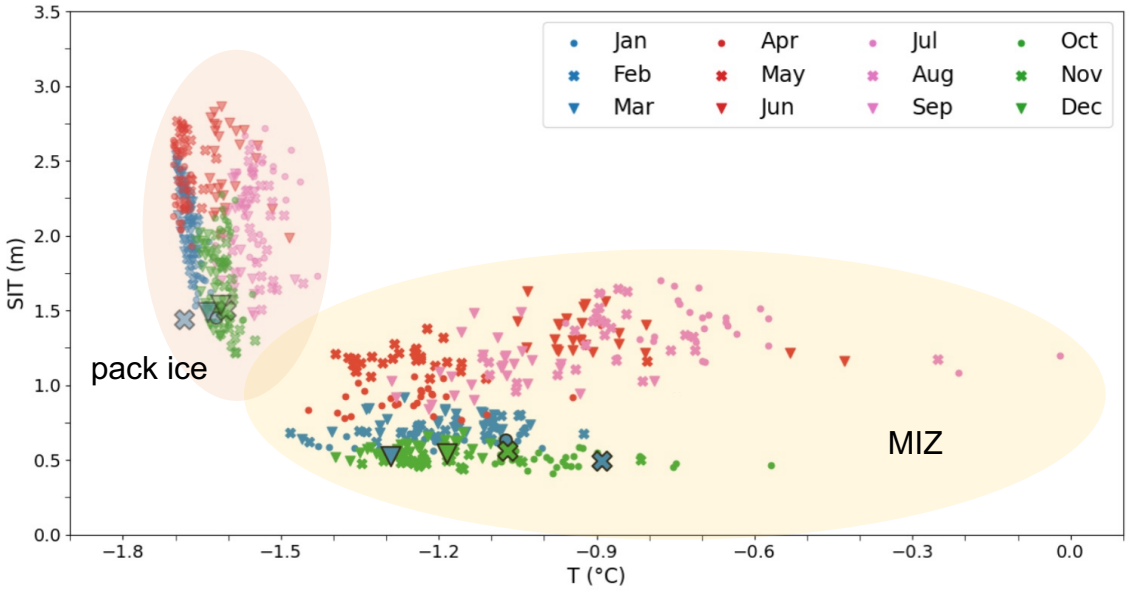


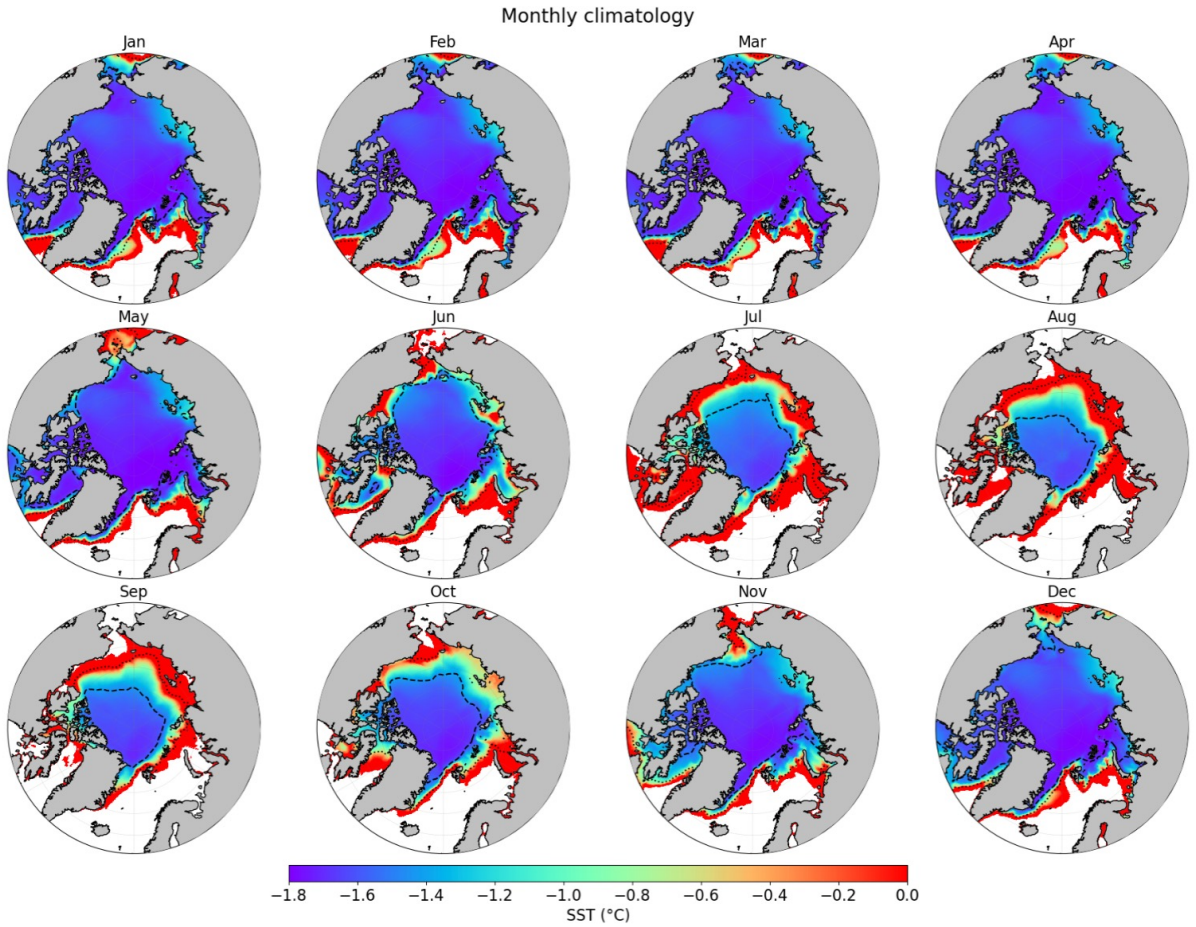
Cocetta et al. (in prep.)

Ocean temperature below sea ice

The characterization of Arctic regimes is enhanced by integrating under-ice ocean temperature.

- Ocean-sea ice reanalyses are ideal for this integrated perspective, as they provide **physically coherent fields.**
- The under-ice ocean temperature (extracted from the first level of the ocean model) is linked with average SIT.

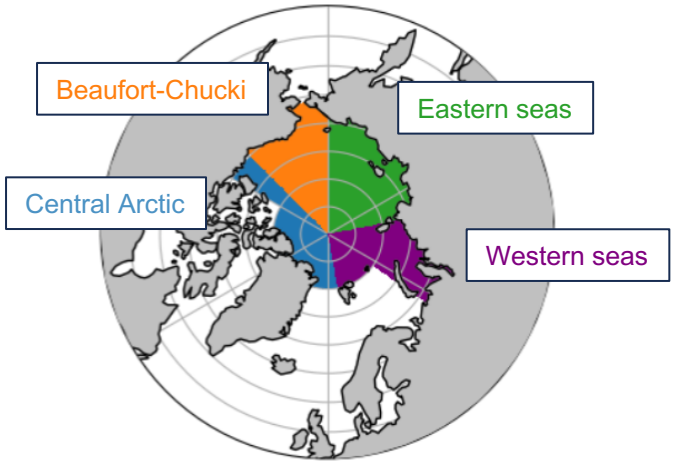


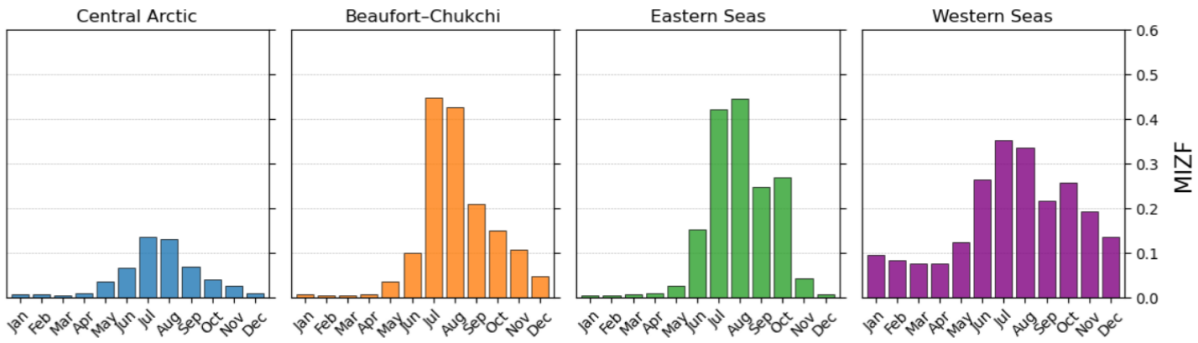


A regional analysis of Arctic sea ice

The strong spatial heterogeneity of sea ice and upper-ocean properties motivates a regional analysis.

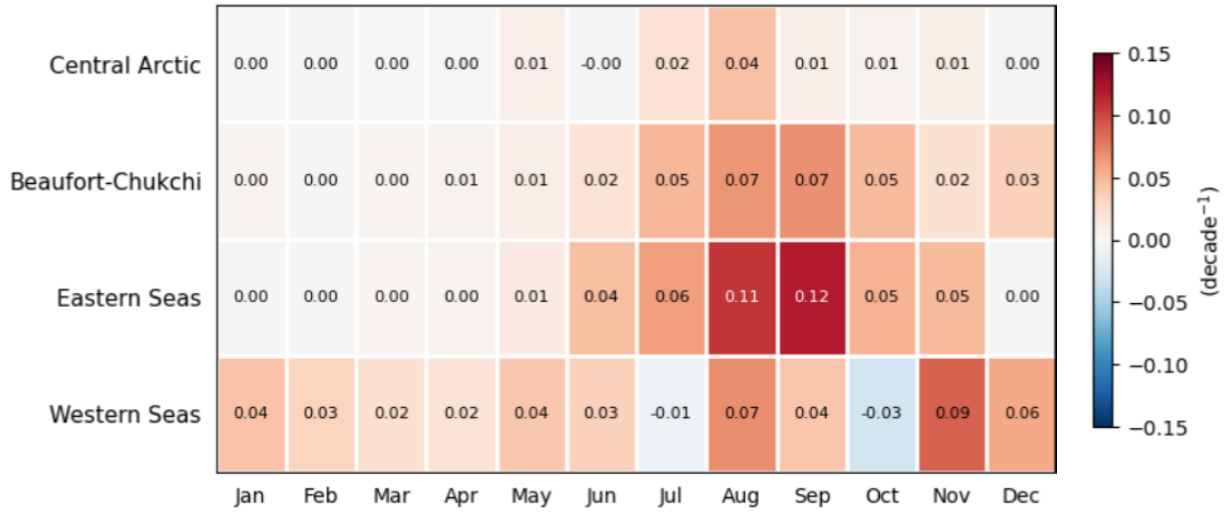
- The choice of Arctic Ocean sectors reflects the **regional variability in the MIZF seasonal cycle.**
- The Central Arctic and Western Seas represent opposite MIZ seasonality.





The regional study quantifies the **monthly MIZF trends** in each Arctic sector, highlighting their seasonal and spatial variability:

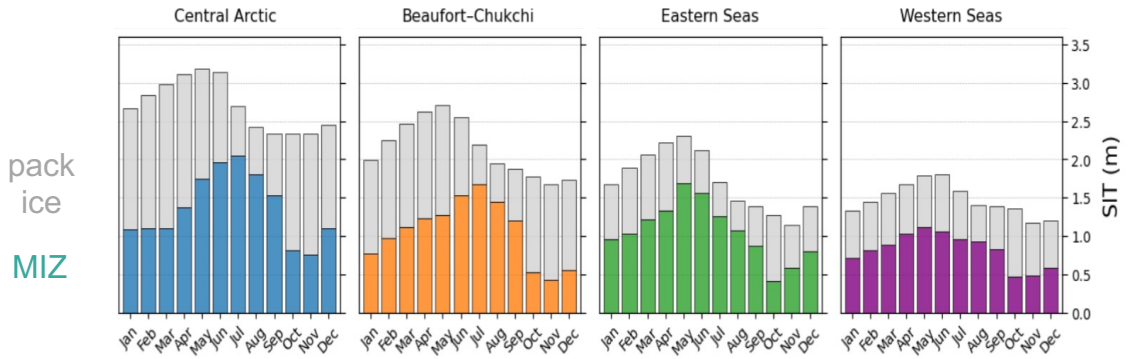
- All sectors show an **increase in MIZ significance during summer**, while Western Seas exhibit this trend througout the year.
- Eastern seas display the maximum increase in MIZF (more than 10%/decade).

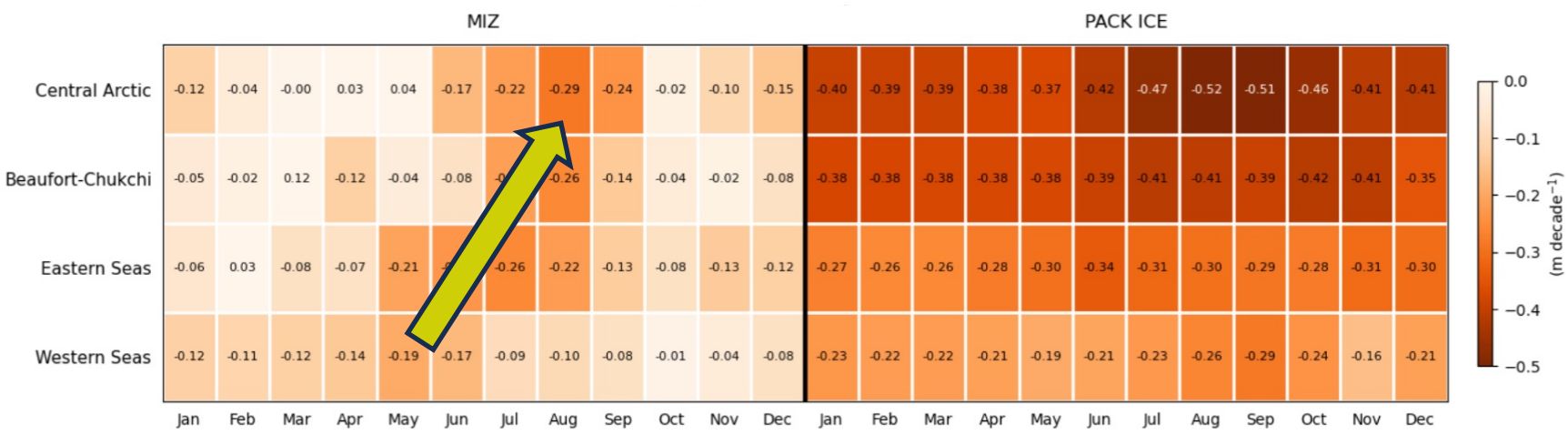


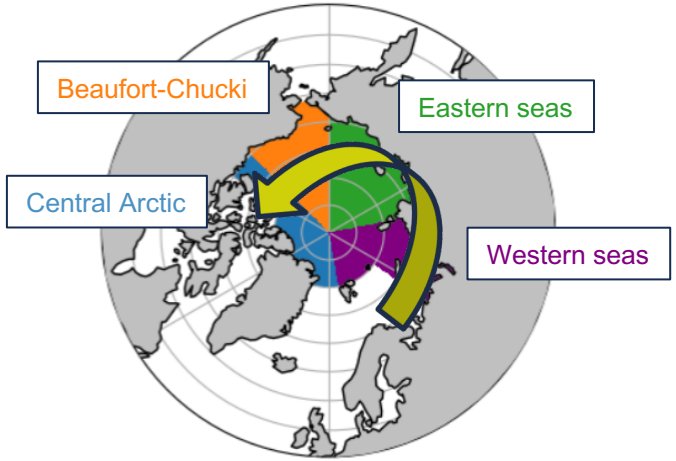
A regional analysis of Arctic sea ice

Selected Arctic sectors are characterized by decreasing in SIT going from Central Arctic toward marginal seas.

- **Seasonal cycle in SIT** is similar across sectors for pack ice, whereas differences arise in MIZ.
- **Sea ice thinning** is observed in all sectors for pack ice and MIZ, exceeding 0.5 m/decade in Central Arctic in summer pack ice.
- **Maximum monthly SIT trends** within the MIZ are temporally and geographically aligned with the path of Atlantic inflow.



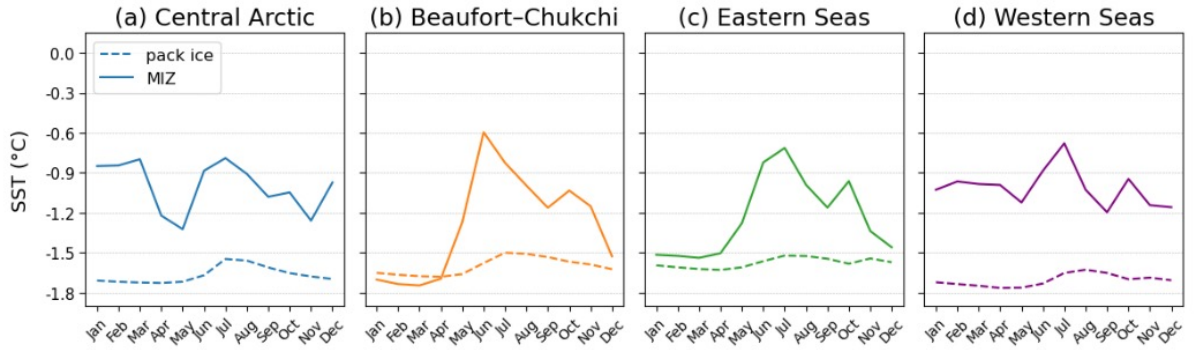


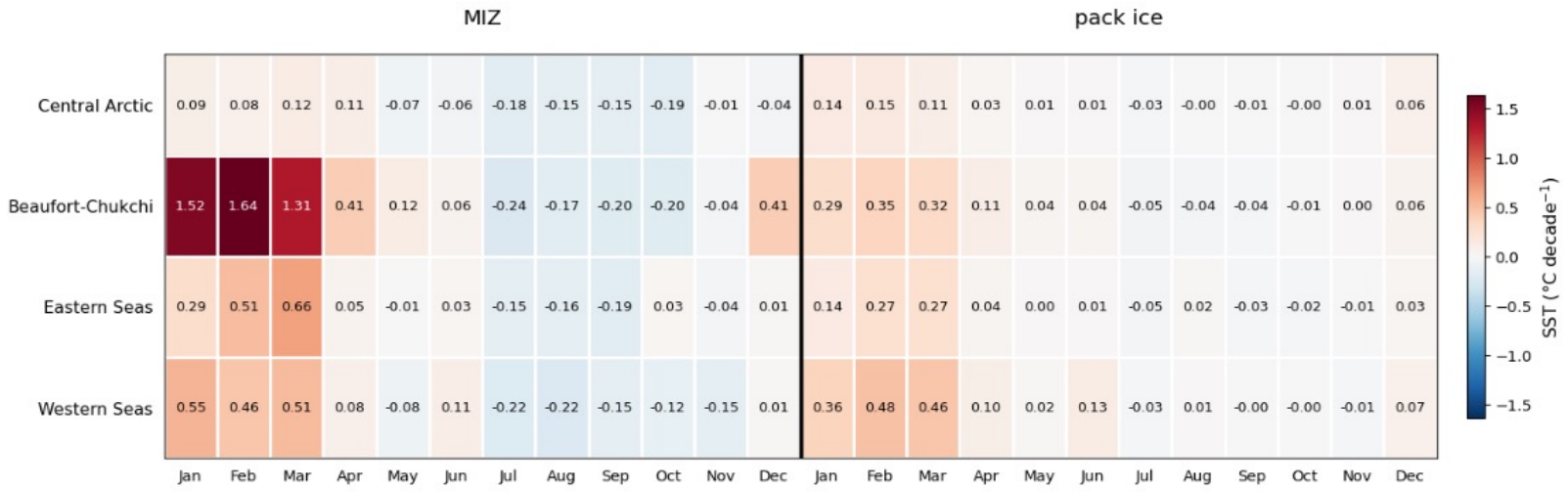


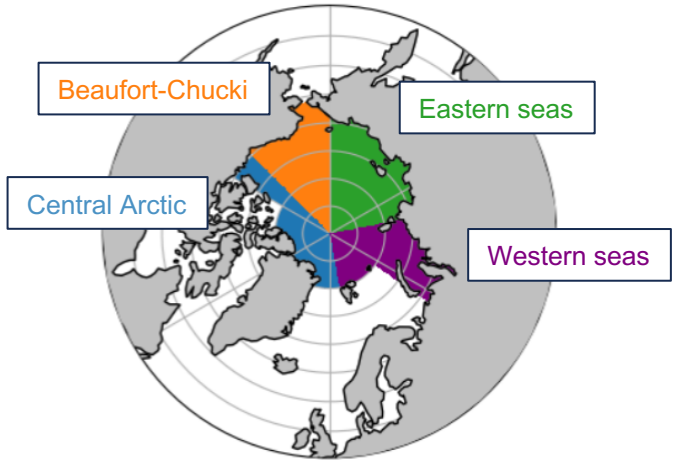
A regional analysis of Arctic sea ice

Under-ice ocean temperature beneath sea ice increases in winter and decrease in summer.

- **Under-ice temperature seasonality** shows large spatial variability within MIZ compared to ocean temperature below pack ice.
- **Monthly decadal trends** are driven by the MIZ expansion and its northward migration, allowing increased ocean-to-atmosphere heat flux.







Take home messages

- Discrepancies among SIT observations in the MIZ, combined with observational challenges during the melting season, reinforce the value of **global ocean-sea ice reanalysis for Arctic sea ice characterization**.

- The **crucial role of the MIZ in climate projections** necessitates updating traditional diagnostic metrics, as well as existing sea ice models that were historically developed and tuned for consolidated sea ice.

- **Integrated ocean-sea ice analysis** enables to distinguish between pack ice and MIZ. However, the increasing summer similarities between the two regimes suggest that the seasonal evolution of Arctic sea-ice variability is transitioning from being pack-ice driven to being governed by seasonal and MIZ regimes.

- The four-sectors regional framework highlights that no single region represents pan-Arctic conditions. The **MIZ is highly sensitive to regional dynamics**, leading to strong contrasts in seasonal and inter-annual evolution across sectors.

Thanks!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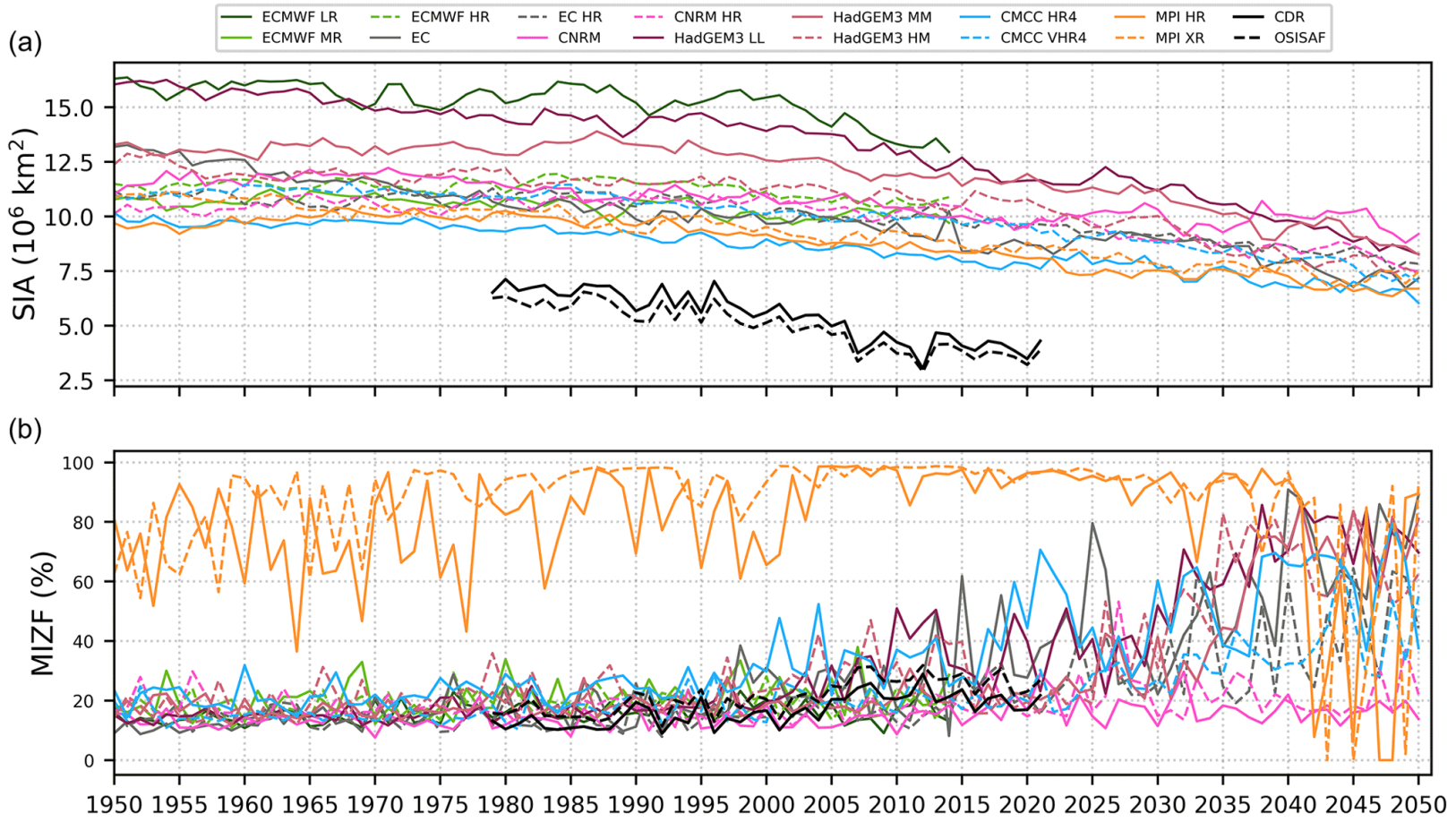
(a) GREP ensemble mean
total ice
pack ice
MIZ
SIT (m)
(b) Pack ice: GREP members minus GREP ensemble mean
CGLORS
ORAS5
GLORYS2
FOAM-GloSea5
SIT (m)
(c) MIZ: GREP members minus GREP ensemble mean
SIT (m)
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

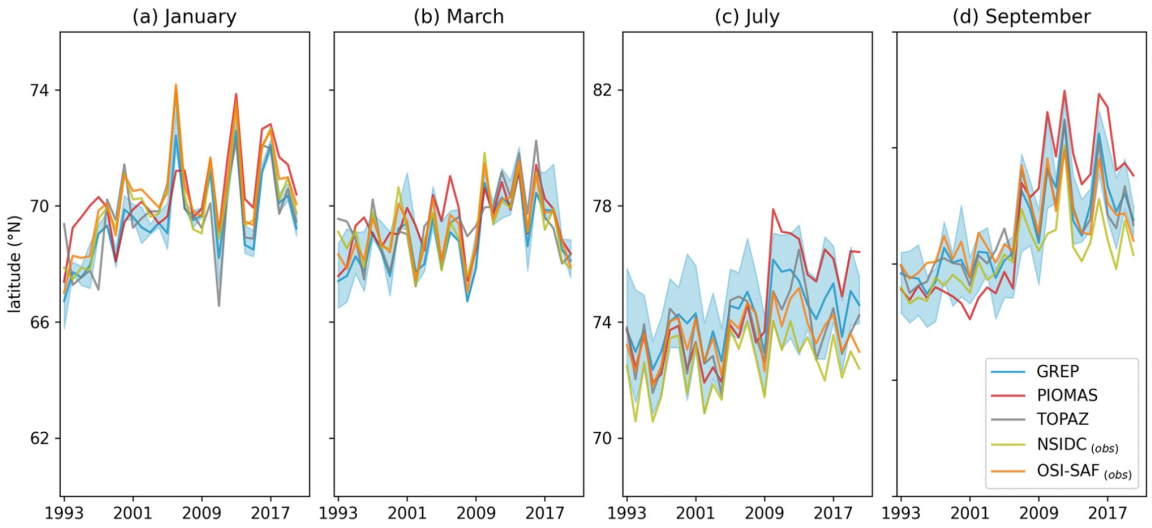
HiResMIP


ECMWF LR
ECMWF MR
ECMWF HR
EC
EC HR
CNRM
CNRM HR
HadGEM3 LL
HadGEM3 MM
HadGEM3 HM
CMCC HR4
CMCC VHR4
MPI HR
MPI XR
CDR
OSISAF
(a)
SIA (10^6 km^2)
15.0
12.5
10.0
7.5
5.0
2.5
(b)
MIZF (%)
100
80
60
40
20
0
1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050

MIZ location over the years

The MIZ is simultaneously expanding and moving Northward.

- The average latitude of MIZ indicated that the fastest movement occurs in September



GREP	January	March	July	September
°/decade	1.00 ± 0.28	0.69 ± 0.24	0.70 ± 0.20	1.42 ± 0.25

- Comparing the **2011–2020** and **1993–2002** decades reveals that the rise in average latitude occurs from **pack ice transitioning to MIZ** and simultaneous conversion of MIZ to open ocean
- In September, the MIZ region migrates almost entirely northward, with the stable MIZ barely visible (orange) and large new open ocean areas (red)