CLIVAR REPORT

Climate and Ocean: Variability, Predictability, and Change

Workshop Report

Final Report on the NORP-SORP Workshop on polar fresh water: Sources, Pathways and ImpaCts of frEsh water in northern and soUthern Polar oceans and seas (SPICE UP)

Online, 19-21 September (3 half-days), 2022

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WCRP World Climate Research Programme
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1. Description

The workshop on polar fresh water: Sources, Pathways and ImpaCts of frEsh water in northern and soUthern Polar oceans and seas (SPICE UP), co-organized by the CLIVAR/CliC Northern Oceans Region Panel (NORP) and CLIVAR/CliC/SCAR Southern Ocean Region Panel (SORP), was successfully held on 19th-21st September, 2022. More than 140 participants from 21 countries participated this workshop.

Fresh water is a key player in the polar oceans setting stratification and water mass properties. In both hemispheres, export and transport of fresh water—liquid and solid— driven by the large-scale ocean and atmospheric circulation has a tremendous influence on branches of the meridional overturning circulation. Fresh water processes are strongly affected by global climate change. The fresh water-associated feedback via the atmosphere and various ocean pathways are changing.

The Arctic and the Southern Ocean are different in many ways, yet, there are similarities: the circulation is influenced by changes in regional fresh water either from river runoff or ice melt. This is exemplified by variations in the salinity-induced stratification, in turn influencing ocean circulation. In the generally quiescent Arctic with an overall strong halocline in the basin, few hotspots modify even intermediate water masses. The relative “freshness” of water (and sea ice) exported to the subpolar North Atlantic and Nordic Seas plays a key role in water mass transformation in those regions. In the Antarctic marginal seas freshwater fluxes tightly related to sea-ice formation shape strongly differing ocean conditions, which define the potential to melt ice shelves and the “flavour” of dense water masses feeding the deep overturning circulation.

To date, many of these processes are not well represented in model simulations involving the ocean. State-of-the-art climate and earth system models predict a wide range of fresh water distribution in the northern hemisphere for the later part of the current century. The rate of freshening in southern high latitudes is still unclear due to lack of knowledge and uncertainty in modelling strategies of ice-ocean interaction.

This workshop reached out to observational, modelling, remote sensing and assimilation communities to gain a holistic overview of the role of freshwater and the future evolution at high latitudes. Both regional and global ocean communities attended the workshop.

This workshop brought together for the first time bipolar ocean communities to work on outstanding scientific questions about the cycle of freshwater and its impacts. It was also a successful pilot of virtual events by taking advantage of online tools to facilitate synergies and communication among the participants. Dialogue-style keynotes featuring speakers from both poles sparked productive discussion sections. By using online editing tools, everyone could express their ideas through both oral and written forms, which improved the efficiency of interaction.

2. Logistics and experience

2.1 Logistics preparation

A large amount of preparation work was done before the beginning of the meeting. Before the workshop, the scientific committee organized more than 10 meetings to discuss the platform and format, the scientific theme and the time allocation to accommodate participants from different time zones.

The organizers, together with the keynote speakers, deliberately selected the discussion topics by themes (Annex 2). This was prepared before the registration opened, when people were asked to provide their field of expertise in fixed categories, and to provide open questions or ideas when they registered. The inputs from the participants contributed to the final discussion topics.

It was a huge challenge for the fully online meeting to allocate each session's time, considering the different time zones of the participants. Based on the information collected from the registration, organizers split the whole workshop into three main sessions, with several timeslots for each session. Registers then signed up via a Google Sheet, indicating which timeslots they could attend, and whether they would like to be the potential discussion co-moderators/note takers of each discussion session. Finally, 92 registers signed up the form, among them 13 participants volunteered to be potential discussion co-moderators. In addition, a number of Early Career Scientists volunteered to be note takers, which was an important part of the whole workshop. To make the discussion efficient, timeslots with large participant numbers were further split into several breakout rooms (Figure 1).

Speakers and moderators for each slot					
Time	**Session**	**Format**	**Breakout I / plenary**	**Breakout II**	**Breakout III**
19/09/2022 14:00:00	Welcome and Keynote 1: "Sources and sinks"	zoom plenary	Tom Haine Alex Haumann	--	--
19/09/2022 15:15:00	Discussion 1A	zoom breakout room	Juliana Marson Benjamin Rabe	Torge Martin Alexander Haumann	Karen Assmann Georgi Lauke
19/09/2022 21:00:00	Discussion 1B	zoom breakout room	Erica RosenblumAmy Solomon	Paul MyersXiangdong Zhang	--
20/09/2022 07:00:00	Discussion 1C	zoom breakout room	Torge Martin Karen Assmann	--	--
20/09/2022 16:00:00	Discussion 1D	zoom breakout room	Georgi Laukert Xiangdong Zhang	(Alexander Haumann) Elisabeth Sikes	--
20/09/2022 20:00:00	Keynote 2: "Change in ocean structure and circulation""	zoom plenary	Erica Rosenblum Louise Biddle		
20/09/2022 21:00:00	Summary of Discussion 1 (not	zoom plenary	Speakers moderate, discussion leads report		
20/09/2022 22:15:00	Discussion 2A	zoom breakout room	Xiangdong Zhang Erica Rosenblum	Amy Solomon Thodoris Karpozoglou	--
21/09/2022 07:00:00	Discussion 2B	zoom breakout room	Louise Biddle Benjamin Rabe	Karen AssmannTorge Martin	--
21/09/2022 14:00:00	Summary of Discussion 2	zoom plenary	Speakers moderate, discussion leads report		
21/09/2022 15:00:00	Keynote 3: "Global linkages (bipolar and polar-low-latitude links)"	zoom plenary	xandra Jahn Alberto Naveira Garabato		
21/09/2022 16:15:00	Discussion 3	zoom breakout room	Alexandra Jahn Xiangdong Zhang	(Alexander Haumann) Benjamin Rabe	Amy Solomon Karen Assmann
21/09/2022 17:30:00	Summary of Discussion 3	zoom plenary	Speakers moderate, discussion leads report		
21/09/2022 18:30:00	Wrap-up and close	zoom plenary	SOC... (including planned summer school)		

Figure 1 Agenda of the workshop

An online editing system was established before the beginning of the workshop (Figure 2). There was a "master" file which contained all the links to recordings, documents for the notes of breakout discussions, as well as the slides for all the sessions. This helped participants to quickly access the files they needed during the workshop.

SPICE-UP workshop				
organised by NORP & SORP				
19-21 Sep 2022				
ALL TIMES IN UTC	*Note: Each slot will last 1 h (discussion approximate)*			
Time	**Session**	**Breakout I**	**Breakout II**	**Breakout III**
19/09/2022 14:00:00	Welcome and Keynote 1 "Sources and sinks" (recording)			
19/09/2022 15:15:00	Discussion 1A	Discussion1A-breakout1	Discussion1A-breakout2	Discussion1A-breakout3
19/09/2022 21:00:00	Discussion 1B	Discussion1B-breakout1	Discussion1B-breakout2	--
20/09/2022 07:00:00	Discussion 1C	Discussion1C-breakout1	--	--
20/09/2022 16:00:00	Discussion 1D	Discussion1D-breakout1	Discussion1D-breakout2	--
20/09/2022 20:00:00	Keynote 2: "Change in ocean structure and circulation" (recording)			
20/09/2022 21:00:00	Summary of Discussion 1 (note: time changed !) (recording)			
20/09/2022 22:15:00	Discussion 2A	Discussion2A-breakout1	Discussion2A-breakout2	--
21/09/2022 07:00:00	Discussion 2B	Discussion2B-breakout1	Discussion2B-breakout2	--
21/09/2022 14:00:00	Summary of Discussion 2 (recording)		--	--
21/09/2022 15:00:00	linkages (bipolar and polar-low-latitude links)" (recording)			
21/09/2022 16:15:00	Discussion 3	Discussion3-breakout1	Discussion3-breakout2	Discussion3-breakout3
21/09/2022 17:30:00	Summary of Discussion 3			
21/09/2022 18:30:00	Wrap-up and close (recording)			
	Wrap-up slides			
	Note: wrapup slides now editable by all with the link!			

Figure 2 "Master file" for information sharing

2.2 Platform and format

To make the format as simple as possible, the workshop selected ZOOM as the online meeting platform, and Google Workspace as the synergetic editing tool. As mentioned above, all the sessions and breakouts were held on ZOOM. Workshop organisers and volunteers from the participants shared the moderation of the discussion sessions and reporting using the Google Workspace to document and summarize the discussion on slides.

The workshop was comprised of three main sessions. Each session started with a keynote, followed by discussion sessions allocated to different timeslots. The time slots with large participant amount was further split into several breakout rooms to enable the participants fully express their ideas. After all the discussions of each session, a summary part was organized to synthesize the outcomes of those discussions. Please see Annex 3 for the main content.

The keynote was a combination of a specific topic from both the perspective of northern and southern polar regions. The theme of keynote 1 was Source and Sinks (Figure 3), reported by Tom Haine and Alexander Haumann. In keynote 2, Louise Biddle and Alexandra Jahn discussed the theme “Change in ocean structure and circulation” together (Figure 4). The theme of Keynote 3 was "Global linkages (bipolar and polar-low-latitude links)" (Figure 5), made by Alberto Naveira Garabato and Erica Rosenblum. The keynotes started each meeting day and were followed by breakout discussions and discussion summaries focusing on these three themes.

This kind of “dialogue” format of the keynote proved to be very successful and actually practised a hand-shaking of science from the south and north poles. The slides made by the keynotes were requested by participants for use in university lectures.

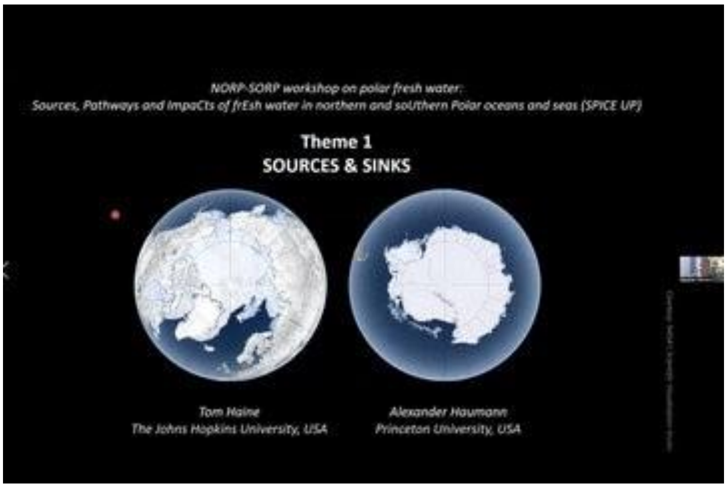

Figure 3 Keynote 1 Source and Sinks

Figure 4 Keynote 2 Change in ocean structure and circulation

Figure 5 Keynote 3 Global links

2.3 Distribution of the participants

There are 144 people from 21 countries (Figure 6) registered this workshop. The US participants are the most, followed by Canada. We are happy to see the participants from country of global south (South Africa) and small island country (Sri Lanka). The online format provides more possibilities for people to access high-level workshops and conferences, especially those who have difficulty paying for their travel expenses.

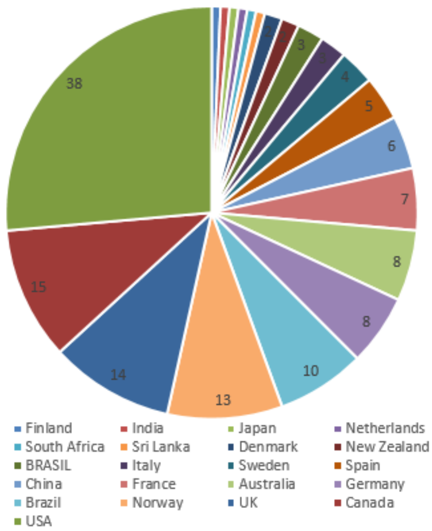

Figure 6 Distribution of countries of the participants

Another thing that needs to be highlighted is that the Early Career and the women scientists are playing more and more important roles in scientific research. From figure 7 we can see that the percentage of Early Career Scientist (ECS) is 58%, far more than the non-ECS. The female participants are also more than the male participants.

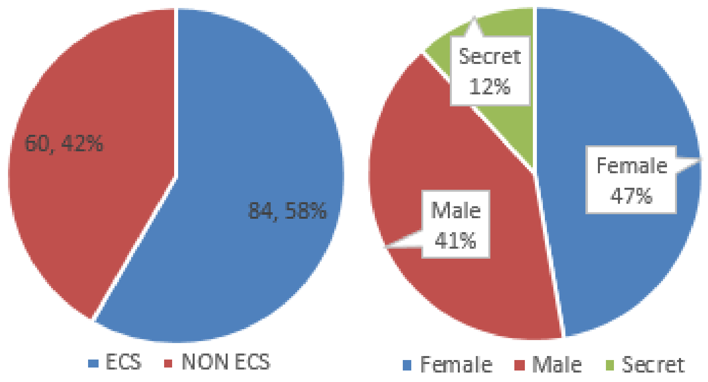

Figure 7 The career stage and gender distribution

2.3 Experience

This workshop took full advantage of synergetic interactions enabled by the online format. The breakout made extensive use of discussion rooms. By intention, there was no poster session, as the workshop was planned as a discussion forum. This proved to be successful and efficient. Although the tools used were simple, they were easy to use and offered ample opportunity for engaging all participants. Most participants were familiar with the tools and platforms used saving valuable time. The idea of having a dialogue between the two polar communities on a specific topic to study similarities and differences turned out to be much appreciated by the participants and offered a holistic view of the processes involved. This workshop really contributed to the polar research community.

3. Main content

The workshop lasted for three days, aiming to give a holistic overview of the role of fresh water and the future evolution of the climate at high latitudes. The workshop featured content from keynotes, breakout discussions based on the pre-prepared topics for each session, and summaries, an excellent overview of the current state of research of the sources, pathways and impacts of fresh water in the Arctic and the Southern oceans, as well as their linkages, similarities, and common challenges. The main scientific outcome will be published in the Bulletin of the American Meteorological Society (BAMS).

4. Acknowledgements

We thank the World Climate Research Programme (WCRP), World Meteorological Organization (WMO), Climate and Ocean: Variability, Predictability, and Change (CLIVAR), Climate and Cryosphere (CliC), Scientific Committee on Antarctic Research (SCAR), International Arctic Science Committee (IASC), Global Ocean Observing System (GOOS), and Global Climate Observing System (GCOS) for their generous in-kind or financial supports! The workshop could not have been successful without their support.

5. Organizing Committee

- Benjamin Rabe, Alfred Wegener Institute, Germany
- Torge Martin, GEOMAR, Germany
- Amy Solomon, CU/NOAA Physical Sciences Laboratory, USA
- Karen Assmann, Institute of Marine Research, Norway
- Ronald Buss de Souza, National institute for Space Research – INPE, Brazil
- Tore Hattermann, Norwegian Polar Institute, Norway
- Elisabeth Sikes, Rutgers University, USA
- Xiangdong Zhang, International Arctic Research Center, University of Alaska Fairbanks, USA

Annex 1 Agenda

Time (UTC)	Session	Format
19/09/2022 14:00:00	Welcome and Keynote 1: "Sources and sinks"	Zoom plenary
19/09/2022 15:15:00	Discussion 1A	Zoom breakout room
19/09/2022 21:00:00	Discussion 1B	Zoom breakout room
20/09/2022 07:00:00	Discussion 1C	Zoom breakout room
20/09/2022 16:00:00	Discussion 1D	Zoom breakout room
20/09/2022 20:00:00	Keynote 2: "Change in ocean structure and circulation"	Zoom plenary
20/09/2022 21:00:00	Summary of Discussion 1 (*note: time changed !*)	Zoom plenary
20/09/2022 22:15:00	Discussion 2A	Zoom breakout room
21/09/2022 07:00:00	Discussion 2B	Zoom breakout room
21/09/2022 14:00:00	Summary of Discussion 2	Zoom plenary
21/09/2022 15:00:00	Keynote 3: "Global linkages (bipolar and polar-low-latitude links)"	Zoom plenary
21/09/2022 16:15:00	Discussion 3	Zoom breakout room
21/09/2022 17:30:00	Summary of Discussion 3	Zoom plenary
21/09/2022 18:30:00	Wrap-up and close	Zoom plenary

Annex 2 Discussion themes and suggested topics

Theme 1: Sources and Sinks
What is the contribution and what are the relevant processes in the coastal Arctic and Antarctic ice? (sea-ice, surface and basal melt on ice shelves and outlet glaciers…)
What is the role of icebergs in redistributing fresh water?
The role of snow in the freshwater budget
What is needed to close the freshwater budgets in the NH and SH? What processes are inadequately measured? How does this differ in the NH and SH?
Theme 2: Change in ocean structure and circulation
Are we close to a transition between salinity-dominated stratification to temperature-dominated stratification? In the NH but not the SH?
Are we expecting a decrease or increase in stratification with changing freshwater inputs? What are the feedbacks with sea ice and other freshwater sources?
What is the role of the regional scale circulation and small-scale processes (e.g., eddies, shelf waves, tides) in re-distributing freshwater?
What determines the vertical freshwater distribution on the water column?
Does the regional circulation enhance or oppose freshwater distribution by sea ice drift?
What are the feedbacks from changing freshwater input on the circulation?
Methods: how do we measure and/or quantify freshwater transports with the circulation and trace their origin? E.g., chemical tracers?
Theme 3: Global linkages (bipolar and polar-low-latitude links)
What is the impact on deep and bottom water formation under global warming?
What are the major export routes to lower latitudes (equatorward of 55˚ lat)?
Will enhanced freshwater input into the polar oceans trigger feedbacks with lower latitudes?
Does polar freshwater impact biogeochemical processes at lower latitudes (past, present, future)?
Can we track polar freshwater from different sources (chemical signature) throughout the global ocean? How (methods)? If not, why? Would this be useful?
What are the expected benefits in global climate simulations by improving representation of polar freshwater sources, such as Greenland runoff or Antarctic ice-shelf interaction?

Annex 3 Resources

For the convenience of the reader, we synthesized all the contents in the files in links of figure 2, which were mainly the notes of each breakout discussion, the summaries of all the topic sessions, as well as wrap-up (Figure 2）. We thank the monitors and the note takers (Figure 1).

Summary of topic 1: Source and Sinks

Arctic Ocean

- Find consensus on passage and region definitions (the “Arctic” is often framed differently)
- Find optimal approach to monitor in-/outflows through passage, including modelling
- Identify physically-sound approaches or constraint to reduce the spread of precipitations (including snowfall) across different datasets
- Possibility to use geochemical tracer data to compose shelf sea circulations that is a driver directing river water distribution
- Look at smaller scale processes and local impacts that might have downstream implications

Southern Ocean

- While the Arctic science community discusses anthropogenic influence, the SO community is still trying to get hold of the mean state
- Vast open ocean (vs. Arctic gateways) major problem for identifying key locations for in-situ measurements
- Isotope/tracer measurements allow attribution to meltwater sources
- Focus on mixed layer budgets, but freshwater also found at intermediate depth
- A southern “MOSAiC” campaign would be extremely helpful, especially as fall and winter observations are very rare.

Concerning both hemispheres

- The basic issue of a reference salinity being used to compute FW content (is there a useful global number?)
- Satellite data is considered a cornerstone in closing the FW budget
- Iceberg meltwater distribution from observations and improved modeling of iceberg processes
- Uncertainties of shelf seas and coastal sea ice thickness and ocean circulations
- Freshwater-related processes governing upper ocean mixed layer depth in both the Arctic and Southern Ocean

- Need for more tracer data and more reliable tracers for sources and inputs (18O and Nd… others?)

Summary of topic 2: Ocean Structure and Circulation

Arctic Ocean

- CMIP6 model studies show that towards the end of this century the Arctic ocean will continue to be salinity dominated (Canada Basin and Eurasian sector). Temperature becomes more important as Atlantic inflow increases but the Eurasian basin will still be salinity dominated (Muilwijk paper in review).

  Question: Is there a similar finding for the SO? Is this consistent with observations?

- In the Barents Sea, observations show a turning to temperature stratification.

  Question: Is this due to Atlantic Water inflow? Is this consistent with model studies?

- Towards the end of this century, climate models show that even Atlantic inflow will freshen. Both the surface layers and the intermediate layers.

  Questions: Is this an Arctic signal that goes into the North Atlantic and flows back again. Is the freshening from in-situ precip or Greenland glacial melt? What do observations show currently?

- Resolving coastal currents can cause rapid redistribution of the freshwater along the shelf and slope currents can trap the melt water along the shelves. Both currents impact the vertical redistribution and transport of freshwater. These currents are not resolved in 1 degree climate models.
- In the Fram Strait we already see that the average 100m velocity peaks at the same time as the increase in the freshwater content because of changes in ocean density gradients.

  Question: Would the Transpolar drift also accelerate by this mechanism?

- In Greenland FW enters the ocean from Fjords where the water has been glacially modified and enters the ocean at intermediate levels. Tracer studies can identify how FW is modified as it flows from Greenland into the deeper ocean, flows through sea ice, mixes with other waters, etc.
- Many competing feedbacks in how momentum transfer will impact stratification due to increasing FW as open water increases and sea ice characteristics change. New results coming out of MOSAiC looking at changes in momentum transfer due to different ice types and roughness.
- Atmospheric circulation sets mean state of Arctic FW content (in Bft Gyre) as well as recent brief recovery in Barents Sea …

Southern Ocean

- SO less strongly stratified as Arctic, thermobaric effects may trigger instabilities in the open ocean, sea ice formation causes deep convection in some shelf seas.

- Salinity controls stratification except for seasonal effects in the northern sea ice zone.
- Climate models overrepresent deep convection in the open ocean.
- A more divergent sea ice cover allows for more momentum transfer by wind and waves.
- Freshwater from ice shelves exits at depth, but its effect on the stratification on the open shelf depends on feedbacks with the water column outside the cavity.
- Atmospheric forcing (temp, winds) can have major impact on mixing, shelf water mass transformation, hence explains regional temperature patterns; also important factor in sea-ice export
- Concerning both hemispheres
- Currently, temperature only locally influences stratification significantly in upper polar oceans, both NH and SH; may change with future changes in salt or FW input
- Atmosphere as major driver not to be forgotten; influence of lower lat climate modes on polar regions; FW export to lower lat then some sort of feedback through ocean
- Stratification often deviates from observations in climate models (issues with vertical resolution, parameterizations, etc.); mixing paramterization depending on alpha vs. beta (T vs S) stratified ocean or ice covered?
- Uncertainty in seasonality in land-ice meltwater, i.e. time lag between grounding line flux, calving, ice-shelf melt, fjord export, …
- Depth of where FW enters the open ocean: may depend on local / small-/meso-/submeso-scale processes… Representation in models? Parameterisation based on few observations or only theory? Tuned to optimise mid-latitudes…

Summary of topic 3: Global Linkages

Arctic Ocean

- How does Arctic FW affect AMOC…
- GSAs fairly common (about every decade) → impacts, how well represented in models ? (e.g. boundary currents, eddies, Ekman transport); causes of GSAs? Only Arctic winds or more sources?
- Improving representation of polar FW sources in global models (Greenland, Antarctic ice shelves…), and circulation pathways
- Can track FW in global ocean using observations? (radionucleides?)
- Uncertainties in AMOC predictions (reduction in 21st cent. Correct? OSNAP..)
- Davis Strait fluxes (and timing) differ between CMIP6 models

Southern Ocean

- Enhanced ice sheet melting → lighter shelf waters and lighter AABW (no longer at bottom); BUT FW may not reach that deep (into AAIW)

- Export pathways of FW not well known; same for pot. accumulation locations
- Models potential tool for tracking freshwater (passive tracers/lagrangian studies) but prone to biases
- Direct FW input vs. secondary impact by process changes; also recycling of freshwater (e.g in sea ice formation); isotopes/noble gas observations
- How does ocean potentially feedback to atmosphere (acknowledging atmosphere serving as driver/trigger in the first place)
- Response to enhanced FW release will take time, ocean sensitive to cumulating FW rather than rate of FW input

Concerning both hemispheres

- Bathymetry not always well known, can influence local processes
- Jointly plan observational and modelling efforts: focus (profiles, bathymetry, other coverage, process focus…)
- Pathways of FW vary depending on release depth
- Role of tracers and drifters to follow FW to lower latitudes (e.g. CFC)?

Wrap-up

Arctic

- Local processes on the (sub-)mesoscale and smaller are responsible for FW dispersion and export, but most of those processes and associated features, such as boundary currents, are not resolved in 1deg-resolution climate models (also true for south?)
- Greenland Fjords can inject FW at intermediate depths and into sea ice
- The role of momentum transfer in changing Arctic upper ocean mixing is, yet, unclear
- Atmospheric circulation strongly influences upper ocean and FW distribution, feedback ocean-to-atmosphere may be important
- Consensus on domain / passages and optimal monitoring approach (obs., models)?
- Identify physically-sound approaches or constraint to reduce the spread of precipitations (including snowfall) across different datasets
- Tracer studies important to understand sources and pathways, in particular, towards lower latitudes ! Great Salinity Anomalies fairly common (~decadal)
- Need to improve polar FW sources in global models (Greenland and Antarctic ice shelves …)
- OSNAP observations → check on CMIP6 AMOC reduction in 21st century

Southern Ocean

- Southern Ocean is a vast region: where are crucial locations for observations?

- Iceberg processes still major unknown
- Tracer/isotope/noble gas measurements critically help to identify meltwater sources and track glacial meltwater
- FW exiting ice-shelf cavities at depth; effect on stratification depends on interaction with water column in front of ice shelf
- A southern “MOSAiC” campaign would be extremely helpful, to enhance process understanding, especially fall and winter observations are very rare
- FW does not only affect dense (bottom) water formation but als intermediate water transformation (sea ice export!) and hence FW changes may affect heat and carbon uptake
- Climate models show FW impact all the way to the subtropics (for FW input to be expected towards 2100); but how good are these projection? Key shortcomings/biases in models all converging on mixing issues?

Both (linkages, similarities, same challlenges)

- Even in a future warming ocean, stratification in both north and south polar oceans is likely to be governed mainly by salinity, albeit local thermal effects could be important; Southern Ocean less strongly stratified
- True for north and south?? Local processes on the (sub-)mesoscale and smaller are responsible for FW dispersion and export, but most of those processes and associated features, such as boundary currents, are not resolved in 1deg-resolution climate models
- Bathymetry not always well known, can influence local processes
- Jointly plan observational and modelling efforts: focus (profiles, bathymetry, other coverage, process focus…)
- Pathways of FW vary depending on release depth
- Role of tracers and drifters to observationally follow FW to lower latitudes (e.g. CFC)?
- The “pesky” reference salinity discussion is not, yet, over…

Notes of topic 1

Suggested questions for discussion:

1. What is the contribution and what are the relevant processes in the coastal Arctic and Antarctic ice? (sea-ice, surface and basal melt on ice shelves and outlet glaciers…)

2. What is the role of icebergs in redistributing fresh water?

3. The role of snow in the freshwater budget

4. What is needed to close the freshwater budgets in the NH and SH? What processes are

inadequately measured? How does this differ in the NH and SH?

Breakout 1A1

Questions for Tom:

- *Fill gaps in exchange fluxes Fram Strait?*

  - A: challenge, even with many moorings. Measurements in EGC also downstream, augment with models.

- *Straits in Arctic: Local control or upstream?*

  - A: Mainly upstream changes (atmospheric modes of variability); for large export of ice, need ice upstream. Bering Strait flow unidirectional, dynamically simpler than Fram or Bering straits.

- *Observations in Canadian Arctic Archipelago? Baffin Bay?*

  - A: Some observations in small straits in Canadian Arctic Archipelago; upstream of Davis Strait, main flow Nares Strait and Lancaster Sound – few years of records early 2000s (Lancaster has been resumed!); “CAA is not just plumbing” (H. Melling) – air-sea interaction, inflow from south …

- *Differences in land ice contributing to flux into ocean in north (Greenland mainly calving) and south (parts calving and parts basal melt)*

  - A: accessibility of warm Atlantic Water to land ice less than similar warm water in south; part of Greenland is submarine melt !

- *Greenland melt accelerating, expected to contribute significantly to FW input to Arctic?*

  - A: yes, yes and yes… Total flux from Greenland to arctic control volume 10 % of river influx; large parts of Greenland drain into Nordic Seas / North Atlantic…; 10% increase to Arctic influx, 1% of total river influx, so acceleration of Greenland negligible. But impact on North Atlantic different story ! Where input happens, important; Greenland may impact significantly in North Atlantic in near future (coming few years / decade).

Further discussion:

- Figure by Juliana (Figure 8, Marson et cl., 2021):

  - NEMO simulation (¼ deg simulation), passive tracers in Greenland runoff; liquid discharge stays largely close to Greenland, icebergs penetrate deeper into interior NA subpolar gyre; INSERT FIGURE ? ; carving predicted to increase → reach further into basins; BUT Baffin Bay circulation can also change with liquid input

  - Discussion:

    a. CMIP model output predict reducing deep convection, likely strongly due to Greenland FW input; diffusivity in CMIP models high (high-res. models mainly through boundary currents, import to NA subpolar gyre diluted / weak signal)

    b. Much FW introduced to boundaries, effect of higher res. Models? Gent-

McWilliams appropriate for high-res. Models?

c. Shelf-basin-exchange off Greenland: large fluxes near troughs / Fjords in high-res. models (e.g. 500 m), both non-/hydrostatic simulations; very dynamics, not all processes captured; process studies important to understand process effect expected in models, but parameterisation may be tricky (each trough specific); west of Greenland more polar than east; exchange in 1/60 deg resolution, Gou et al., 2021/2022, with Paul Myers; drifters / floats can be useful;

- Snow input from land (e.g. Greenland, similar to Antarctic, where it's signficant)?
- Discussion on Pemberton et al. (2015): water mass transformation in S-T coordinates
- Tundra melt / permafrost melt as a source? Bamber et al. (2018), includes Tundra; not important on Arctic-wide scale for FW volume (more biogeochemistry); local impact? Probably quickly dissipated? (continous source?)
- Bering Strait trends? E.g. http://psc.apl.washington.edu/HLD/Bstrait/Woodgate_BeringStrait_ASOF_Apr2018Final.pdf say that the volume flux has been increasing → pressure head largely responsible for trend, less regional winds; main change coming from Arctic !
- No evidence in large discharge event from Beaufort Gyre; wind and net stress (sea ice important) at surface may change; may depend on sea-ice properties… which are changing! Martin et al. (2014) model study → "sweet spot" for sea-ice concentration, most effective momentum transfer
- Davis Strait important for any signal from Arctic into NA

References:

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Breakout 1A2

- Delta O18 measurements useful in closing the FW budget in the SO but also for in- and outflow to AO
- Salinity still needs to measured and calibrated (bottles) on all cruise as standard
- Tracing iceshlf meltwater c13 and isotopes track these well
- How is (meteoric) freshwater accumulating
- Use high-resolution ocean models with passive tracers to provide a regional-scale idea of pathways and accumulation places of FW
- Better quantify uncertainty in models and observations
- How to catch up with Arctic, the SO is wide open space
- FW is exported at surface to mid-depth
- Work more with mixed-layer budgets, try to better understand ML salinity and how it reflects sources
- What can we gain from floats if FW is near surface? For AAIW certainly; under ice floats will miss top-most meters
- Icebergs: berg meltwater always put in at surface in models (under construction though); for icebergs main export pathways are pretty well known ; if iceberg keel is deep enough it may interact with CDW
- Targeted iceberg campaign; BAS has campaign around S. Georgia; very local signal, meltwater disperses quickly
- Is reference salinity for FW calculation different is SO and AO? Should it be one global number? There is a unique definition , like the average salinity along the cross-section that is investigated, i.e. global number should be possible (see Talley book on physical oceanography for definition); 35 a suitable global number?
- Regional vs global estimate, i.e. FW being transported around Antarctica
- As a community push for observations, also in seasons like fall and winter
- No ITPs because ice cannot hold them
- top 50m is really tricky, learn from Arctic/Greenland community? Seal data can possibly cover surface layers
- Go far local all-quantity campaign or spread out and cover circumpolar; what is most useful for increasing knowledge future changes of the system; process studies to understand mechanisms and constrain models; monitor the system every X years
- SO still looking for mean state; in AO already discussing anthropogenic
- Are saildrones in the ice-free SO useful for FW?
- MOSAIC for the SO would be fabulous
- Mixed layer is highly variable, needs more observations

Breakout 1A3

- Icebergs in the Arctic: not quantified very well, magnitude very uncertain, probably localized, smaller & might not travel as far, in the Arctic Basin vs Greenland Coast
- Icebergs in the Antarctic: about the same as ice shelf melt, distribute FW off the continental shelf, large icebergs with potential to travel longer distance and distribute FW
- Liquid FW vs sea ice FW transport: sea ice responds more easily to winds, detached from large scale currents,
- Arctic: Transpolar drift in sea ice vs ocean circulation that is more constrained by bathymetry, Fram Strait also has FW export as Pacific Water (hard to estimate, might be up to 60% depending on different methods, this needs tracers), and FW export between and EGC and sea ice show decoupling, liquid FWC in Fram Strait has increased after 2010 vs decreased sea ice export
- Antarctic: large scale sea ice drift corresponds approximately to large gyres for northward export, ACC as northern boundary
- small-scale processes: effects of sea ice breaking up at the ice edge
- Closing the budgets:
- Arctic gateways vs long boundary in the Antarctic, SO FW budget much less clearly constrained
- Ice thickness estimates in the SO to quantify actual sea ice volume exports, new satellites will help with this and other parts of the budgets
- Arctic budget much closer to being closed than Antarctic/SO, refine understanding of sources, e.g. PW, river sources
- Other impact of FW e.g. nutrient imports - rivers in the Arctic with different signatures, signals exported into the Transpolar drift - large-scale impact
- Ice shelves and icebergs as source of iron, but ice shelf part likely confined to continental shelves, icebergs have local blooms, but large scale impact unclear.
- Liquid FW content - that pesky reference salinity. To compare regional liquid FW content we would need common reference salinity - especially if doing this between hemispheres. Local and regional studies generally use a tailored value. Salt content (anomaly) as an alternative?

Note of topic 2

Suggested questions for discussion:

1. Are we close to a transition between salinity-dominated stratification to temperature-dominated stratification? In the NH but not the SH?

2. Are we expecting a decrease or increase in stratification with changing freshwater inputs? What are the feedbacks with sea ice and other freshwater sources?

3. What is the role of the regional scale circulation and small-scale processes (e.g., eddies, shelf waves, tides) in re-distributing freshwater?

4. What determines the vertical freshwater distribution on the water column?

5. Does the regional circulation enhance or oppose freshwater distribution by sea ice drift?

6. What are the feedbacks from changing freshwater input on the circulation?

7. Methods: how do we measure and/or quantify freshwater transports with the circulation and trace their origin? E.g., chemical tracers?

Breakout 1B

Lack of observations in the Arctic, specifically Russian sector and river discharge, can produce misleading conclusions about accumulation of FW (work by Morison and others).

Big gaps:

1. In Arctic: Russian sector, north of Greenland, river discharge
2. For Antarctic: Very few in-situ thickness measurements, even SIC measurements are limited, satellite measurements are not as reliable in the SH (too much snow, negative freeboard, flooding of the sea ice), connectivity between the shelves very important (interactions between shelves) (and linkages across the different parts of the system: sea ice growth, surface stratification, ice shelf cavity circulation, ice shelf basal melt, iceberg calving/transport/melting...)

Inverse methods are useful but still limited by lack of observations.

Role of icebergs. How does the impact of icebergs differ in the Arctic and Antarctic? :

1. Liquid runoff comes off in summer. Icebergs can last up to a year and can cause a delay in the system freshening. FW from icebergs can get into the interior of the basin more efficiently than liquid freshwater.
2. In the Antarctic: Icebergs reduce the freshening along the coast due to the delay and the melting farther from the coasts.
3. Also, models parameterize (or ignore) the ice shelf processes, e.g., no ice shelf cavities in almost all climate models.

Role of snow in the FW budget:

1. Different impact in NH and SH? What about rain on snow effects? Limited observations in the SH, however, there was an atmospheric river event this past year which caused a rain event in east Antarctica.
2. Blowing snow causes large biases in precip measurements (50-100% errors). Snow redistributes the FW (because of moving sea ice) compared to liquid precipitation.
3. Depending on the season, snow can contribute to the growth of sea ice or runoff into the ocean. Flooding of the sea ice by the melting of the snow can cause thicker sea ice

(by re-freezing to form snow ice, particularly an issue for Antarctic pack ice), and snow cover without flooring can cause thinner sea ice (by insulating it).

4. New satellite measurements in the Arctic are being used to estimate snow depth on sea ice.

What is needed to close the freshwater budgets in the NH and SH? What processes are inadequately measured? How does this differ in the NH and SH?

1. The Antarctic has only seasonal ice while the Arctic has multi-year ice.
2. River runoff in the Arctic, not in the SH.
3. Deep ocean in the SH, not in the NH.
4. Fresh water accumulates in the Beaufort Gyre due to atmospheric circulation, which can be released through the Fram Strait. What about in the SH? Atmospheric circulation traps FW on the shelves?

Additional questions:

1. Limited understanding about how different FW processes interact (feedback processes).
2. How do we move forward given that we will never have all the observations we need? Use inverse models to identify where observations are most needed to reduce uncertainties?

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Notes of topic 3

Suggested questions for discussion:

1. What is the impact on deep and bottom water formation under global warming?

2. What are the major export routes to lower latitudes (equatorward of 55˚ lat)?

3. Will enhanced freshwater input into the polar oceans trigger feedbacks with lower latitudes?

4. Does polar freshwater impact biogeochemical processes at lower latitudes (past, present, future)?

5. Can we track polar freshwater from different sources (chemical signature) throughout the global ocean? How (methods)? If not, why? Would this be useful?

6. What are the expected benefits in global climate simulations by improving representation of polar freshwater sources, such as Greenland runoff or Antarctic ice-shelf interaction?

Breakout 1C

- Models are challenged by uncertainty in polar processes, how to constrain models better with observations?
- SSS from SMOS useful for freshwater observation from space? 25km resolution is relatively coarse
- **Satellite observation key to close budgets**
- **Find consensus on define passages and Arctic region**
- Satellite good for surface but change also happens in intermediate layers
- SMOS in SO product being developed, only up to sea ice edge
- SO sea ice does not support ITP for deep measurements
- float obs in SO? (RAFOS/SOFAR???, ARGO)
- floats have bad positioning under ice; floats parked under ice
- **sustainable under ice observation would be a big step forward**
- Need for repeat sections to understand variability -> coordination among institutes required to maintain sections
- What are the key sections for the Arctic: working group Arctic-Atlanitc DBO (ESTABLISHING THE ATLANTIC DISTRIBUTED BIOLOGICAL OBSERVATORY: https://arcticpassion.eu/adbo/)
- Is there anything similar being discussed for the SO?
- Can we characterize SO freshwater (export) by impact on ocean fronts (observable by satellite SST and SSS)?
- Modelling ocean fronts requires higher resolution than used by climate models
- FW content balance between Arctic and Antarctic; data gap on shelves
- Salinity is a major issue in models, shelf processes not well resolved or parameterized, sea ice thickness observation lacking
- Not only more data but better products from data are needed
- Models issue is restoring to outdated climatology
- SSS assimilation difficult because model is forced to adjust with “prescribed” surface layer
- Inside Greenland’s fjords: salinity (FW) strengthens stratification and hence impacts melt, not only temperature needs to be monitored to understand glacial melt
- **Gap in observations in top 5 m between satellite, ships and ARGO floats; in SO also seal data is being used**
- FW fluxes always function of the reference salinity

- FW export is more important for Arctic FW balance than Atlantic water inflow salinity variations
- Fjord-shelf exchange an important not well understood
- In SO big FW sources are the smaller ice shelves rather than the big ones (this is mean state , not only global warming)
- **From obs point of view challenges are similar between north and south because fjords are tricky to access as are ice shelf cavities; can we learn from each other?**
- Especially Antarctic Peninsula has similar topography to Greenland
- If you do study fjords, also take observations in front of the fjord on the shelf; know the embiant water masses to detect and identify sources of meltwater; gliders may help
- AWI used tubes to protect mooring not just thin wire, or a winch at sea floor to protect instrument from getting hit by ice
- **Sea ice capable gliders would make a huge difference**
- There have been moorings lowered through ice shelves

Breakout 1D1

- Basically there is a lack of observational data, especially for Antarctica.
- Water samples for the Southern Ocean, Geochemical tracers can help trace FW – coordinate with shipboard sampling for SOCCOM BGC Argo float deployments from 2022-2023 (year 9), and coordinate with GO-SHIP sampling as well.
- Geotracers help look at budgets, circulations, …
- Ship cruises will deploy CTD to get deeper layer water samples
- Use geotracers to identify sources of FW, such as rivers. Water discharges from different rivers have their own features. Sampling in 2015 covered the Canadian Arctic basin.
- Uncertainties in percentage of Pacific water exports via Fram Strait
- Isotope can also identify Greenland melt water
- MOSAiC did not deploy important tracers.
- Can trackers help trace icebergs?
- Reference salinity used for observations and models for quantifying FW budgets and pathways.
- Question from LT - are the OSNAP arrays fully capturing the FW transport into the Atlantic? Davis and Fram Straits?

Breakout 1D2

- Discussing 18O as a tracer for water masses.
- Lynne Says SOCCUM is going to the Ross Sea this year and will deploy floats in the circumpolar part. And will be doing CTDs
- Would it be useful to take samples.
- Have we been in contact with the other Geotraces groups?
- Doing 18O with Nd in the Arctic (Georgi).

- This perhaps should be done with GoShip.
- The importance of the choice of reference salinity.
- Arctic sources of fresh water – what can we get from the observations. 18O gives us marine versus terrestrial. The Nd – each river has a different signature – and this can be traced offshore. There was a 2015 Geotraces in 2015 in the Canadian Arctic (not published)
- Nutrients can also trace Atl. vs Pac sources – but these can be modified on the shelf.
- These issues (nutrient method) puts large errors on the % of Pacific water that is exiting Fram Strait. (up to 60% error?)
- Using Nd it suggests nearly 0% Pacific exiting Fram Strait.
- Georgi suggests that we need something more beyond Geotraces in both oceans.
- 18O or trace metals are not getting included in many studies.
- 10ml for Nd – but it needs to be filtered and collected in acid clean vials and for isotopes you need ~10 liters
- How can tracers help us figure out the budget of fresh water? Can this inform the models?
- Combining proxies can paint a better picture – and this is a young field in the Arctic – need to have more composite analyses.
- General question is there a fresh water budget for the Arctic that we agree on? Per believes is there is a budget – but the biggest uncertainty is Fram Strait– the flows are large and bi-directional.
- For Fram S. There is much discussion about the reference salinity…. So the usefulness of tracers seems important.
- Comment: But if you balance mass this should work – the issue is steady state.
- The reference salinities are useful for models….
- Convergences versus absolutes.
- Fresh water tracing based on N:P ratios despite the problems – and inconsistencies in the methods. And proportions that are “impossible” suggesting other controlling factors that provide shelf water effects on the nutrients – P enrichment in the winter inputs (in the Lena) and this is incorporated into the bottom layer and exported – and can be calculated as “Pacific” and coming from the Chukchi sea.

Breakout 2A

1. *Are we close to a transition between salinity-dominated stratification to temperature-dominated stratification? In the NH but not the SH?*
   a. CMIP6 model studies show that towards the end of this century the Arctic ocean will continue to be salinity dominated (Canada Basin and Eurasian sector). Temperature becomes more important as Atlantic inflow increases but the Eurasian basin will still be salinity dominated (Muilwijk paper in review). Even given the uncertainties in climate models, this is a robust result. The amount of heat you would have to add to

change the balance is huge, but it depends on where in the water column you input the heat and freshwater.

b. Towards the end of this century, climate models show that even the Atlantic water will freshen. Both the surface layers and the intermediate layers. Is this an Arctic signal that goes into the NA and flows back again. Is the freshening from in-situ precip or Greenland glacial melt?

c. Morven's preprint: https://eartharxiv.org/repository/view/3361/

2. *Are we expecting a decrease or increase in stratification with changing freshwater inputs? What are the feedbacks with sea ice and other freshwater sources?*
    a. Momentum transfer is important in this.
        i. Less sea ice so more wind stirring.
        ii. Also, faster sea ice motion, but this depends on changes in keel depths.
        iii. Sea ice has to be getting smoother, right?
        iv. But smaller ice flows can crash together more and form deeper ridges/keels.
        v. New results coming out of MOSAiC looking at changes in momentum transfer due to different ice types and roughness.
        vi. What is the net impact of more open water, more wind stirring, and increased surface freshening?
        vii. New work on flows over bottom ridges
    b. And also where the freshwater is added to the column.
    c. There is lateral transport as well so you can't think of this as a 1-d problem.
    d. Freshwater will generally increase stratification but if you have less sea ice you can have more vertical mixing, which would decrease the stratification.
    e. Change in the ice cover will change the horizontal distribution of the momentum transfer. (and ekman pumping from changes in lead formation)

3. *What is the role of the regional scale circulation and small-scale processes (e.g., eddies, shelf waves, tides) in re-distributing freshwater?*
    a. Freshwater tends to come in at the coast, it is the small-scale processes that bring the fresh water from the shelves to the deep ocean.
    b. Studies of tracers in rivers show that you need fast ice or fresh water is transported too far into the basin.
    c. Small scale sea ice processes are important in the shelf regions but tend to be missing in models.
    d. Resolving the Antarctic coastal current can cause rapid redistribution of the freshwater along the shelf and slope currents can trap the melt water along the shelves. Both currents impact the vertical redistribution of the freshwater. These currents are not resolved in 1 degree climate models. Same processes are important in the Arctic…

4. *What determines the vertical freshwater distribution on the water column?*

a. Covered in points above…

5. *Does the regional circulation enhance or oppose freshwater distribution by sea ice drift?*
   a. Not clear how to respond to this. Ice-ocean governor in the Beaufort.
   b. When does the wind driven circulation oppose the pressure-driven flow?
   c. "Ice factories" on shelves cause redistribution of freshwater and this is changing in the "New Arctic".
   d. In the SO, changes in ocean circulation is changing sea ice drift and where the sea ice is melting. Westerlies are projects to accelerate and move closer to the pole, which would cause larger sea ice export northward.

6. *What are the feedbacks from changing freshwater input on the circulation?*
   a. Should we expect an intensification of the Transpolar drift due to changing freshwater distribution in the Arctic Ocean
   b. In the Fram Strait we already see that the average velocity of the 100m peaks at the same time as the increase in the freshwater content. Because of changes in ocean density gradients. Would the Transpolar drift also accelerate by this mechanism?
   c. Most transport occurs near the surface and added freshwater can disconnect surface flow from deeper flows.
   d. Many feedbacks between changes in surface and deep water flow.
   e. Freshwater hosing exps have conflicting results (mostly in SO). Many feedbacks are missing in models (like ice sheets) giving conflicting results of the impact of freshwater on the coupled system.
   f. In Greenland FW enters the ocean from Fjords where the water has been glacially modified and enters the ocean at intermediate levels.

7. *Methods: how do we measure and/or quantify freshwater transports with the circulation and trace their origin? E.g., chemical tracers?*
   a. Needed for identifying how FW flows from Greenland into the deeper ocean, see previous question (using noble gases).
   b. Can be used to identify sources of FW.
   c. Open questions: can you use tracers to identify the transformation of FW in time?
   d. Can tracers be used to identify Atlantic from Pacific inflow waters?
   e. Sea ice vs meteoric waters can be constrained with tracers.
   f. Can be used to identify to what extent FW passes through the sea ice.

8. *Methods: The use of freshwater transport requires caution due to the nonlinear dependance of the variable on a reference salinity with (seemingly) no physical constraints. The advantage of the variable is that it reflects changes in both the salinity and velocity field. Salt transport is a reference-free alternative to freshwater transport but it is not sensitive to changes of the salinity field. How should the community proceed?*

a. (didn't have time for this question)

Discussion 2B

- *Are we close to a transition between salinity-dominated stratification to temperature-dominated stratification? In the NH / Arctic?*
  a. Despite warming contribution of temperature to stratification in Arctic still small, e.g. CMIP6 model study (in revision)

  b. Barents Sea: Parts are turning to temperature stratification, near Atlantic Water inflow?
- *Southern Ocean:*
  a. Near surface, seasonally ice-covered zone, temperature can have strong influence intermittently

  b. Likely need salt input in addition of cooling in autumn to start mixing in MIZ in autumn at present - from observations

  c. Deep waters stratification still dominated by salinity
- *Observational bias in observations? (in-situ near-surface gap; satellite only very close to surface …) → stratification; fresh lenses…*
- Representation of stratification in climate models has similar issues to Arctic in the SO - open ocean convection issues in climate models (Bottom water formation).
- SO stratification weaker than in the Arctic (open ocean/MIZ). Weak enough to allow for deep convection for smaller (?) deviations from observed state in models. Thermobaric effects can trigger deep convection - Maud Rise/Weddell Sea Polynya.
- SO seasonal processes
- Cold shelf seas with deep convection vs warm shelf seas with large enough FW input from ice shelves, P-E, sea ice preventing convection to bottom in winter vs fresh shelves (cold, but no salty CDW on shelf)
- *What determines the vertical freshwater distribution on the water column?*
  a. European vs Canadian Arctic

  b. Influence of fresher inflows on Arctic freshening - will change where FW ends up in water column vs sea ice/rivers that enter at surface

  c. Cold Halocline - advective vs convective formation vs combined - erosion and change of processes involved in formation

  d. Newly open ocean due to sea ice retreat - enhanced momentum transfer due to winds/waves - do we see this effect on stratification on models? Or does it gets lost in the change of the FW input from sources?

  e. Model parametrisations highlight certain processes involved in momentum transfer and neglect others - effect of keels vs internal waves.

f. Smaller processes e.g. double diffusion or sub-mesoscale eddies locally important - what about their role in the bigger picture? How to assess this and include in models?

g. How do we translate/include small-scale processes that observational process studies show to be important into the bigger picture/climate models?

h. How far can we trace FW from its source? When does it become part of a (fresh) water mass, e.g., Polar Water exiting the Arctic?

i. Effect of waves on the sea ice cover - can see waves propagate up to 200km into the sea ice cover, but lack concurrent ocean observations to investigate effects. (More SO?)

j. Models can be used to test these effects - but need observations to evaluate.

- Seasonal cycle in the SO - pre-conditioning of shelf water masses through exchange processes along the shelf
- Seasonality of land-ice FW input not well known, e.g., iceberg calving, ice shelf basal (frontal, Greenland) melt, sub-ice FW
- Vertical distribution of ice shelf melt water depends on basal melt rate, high melt vs low melt, feedback with stratification outside the ice shelf cavity, seasonal and interannual variability
- Bridge the gap between satellite observations and in-situ observations.

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Krumpen et al. (2011) seasonal preconditioning and regional conditions strongly influence polynya formation in winter and subsequent vertical transfer of salinity signals: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010JC006545

Re Antarctic shelf areas, Alek Petty showed that the "stratified" warm shelf and the "convectively mixed" cold & desne sheves are entirely a result of the atmospheric forcing, with all implications for resposne to change: https://doi.org/10.1175/JPO-D-12-0172.1

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Warm and cold shelves in Antarctica and the Antarctic slope current: Thompson, A. F., Stewart, A. L., Spence, P., & Heywood, K. J. (2018). The Antarctic Slope Current

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Southern Ocean mixed layer in climaet models: Sallée, J.-B., E. Shuckburgh, N. Bruneau, A. J. S. Meijers, T. J. Bracegirdle, and Z. Wang (2013), Assessment of Southern Ocean mixed layer depths in CMIP5 models: Historical bias and forcing response, J. Geophys. Res. Oceans, 118, 1845–1862, doi:10.1002/jgrc.20157.

Also more recent on summertime stratification and mixed layer: JB Salee et al. paper from 2021 https://hal.archives-ouvertes.fr/hal-03184114/document

Breakout 3A1

- *Can we track polar freshwater from different sources (chemical signature) throughout the global ocean? How (methods)? If not, why? Would this be useful?*
  a. Gallium: A New Tracer of Pacific Water in the Arctic Ocean? https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JC015842
  b. Probably use the signal pretty quickly n the Atlantic
  c. Maybe the nuclear reprocessing tracers?
  d. Otherwise in models?
- *What are the expected benefits in global climate simulations by improving representation of polar freshwater sources, such as Greenland runoff or Antarctic ice-shelf interaction?*
  a. Help with the bottom water formation simulations around Antarctica
- Relative roles of deep convection between the Labrador Sea and the Nordic Seas in driving AMOC.
- Impacts of “sea change”, instead of the Labrador Sea deep convection, on AMOC
- GSA relationship with FW export (at large-scale) or Laborado Sea mesoscale eddies.
- FW export via Fram Strait and Davis Strait in CMIP projections.
- Variability (large) vs. Anthropogenic forcing signals
- Is large variability events related to events in FW source? Or just due to changes in wind changes?
- Greenland ice sheets melt water into the coastal currents in the Labrador Sea and then down to subpolar gyres.
- Multi-model simulations of solid and liquid FW exports - large variability and spread
- Do models agree where we’ll see the anthropogenic signal first in liquid ocean freshwater fluxes?
- Uncertainties in AMOC strength simulations/projections in models.
- Do models agree with OSNP measurements? Will tell us where we are in terms of current AMOC strength, which may be helpful to better understand how well or bad the models do.

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Breakout 3A2

1. What is the impact on deep and bottom water formation under global warming?

a. Standard idea: SO: enhanced ice sheet melting leads to lighter shelf waters and lighter AABW that might not be BW anymore because existing BW is heavier
b. But a lot of melt water from ice shelves stays in the surface and does not make it into dense shelf waters or AABW?
c. What about intermediate water formation? Faster storage of heat and carbon.
d. What does the additional melt water do to water mass structure - upper ocean, on the shelf, transport between shelf seas?
e. Direct FW input vs FW-driven process change
f. Need to actually work out where the FW from ice shelf melting goes.
g. Bathymetry in part of the SO (shelf seas, ice shelf cavities) is uncertain or unknown - effect on circulation (This is also an issue in the Arctic Basin or fjords (sill depths)).
h. Models as tools to trace FW from ice shelf melting? As a two-way process - plan observational projects and modelling efforts together. (Drifters have been used to validate model pathways in eastern Greenland.)
i. Shift in FW sources: less sea ice and more ice sheet FW input (basal melt, runoff, calving) - effect on water mass formation?
j. “FW recycling” - how to trace and separate meltwater sources and pathways, use of geochemical tracers, e.g., noble gases
k. Arctic bathymetry gathers and contains FW, SO allows it to spread
l. Pathways of FW vary depend on release depth
m. Tracers show that glacial melt hugs the coast, more sea ice melt further out on the shelf - sea ice melt part of the seasonal cycle, glacial melt may reside too deep to be affected by winter mixing
n. CFCs as a tracer in the SO? Change in ventilation - increase in AAIW ventilation.

2. What are the major export routes to lower latitudes (equatorward of 55° lat)?

a. Conventional wisdom: most Antarctic FW will remain south of the polar fronts.
b. Arctic outflow: most outflow from the Arctic Basin may come out west of Greenland, not through Fram Strait after last GSA.
c. What does that imply for the fate and effect of the Arctic Polar Water?

d. Ongoing release of surface drifters east and west of Greenland.
e. Argo floats do not capture shelf circulation (Greenland)
f. Arctic Ocean is considered as storage for FW, but we do not think of the Antarctic SO as storing FW - what about SO gyres?
g. Satellite data can capture sea ice, SSH when the ocean is ice-free - but this doesn't generally work for the Antarctic boundary currents and shelves.
h. Icebergs distribute FW in space and time - but we do not know if this has changed or is changing, still working on mean state.

3. Will enhanced freshwater input into the polar oceans trigger feedbacks with lower latitudes?

a. Ocean-atmosphere feedbacks: shifting fronts (frontal filaments) (may) affect winds. (Kerguelen Plateau steers ACC and may affect regional winds).
b. Atmospheric rivers from Amundsen to Weddell Sea. Potential effect on cloud cover.
c. Ocean-atmosphere feedback better investigated in Arctic, e.g., moist intrusions.
d. Links between Antarctic and subtropics: FW release experiment in models show effects in tropical precipitation (but late 21st century with large FW releases)
e. Feedbacks between upwelling warm water masses (CDW), ice etc. - but what are the consequences for lower latitudes?
f.
g. Atmospheric changes triggered in lower latitudes (wave trains) affect deeper ocean and ice shelves and then may feed back to lower latitudes - different time scales.
h. SO has a much more immediate connection between deep ocean and surface than Arctic Ocean

4. Does polar freshwater impact biogeochemical processes at lower latitudes (past, present, future)?

a. Iron export from Canadian Archipelago larger than atmospheric sources.
b. Nutrient etc. enhancement by throughflow through shallow areas.
c. Very shallow meltwater lenses under the sea ice during MOSAIC in summer - effect on local sea ice.
d. In-situ turbulence vs beryllium-7: instantaneous vs more integrated measures of turbulence

5. What are the expected benefits in global climate simulations by improving representation of polar freshwater sources, such as Greenland runoff or Antarctic ice-shelf interaction

a. SO is most sensitive to cumulative amount of FW rather than FW fluxes/inputs. Effects may be therefore be delayed.
b. FW accumulates in SO surface south of fronts.

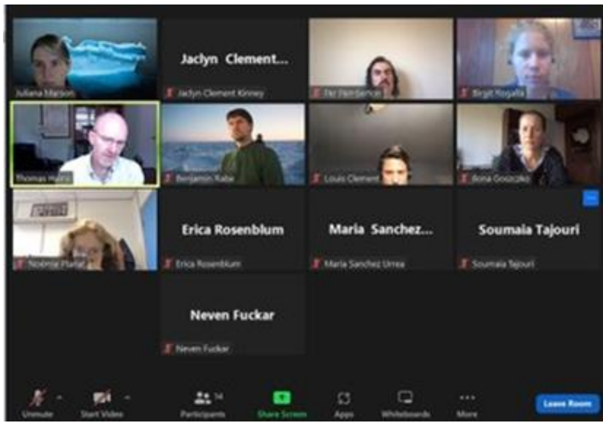
c. Greenland runoff - from modelling: impact may not be instantaneous, but more at longer timescales, impact of large melt events hard to determine.
d. Polar Water from the Arctic is a large FW source along East Greenland and can react to changes in wind regime.
e. Similarly, wind changes can change upwelling in CDW and associated heat and FW fluxes.
f. Since some of these changes are slow, we need longer monitoring time series.

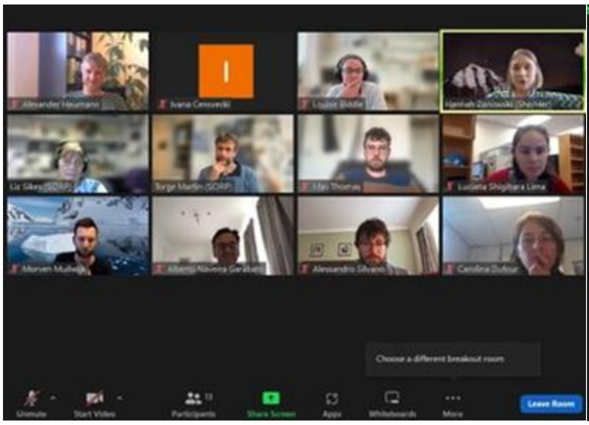
References:

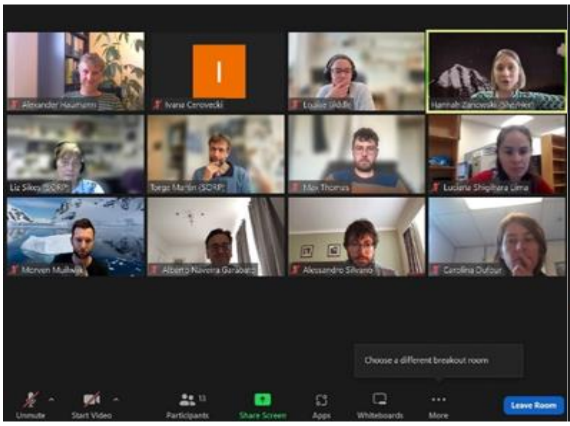
Dukhovskoy et al. (2006): http://dx.doi.org/10.1029/2004JC002820

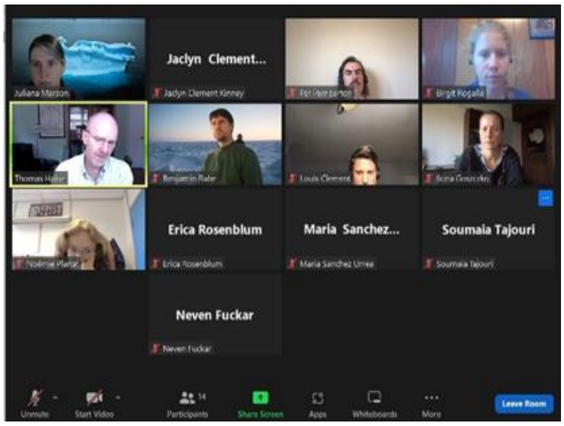
Torres-valdes et al. (2013) https://doi.org/10.1002/jgrc.20063

Annex 4 Pictures





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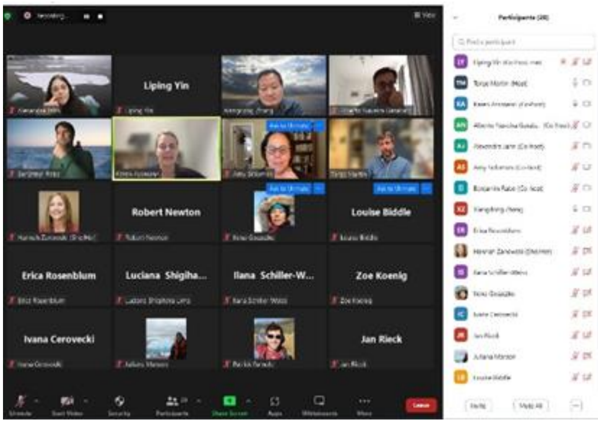
Erica Rosenblum
Maria Sanchez...
Soumaia Tajouri
Neven Fuckar
Leave Room
Unmute
Start Video
Participants
Share Screen
Apps
Whiteboards
More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Ilana Schiller-W...
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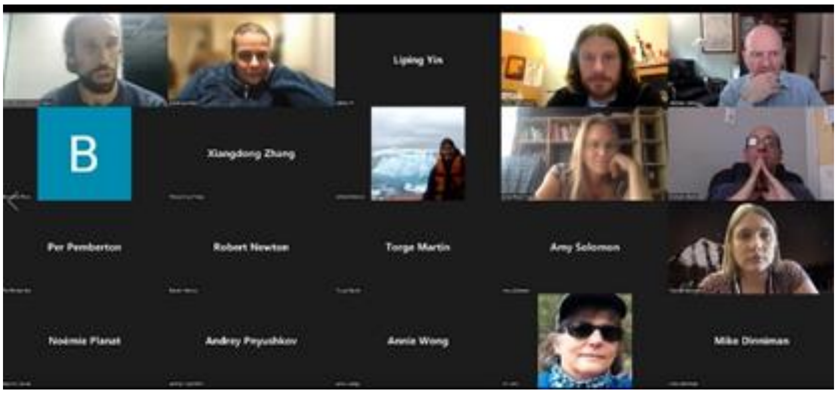
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Noémie Planat
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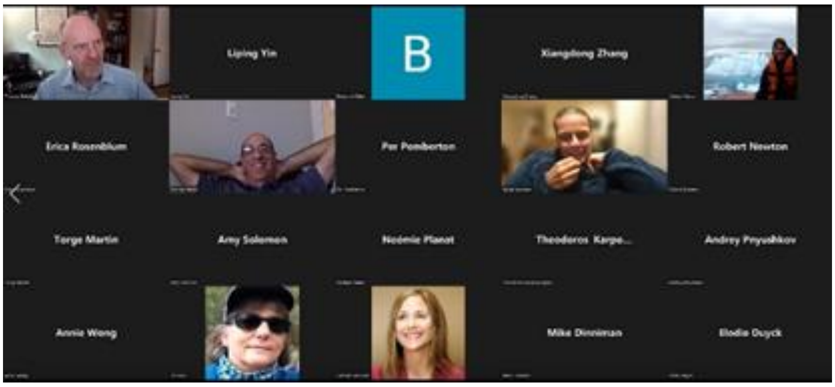
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Robert Newton
Torge Martin
Amy Solomon
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Theodoros Karpo...
Andrey Pnyushkov
Annie Wong
Mike Dinniman
Elodie Duyck