CLIMATE-SPACE - THEME II: CROSS-ECV ACTIVITIES

ARCFRESH (ARCTIC FRESHWATER BUDGET)

Scientific methodology strategy (SMS)

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Change Log

Issue	Author	Affected Section	Change	Status
0.5	D. Fantin, S&T	All	Document created	
1.0	H. Regan, NERSC	All	V 1.0 consolidated	Released to ESA

Acronyms and Abbreviations

CCI	Climate Change Initiative
CMEMS	Copernicus Marine Environment Monitoring Services
CPS	Climate Processes Section
CRD	Climate Research Division
DTU	Technical University of Denmark
ECCC	Environment and Climate Change Canada
ECV	Essential Climate Variabke
ENVEO	ENVironmental Earth Observation
EO	Earth Observation
ESA	European Space Agency
FWF	Freshwater flux
GCOS	Global Climate Observing System
GIS	Greenland Ice Sheet
GIS	Greenland Ice Sheet
GRACE	Gravity Recovery and Climate Experiment
IPCC	Intergovernmental Panel on Climate Change
IV	Ice Velocity
METNO	Norwegian Meteorological Institute
MFID	Mass Flux Ice Discharge
NERSC	Nansen Environmental and Remote Sensing Center
NORCE	Norwegian Research Centre
NPL	National Physical Laboratory
OBP	Ocean Bottom Pressure
RCM	RADARSAT Constellation Mission
S1	Sentinel-1
SAR	Synthetic Aperture RADAR
SEC	Surface Elevation Change
SIM	Sea Ice Motion

SMB	Surface Mass Balance
SMHI	Swedish Meteorological and Hydrological Institute
SoW	Statement-of-Work
SSH	Sea Surface Heights
SSS	Sea Surface Salinity
TBA	To be announced
TOPAZ	Towards an Operational Prediction system of the North Atlantic and the coastal Zone.
UBO	Université de Bretagne-Occidentale

1 Introduction

1.1 Applicable Document

This document contains the Scientific methodology strategy (SMS) for the ARCFRESH project for CLIMATE-SPACE - THEME II: CROSS-ECV ACTIVITIES, in accordance with the contract [AD1], SoW [AD2] and proposal [AD3-AD10].

The purpose of this document is to outline the methodology that will be applied to each observational dataset and the modelling strategy in order to analyse the freshwater flux (ST1), regional budgets (ST2) and impact of extreme events (ST3) that will be carried out in WP5. A brief introduction to geographical and freshwater computation definitions is provided, although, to avoid duplication, we will also refer to the Uncertainty Propagation Strategy (UPS) for further details of these.

1.2 Applicable Document Contents

This document is structured as follows:

- Chapter 1 introduces this document.
- Chapter 2 gives some general definitions, including geographical ones.
- Chapter 3 details the observation-based methodologies
- Chapter 4 details the numerical modeling methodology
- Chapter 5 outlines the next steps towards the final document
- Chapter 6 provides a list of references

1.3 Applicable Document

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD-1	4000145884/24/I-LR	ESA Contract No. 4000145884/24/I-LR	27/09/2024	NA
AD-2	ESA-EOP-SC-AMT-2023-21	Stetement of Work and Annexes and Appendexes	01/12/2023	1.0
AD-3	DTU-ESA-ARCFRESH-CL-001	ARCFRESH Cover Letter	22/02/2024	1.0
AD-4	DTU-ESA-ARCFRESH-TPROP-001	ARCFRESH Technical Proposal	22/02/2024	1.0
AD-5	DTU-ESA-ARCFRESH-IPROP-001	ARCFRESH Implementation Proposal	22/02/2024	1.0
AD-6	DTU-ESA-ARCFRESH-MPROP-001	ARCFRESH Management Proposal	22/02/2024	1.0
AD-7	DTU-ESA-ARCFRESH-FPROP-001	ARCFRESH Financial Proposal	22/02/2024	1.0
AD-8	DTU-ESA-ARCFRESH-CPROP-001	ARCFRESH Contractual Proposal	22/02/2024	1.0
AD-9	DTU-ESA-ARCFRESH-BF-001	ARCFRESH Background and Facilities	22/02/2024	1.0
AD-10	DTU-ESA-ARCFRESH-CV-001	ARCFRESH Curricula Vitae	22/02/2024	1.0

Note: If not provided, the reference applies to the latest released Issue/Revision/Version

2 Definitions

This section corresponds to the first step of the QA4EO five-steps analysis that is further detailed in the UPS.

The scientific literature mostly considers freshwater fluxes in the Arctic, although Schauer and Losch (2019) made a compelling scientific argument for using salt fluxes (along with mass conservation) as a better defined currency. Where possible, both freshwater and salt fluxes will be presented.

The exact definitions are given in Section 2 of the UPS.

2.1 Variable definitions

The definitions of ocean salinity and freshwater are given in metrological terms in the UPS (Section 3.2.2). Essentially, freshwater is defined in relation to a reference salinity, as follows:

$$FW = (S_{ref} - S_{FW})/S_{ref} \tag{1}$$

where *FW* = freshwater, *S* = salinity and *ref* = a reference value. The most commonly used reference salinity is 34.8 psu; this will be used in order to make the results comparable to much of the available literature, although if there is the possibility of recomputing against others (for example, 34.9 psu), then this will also be done to test the sensitivity to this choice. The caveats of using a reference salinity are explored in the UPS (Section 3.2.2). Once computed, freshwater in the water column is typically multiplied by the volume or "thickness" to obtain freshwater content in metres cubed or metres.

Sea ice has a low salinity between 1 and 6 psu in the Arctic, so for this input, we will assume it to be fully freshwater.

Freshwater volume flux is computed through the surface or gates/sections of a given (sub-)region (shown in Figure 2.1). ST1 focuses on computing these fluxes for each observational component (and improving where deemed necessary). Once each component has been estimated, the freshwater content (FWC) change (ST2) is estimated as

$$\Delta FWC = \Delta(P - E) + \Delta RD + \Delta LIce + \Delta SIce + \sum OG \tag{2}$$

where *P-E*, *RD*, *LIce*, *SIce*, and *OG* are precipitation minus evaporation, land ice, sea ice, and ocean gates, respectively, thereby contributing all terms that can influence the freshwater content in a given region. We define those fluxes going into the Arctic Ocean (i.e. land ice loss) as positive. Working with a change in FWC rather than total means that the freshwater content itself does not need to be estimated, which would not be possible with the available data.

2.2 Geographic definitions

The Arctic region and its sub-regions to be used in ARCFRESH are shown in Figure 2.1. In order to compute the freshwater budget from different CCIs and the model, it is important to use the same sub-regions/gateways for each product; uncertainty associated with aligning these from products with different grids is described further in WP4. The regions have been chosen to represent shelf seas with similar oceanography (note that the East Siberian Sea and Chukchi Sea have been combined), and the deep ocean bounded by the continental shelf break, with the exception of the beaufort_sea region which extends further north to also encompass the Beaufort Gyre (for the silver period, this shelf region will be limited by 80.5 N for some satellite products). The northern boundary of the Norwegian Sea has been selected to align with satellite products (Pass 481 of the Sentinel-3 altimeters).

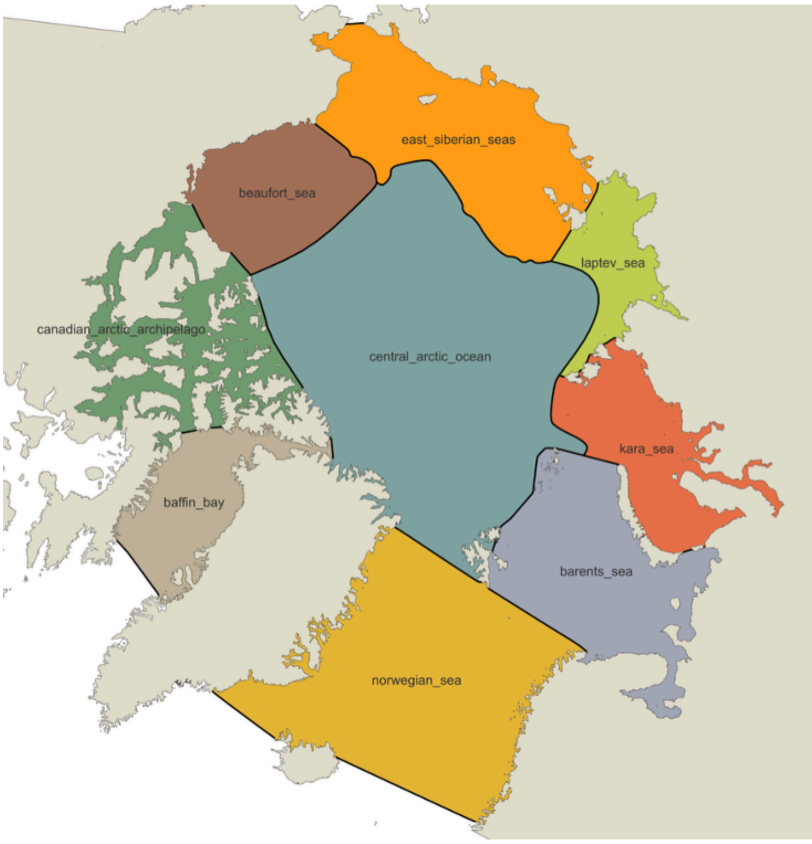

Figure 2.1. Sub-domains of the Arctic region that are used to partition fluxes. The total Arctic region is the sum of the sub-regions, and Arctic boundary fluxes are through the southern boundaries of the east_siberian_seas, canadian_arctic_archipelago, baffin_bay, and norwegian_sea.

2.3 Temporal frequency

The fitness-for-purpose analysis has converged on a common temporal frequency of one month for all observations and model estimates. This is required because some products are only available at a monthly resolution (e.g. GRACE). In the fit-for-purpose report (F4PR), it has been noted that some products also have gaps in some seasons, such as sea ice thickness; in such cases, other supplementary products (in that case, the product by Landy et. al. (2022)) are used during the golden period, but developments/assumptions in the silver period will need to be made. Version 2 (V2) of this document will update these once work has started in WP5. The modelling task of WP5 (Section 4 below) will compute monthly mean fluxes from the daily model outputs to assess the effect of temporal resolution on results.

3 Observation-based estimates (DTU)

We detail here how the freshwater fluxes can be estimated from each of the observational products. Note that, as per the F4PR, the observations have been assessed as being fit for purpose if they are suitable for the golden period (2015-2019); therefore, some of the initial work with the CCIs will be to extend it to the silver era; the ECV database details where this ís relevant. Note also that the F4PR details some post-processing required that inherently includes the freshwater computation in some cases; we have not duplicated that here in order to remain concise. If data are available in higher resolution than monthly, they will be averaged into monthly data to allow for ease of comparison and addition of other datasets.

3.1 Ocean gates and Freshwater content (DTU, LOPS) (ST1)

Freshwater fluxes through the main Arctic gateways are estimated from altimetric sea surface height (SSH) data by deriving the Dynamic Ocean Topography (DOT), defined as SSH relative to the geoid. DOT reflects horizontal pressure gradients that drive surface geostrophic currents. By measuring the slope of DOT across each gateway, surface geostrophic velocities are calculated and integrated across the cross-section to obtain the volume flux. To maintain physical consistency, DOT slopes are computed only within the portions of each section that carry inflow or outflow. For example, the Fram Strait and the Davis Strait each contain distinct inflow and outflow branches that must be treated separately.

For narrow gateways such as Bering, Davis, and Denmark Straits, high-resolution along-track data from Jason-1 and Jason-2 (10-day repeat) are used, while for broader straits such as the Fram Strait and the Barents Sea Opening, the weekly gridded ESA CCI Sea Level Budget Closure (SLBC) dataset (Rose et al., 2019) is applied. All SSH data are referenced to the common OGMOC geoid. The resulting geostrophic velocity mainly represents the surface and upper-layer flow, containing both baroclinic (density-driven) and barotropic (mass-driven) components.

To estimate the freshwater component of the transport, either in-situ salinity observations or the ESA CCI Sea Surface Salinity (SSS) product is used, depending on data availability at each gateway. Over Arctic shelf regions (2010–2024), SSS has been shown to be a good proxy for depth-integrated salinity and freshwater flux, primarily due to strong riverine influence (Hall et al., 2023). While SSS can provide valuable information on depth-integrated salinity, such as the Fram Strait, its use is limited in seasonally ice-covered regions where satellite retrievals are not available. In other gateways, such as Davis Strait, freshwater flux variability is less directly related to surface salinity, and satellite measurements cannot resolve the full vertical structure of baroclinic flow. To address these limitations, existing mooring-based freshwater flux time series (e.g., de Steur et al., 2018) are used to calibrate and validate the satellite-derived flux estimates, ensuring consistency between observation-based and in-situ data.

CCI SSH data from multi-mission altimetry (Rose et al., 2019) and SSS, in combination with GRACE and GRACE-FO ocean bottom pressure (OBP) observations, are used to estimate freshwater content across the Arctic basins. GRACE has provided OBP since 2003, excluding the 2017–2018 mission gap. Together, SSH and OBP allow estimation of freshwater mass and storage, including under the permanent sea-ice pack where SSS retrievals are unavailable.

As no single pan-Arctic SSS dataset spans the full observation period, in-situ data from Ice-Tethered Profilers (ITPs), ship-based CTDs, and Argo floats are combined using the budget approach of Armitage et al. (2016) and Raj et al. (2020)

to relate surface salinity to column-integrated freshwater content. These in-situ measurements provide essential ground truth to validate satellite-based SSS and sea-level-derived freshwater estimates, ensuring internal consistency between regional ocean-gate fluxes and basin-scale freshwater storage calculations.

3.2 River discharge (SMHI) (ST1)*[1]

The river discharge freshwater flux (FWF) will be extended to the period from 2003 to present using the same methodology as described for the period 2015-2019 (Arctic-HYPE model constrained by available in-situ and satellite-based observations of river discharge, snow water equivalent, and snow cover fraction). A challenge for the last part of the period is an expected lack of in-situ observations from Russian rivers, where data is made available with a latency time of at least 2 years. The satellite-based discharge data that is expected to be available from the ESA CCI river discharge project would be highly useful to compensate for this potential lack of in-situ data. However, the uncertainty and temporal and spatial coverage of this dataset is still unknown.

A subset of the in-situ discharge and snow data will be used for a thorough evaluation and uncertainty assessment, also of the extended river discharge time series. However, hydrological modelling across the Arctic corresponds to an underdetermined system with a large portion (at least 40% of the PADB) of ungauged basins where uncertainty estimates have to rely on extrapolations from areas with observations. The task is further complicated by the fact that most temperature and precipitation observations are incorporated in the datasets used to generate the meteorological forcing data for Arctic-HYPE (HydroGFD, Berg et al, 2021). In addition to the assessment versus independent discharge and snow observations, we suggest analysing the internal variance of simulated hydrological variables, in relation to other ECV. For this analysis, we will develop methods to assess the leading modes of variability for the simulated river discharge based on linear algebra, using, e.g. empirical orthogonal functions – EOF, to assess the shared variance between chosen variables (X-ECV). We will focus on the covariance between mean sea-level pressure (MSLP) and relevant ECV for hydrological modelling (river discharge, snow cover, temperature, precipitation), to identify how their variability patterns are related to the Arctic Oscillation. Once validated, this method can also be applied to other ECVs.

3.3 Land ice discharges (ENVEO, DTU Space) (ST1)*[1]

The processing system for calculating the ice discharge of marine-terminating outlet glaciers heavily relies on the dense time series of ice velocity maps enabled by the dedicated and continuous polar acquisition of Sentinel-1. Before the Sentinel-1 era (pre-Oct 2014), the availability of ice velocity data is temporally and spatially very limited. An extension before this period therefore requires sophisticated interpolation schemes based on existing data sets. Solid ice discharge estimates back to 1986 are available at varying temporal and spatial sampling from Mankoff et al. (2017) based on velocity datasets from NASA Measures in the early period, but the temporal distribution varies from 1 to a few velocity maps per year from 1986 to 2015.

The CCI Greenland Surface elevation change data are available since 1992. The basal melt fluxes from the Greenland Ice Sheet from Karlsson et al. (2023) are available for the time period 2010-2020. This will be extended back to 2003 by assuming no significant changes in the regional fluxes between 2003 and 2010. We will evaluate this assumption by analysing Ice velocities and runoff from CARRA in that time period to confirm that no significant changes have occurred. The basal heat is constant and will not change.

[1] *Note that sections 3.2, 3.3 and 3.4 are currently unchanged from the proposal.*

3.4 Sea ice (NORCE, METNO, ECCC) (ST1)*[1]

Note that this section is currently unchanged from the proposal, except for the final paragraph.

Sea Ice Concentration already covers the 2003-present period and does not require additional activity. The Sea Ice Drift Climate Data Record (OSI-455, from OSI SAF) currently ends at the end of 2020. In ARCFRESH, we will prepare an extension to this dataset with one of the two approaches (TBD in the project): 1) use the near-real-time sea-ice drift product of the OSI SAF OSI-405 (the OSI-405 data files exist already, but they require additional post-processing to make them compatible with the OSI-455, and a specific study of the temporal consistency across Dec 2020 / Jan 2021), or 2) operate the OSI-455 processing chain and prepare an extension to OSI-455 for use in ARCFRESH (we will then liaise with the OSI SAF team for them to publish the CDR extension).

The sea ice thickness CCI CDR covers the period 2003-present. For the common period 2015-2019, we will also consider the summer sea ice thickness estimates from Landy et al. (2022) to close the summer gap in the CCI data records for this short period. This will include a potential bias correction on the summer data to match the CCI data in April and October. For the winter, we use the CCI thickness data records, as we also rely on them for extending the time series back to 2002, where summer sea ice thickness estimates do not exist.

The interpolation of the pole holes is an activity of the CCI+ project, and we will use updated sea ice thickness fields with interpolated pole holes if available during the project.

Once data is obtained and projected on the same grids, the sea ice volume flux can be computed by multiplying the grid cell area, sea ice thickness, sea ice concentratio,n and drift in x and y directions to obtain daily fluxes for each gate in the subregions. Other sea ice motion data from SAR will be used to validate the ice drift. More details about the sea ice flux computation can be found in the F4PR (Section 3.1.3).

3.5 Evaporation - minus - precipitation (METNO) (ST1)

Precipitation and evaporation from the ERA5 reanalysis (Hersbach et al., 2020) are globally available from 1940 onwards with hourly and 0.25° resolution. The difference of precipitation and evaporation (P-E) defines the vertical fresh water flux. This difference will be averaged over the Arctic region and its sub-regions (Fig. 2.1), after masking land and sea-ice areas to derive P-E over the open ocean. The data will be provided as gridded NetCDF data.

3.6 Total fluxes (DTU) (ST2)

Computation of the total freshwater fluxes, to compute the freshwater budget in each region, will be carried out using Equation 2. This will be done based on the inputs described in Sections 3.1-3.5 above. Uncertainty estimates are described further in the UPS.

This pan-Arctic freshwater change will be validated against the satellite-derived change in FWC (see Solomon et al, 2021, eq. 1,2), assuming a reference salinity and a two-layer model. These satellite-derived FWC changes are defined sub-regionally and can hence be used for both pan-Arctic and sub-regional validation and will help determine the feasibility of the x-ECV-derived freshwater fluxes.

During this computation, care will be taken to identify particularly strong variability in one of the fluxes, or a period of significant or very low freshwater content change. This can then feed into the choice of perturbation runs for the TOPAZ model simulations in ST3.

4 Model-based estimates (NERSC) (ST3)

The TOPAZ modelling system will be employed in order to assess the sensitivity of the Arctic freshwater budget to a change in freshwater forcing, mimicking potential changes in particular freshwater inputs. This can be used for testing both sensitivity to "extreme events" and the impact of uncertain forcings.

4.1 Model setup

The TOPAZ model (Sakov et. al., 2012) uses the HYCOM ocean model coupled to the sea ice model CICE. It uses an isopycnal vertical coordinate system, using z-coordinates in the mixed layer to ensure that the layers do not get too thin. The domain covers the Arctic and North Atlantic, meaning that additional analysis on the downstream effects of freshwater change in the Arctic Basin can be explored if deemed necessary following the initial analysis (for example, significant fluxes or variability occurring in observations in the Fram Strait) - this will be revisited in V2 of this document. The model will be run without assimilation in order to allow the model to freely respond to freshwater changes and to conserve model parameters across timesteps, which is important when computing a time-varying freshwater budget. The TOPAZ spatial resolution is 12-16 km in the domain, which enables us to run the control and 18 additional proposed perturbed runs (see details below) over the silver period of the observations with reasonable computational expense. If there are significant findings in ST1 and ST2 that would indicate a change, some of the proposed perturbed runs would be beneficial, and such a change would benefit from a higher-resolution, eddy-resolving simulation, this could be tackled by running TOPAZ5 (approximately 6km) over the golden period. Confirmation of this will be done in V2 of this document, once work on WP5 has results.

4.2 Model inputs

Below, we describe the model inputs (and, where applicable, their links to freshwater) and the proposed simulations to complement ST2 and answer ST3.

4.2.1 Atmospheric inputs

Surface fluxes from the atmosphere are coming from the ECMWF reanalysis ERA5 (Hersbach et al., 2020), including liquid and solid precipitation. The bulk formulas for heat fluxes and evaporation-minus-precipitation follow the COARE 3.1 standards.

The evaporation and precipitation used in the model are the same as the product that will be used to compute the "observed" E-P, enabling full consistency between the E-P observations going into the freshwater budget and the model input. This model input field can be easily modified for perturbation runs.

4.2.2 Lateral boundary conditions

Lateral boundary conditions (currents, temperature, salinity) are taken from the global Mercator Ocean International model reanalysis GLORYS (Lellouche et. al., 2021) at the South of the Bering Sea and across the North Atlantic between France and Newfoundland so that all of the Arctic and Greenland are fully included in the TOPAZ model domain. Figure 4.1 shows the location of these boundaries in TOPAZ. The freshwater terms across the boundary will be considered as uncertain within the project.

While these lateral boundary conditions are not the same as the observations, the observations from Bering Strait can be compared against the modelled Bering Strait freshwater flux. If there is a significant difference, the perturbation runs associated with this input (see 4.4) can be adapted accordingly, as modifications made to the southern Bering Sea boundary will propagate up to the Bering Strait without significant water property transformation.

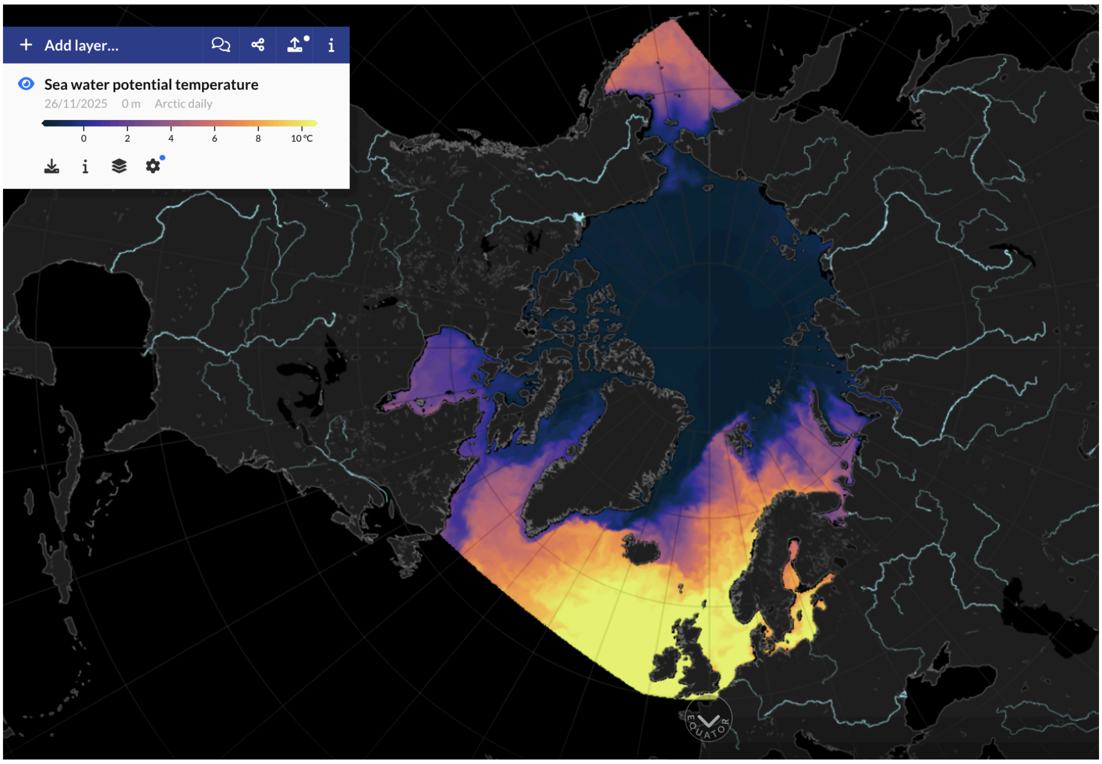

Figure 4.1: Domain of the TOPAZ system, with its lateral boundaries in the Bering Sea and North Atlantic. Variable shown is a snapshot sea water potential temperature from the higher resolution (TOPAZ5) simulation, which might be an option in perturbation runs in SMS V2 (see Section 4.4).

4.2.3 River and land ice inputs

Currently, TOPAZ is set up to run with river discharge composed of several rivers taken from the following datasets:

- The Arctic-HYPE climatology (1979-2013)
- The E-HYPE climatology for the European Rivers included in the TOPAZ model domain

This climatological river forcing naturally does not provide any interannual variability, which is problematic given observed changes. Recent work with the TOPAZ model system within a different project has demonstrated that using time-varying rivers from GloFAS has significant effects on the freshwater content within the Arctic Basin (Figure 4.2).

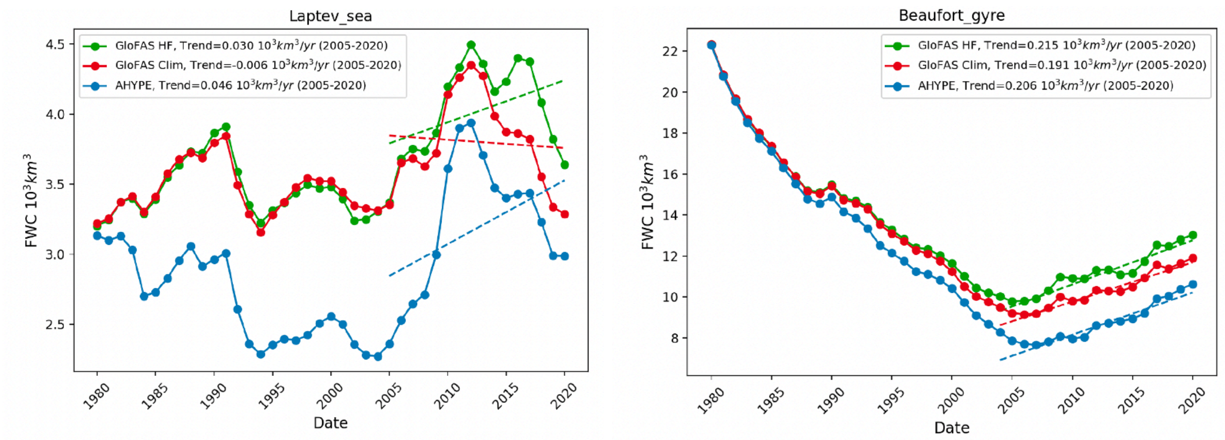

Figure 4.2: Effect of running the TOPAZ model with different rivers: A-HYPE (climatology), GloFAS (climatology) and GloFAS HF (time-varying). The resulting total freshwater content in the Laptev Sea and Beaufort Gyre regions is shown. Figure courtesy of Adrien Acchiardi (NERSC).

For ARCFRESH, the code changes required to allow for time-varying forcing (developed for the GloFAS input) will be used in conjunction with the time-varying Arctic-HYPE-2 river discharge dataset being produced as part of ARCFRESH. This will enable consistency between observations contributing to the observed budget and model inputs affecting the freshwater content in the model. The large FWC offset between GloFAS and A-HYPE forced simulations is caused by offsets in the Ienissei discharge and differences in the seasonal cycle between the two hydrological models. Figure 4.3 shows the significant effect that bias-correcting can have on river discharge for the Yenisei, Lena and Ob rivers.

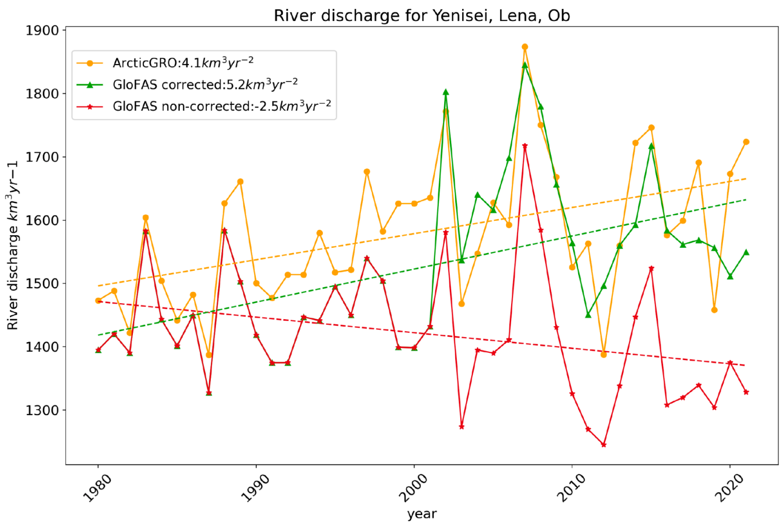

Figure 4.3: Effect of bias-correcting three large Arctic rivers (Yenesei, Lena, and Ob) on their total annual river discharge. Correction is applied to the GloFAS river discharge (green versus red lines) and shown against the ArcticGRO, a daily dataset of river discharge from 17 Arctic rivers (The Arctic Great Rivers Observatory. 2024. Discharge Dataset, https://www.arcticrivers.org/data).

The land ice inputs for the simulations are the Greenland Ice Sheet CCI data (Based on linear trends of the GRACE data from Uni. Dresden, 2019) from 8 regions redistributed to the 30 largest terminal glaciers. Updates to the CCI data as part of ARCFRESH will be incorporated, if possible, within the timeframe of the project. There are no land ice inputs from other Arctic glaciers in Svalbard, Franz Jósef Land or Novaya Zemlya.

4.2.4 Other considerations

It should be noted that, of the five variables in the freshwater budget in Equation 2, four can be somewhat a) be used to force the model, and a) varied in perturbation runs. This is not the case for sea ice, which is explicitly modelled and will vary freely during the simulation in response to atmosphere and ocean properties. Sea ice model parameters can be tuned, for example, to produce more melting or freezing in response to surface conditions, but this cannot be done without impacting other aspects of the simulation. Therefore, our freshwater budget for the model has a component that we cannot easily perturb. Instead, the model's sea ice will be validated against the freshwater flux obtained from ST1 in order to evaluate the model's performance and act as a barometer in all of the perturbed simulations.

4.3 Control run

As shown in Figure 4.4, the first simulation will be a control run with standard inputs (sections 4.2.1 - 4.2.3) and settings spanning a spin-up period (1980-2002), followed by the silver period (2003-2022). This control run will be used to compute our best estimate of physically-consistent freshwater fluxes and budget in the model framework, for comparison with ST1 and ST2 observed outputs. It will also form the baseline for the extreme events analysis for ST3.

Initial conditions will be taken from World Ocean Atlas 2023 (Reagan et al., 2023. The simulation will be started in 1980 in order to allow for an adjustment to initial conditions and the northward propagation of Atlantic Water, but also to provide a baseline to see how interannual and decadal variability in the control run itself manifests. This is important because it allows for a better understanding of how the Arctic freshwater budget has been changing in general, before perturbations are applied. It will then provide more insights and context to the perturbation runs, for example, if there is a trend emerging that is amplified or cancelled by a change in freshwater flux. The output frequency will be daily files. The standard HYCOM ocean outputs are in .ab binary format; to make the outputs more easily accessible to other WPs, they will be converted into netCDF files before being shared.

As an additional support to the work in WP4, the freshwater analysis will be carried out directly on the daily files, and also on monthly-averaged outputs in order to assess the influence of temporal resolution on the computations.

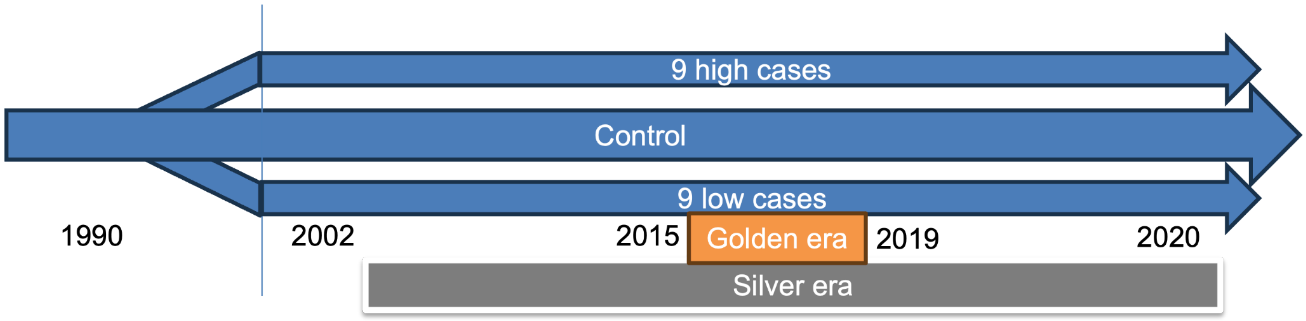

Figure 4.4: schematic showing the proposed control and perturbation runs. The control run spans 1980-2023, with perturbation runs starting in 1995 from restarts from the control run, allowing a spin-up of 7 years to the adjusted forcing, and then simulating the silver era (2003-2023), which encompasses the golden era (2015-2019).

4.4 Perturbed runs

The basis for running perturbation simulations is primarily to assess what will happen if one of the freshwater inputs is amplified or decreased over the simulation period - i.e., a persistent change in the forcing, as opposed to a short-lived shock. The motivation behind this is twofold; firstly, if there is a continued change in one of the forcings, for example, if river discharge were to be double what it currently is, we are able to investigate the impacts of that scenario. Secondly, if there is a bias in one of the observations and/or inputs, the impact of this can be tested by adjusting a relevant parameter in the model accordingly. The idea is to sufficiently shock the system to be sure that the changes we are seeing are related to the change.

4.4.1 Strategy

We will vary parameters one at a time in order to attribute the cause more easily and ensure that if there is a response, it is more likely to occur within the simulation period. As mentioned, we will carry out the same analysis as for the control run, resulting in timeseries of freshwater fluxes and changes in each subregion to compare across simulations. By partitioning into many subregions and adjusting different parameters independently, we can gain an idea of where freshwater content changes the most, and why, not just that it does, and which regions are more sensitive to change than others.

The simulations will start from a restart of the control simulation in 1995. This gives 7 years before the silver era begins, which will be enough time for the upper ocean to adjust to the changes. A systematic approach is taken, with “high” meaning control multiplied by 2 and “low” meaning control divided by two. The perturbed simulations are as follows:

- Precipitation: two simulations, one high and one low
- River discharge and land ice: 8 simulations (see Table 4.1). These are varied both independently (keeping one parameter as standard) and together (varying both) because they both constitute an input coming from the coast.
- Bering Strait inflow: varying both the salinity of the inflow (high/low) and the volume flux (high/low), resulting in 8 simulations.

Table 4.1: Description of perturbed runs when two parameters are to be varied. "P" represents the perturbation simulation number; for two parameters, there are 8 possible combinations, not including the control simulation.

		Parameter 2		
		Low	Standard	High
Parameter 1	Low	P1	P2	P3
	Standard	P4	*control*	P5
	High	P6	P7	P8

As mentioned, it is not possible to directly change the freshwater flux from sea ice, but this will be an important output parameter to analyse, particularly as it may be non-negligibly altered by any of the perturbed inputs.

4.4.2 Important influence of results from WP5

As mentioned at the beginning of Section 4.4, some of the freshwater inputs will be updated during the ARCFRESH project. As well as this affecting the control run, it may also affect the choice of perturbations. If an extreme freshwater event is found in one of the fluxes or a large uncertainty is identified, there is the possibility of modifying the perturbation strategy to directly test this. This is dependent on WP5 and ST1 initial results, and so this section is particularly open to evolution in V2.

4.5 Freshwater budget in the model

Computation of the freshwater from the model will happen in two stages: the first will be an analysis of each freshwater term individually (primarily based on the model inputs over the Arctic domain), and the second will be producing timeseries of the overall freshwater change timeseries in the full domain and subregions (Equation 2). These will be compared to the timeseries from the observations. This analysis will then be replicated for each perturbation run, providing a simple but consistent metric with which to assess FW changes and their subsequent propagation around the full domain.

Surface FW fluxes will be computed in each subregion by applying a mask generated from the shapefile of the map shown in Figure 2.1. River discharge and land ice will be added to the relevant subregions as a freshwater volume flux.

To compute lateral FW fluxes in the ocean from the model, modifications to existing post-processing tools will be used. The standard version of the "m2transports2" tool computes heat and volume transports across given sections. This script has been adapted to also compute freshwater volume transport by using the same code structure for the heat transport but with salinity instead of temperature and a chosen reference salinity (to start with, 34.8 psu has been used). Sections from the shapefile represented in Figure 2.1 have been extracted into text files, which have then been processed to make them readable by the computation script. The default code allows sections to be defined by multiple points, and multiple sections can be defined in the input files, but there cannot be more than 50 rows of points in total in the input file. This means that the complex ocean gates defined in the subregions in Figure 2.1 sometimes have to be split into multiple subsections, and the function must be called multiple times in order to compute results over all subregions. Scripts have been produced to loop over all of the sections in all subregions and run m2transports2 on each. Additionally, for the script to run with the model grid, points that are too close together in distance have been removed (a threshold of 50 km was used).

Sea ice (solid FW) will be computed along the same boundaries using a similar code, in order to compare to the sea ice computations from ST1 where applicable.

5 Conclusions

The Scientific Methodology Strategy Version 1 represents a summary of the proposed steps required to obtain freshwater fluxes and a freshwater budget from CCI products and the TOPAZ model. It also proposes how the model will be used to analyse sensitivity to changes in Arctic freshwater fluxes.

The methods are based on the knowledge of CCI experts, and caveats and potential difficulties have been noted where applicable, either here or in the F4PR. As such, as ARCFRESH progresses, some changes may need to be made. While some are unforeseen, it is more certain that some things will need to be revisited in Version 2. These are listed below.

1) Verify that the methodology described above, based on the available data assessed in F4PR for the golden period, is suitable for the silver period, or if adjustments need to be made. In particular, this is relevant to the time frequency of data output. This may become clearer in some CCIs only when work begins in WP5. Update the methods to describe how this transition was done.
2) Add figures for each freshwater flux to demonstrate better that the method is feasible and in a form ready to be combined into Equation 2
3) Finalise choice of inputs to TOPAZ simulations - if some outputs from ARCFRESH are feasible as inputs, or if current standard inputs should remain
4) Finalise choice of perturbation runs based on initial findings from ST1 freshwater flux analysis and evaluation of uncertainties. Decide if certain events should be simulated or if the more systematic approach proposed here is preferred. Decide if it is preferable to have so many long runs, or if some should be done at a higher resolution to investigate certain findings from ST1 and ST2.

Additionally, in some parts, the F4PR and UPS documents have been referenced in order to avoid duplication. For Version 2, it is important to decide what should be referenced and what is required to be explicit in the SMS.

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