Experimental Protocol for computation of Arctic Climate Response Functions (Jeff Scott, John Marshall, MIT; Andrey Proshutinski, WHOI)

We describe here the procedure we have followed in calculating 'Climate Response Functions' (CRFs) for the Arctic – see Marshall, Scott and Proshutinski (GMD, 2017, http://www.geosci-model-dev-discuss.net/gmd-2016-316/#discussion) for a more detailed discussion of the rationale and the form of CRFs based on the MITgcm. It would be very interesting to determine how robust the CRFs are across models. To this end we encourage other groups to carry out such calculations. Groups would choose their `best' Arctic simulation (by comparing to observed variables: ice thickness, ice extent, freshwater content, Atlantic water circulation and ability to capture major halocline parameters and arctic water masses) and perturb it in the manner described below. The anomalous forcing fields would be identical in all models participating in the CRF experiments and can be obtained as described below. 30-50year runs would be appropriate with five-member ensemble spawned from perturbed initial conditions.

Experimental Procedure

An unforced climatology control run is integrated over a historical period. For the MIT setup, JRA25 reanalysis data was obtained over 1979-2013, which permitted a 35-year integration of our Arctic model. Other groups may use different reanalysis products with longer or shorter data availability periods. Regional models may use a "normal year" dataset to specify open boundary conditions, or if available, may use data from actual years. Groups using fully coupled models are likely to be more flexible in their choice of time period, but should attempt to simulate the last 30-50 years or so.

Arctic CRF experiments are carried out by modifying the forcing fields at run onset. As general good practice, it is usually wise to use a run that has been "spun up" for some period of time prior, rather than starting the forcing experiment from a climatological T,S dataset. The perturbed runs should occur over the same time range as the climatology run; difference fields between the perturbed run and the control are used to compute the CRFs.

Forcing functions

The following Arctic change experiments are proposed:

- Anomalous high pressure centralized in the Beaufort Gyre region (BG+)
- Anomalous low pressure centralized in the Beaufort Gyre region (BG-)
- Anomalous low pressure centralized in the Greenland Sea region (GS+)
- Anomalous high pressure centralized in the Greenland Sea region (GS-)
- Anomalous (3x) river runoff into the Arctic Circle (RUN3x)
- Including Greenland runoff (GRUN)
- Anomalous warm flow through Fram Strait (FRAM)

In all cases, the anomaly in forcing is applied as a step function.

WIND

For the anomalous pressure scenarios (BG+, BG-, GS+, GS-), we provide a netcdf file with these surface pressure anomalies, gridded in lat-lon coordinates at 0.5° resolution. The center of the BG pressure anomaly is located at (77.34°N, 149.08°W) and the center for the GS anomaly is located at (70.55°N, 6.04°W) [see Figure 1]. The magnitude of the anomaly is the same for all experiments, with a central maximum/minimum of 4 mb with a radius of influence on the order of 1000 km. To compute surface winds from these pressure anomalies, the following relation is used:

$$W_s = 0.7 \times \begin{bmatrix} cos30^{\circ} & -sin30^{\circ} \\ sin30^{\circ} & cos30^{\circ} \end{bmatrix} \cdot W_g$$

where W_g is geostrophic wind from the pressure anomaly, and W_s is the applied surface wind anomaly.

Data (netcdf files) for slp anomaly and associated u,v anomaly is available here:

http://svante.mit.edu/~jscott/FAMOS/

We have included surface wind anomalies, gridded in lat-lon coordinates at 1.0° resolution. This may be used directly instead of computation from surface pressure. Note that wind stresses are not provided — these will be computed using bulk formulae in each respective group's model, as a function of local ice/ocean cover. Also note that wind anomalies should affect all bulk formulae, i.e., will alter evaporation and other fluxes that have a wind strength dependence.

RUNOFF

For the anomalous river runoff experiment (RUN3x), the freshwater input from all rivers which drain into the Arctic Circle (66°N) is multiplied by a factor of three. This can be achieved by increasing actual freshwater input to a non-linear model free surface, or through the use of virtual salt fluxes and a rigid lid or linearized free surface; specifics here will differ by modeling group. In our regional Arctic setup, no effort was made to balance this anomalous fresh water input with additional evaporation, and we leave it up to any participating global models as to whether (or how) they balance global EmPmR. For our Greenland runoff experiment (GRUN), J. Bamber's data set (available to all FAMOS participants) should be used to augment one's runoff file (or, for coupled models, added as additional river runoff). Bamber's data set has a monthly time history from 1958 to 2010, although for simplicity I processed the data into a normal year which I then applied as a step function to compute CRFs.

FRAM STRAIT

The main idea of this experiment (FRAM) is to increase the temperature of water flowing through the strait into the Arctic, without concomitant density change. This was accomplished by rapid restoring of temperature with simultaneous compensating restoring of salt in a sub-region of the Strait. The restoring temperature was T+2K and restoring salinity was S+0.253 psu, using both T and S diagnosed monthly from a 35-year control run. For convenience, we make use of our tracer release area (78.7°N-79.2°N, 0.0°-11.5E, as defined below; this also corresponds with observed mooring data). Note that temperature and salinity are only restored from the surface to 440m depth (see Figure 3). Restoring time constant was set to 9 days for both T and S.

Tracers

To the extent possible, we encourage groups to include the following tracers in the climatology and perturbed forcing runs (thanks to Lars Smedsrud, Mehmet Ilicak, and Morven Muilwijk for working out the details of the tracer release diagnostics). CRFs of tracer concentrations can be computed by storing monthly means of the 3D tracer field. Eight tracers (a-i) have been defined; release areas are shown in Figures 4.

a. Fram Strait, all depths:

(79.2°N, 0.0°E)	(79.2°N, 11.5°E)
(78.7°N, 0.0°E)	(78.7°N, 11.5°E)

b. Barents Sea Opening, all depths:

(74.0°N, 19.0°E)	(74.0°N, 20.5°E)
(70.2°N, 19.0°E)	(70.2°N, 20.5°E)

c. Bering Strait, all depths:

(66.0°N, 171.0°W)	(66.0°N, 166.5°W)
(65.5°N, 171.0°W)	(65.5°N, 166.5°W)

d. Norwegian Atlantic Current, all depths:

(64.65°N, 0.5°E)	(62.5°N, 6.5°E)
(64.15°N, 0.5°W)	(62.0°N, 5.5°E)

e. Kara Sea, river tracer (surface only):

(77.0°N, 55.0°E)	(77.0°N, 100.0°E)
(66.0°N, 55.0°E)	(66.0°N, 100.0°E)

f. Laptev Sea, river tracer (surface only):

(77.0°N, 102.0°E)	(77.0°N, 140.0°E)
(70.5°N, 102.0°E)	(70.5°N, 140.0°E)

g. MacKenzie River outflow region, river tracer (surface only):

(73.5°N, 150.0°W)	(73.5°N, 115.0°W)
(68.5°N, 150.0°W)	(68.5°N, 115.0°W)

h. Beaufort Gyre, surface only:

(79.34°N, 154.1°W)	(79.34°N, 144.1°W)
(75.34°N, 154.1°W)	(75.34°N, 144.1°W)

i. Greenland runoff, surface only: For this tracer, use only Greenland runoff (that prescribed from J. Bamber et al. dataset)

For tracers *a-d*, all gridpoints that fall in the respective region, for all depths, should be relaxed to a value of 1.0 with a time constant of 6 hours (or, simply prescribed to a value of 1.0). For tracer *h*, only the surface box in this region should be restored to a value of 1.0. Tracers *e, f, g*, and *i* are "river tracers": tracer flux should be prescribed by converting river runoff to a flux of tracer. For example, given a river outflow of 1000 m^3/s into a grid cell, tracer should simply be prescribed as 1000 tracer units •m^3/s. This should result in surface tracer concentrations of O(1) after several years. Tracer *i* is intended primarily for use in the GRUN experiment, whereas *a-h* can be tracked in all experiments.

All tracers except *d* and *i* are defined by lat-lon quadrangles, thus any grid can be easily masked. For *d*, I used matlab's inpolygon routine to determine my mask for this quadrilateral area, which isn't quite exact if one wanted to define the area with great circles, but close enough for the point of this exercise.

Diagnostics and Computation of Metrics for response functions

For both the climatology and Arctic change experiments, monthly mean data should be stored (specifically, S, T, u, v, ice fraction and thickness, heat transport, and any other fluxes or transports deemed to be useful). CRFs and other diagnostics and metrics will be computed from these fields as needed.

Freshwater content (FWC) is defined as follows:

$$FWC = \int_D^{\eta} \frac{S_{ref} - S(z)}{S_{ref}} dz$$

where η is the free surface, and we choose S_{ref} = 34.80 and D is the depth where S=S_{ref}.

Freshwater flux (FWF) is defined across a section (here, defined for constant latitude) and calculated as follows:

$$FWF = \iint_D^{\eta} \overline{v(x,z)} \, \frac{S_{ref} - \overline{S(z)}}{S_{ref}} dz\, dx$$

where η, D, and S_{ref} are defined similarly as before, and the overbar indicates monthly mean. (time averaging done here to avoid the need for added in-line diagnostic code into the model)

Ensembles

To create an ensemble for each experiment, we suggest the following procedure: for ensemble member #1, delay the onset of the forcing step function change to the start of year 2; for ensemble member #2, delay the onset of the forcing step function change to end of year 3, etc. Five ensemble members are sufficient for each different forcing experiment. This approach not only reflects a perturbation in the initial condition (i.e. at the onset of the step function in forcing), but also permits one to assess the robustness of the CRF with respect to interannual variability.

Area Definitions

Regions of interest are defined for diagnostic purposes; very likely, this list will grow as new scientific hypotheses are developed and tested. See Figure 2.

BG Region: 130°-170°W, 70.5°-80.5°N
GS Region: 15°W-5°E, 72°-77°N

Sections:

Barents Sea Opening: (20.0°E,70.0°N) to (20.0°E,78.5°N)
Fram Strait: (20.0°W,79.5°N) to (11.5°E,79.5°N)*
Baffin Bay/Davis Strait: (62.0°W,66.5°N) to (53.5°W,66.5°N)
Bering Strait: (171.0°W,66.0°N) to (166.5°W,65.8°N)

*Moorings are located at 79°N, and both our defined tracer release area and defined restoring area are coincident with these observations. However, diagnostic section is defined 0.5° further north so as to be upstream of the restoring area.

Please contact Jeff Scott if you have any problems or if anything is unclear:
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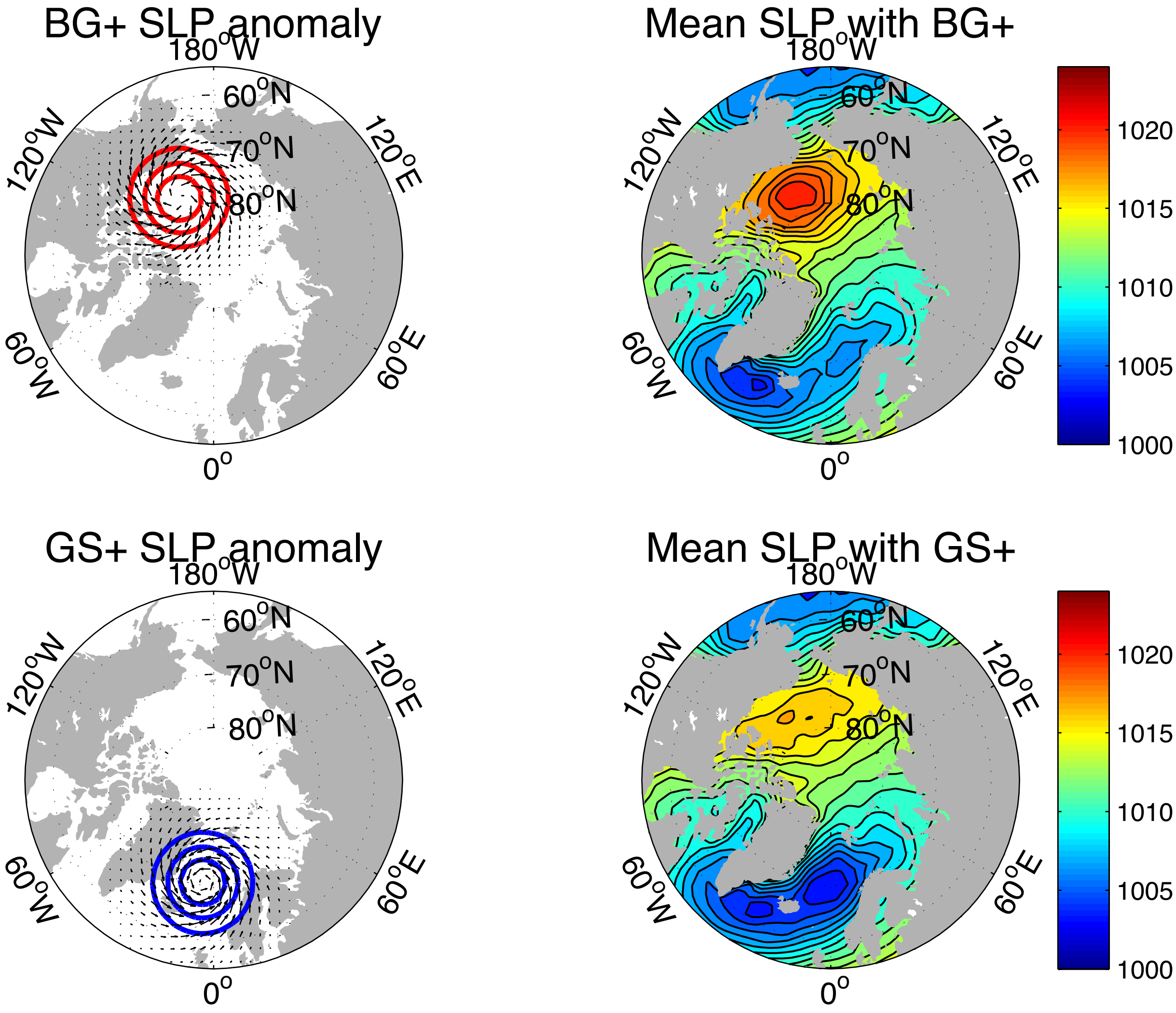

Figure 1: (Upper left) Idealized sea-level pressure anomaly with anomalous 10m winds constructed for the Beaufort Gyre (BG). Note that BG+ corresponds to anomalously high pressure. (Upper right) BG+ sea level pressure (SLP) anomaly added to a 1981-2010 climatology. (Lower left) Idealized sea-level pressure anomaly with anomalous 10m winds constructed for the Greenland Sea (GS). Note that GS+ corresponds to anomalously low pressure. (Lower right) GS+ sea level pressure (SLP) anomaly added to a 1981-2010 climatology.

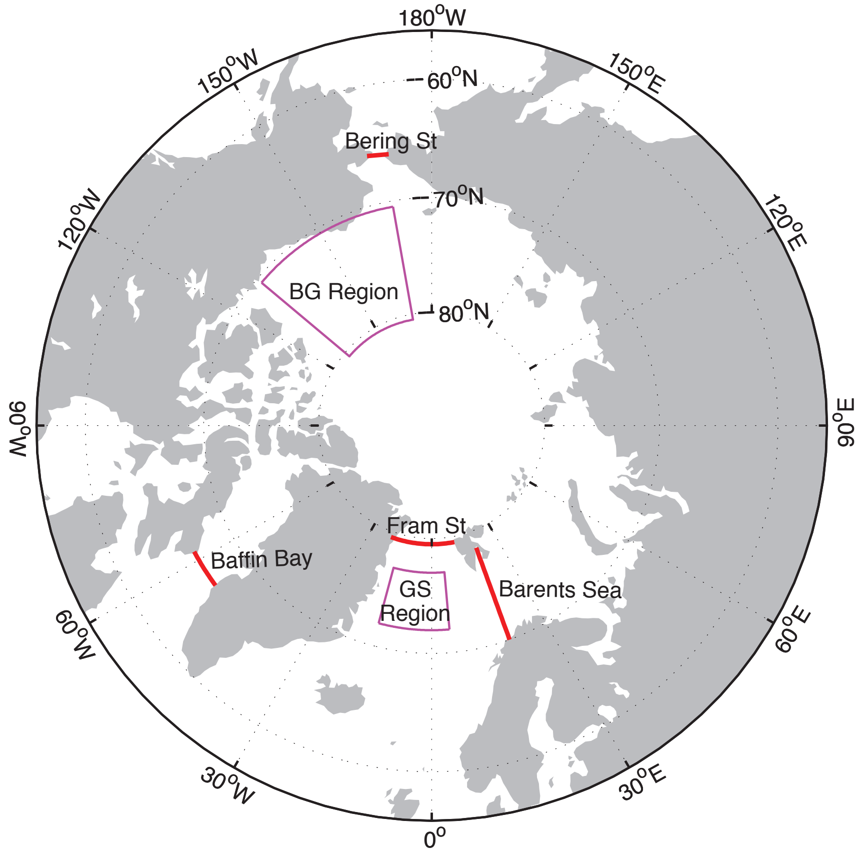

Figure 2: Geography of regional model showing Fram Strait, Barents Sea, Baffin Bay (Davis Strait), and Bering Strait sections. Also shown are our Beaufort Gyre (BG) and Greenland Sea (GS) defined areas.

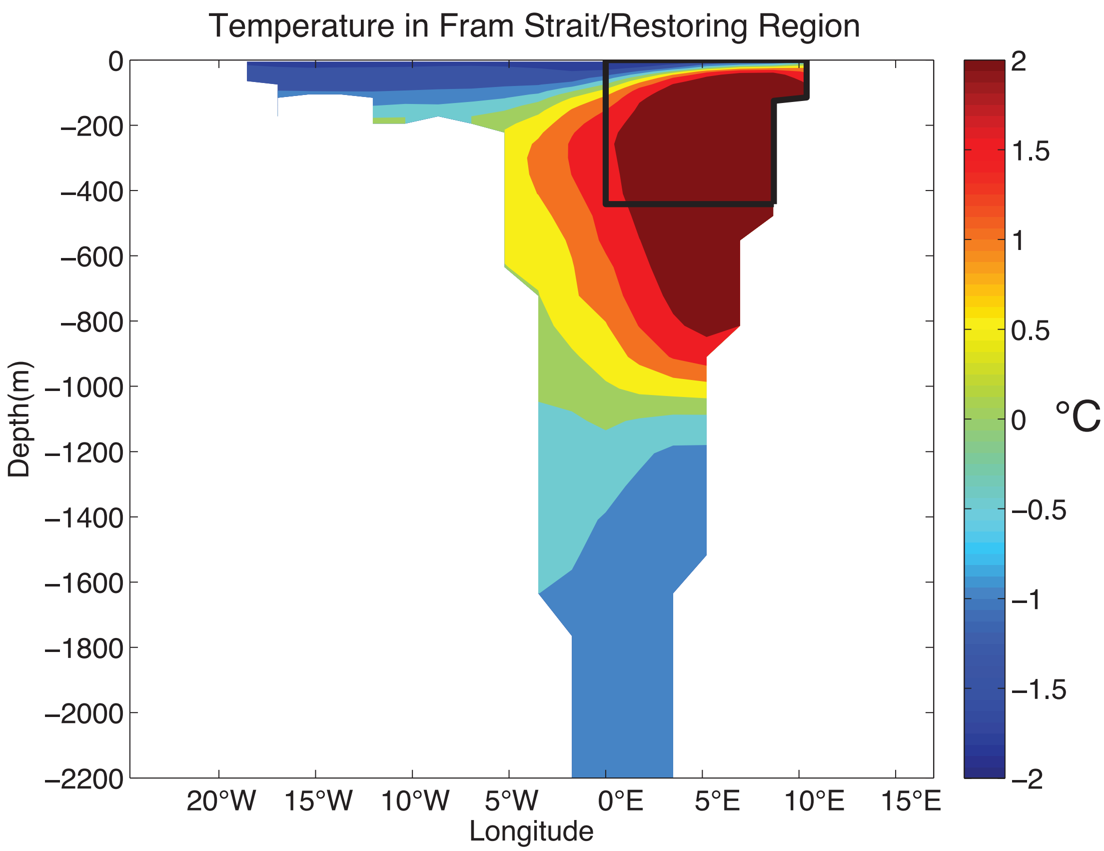

Figure 3: Annual-mean temperature section through Fram Strait (MITgcm model result), oriented looking northward into the Arctic.

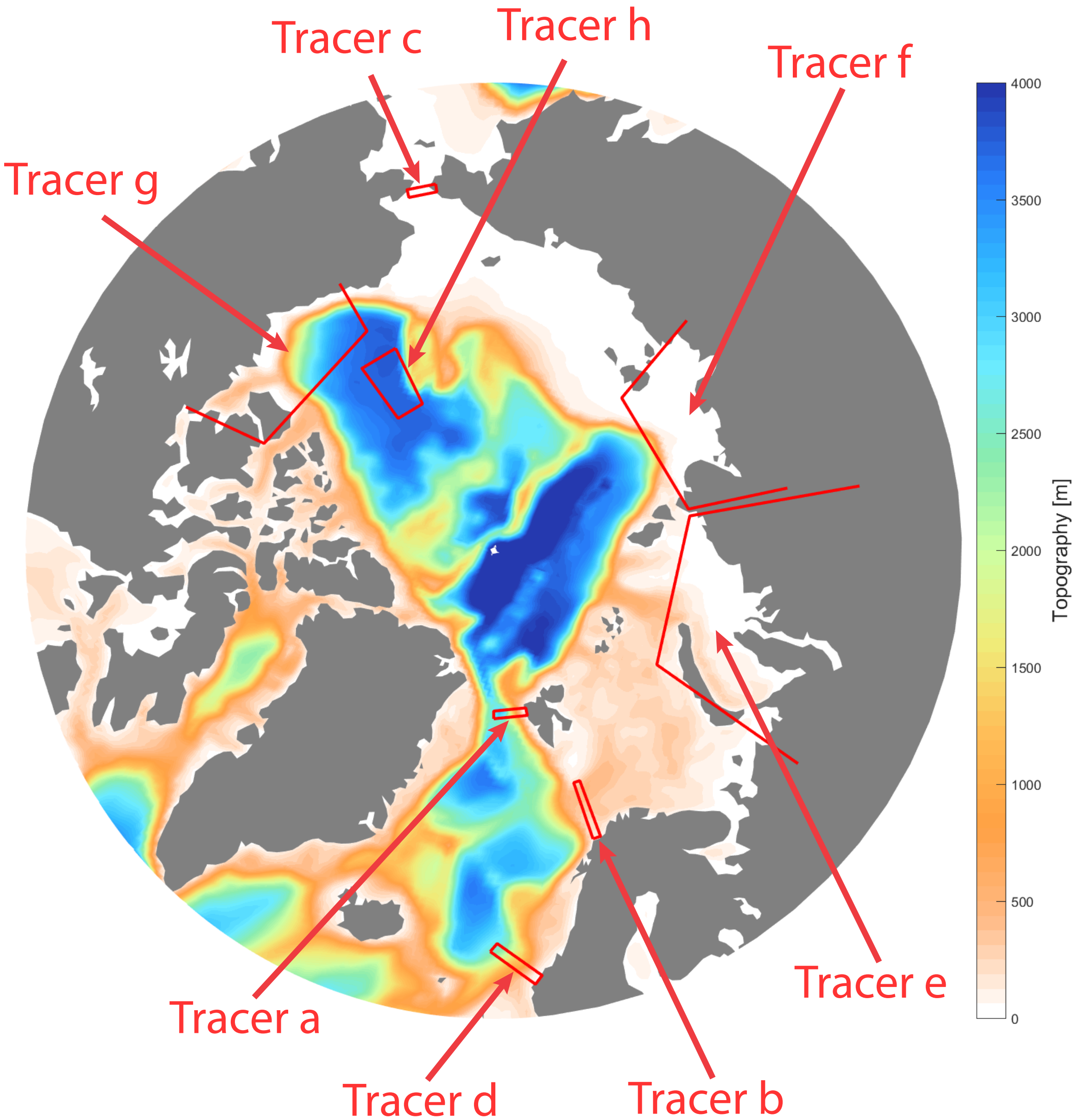

Figure 4: All-depth tracers (*a*-*d*), river tracers (*e*-*g*), and surface tracer (*h*). (thanks to Morven Muilwijk for providing this figure)

Figure 5: Plot of Greenland runoff in km^3/month for July 1958, from J. Bamber's dataset.