Replies to reviews of Forryan et al. "Arctic freshwater fluxes: sources, tracer budgets and inconsistencies".

Tom Armitage (TA) and Wilken-Jon von Appen (WA) provided reviews of our manuscript, and also Paul Dodd (PD) wrote an interactive ("short") comment. These three will be well aware that not all reviews are helpful. In the present case, all three caused us to examine certain matters more closely, with the result that our Section 4 (Discussion and Summary) has been overhauled and is now quite different, and there are major edits elsewhere. We also became conscious that aspects of our use of language were opaque in some cases, in particular around: ice-modified waters, where we now simplify to "sea ice melt water" and "brine"; the distinction between what we now call "oceanic water", meaning the complex of all components, distinct from ocean (Atlantic / Pacific) seawater sources, which we now call "seawater"; and the terminology around "freshwater fluxes" and also around methods is now made explicit. The relevant material appears in Sections 1 and 2, and specific instances are detailed below. We believe that the manuscript is significantly improved, and we express our sincere thanks. We reply to specific comments (in italic font) below, after first replying to a general point.

Regarding choice of journal

We selected The Cryosphere for a number of reasons. On The Cryosphere's home page (https://www.thecryosphere.net), it is stated that the journal is "dedicated to ... all aspects of frozen water". Furthermore, The Cryosphere remit includes publishing articles "including studies of the interaction of the cryosphere with the rest of the climate system". The Cryosphere is about more than ice – it is about the cryosphere, which is what has made it a distinctive and excellent vehicle for the publication of articles about the cryosphere since its foundation over a decade ago. As a relatively early example of a paper that took an approach analogous to ours, we cite Serreze et al. (2009, https://doi.org/10.5194/tc-3-11-2009), entitled "The Emergence of Surface-Based Arctic Amplification.", and which is "about" the Arctic atmosphere, while treating sea ice as an essential component of the Arctic climate system. This article has been cited over 400 times since its publication. As another instance, we note the publication by TA and one of us (SB) of an article in The Cryosphere in 2017 entitled "Arctic Ocean surface geostrophic circulation 2003–2014" (https://doi.org/10.5194/tc-11-1767-2017), which is mainly "about" the (liquid) Arctic Ocean.

In the present case of our manuscript, sea ice is a fundamental component of our analysis. It appears *per se* as a key element of the net freshwater budget of the Arctic ice and ocean system, and without the impression made by sea ice processes on the oceanic concentrations of oxygen isotopes, our analysis would not function. We believe that by presenting our work through The Cryosphere, our article will directly reach the audience that can best appreciate it.

Reviewer 1 (TA)

P2L2 and p23L11 – "traditionally divergent" to me implies that the divergence is somehow inevitable, or done on purpose historically. Maybe use "generally divergent" instead.

Done

P2L3 – split the sentence: "...reconcile. The..."

Done

P3L4-10 – I'm not sure the discussion of mid-latitude linkages and AMOC disruption by Arctic FW are really warranted here. Also, my (admittedly limited) understanding of both of these phenomena is that they

are highly contentious, and an accurate mention of them would have to also say that some researchers claim there is no evidence that they are occurring or will occur.

These references are included as part of the introduction to inform the reader of the potential wider impact of changes in the Arctic. Both the relevant statements have caveats (underlined below):

P3 L12 Changes in the Arctic heat budget <u>may</u> affect the strength ...

and

P3 L16 Arctic freshwater export also has the potential to change ...

These statements are uncontentious and we prefer to leave them unchanged.

P8L5-7 – could you give some indication of the uncertainty associated with the optimal interpolation of the geochemical data?

The section covering optimal interpolation has now been revised.

P8 L22 The δ^{18} O and nutrient data were optimally interpolated (Roemmich, 1983) vertically in pressure and horizontally in distance to match the TB12 model domain (Fig. 2). The interpolation recovers the measurements for each sample point and interpolates between values to fill the unsampled areas of the domain. The resulting nutrient fields show typical features, including low concentrations in the upper, sunlit layers as a consequence of nutrient utilisation during primary production, and concentrations that increase with depth due to remineralisation and/or dissolution of sinking particles; see also Torres-Valdés et al. (2013). The δ 18 O sample resolution is mainly adequate to capture the significant Arctic Ocean features, although in the Fram Strait section around 6 ° W, there is only a single station to represent the East Greenland Current, so that horizontal gradients to either side of this station will only be approximate, therefore.

P9L5 – What is a Redfield nutrient ratio? Certainly my lack of knowledge, but I'm probably fairly representative of the Cryosphere audience...

A fair point. A gloss on the Redfield ratio is now included:

P5 L27 Concentrations of dissolved inorganic nutrients in seawater and the elemental composition of phytoplankton populations are observed to occur at broadly the same stoichiometric rations (Redfield et al., 1963). Where nutrient availability does not limit phytoplankton growth, this indicates that the ratio of the uptake of nutrients (the ratio of nitrate to phosphate, in this case) by phytoplankton, known as the "Redfield ratio", is fixed. In the Arctic context, this implies that deviations from typical Redfield ratios of seawater concentrations of these inorganic nutrients may serve as tracers of the geographic origin of seawaters, which would be useful to understand seawater pathways through the Arctic Ocean.

Figure 2 – (caption) I think the gateways are shown anticlockwise from Davis i.e., Davis, Fram, BSO, Bering? I think you should write on all of these Figures (2 and 5-10) which opening is which, for clarity and ease of interpretation.

All the relevant figures have been updated to include labels on the gateways.

P11L4-6 and Figure 3a/b – the fits to the green points (Fram) are poor, or rather the data are clearly not linear, which you attribute to the presence of Greenland Ice Sheet meltwater. Is there a way to exclude the Greenland water masses from your data in order to improve the fits? The linear regression to the green points in fig 3A especially is clearly not suitable and shouldn't be used for further analysis.

The linear fit lines originally plotted on the inset to Figure 3a were intended to give an indication of how closely these data conform to the mixing lines of the plotted end-points, and to demonstrate that the data used are representative, meaning that the calculated end point fell within both the range of the literature end-point values and within the end-point distribution used for the Monte-Carlo simulations. The deviations exhibited by the Fram section are explained in the text (as noted). The linear regression values are not used, outside this, in any analysis. To avoid confusion, the regression lines have now been removed from the figure. Figure 3 caption now reads:

P41 Panel a: Salinity – δ^{18} O relationship for all samples used in this manuscript; mean literature end-points (± standard deviation) are marked. Red crosses indicate the mean values of literature end-points and black dashed lines the mixing lines between them. Panel b: Nutrient data for all samples used in this manuscript compared to the published N:P relationships of Jones et al. (2008), Dodd et al. (2012), Sutherland et al. (2009). The dashed red line indicates a best fit to the Bering Strait nutrient data presented here. Symbols denoting the data from each section are common to both panels. Note Dodd et al. (2012) uses the same Pacific relationship as Jones et al. (2008).

P13L25 and Figure 6 – is flux positive in or out/positive or negative? Say explicitly early on for ease of interpretation.

The statements have now been clarified as suggested. Figures 5 and 6, **Tables 4–13**, Positive values indicate flux into the Arctic.

P14L1 – "positive fluxes indicating an export of high-salinity waters", is this equivalent to an import of freshwater? Seems more intuitive to talk about freshwater fluxes as that's the main focus of the paper.

While what you say is true, we frame this point in terms of the physical process (export of high-salinity waters) and not in terms of the impact on the freshwater flux calculation, because we are describing fluxes of source fractions. For this reason, we prefer to leave the text unchanged.

P14L11-17 and Tables 3-8 – I find reading data off tables pretty unhelpful in general, but especially when we are trying to compare data between different tables as here. I think you could easily summarise the budgets presented in tables 3-8 in one figure with multiple panels, or in a couple of separate figures. Personally I would use bar charts with error bars, and you could also include the Fram Strait break down as 'sub-bars' of the Fram bar. Would highly recommend this as it would make interpretation/comparison between the model runs much easier

We have a lot of sympathy with the sentiment because there is no doubt that tabulation is cumbersome. However, bar charts are much worse because the range of volume flux values is so large – three orders of magnitude – so that small but important freshwater fluxes (of some tens of mSv) become invisible. Therefore we leave the tables as they are, but this comment did prompt us to expand a little on the explanation of the approach and method in Section 2.3, to illustrate the origins of this range in various physical processes apparent in (for example) Figure 3, panels (a) and (b).

P14L27 – the ice-modified water in the WSC is from recirculation, right? State this here

There are several δ^{18} O samples in this area that lead to the apparent presence of ice modified water (brine). Closer examination of our results and also of source water properties (Frew reference below) led us firstly to make a new run of the 3EM model, and secondly to revise our reasoning and text. In the new Section 4.1, we write as follows.

P20 L 1 Section 4.1 The models generate apparent brine imports in the WSC and the Barents Sea Opening, both of magnitude ~ 45 mSv, a total of ~ 90 mSv with a large relative uncertainty of ~ 50 mSv. If correct, this is a substantial component of the Arctic Ocean freshwater budget. These (apparent) fluxes are too small to be visible on Fig. 5, but for scale, note that each new (oceanic water) inflow is ~ 3 Sv, 1 % of which is 30 mSv. These brine fluxes are consequences of weakly positive δ^{18} O anomalies centred around ~ 300 m depth in both locations, each about 200 m thick and each spanning ~ 200 km. The presence of these features in both Fram Strait and the Barents Sea Opening suggests that they are source water (Atlantic seawater) properties and not the result of modifications by local processes. Frew et al. (2000) examine the oxygen isotope composition of northern North Atlantic water masses from measurements made in 1991. Considering the waters of interest here – the upper ~ 500 m in the eastern North Atlantic (their stations 10, 24, 26, 72) – we find (broadly) salinities and δ^{18} O values in the ranges 35.0 - 35.2 and 0.2 - 0.4 ‰orespectively (their Fig. 2). This combination and range describes the part of the dense cloud of points heading a short distance "north-eastwards" in phase space away from the seawater endpoint (Fig. 3 panel a inset).

A consistent interpretation of the apparent WSC and Barents Sea Opening brine imports, therefore, is that they are actually manifestations not of local processes but rather of source water variability, in the light of our salinity (34.662) and δ^{18} O (mean 0.2 ‰) endpoints.

P15L26 – "large uncertainty", the uncertainty is actually smaller than for the 3EM/4EM models, the relative uncertainty is larger though if that's what you mean.

The statement has been revised - what we meant was:

P17 L12 smaller with a large relative uncertainty

Section 4.1 – Is the apparent consistency between the 3EM and 4EM models a surprise given that the difference between them is just the use of the geochemical data to partition the seawater into Atlantic/Pacific fractions? In Figures 11, 12, and 13 I can see no difference between the 3EM/4EM fluxes. In other words, are the 3EM/4EM fluxes consistent just by construction? If so you should say this, as it is misleading to say they are "consistent" when they are simply the same by construction. Perhaps my misunderstanding.

The difference between 3EM and 4EM models is the use of inorganic nutrients to attempt to discriminate between seawater of Atlantic and Pacific origins, which we now state as such (P16 L19).

P22L8-12 – while you cannot ascertain exactly the source of this water transformation, could you speculate at all? At least on the classes of processes that might cause this?

Torres-Valdes et al. (2016) tested one hypothesis regarding the possible role of dissolved organic nutrients, only to eliminate that option. Their final section comprises a logical conspectus of research avenues to pursue to resolve the problem. We do not wish to repeat that text, but we have written a new Section 4.2 on "Pacific" water. The new text begins by devoping a hypothesis around denitrification (a new paper Matthew Alkire was very useful) as below, and continues, using the suggestion by WA (see below) to look at recently-published material on more exotic tracer species, which supports our development of the hypothesis into dense water formation in the Barents Sea. Section 4.2 begins as below; refer to the manuscript for the full text.

P 23 L1 A credible hypothesis to explain all these observations – the doubling of Pacific export over import, the transformation of Atlantic water, and the deep presence of Pacific water – concerns denitrification, the process that occurs in ocean sediments and removes nitrate from the ecosystem by discharging N₂. Chang and Devol (2009) estimate a net pan-Arctic denitrification rate of ~ 13 Tg-N yr⁻¹, with much of that expected to occur in the shallow waters of the Barents and Chukchi Seas (6 and 3 Tg-N yr⁻¹ respectively). They further note the likelihood that the process is a consequence of sea ice retreat enabling increased primary production through increased shelf-break upwelling, which delivers nutrient-rich waters to upper-ocean waters with greater light availability; the resulting increase in export production then fuels higher rates of sedimentary denitrification.

Section 4.3 – I was wondering if you could also provide a paragraph with some perspectives on 1) future research using these methods/datasets, and 2) implications for Arctic Ocean climate monitoring in terms of observation systems and optimal approaches at analysis/modelling.

We have re-written Section 4.4 Perspectives, which now concludes as follows.

P26 L23 We envisage that sustained measurement of suitable tracers around the Arctic boundary has the potential to further our quantification and understanding of key processes, variability and timescales and to help mitigate the scarcity of observations in the Arctic Ocean interior. More (and more reliable) tracers are needed, more observations of more "traditional" tracers are needed through the water column (from surface to sea bed), more of those observations are needed in seasons outside summer-autumn, and we need better understanding of Arctic Ocean biogeochemical processes.

Reviewer 2 (WA)

p217 "(liquid) freshwater fluxes" and p2123 "freshwater" Please give a clear definition of what you mean by freshwater. Is this H2O? At this point there are too many different (sometimes meaningful) definitions in the literature that you cannot assume the readers know exactly which one you are using here.

We agree with the reviewer's sentiment here. Freshwater flux is now defined in the introduction.

P3 L 20 We define a flux of freshwater to mean the rate of addition of pure water to (or its removal from) the ocean surface, by exchanges with the atmosphere (evaporation [E] and precipitation [P]) and by input from the land (runoff [R]). The total ocean surface freshwater flux F is then F = P - E + R.

p4l12-14 This equation appears to only hold for 1 constant salinity at the inflow and another constant salinity at the outflow from the box. For the Arctic Ocean, that is clearly not given. To me it is not clear from this manuscript or from Bacon et al 2015 whether Sbar is an area mean or a transport weighted mean salinity over the boundary. I would appreciate it if the authors could clarify this here.

Our original intention was to avoid over-complication, but again, we agree with the reviewer's sentiment, so as part of the new text in response to the preceding comment, we have revised section 2.4 accordingly :

P14 L 8 where the integral is taken around the ocean boundary, from seabed to surface, and including sea ice; the overbar indicates area mean and prime indicates deviation from the mean (and following text).

p512-3 and 16-7 "accurate estimates of freshwater flux require the definition of an appropriate reference salinity (Sbar)" and "the boundary-mean salinity is the only appropriate reference salinity" I do not think

that either of these sentences is correct. But rather than arguing over whether they are correct, I would suggest to leave them out as they are in fact not crucial to anything that follows later in the manuscript.

We thought about this, and yes, we agree. Material discussing appropriate "reference salinities" has been removed. The text now appears as below.

P4 L14 The second way to estimate F is what Aagaard and Carmack (1989) call the "indirect" approach, which we call the "budget" approach. The budget approach recognises that ocean salinity is sensitive to dilution (or concentration) by addition (or removal) of freshwater. Therefore with knowledge of fields of velocity and salinity around the boundary of a closed volume (to ensure conservation of mass), the surface freshwater flux within the volume may be calculated; see (Serreze et al., 2006; Dickson et al., 2007; Bacon et al., 2015).

p5l29 Nd isotopes and REEs have also been used as conservative tracers of different rivers in the Arctic Ocean, e.g. doi:10.1016/j.gca.2016.12.028

An extremely interesting and useful pointer to material of which we were unaware; thank you. The discussion (Section 4) of the manuscript has been expanded to include the use of exotic tracers:

P26 L10 Nevertheless, other, more exotic species, may prove useful. For instance, Laukert et al. (2017) show that the distri bution of neodymium isotopes in Fram Strait that bears a considerable resemblance to our

"Pacific" water distribution (our Fig. 9, their Fig. 3), and with a similar interpretion to ours (Section 4.2 above) as to the provenance of the water mass. Furthermore, Wefing et al. (2019) analyse isotopes of iodine and uranium, sourced from UK and French nuclear reprocessing plants, which trace Arctic Ocean circulation pathways and residence times, showing that some fraction of the near-surface freshened oceanic waters in the west of Fram Strait, which appear to be of Pacific origin from the N:P analysis, may actually have originated from the Norwegian Coastal Current

p6l14-17 Again, while this is an appropriate step to take at this point (and better results might not be obtained from data at this point), it should still be pointed out that this is not perfect and there are in fact possibly large systematic errors arising from the sampling locations and/or spatially (potentially) insufficient sampling. It would be nice to mention these points with at least a few sentences.

We have deleted this text as part of our overhaul.

p7l8 The correct statement would be that this "conserves volume and salt transports", not that it "conserves volume and salinity transports"!

No, this is wrong. The measured property that is transported is called *salinity*. "Salt" in this context is a colloquialism, however commonly it may be used. If you want to check on the history and background, then Bacon et al. (JAOT 2007, 10.1175/JTECH2081.1) give a reasonable overview in the first two sections, and that paper is usefully supplemented by McDougall (Ocean Sci. 2012, 10.5194/os-8-1123-2012) on 'absolute salinity'.

p7l14 Please say what you mean by the plus/minus here. E.g. it could be standard deviation or standard error.

How we define the +/- has now been included :

p7 L21 (\$\pm\$ standard deviation)

p7l15 "1.0 +- 0.2" not "1 +- 0.2"

p7l18 "Sv" not "sV"

Both errors have now been corrected as indicated.

p7l24 Please state where your information on sea ice export is from, e.g. satellite observations of sea ice drift and sea ice volume?

The terms reported here are outputs from the TB12 model. How the sea ice flux was initialised in the model is detailed in TB12 (see para. 39), but in brief, they used remote-sensed area flux (due to Ron Kwok) in combination with thickness flux (due to Edmond Hansen).

We edit our text to:

P7 L29 The net surface freshwater flux (both liquid and solid) calculated by TB12 is 187 ± 44 mSv, manifest as 147 ± 42 mSv in the liquid ocean plus 40 ± 14 mSv in sea ice.

p8l5 "nutrient and delta18O data were optimally interpolated" Comment on whether the spatial distribution of the data was sufficient or whether there could be interpolation issues.

Reviewer 1 asked a similar question and we refer to our reply above.

p819 "grid cells as hydrographic stations" I see where this is coming from, but it is still a strange way to formulate it.

The statement has now been clarified:

P8 L16 Our domain comprises a total of 147 hydrographic stations, which includes data from 16 general circulation model grid cells in the Barents Sea Opening that are used as hydrographic stations, covering a total oceanic distance of 1803 km, with a total (vertical) section area of 1050 km².

p8l15-27 For me this was totally incomprehensible upon first reading. The terms "3EM", "4EM" and "4EM+" are not self explanatory. I would strongly advise to make a diagram or a table. A suggestion would be a table like this (columns could not be formatted in plain text, so the individual lines of the table are *grouped together*): Model name Constraints End members that are solved for Comments new line 3EM Volume conservation, salinity data, delta180 data Seawater fraction, meteoric water fraction, ice melt water fraction Seawater is water with S=35 irrespective of whether it enters from the Atlantic or the Pacific new line 4EM

Volume conservation, salinity data, delta18O data, P* data Atlantic water fraction, Pacific water fraction, meteoric water fraction, ice melt water fraction Atlantic water and Pacific water are defined to have identical S and delta18O end member characteristics, but different P* new line 4EM+ Volume conservation, salinity data, delta18O data, P* data Atlantic water fraction, Pacific water fraction, meteoric water fraction, ice melt water fraction Atlantic water and Pacific water are defined to have different P* and similar, but not identical S and delta18O end member characteristics

This is a sensible suggestion, so we have added a new Table 1, appropriately referenced in the manuscript text, as a compact display of the three model schema.

I would also already add a sentence like the following one here, because (anyways for me) it was not clear why you do these two versions with 4EM and 4EM+: "4EM+ is degenerate (meaning that numerical values are strongly affected by small perturbations) because the distinct source salinity and delta18O values of Pacific water are on a mixing line between the meteoric and Atlantic Water end member quantities.

We include the 4EM+ schema as despite it being degenerate, this represents what is becoming common practice in geochemical tracer studies as noted in the text :

P9 L28 Thirdly the 4EM scheme is applied again, but now adopting distinct end-member properties for both ocean-source salinity and δ 18 O (4EM+), replicating previous practice (Dodd et al., 2012; Jones et al., 2008; Sutherland et al., 2009). The properties of the three schemes are summarised in Table 1.

Comments about the degeneracy of the 4EM+ scheme are made in the discussion (see point below).

p9l14 1 sentence here why you use Pest: in order to judge the method, not for use in the method itself

Pest (now P_oce) is used to calculate end-member values of P*. The text has now been updated to make this clearer:

P10 L17 where P_oce is the estimated concentrations of phosphate from the relevant ocean (either Atlantic and Pacific) waters and the subscripts slope and int indicate the slope and intercept of the relationships.

p10l5 Again, I think this would be much clearer if you could refer to the table as I suggested above.

A reference to the table is now included.

p11l14 refer to Table 2 in this sentence

A reference to the table is now included.

p12l16 Again, area mean or transport weighted mean?

This has now been clarified in the text:

P14 L5 Seawater salinity for 3EM and 4EM models is fixed at the boundary area mean salinity for the TB12 model (34.662).

p14l1 m/s (see my comment below on Figure 6)

The units of Sv are correct - in all cases we take a volume flux from the TB12 model, which is calculated as a velocity (v) * grid cell area (horizontal distance ds x vertical distance dz) and scale it by the estimated water type fraction.

p14l11 It might be helpful to remind the reader that your +- values stem from the Monte Carlo simulations.

A reminder has been now included in the text :

P16 L2 For the 3EM model schemes, the net seawater volume flux is effectively zero (0.002 ± 0.006 Sv, Table 4, Monte Carlo uncertainty quantification).

p15l2 Also, here 1 sentence would be in order repeating what the difference between 4EM and 4EM+ is and why you do both calculations.

We have revised the text as suggested :

P16 L11 The 4EM scheme extends the 3EM scheme through use of inorganic nutrient (nitrate and phosphate) data, aiming to discriminate between Atlantic and Pacific seawater origin. The 4EM scheme retains single end-points for salinity and δ^{18} O, as in 3EM. In the 4EM+ scheme, distinct salinity and δ^{18} O end-member properties are attributed to Atlantic and Pacific seawaters, replicating previous practice (Dodd et al., 2012; Jones et al., 2008; Sutherland et al., 2009).

p15l22-23 and l25-26 Please don't just show both sets of numbers, but also comment on which one you think makes more sense.

This text is no longer in the manuscript.

p16l16 Add a sentence such as: "Both of these numbers should be approximately 0 and therefore, we consider this a model/methodological/data(?) mistake for the following reasons..." and

p16l21 You are only looking at data from 1 summer month. Discuss whether all of this should be balanced in the quasi-synoptic view of the data you use.

This text is no longer in the manuscript.

p17l16-18 Neither of these views seems plausible for the West Spitsbergen Current. Should the Atlantic water salinity not rather match the WSC closely?

We have added a new and detailed discussion of the WSC attribution to the manuscript, in Section 4.1 on ice-modified waters, starting as below.

P20 L1 The models generate apparent brine imports in the WSC and the Barents Sea Opening, both of magnitude ~ 45 mSv, a total of ~ 90 mSv with a large relative uncertainty of ~ 50 mSv. If correct, this is a substantial component of the Arctic Ocean freshwater budget. These (apparent) fluxes are too small to be visible on Fig. 5, but for scale, note that each new (oceanic water) inflow is ~ 3 Sv, 1 % of which is 30 mSv.

These brine fluxes are consequences of weakly positive δ^{18} O anomalies centred around ~ 300 m depth in both locations, each about 200 m thick and each spanning ~ 200 km. The presence of these features in both Fram Strait and the Barents Sea Opening suggests that they are source water (Atlantic seawater) properties and not the result of modifications by local processes. Frew et al. (2000) examine the oxygen isotope composition of northern North Atlantic water masses from measurements made in 1991. Considering the waters of interest here – the upper ~ 500 m in the eastern North Atlantic (their stations 10, 24, 26, 72) – we find (broadly) salinities and δ^{18} O values in the ranges 35.0 – 35.2 and 0.2 – 0.4 ‰ respectively (their Fig. 2). This combination and range describes the part of the dense cloud of points heading a short distance "north-eastwards" in phase space away from the seawater endpoint (Fig. 3 panel a inset). A consistent interpretation of the apparent WSC and Barents Sea Opening brine imports, therefore, is that they are actually manifestations not of local processes but rather of source water variability, in the light of our salinity (34.662) and δ^{18} O (mean 0.2 ‰) endpoints.

p18l14-15 Should this not be considered everywhere?

This text is no longer in the manuscript.

p19l2 "solid (sea ice) fraction" instead of "solid, sea ice, fraction"

The discussion has been substantially updated and these lines are no longer present.

p19l27 "(at least when considering full depth assessments)" It is not clear why that caveat is necessary and why the sentence is not correct without the added information in brackets.

This text is no longer in the manuscript.

p2016 How can a river be a sink? Processes on the continental shelf near the river could be sink processes.

This text is no longer in the manuscript. The discussion of nutrients in Section 4.2 is substantially re-cast.

p20l20 no ":"

This text is no longer in the manuscript.

p20l25 Explain how I would see that from Figure 3 and what degenerate means in that context.

We discuss degeneracy now at the end of Section 4.2 (P24 L10), in the new Section 4.3 (P25 L1-13), and Section 4.4 (P26 L4-7).

p2111 "boundary mean salinity" Again, where do I "see" that in Figure 3?

This text is no longer in the manuscript.

p21112-24 This text and the associated Figures 11-13 should in my opinion be removed from the manuscript as it is unclear what you mean by "oceanic origin freshwater". Additionally, there is no insightful information contained in them.

We retain Figure 11, since it is a useful visualisation, but otherwise, yes, you are right, so we have removed Figures 12 & 13. The "oceanic freshwater" comment was removed as part of our clean-up of terminology mentioned in our introductory comments to these replies.

p22l17 "Carmack et al. (2016, Appendix)"

This text is no longer in the manuscript.

p2316 "salt conservation"!

This text is no longer in the manuscript.

Tab1 Why is there a larger line break after the first line of delta180 and salinity?

Table format has been corrected.

Tab1 2nd line under ice melt: What is "surf"?

The table has been updated and the caption expanded to clarify this point:

Table 2 caption End-member values for salinity and $\delta^{18}O$ (‰) from the literature. Note Bauch et al. (1995) calculate ice melt $\delta^{18}O$ by multiplying measured surface seawater $\delta^{18}O$ (surf) by a "fractionation factor" of 1.0021.

Tab3 Similar to p7l24, where is the information about -0.040Sv solid ice melt from?

The caption has now been updated to make this clear :

Table 4 caption Values of solid freshwater flux from Tsubouchi et al. (2012).

Fig2 I think the other piece of interpolated data that your study is based on is cross-sectional velocity. I would recommend to add this as a top (4th) panel to Fig2. In that case the reader does not need to refer back to TB12 to get that information

We haven't done this because it would be the same as the volume transport plot (panel d), apart from scale.

Fig2 caption l1 "P*" should be with a superscripted "*"

Now corrected.

Fig2 caption 14 Repeat what the main Arctic water masses are so that the reader does not need to refer back to TB12.

and

Fig2 caption Add: "Note the broken scaling of the y-axis."

Definitions of the Arctic water masses from TB12 have now been included in the figure caption as has the comment about the y-axis scale.

Fig 2 Caption Sections of δ^{18} O (panel a), salinity (panel b), P* (panel c) and volume flux from Tsubouchi et al. (2012)(panel d) after optimal interpolation onto the Tsubouchi et al. (2012) CTD station positions, clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the potential density (σ) surfaces separating the main Arctic water masses grouped as follows, surface water (σ 0< 26.0), subsurface water ($26.0 < \sigma$ 0 < 27.1), upper Atlantic water ($27.1 < \sigma$ 0 < 27.5), Atlantic water (σ 0=27.5 to

 σ 0.5=30.28), intermediate water (σ 0.5=30.28 to σ 1=32.75), and deep water (σ 1 > 32.75); definitions from Tsubouchi et al. (2012). Note the broken scaling of the y-axis.

Fig3 Your 3EM model solves the classical end member decomposition in the triangle that is drawn in panel a. Your 4EM models essentially are the same, only that they solve the end member decomposition in the tetrahedron that would result if you were to extend panel a in the vertical with the vertical axis being P*. Since you can't add a 3 dimensional figure to the paper, I would recommend to at least add plane views of this tetrahedron with the data and dashed lines plotted into the panels just as you are doing in panel a right now. Common axes can be aligned with each other. My suggestion: 4 panel figure. top left panel as your panel a. top right panel x-axis P* y-axis delta18O, bottom left panel x-axis salinity y-axis P*, bottom right panel your current panel b. Also please substitute the current legend in panel b by a legend for the dashed lines and comment in the figure caption that all symbols and lines are the same in all panels. The 18 in the ylabel of panel a should be superscripted not subscripted. and

Fig3 caption l4 "Dashed thick"

We think it would over-complicate to attempt to graphically reproduce in 2 dimensions a 3-dimensional phase space; we have made the other corrections have now been made as indicated.

Fig 3 caption Panel a: Salinity - δ 18 O relationship for all samples used in this manuscript; mean literature end-points (± standard deviation) are marked. Red crosses indicate the mean values of literature end-points and black dashed lines the mixing lines between them. Panel b: Nutrient data for all samples used in this manuscript compared to the published N:P relationships of Jones et al. (2008), Dodd et al. (2012), Sutherland et al. (2009). The dashed red line indicates a best fit to the Bering Strait nutrient data presented here. Symbols denoting the data from each section are common to both panels. Note Dodd et al. (2012) uses the same Pacific relationship as Jones et al. (2008).

Your units in Figs 6/8/10 and 11a/b are wrong. They should be "Sv/m/km" or more conventionally "m/s". Note that you only arrive at units of transport (Sv) after integrating the data in the figures in the horizontal and vertical dimensions. Same applies for Figs 12/13 where your units should be m²/s or Sv/km or similar.

We apologise sincerely for an error here (application of mistaken scaling). What we should have plotted was indeed volume transports (gridded v x area), but the units should have been mSv and the range more like ± 20 mSv. This has been corrected.

Fig7 What is plotted in panels 7a and 7b is different from what is plotted in panels 5a and 5b, yet the values in the Met. and Ice Melt columns of Tables 3 and 5 are identical. In my opinion, only either one of those can be correct.

This was a problem with contour levels in the figures. The tables are, in all cases, definitive. All figures have all been re-contoured (all corresponding panels use the same level boundaries for ease of comparison).

Fig11/12/13 can in my opinion be deleted from the manuscript. One of the reasons is that I do not understand what the black line in Fig12/13 is supposed to be.

As noted above, we largely agree.

The legend has now been updated as suggested.

p48l14-16 A correct reference to this data publisher contains the complete DOI and it is not a tech report. Compare how the citation is provided on the webpage of the data set. In addition, you have the wrong title which means that it took me some time to find the data set you are referring to! "Kattner, Gerhard (2011): Inorganic nutrients measured on water bottle samples during POLARSTERN cruise ARK-XXI/1. PANGAEA, https://doi.org/10.1594/PANGAEA.761684"

Thank you very much for the updated reference. This has now been added.

Short Comment (PD)

We note first that we have substantially altered our text around these issues: see the new Section 4.2 on "Pacific" water that elaborates on our responses below.

My first comment regards the implementation of the N:P ratio method used to identify Pacific Water. Figure 7 in your paper shows low fractions (10 - 20 %) of Pacific Water along much of the boundary section in places that seem unlikely. For example, much of Fram Strait is filled with low fractions of Pacific Water below 1000 m. Pacific Water is buoyant and enters the stratified Arctic through a 60 m deep channel, so it seems unlikely that Pacific Water should be found at the bottom of Fram Strait. I think these apparently-spurious Pacific Water fractions might need be addressed before we can expect good results from the inverse model.

The N:P ratio method has been around for over twenty years now, and depends on the perception that Atlantic and Pacific source waters occupy distinct locations in nitrate:phosphate phase space. Measurements cluster around two lines with similar slopes, and where the Atlantic-origin waters are offset relative to Pacific waters: for a given phosphate concentration, Pacific nitrate concentration is lower than Atlantic. The offset is ~10 µmol-N / kg.

We contend that, while the source-water attribution is uncontentious, the product-water attribution is suspect. We accept, of course, that much is presently unknown with regard to Arctic biochemical nutrient cycling, and we (or rather, some of us) listed the major issues in the conclusions to Torres-Valdes et al. (GRL 2016). Denitrification is a key process in the Arctic that converts nitrate to N_2 , where it is lost to the system. Chang & Devol (DSR 2009) examine Arctic denitrification rates, finding total rates in the broad range 14-66 kmol-N / s. They find that denitrification occurs mainly in two areas, the Chukchi Sea (for 26% of the total) and the Barents Sea (for 43% of the total).

Consider now, therefore, how denitrification might "convert" Atlantic water into "Pacific" water, by removing nitrate at the observed offset rate of 10 μ mol / kg. Take (for scale) 1 Sv of Atlantic water; that is 10⁶ m³ / s, or 10⁹ kg / s. Then the required nitrate removal rate is 10 μ mol / kg x 10⁹ kg / s = 10 kmol / s, which is well within the limits of the Chang & Devol estimate. So it is actually easy to imagine that some "Pacific" water export might actually have originated as Atlantic water, which now carries a denitrification signal.

This hypothesis gives a further clue as to the reason for the presence of low concentrations of "Pacific" water below 1000 m in Fram Strait. Dense water formation in the Arctic is difficult to observe, but given that the lowest deep and bottom water temperatures occur in the Nansen and Amundsen Basins, and their likely origin through winter-time dense water formation is the Barents Sea, it is reasonable to suppose that denitrification of Atlantic waters also explains the sub-1000 m presence of "Pacific" water. This view is further supported by the Laukert et al. view of neodymium isotopes in Fram Strait.

The recently-published Alkire et al. (GRL 2019) note in their Introduction ways in which traditional identification of Pacific-origin seawater, via silicate concentrations and nitrate:phosphate ratios, may be growing unreliable as reduction in sea ice concentrations over the East Siberian Sea has enabled interactions with sediments leading to production of Halocline waters that are geochemically similar to Pacific waters.

There are a couple of ways in which this might be achieved:

1) Some of the apparently-spurious low Pacific Water fractions might arise from uncertainties in the endmember properties. If the low fractions are not significantly different from zero it might be justifiable to suppress them.

The concentrations are low but still significantly greater than zero; they are not explained by endpoint uncertainty.

2) An alternative approach could be to apply the N:P technique only in the depth range where Pacific Water is likely to be found, assuming fractions below some depth threshold to be zero. The N:P ratio method has a large errors associated with it and if it is applied indiscriminately over large areas where we would not expect to find Pacific Water the accumulated systematic errors probably become quite significant.

Considering the wider Arctic Mediterranean, extending to include the Nordic Seas southwards to the Greenland-Scotland Ridge, there is no exchange with the wider world deeper than 800 m (in the Faroe Bank Channel). The circulation in Fram Strait below 1000 m is in near-balance (transport northwards is nearly equal to transport southwards). Combined with the near-uniform distribution of "Pacific" fraction, it has a negligible impact on "Pacific" water fluxes. We checked this by repeating our calculations excluding the sub-1000 m layers in Fram Strait, and we still find ~1 Sv excess of "Pacific" water: (roughly) 1 Sv in through Bering Strait, 2 Sv out, mainly through Davis Strait.

However, the limitations of the N:P ratio technique are perhaps not the main reason that the inverse model does not balance for Pacific Water. My second comment regards the application of the inverse technique to Pacific Water in the Arctic Ocean. I'm not very familiar with inverse modelling, but I think the technique assumes that the system is in a steady state. The repeated Pacific Water sections in Dodd et al., 2012 (cited in your paper) indicate that the flow of Pacific Water through the Arctic is not in a steady state. At least in Fram Strait, Pacific Water is released in pulses with peak Pacific Water fractions of up to 80 % interspaced with periods where peak Pacific Water fractions barely exceed 20 %. The duration of pulses is probably of the order of 2 years, which is quite short relative to the time required for Pacific water to cross the Arctic. I'm not exactly sure how this can be best addressed, but I think the paper should at least discuss this steady-state issue.

This is an interesting point. As you rightly say, Dodd et al. (2012) shows high variability in "Pacific" water fraction in Fram Strait. However, what we learn both from that paper and from Torres-Valdes et al. (JGR 2013) as well as from our present manuscript is that Fram Strait is a minority contributor to net "Pacific" water export, so that what Dodd et al. present in Fram Strait is actually low variability around a low mean, leading to high <u>relative</u> variability. The Davis Strait "Pacific" water export is dominant, and there is no version of our calculation that can significantly reduce the mismatch between the 1 Sv Pacific water import and the 2 Sv "Pacific" water export. Using, for example, the 1998 Fram Strait section with its high concentration of "Pacific" water would only increase further the net "Pacific" water export rate.

One reason that the inverse model might balance for salinity/freshwater, but not for Pacific Water, could be that in years when Pacific Water is not present in a given location it tends to be replaced by another halocline water mass of similar density (ie: rather similar salinity).

There is some denitrification in the Arctic and I agree that when using the N:P ratio technique, some Atlantic Water will apparently be transformed into Pacific Water over the shallow shelves. That is indeed a fundamental limitation of the technique. However, if the steady-state issue is as serious as I think it is, then I'm not sure that the results of the inverse model give us much new information about the reliability of the N:P technique. Please do correct me if I am wrong about something here though!

As a final point, Alkire et al. (GRL 2019) use the quasi-conservative tracer "NO", as well as dynamic height, to examine the front separating Pacific and Atlantic halocline waters in the East Siberian Sea. They find that "traditional tracers", meaning the N:P ratio, "used to quantify Pacific water contributions to the Arctic Ocean are no longer accurate". There is no combination of transport uncertainties (as Tsubouchi et al. 2012) with inorganic nutrient concentration uncertainties (Torres-Valdes et al. 2013) that can more than double the apparent Pacific water flux, from ~1 Sv to ~2.5 Sv.

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Arctic freshwater fluxes: sources, tracer budgets and inconsistencies

Alexander Forryan¹, Sheldon Bacon², Takamasa Tsubouchi³, Sinhué Torres-Valdés⁴, and Alberto C. Naveira Garabato¹

¹Ocean and Earth Science, University of Southampton, Southampton, U.K.
 ²National Oceanography Centre, Southampton, U.K.
 ³Geophysical Institute, University of Bergen, Bergen, Norway
 ⁴Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Correspondence to: A. Forryan (af1c10@soton.ac.uk)

Abstract

Abstract The traditionally divergent perspectives of net rate of freshwater input to the Arctic Ocean freshwater budget provided by control volume-based and geochemical tracer-based approaches Paper are reconciled, and the sources of inter-approach inconsistencies identified, by comparing

- both methodologies using an observational data set of has been calculated in the past 5 by two methods: directly, as the sum of precipitation, evaporation and runoff, an approach hindered by sparsity of measurements, and by the ice and ocean budget method, where the net surface freshwater flux within a defined boundary is calculated from the rate of dilution of salinity, comparing ocean inflows with ice and ocean outflows. Here a third
- method is introduced, the geochemical method, as a modification of the budget method. A 10 standard approach uses geochemical tracers (salinity, oxygen isotopes, inorganic nutrients) to compute "source fractions" that quantify a water parcel's constituent proportions of seawater, freshwater of meteoric origin, and either sea ice melt or brine (from the freezing-out of sea ice). The geochemical method combines the source fractions with the boundary velocity
- field of the budget method to guantify the net flux derived from each source. Here it is shown 15 that the geochemical method generates an Arctic Ocean surface freshwater flux, which is also the circulation and water mass properties at the basin's boundary in summer 2005. The control volume-based and geochemical estimates of the Arctic Ocean (liquid) freshwater fluxes are 147 ± 42 meteoric source flux, of 200 ± 44 mSv (1 Sv = 10^6) and 140 ± 67 ,
- respectively, and are thus in agreement. Examination of meteoric, 10⁶ m³ s⁻¹), statistically 20 indistinguishable from the budget method's 187 ± 44 mSv, so that two different approaches to surface freshwater flux calculation are reconciled. The freshwater export rate of sea ice and seawater contributions to the freshwater fluxes reveals near equivalence of the net freshwater flux out of the Arctic (40 ± 14 mSv) is similar to the brine export flux, due to the
- "freshwater deficit" left by the freezing-out of sea ice (60 ± 50 mSv). Inorganic nutrients are 25 used to define Atlantic and the meteoric source to the basin, and a close balance between the transport of solid sea ice and ice-derived meltwater out of the Arctic and the freshwater deficit in the seawater from which the sea ice has been frozen out. Inconsistencies between

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the two approaches are shown to stem from the distinction between "Atlantic " and "Pacific " waters based on tracers in geochemical tracer-based calculations. The definition of Pacific waters is found to be particularly problematic, because of the non-conservative nature of the inorganic nutrients underpinning that definition, as well as the low salinity characterising waters entering the Arctic through Bering Strait - which makes them difficult to isolate from meteoric sources. Pacific seawater categories, and the results show significant non-conservation.

- 5 whereby Atlantic seawater is effectively "converted" into Pacific seawater. This is hypothesised to be a consequence of denitrification within the Arctic Ocean, a process likely becoming more important with seasonal sea ice retreat. While inorganic nutrients may now be delivering
- ambiguous results on seawater origins, they may prove useful to quantify the Arctic Ocean's 10 net denitrification rate. Endpoint degeneracy is also discussed: multiple property definitions that lie along the same "mixing line" generate confused results.

Introduction 1

The global climate is changing (Stocker et al., 2014), and Arctic amplification is increas-

- ing both the rate and the variability of this change in the Arctic (Serreze and Barry, 2011). 15 Despite its relatively small area, the Arctic Ocean The Arctic Ocean surface area is only 3% of the global total, but it receives a disproportionate amount of freshwater - including 10% of global river runoff – and plays a disproportionately large role in the regulation of the global climate (Carmack et al., 2016; Prowse et al., 2015). The permanent halocline, established
- by freshwater input into the Arctic, both promotes sea ice formation through limiting deep 20 convection, and constrains the upward heat flux from deeper warmer waters that promotes sea ice longevity (Carmack et al., 2016). Consequently, changes to the freshwater cycle within the Arctic potentially perturb the formation and melting of sea ice, which has in turn a pronounced impact on both the Arctic heat budget and on planetary albedo (Serreze et al.,
- 2006; Carmack et al., 2016). Changes in the Arctic heat budget may affect the strength 25 of the north-south temperature gradient between the polar and mid-latitudes regions, which has recently been linked to increased probability of extreme weather events at mid-latitudes

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(Screen and Simmonds, 2014; Francis and Vavrus, 2012; Mann et al., 2017). Arctic freshwater export also has the potential to change Atlantic northward heat fluxes through the disruption of deep convection and, consequently, the strength of the Atlantic meridional overturning circulation (e.g. Manabe and Stouffer, 1995). Following the seminal work of Aagaard and Carmack (1989), the Arctic Ocean freshwater budget is usually quantified using either "direct" or "indirect" approaches (Haine et al., 2015; Serrest

. The direct approach uses the net sum of river runoff, precipitation and evaporation, while the indirect approach employs knowledge of ocean (including sea ice) salinity and volume

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the indirect approach employs knowledge of ocean (including sea ice) salinity and volume fluxes across an Arctic boundary (Haine et al., 2015; Serreze et al., 2006; Dickson et al., 2007) ... We define a flux of freshwater to mean the rate of addition of pure water to (or its removal from) the ocean surface, by exchanges with the atmosphere (evaporation [*E*] and precipitation [*P*]) and by input from the land (runoff [*R*]). The total ocean surface freshwater flux *E* is then E = R. E + R. There are then three ways to estimate *E*. The first is to flux F is then F = P - E + R. There are then three ways to estimate F. The first is to measure each of P, E and R – the "direct" approach of Aagaard and Carmack (1989); see 15 also Haine et al. (2015); Serreze et al. (2006); Dickson et al. (2007); Carmack et al. (2016) . Direct measurement of Arctic freshwater fluxes is hampered by the scarcity of observations (both in-situ and remote) and incomplete knowledge and understanding of the physical processes involving air moisture, clouds, precipitation and evaporation (Vihma et al., 2016; Bring et al., 2016; Lique et al., 2016). This scarcity is compounded by uncertainty in the 20 observations themselves (e.g. Aleksandrov et al., 2005) and by sparsely distributed sampling sites (for a full discussion see Vihma et al., 2016). Estimates of runoff are limited by incomplete river observations (with only \sim 70 % of Arctic rivers gauged) and understanding of how river discharge is modified in response to permafrost changes and subsurface / surface water interactions (Bring et al., 2016, 2017). Compensation for ungauged runoff, 25 arising from incomplete river observations, is usually achieved by the use of simple models based on linear regression from gauged regions (e.g. Shiklomanov et al., 2000; Lammers et al., 2007). The use of atmospheric reanalysis products (e.g. Haine et al., 2015) to compensate for the paucity of direct measurements is in turn hampered by the scarcity and

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uncertainty of observations to constrain those reanalyses, which makes accurate modelling of all the physical processes involved problematic and leads to relatively unconstrained model dynamics in the Arctic (Lique et al., 2016).

Indirect measurement of Arctic freshwater fluxes considers the Arctic Ocean to be a basin enclosed by land boundaries and/or by ocean measurements in which inflowing 5 ocean waters are modified by ocean surface and land boundary fluxes, both freshening and cooling, to form outflows. Therefore, The second way to estimate F is what Aagaard and Carmack call the "indirect" approach, which we call the "budget" approach. The budget approach recognises that ocean salinity is sensitive to dilution (or concentration) by addition (or

removal) of freshwater. Therefore with knowledge of net mass (volume) inflows and outflows 10 combined with knowledge of a suitable tracer (in this case salinity), the net surface freshwater flux can be estimated (Serreze et al., 2006; Dickson et al., 2007; Bacon et al., 2015).

Considering the Arctic as fields of velocity and salinity around the boundary of a closed volume box(to ensure conservation of mass), the surface freshwater flux (F_{surf}) can be approximated as:

 $F_{surf} \approx \left(\frac{\delta S}{\bar{S}}\right) V_o$

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where δS is the difference in salinity between import and export from the box, \overline{S} is the boundary mean salinity, and V_o is the boundary volume flux (Bacon et al., 2015).

- within the volume may be calculated; see Serreze et al. (2006); Dickson et al. (2007); Bacon et . Until recently, budgets have been constructed Arctic Ocean surface freshwater fluxes have 20 been estimated using heterogeneous and asynoptic compendia of data which, through many years of work, are now beginning to tell a consistent story, though there is still uncertainty in all the major terms (e.g. Serreze et al., 2006; Dickson et al., 2007: Haine et al., 2015). Recent work-The first quasi-synoptic application of the budget approach, by
- Tsubouchi et al. (2012, hereafter TB12), using guasi-synoptic ocean measurements used 25 ocean measurements around the Arctic boundary from summer 2005, applied applying the

commonly used box-inverse model technique (Wunsch, 1978) for estimating ocean volume fluxes to the Arctic . This approach to calculate ocean (including sea ice) volume exchanges between the Arctic and adjacent ocean basins. TB12 represents a significant advancein Arctic freshwater flux estimates, resulting in the calculation of consistent optimised ocean velocity fields and the first guasi-synoptic estimates of Arctic freshwater and heat fluxes

(TB12) Ocean surface freshwater (and heat) fluxes.

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Salinity is used to quantify Arctic freshwater fluxes (Haine et al., 2015) because it responds only to dilution and concentration through the addition or removal of freshwater, respectively. Thus, it We here introduce a third method as a modification of the budget method, which

- we call the geochemical method, and which requires knowledge of distributions of certain 10 tracers that describe various sources of ocean waters. These tracers can be used to estimate unambiguously net changes in ocean freshwater fluxes. While marine measurements of salinity are routinely made to high precision, enabling a precise estimate of the difference in salinity between import and export from the Arctic to be made (δS above), accurate
- estimates of freshwater flux require the definition of an appropriate reference salinity (\bar{S}) . 15 Pragmatically, following Aagaard and Carmack (1989), this has been taken to be a notional Arctic mean salinity, though some investigators have used different study-specific values (e.g. Dodd et al., 2012). A more recent theoretical treatment of the role of salinity has concluded that the boundary-mean salinity is the only appropriate reference salinity in the case of any (actual or notional) closed-volume freshwater budget (Bacon et al., 2015)generate source fractions, and we aim to combine those source fractions with the TB12 velocity field to Pragmatically, following Aagaard and Carmack (1989), this has been taken to be a notional
- 20 calculate new estimates of source fluxes. We next describe the candidate tracers and their functions.

Salinity is not the only tracer that can be used to determine surface freshwater flux. Discussio Ocean waters that have not been subject to significant evaporation/precipitation Bulk ocean 25 waters display a near-constant ratio of oxygen isotope concentrations (Craig, 1961) and, concentration, measured as the anomaly from the ocean standard value, $\delta^{18}O$: (Craig, 1961; Östl . Distillation (isotopic fractionation) by evaporation and (in the polar oceans) freezing preferentially removes light isotopes from seawater. Evaporated or meteoric water returns to the ocean

directly, as water progresses round the hydrological cycle, isotopic fractionation (evaporation /freezing and precipitation/melting) alters this ratio ($\delta^{18}O$ Östlund and Hut, 1984). Hence, waters of meteoric origin (precipitation, river runoff), rain- and those that have been ice-modified have distinct snow-fall, and indirectly, as river runoff and (in polar regions) as icebergs and melt water from terrestrial ice caps, and these waters have distinctive (low) oxygen isotope anomalies. In addition, sea ice that has been frozen out of seawater also has isotope anomalies. In addition, sea ice that has been frozen out of seawater also has

- a low $\delta^{18}O$ values that can be used to decompose water samples into meteoric origin or ice-modified fractions (Östlund and Hut, 1984); this process leaves behind in the seawater an elevated (positive) $\delta^{18}O$ signal. The $\delta^{18}O$ tracer is conservative, reflecting only the net
- isotopic fractionation that the water sample has undergone. In combination with salinity, 10 it can be used to decompose water samples into fractions of "seawater" (meaning bulk ocean water unmodified by local effects of distillation), freshwater of meteoric origin, and the ice-modified fraction, because the "end-members" occupy distinctly separate locations in $\delta^{18}O$ –salinity space. (Östlund and Hut, 1984). However, unlike salinity, where freshwater
- has a definite salinity of zero, there is much variety in the $\delta^{18}O$ values observed for sea ice, 15 river runoff (Bauch et al., 1995), and glacier ice (Cox et al., 2010). Following Östlund and Hut (1984) there have been many studies using $\delta^{18}O$ to determine fractions of ice melt and meteoric water in the Arctic, most notably in the Fram Strait (Dodd et al., 2012; Meredith et al., 2001; Rabe et al., 2013), in the Canada Basin (Yamamoto-Kawai et al., 2008), and in the East Greenland Current (Cox et al., 2010). In terms of $\delta^{18}O$ signal, precipitation/evaporation 20
 - and freezing/melting are manifestations of

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Concentrations of dissolved inorganic nutrients in seawater and the elemental composition of phytoplankton populations are observed to occur at broadly the same stoichiometric

rations (Redfield et al., 1963). Where nutrient availability does not limit phytoplankton growth, this indicates that the ratio of the uptake of nutrients (the ratio of nitrate to phosphate, in this case) by phytoplankton, known as the "Redfield ratio", is fixed. In the Arctic context, this implies that deviations from typical Redfield ratios of seawater concentrations of these inorganic nutrients may serve as tracers of the same process with opposite signs. Consequently, geographic origin of seawaters, which would be useful to understand seawater pathways 25 geographic origin of seawaters, which would be useful to understand seawater pathways

through the Arctic Ocean. Furthermore, as a decomposition within "seawater", this approach would generate information orthogonal to that provided by salinity and $\delta^{18}Ovalues$ reflecting only net isotopic fractionation are unable to quantify river runoff without the use of another conservative tracer. Initial work suggested the use of barium as a potential tracer of riverine input into the Arctic (Kenison Falkner et al., 1994). However, this tracer has recently been found to be non-conservative (through biological scavenging) in seawater (Abrahamsen et al., 200

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Seawater in the North Pacific has a distinctly different biogeochemical composition from Dis that in the North Atlantic, with Pacific seawater having higher-It is observed that Pacific seawater has higher relative concentrations of phosphate than Atlantic seawater; see (Bauch et al.

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- . Nitrate concentrations of both the inorganic nutrients silicate and phosphate (Bauch et al., 1995) - Silicate and nitrate concentrations (used in combination with oxygen; Ekwurzel et al., 2001), are only quasi-conservative, as both are altered due to biological activity or airsea exchange in surface waters (Alkire et al., 2015), while the use of nitrate:phosphate
- (N:P) nutrient ratios (Jones et al., 1998) is has been considered to be conservative with 15 respect to biological activity. However, there is emerging evidence that the N:P ratio may be becoming non-conservative in the Arctic Ocean as a consequence of sea ice retreat. Denitrification is a process that removes nitrogen from the biogeochemical system, and Bauch et al. (2011) and Alkire et al. (2019) both note that calculations based on the N:P
- ratio overestimate quantities of Pacific-derived seawaters as a result of denitrification of 20 seawater in bottom sediments. Also, and despite the N:P ratios for the Atlantic and Pacific Oceans exhibiting distinct linear relationships with near-constant slopes, there is variation in the exact form of this relationship (Jones et al., 2008; Sutherland et al., 2009; Dodd et al., 2012; Yamamoto-Kawai et al., 2008). In the Arctic Ocean, nutrient ratios have been used to
- trace the circulation of Pacific seawater (Jones et al., 1998; Jones, 2003), and to indicate 25 the likely origins of freshwater sources (Yamamoto-Kawai et al., 2008; Sutherland et al., 2009).

Recent use of fixed ocean installations (moored current meters with temperature and salinity sensors) describing a closed circuit around the Arctic boundary by TB12 has enabled Paper

the first quasi-synoptic calculation of surface fluxes of heat and freshwater for the whole Arctic. We envisage that sustained measurement of suitable tracers around the Arctic boundary has the potential to generate estimates of surface freshwater fluxes with distinct meteoric and ice melt contributions. Such quantitative estimates would go a long way to

- 5 mitigating the scarcity of Arctic observations, and represent a significant advance in Arctic science. Our aims in this study are twofold; (1) to combine two approaches for indirect estimations of freshwater flux using different and distinct tracersOur aims in this study are: (1) to generate new estimates of Arctic Ocean source fluxes using the geochemical approach, (2) to compare the results of the established budget approach to those of the
- ¹⁰ new geochemical approach, and (23) to test the consistency of the various tracers used. To these ends, we aim to use existing nutrient and $\delta^{18}O$ data in combination with the salinity and optimised horizontal velocity fields of TB12 to estimate fluxes of meteoric, ice melt and oceanic source waters. We first describe the data sources and the model used along with the attribution method and schema methods and schemes implemented (Sect. 2). Results are presented (in Sect. 3), and discussed with an examination of the implications for the
- ¹⁵ are presented (in Sect. 3), and discussed with an examination of the implications for the future use of biogeochemical tracers in the Arctic (in Sect. 4).

2 Data and methods

2.1 Measurements

TB12 use an inverse model (Wunsch, 1978; Roemmich, 1980) that considers the Arctic Ocean as a control volume bounded by land and four gateways – Davis, Fram and Bering Straits, and the Barents Sea Opening (Fig. 1) – and is divided into 15 horizontal layers defined by isopycnal surfaces. The TB12 inverse model generates an optimised horizontal velocity field v(s, z), where z is depth and s the along-boundary horizontal coordinate, which conserves volume and salinity transports, based on hydrographic data collected in summer 2005. For further details of the inverse model construction see TB12. For this study, the TB12 volume fluxes are combined with additional tracers to generate source component estimates of liquid Arctic freshwater fluxes, to compare with the existing net (salinity-derived) estimates of TB12.

From the TB12 model, the Arctic boundary circulation is broadly conventional. Atlanticorigin seawater enters through the Barents Sea Opening with volume flux of 3.6 ± 1.1 Sv

- $_{5}$ (± standard deviation). Pacific-origin seawater enters through Bering Strait with volume flux of $1\pm0.2\cdot1.0\pm0.2$ Sv. Fram Strait is a net exporter of seawater, with volume flux of 1.6 ± 3.9 Sv, representing a balance between inflowing (mainly) Atlantic waters in the West Spitsbergen Current in the east of the strait (volume flux of 3.8 ± 1.3 Sv) and outflowing waters in the East Greenland Current in the west of the strait (volume flux of 5.4 ± 2.1 Sv).
- ¹⁰ The net seawater export through Davis Strait has a volume flux of 3.1 ± 0.7 Sv. For details of other, relatively small contributions to the total, see TB12. As a simplified and approximate summary, ~ 8 Sv of Atlantic-origin and ~ 1 Sv of Pacific-origin seawater enters the Arctic, with ~ 9 Sv of variously modified seawater exported. The net surface freshwater flux (both liquid and solid) calculated by TB12 is 187 ± 44 mSv, manifest as 147 ± 42 mSv in the liquid socean plus 40 ± 14 mSv in sea ice.

Biogeochemical data were originally collated and published by Torres-Valdés et al. (2013) for inorganic nutrients and MacGilchrist et al. (2014) for $\delta^{18}O$. Original data sets are described as follows. For Davis Strait: Lee et al. (2004) (with additional data for 2005 supplied $\delta^{18}O$ by Dr. Kumiko Azetsu-Scott, Department of Fisheries and Oceans, Bedford Institute of Oceanography). For Bering Strait: Woodgate et al. (2015). For Barents Sea Opening: The International Council for the Exploration of the Sea Oceanographic Database (http://ices.dk/ocean) for nutrient data, with Schmidt et al. (1999) for $\delta^{18}O$. For Fram Strait: Budéus et al. (2008); Kattner (2011) for nutrient data, with Rabe et al. (2009) for $\delta^{18}O$. There are no $\delta^{18}O$ measurements below ~ 400 m in Fram Strait, so we simply extrapolate the doceant measurement to the better.

²⁵ the deepest measurement to the bottom, for completeness. This depth is close to the Greenland–Scotland sill depths (600–800 m) to the south, so there is little or no net flux below these depths (TB12) and we do not expect the absence of deep $\delta^{18}O$ to significantly impact our results. Sample locations are shown in Fig. 1. All nutrient and $\delta^{18}O$ data were

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optimally interpolated (?) in pressure both vertically and horizontally to match the station positions used by TB12 (Fig. 2).

Our domain comprises a total of 147 hydrographic stations (including, which includes data from 16 general circulation model grid cells in the Barents Sea Opening that function are used as hydrographic stations), covering a total oceanic distance of 1803 km, with 5 a total (vertical) section area of 1050 km². Vertical resolution is 1 dbar, with maximum pressures of 1044 dbar in Davis Strait, 2704 dbar in Fram Strait, 471 dbar in the Barents Sea Opening, and 52 dbar in Bering Strait (for further discussion of the model domain see

- TB12). The $\delta^{18}O$ and nutrient data were optimally interpolated (Roemmich, 1983) vertically in pressure and horizontally in distance to match the TB12 model domain (Fig. 2). The interpolation 10 recovers the measurements for each sample point and interpolates between values to fill the Paper unsampled areas of the domain. The resulting nutrient fields show typical features, including low concentrations in the upper, sunlit layers as a consequence of nutrient utilisation during
- primary production, and concentrations that increase with depth due to remineralisation 15 and/or dissolution of sinking particles; see also Torres-Valdés et al. (2013). The $\delta^{18}O$ sample resolution is mainly adequate to capture the significant Arctic Ocean features, although in the Fram Strait section around 6° W, there is only a single station to represent the East Greenland Current, so that horizontal gradients to either side of this station will only be approximate, therefore. 20

2.2 Approach

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Following established practice, the freshwater content sources of a parcel of seawater is considered to have originated from a number of sources - typically oceanic water are considered to number three or four. The sources are characterised by end-members, which are defined points in the phase space populated by the observed seawater (and liquid (and solid i.e. sea ice) biogeochemical (tracer) properties. Here we tracer properties, so that "oceanic water" means here the sum total of all liquid fractions. The term "seawater" is used to mean the typical source water fraction from the Atlantic (and also Pacific) Ocean;

seawater fractions are always positive. The "meteoric" fraction can in principle be either positive, stemming directly or indirectly from rain- and snow-fall, where the indirect route implies river runoff or terrestrial glacial input to the ocean, or negative, from evaporation. The "ice-modified" fraction is a result of sea ice freezing and melting, and (as will become apparent) appears mainly in oceanic water as negative fractions consequent on the freezing out of sea ice from oceanic water. For simplicity, therefore, we define this (negative) fraction as "brine", following Östlund and Hut (1984), and use "sea ice melt water" for the alternative (positive) case. Velocities into (out of) the Arctic Ocean are signed positive (negative), so that seawater imports (exports) are signed positive (negative), imports (exports) of positive

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¹⁰ fractions (rain, snow, rivers etc.) of meteoric input are signed positive (negative), and brine imports (exports) are signed negative (positive).

We employ three variants of the approach to the calculation of the resulting source fractions. Firstly a three end-member scheme (3EM) is adopted, which uses salinity and $\delta^{18}O$ to identify "plain" seawater, freshwater of meteoric originseawater, meteoric freshwater, and

- ¹⁵ ice-modified seawater (mainly brine). Secondly the 3EM scheme is extended to a four endmember scheme (4EM) through the use of inorganic nutrient data, aiming to discriminate between seawater of Atlantic and Pacific origin, where the salinity and $\delta^{18}O$ end-member properties of both ocean sources are assumed to be the same as for Atlantic seawater. Thirdly the 4EM scheme is applied again, but now adopting distinct end-member properties for both ocean-source salinity and $\delta^{18}O$ (4EM+), replicating previous practice (Dodd et al.,
- for both ocean-source salinity and δ¹⁰O (4EM+), replicating previous practice (Dodd et al., 2012; Jones et al., 2008; Sutherland et al., 2009). The properties of the three schemes are summarised in Table 1.

To discriminate between freshwater of Atlantic and Pacific seawater originseawaters, an additional relationship is formulated in terms of the concentrations of the inorganic nutrients

²⁵ phosphate and nitrate (Dodd et al., 2012; Jones et al., 1998). We form this relationship in terms of the variable P^* , which is an expression describing the excess concentration of phosphate above that which would be expected from typical Redfield nutrient ratios (Redfield et al., 1963), and it employs the observed nitrate concentration:

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 $P^* = P_m - (N_m/16),$

where P_m and N_m are the measured nitrate and phosphate concentrations, respectively. Atlantic and Pacific seawaters are each considered to have a distinct, near-constant, nitrate to phosphate (N:P) ratio (Jones et al., 1998), which can be expressed algebraically as:

5 $\underline{P}_{est} = \underline{P}_{slope} N_m + \underline{P}_{int},$

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 $P_{oce} = P_{slope} N_m + P_{int},$

where P_{est} P_{occ} is the estimated concentrations of phosphate from the relevant ocean (either Atlantic and Pacific) waters and the subscripts *slope* and *int* indicate the slope and intercept of the relationships. Boundary sections of salinity, $\delta^{18}O$ and P^* are shown in Fig. 2.

To quantify freshwater source fractions for each <u>oceanic</u> water parcel (i.e. grid point), we establish the following system of equations. This problem is conventionally treated as "square", with the number of constraints equal to the number of source water fractions to be determined for each water parcel. Each water parcel then has a suite of i = 1, ..., Mmeasured properties x_i . Each measured property is treated as the sum of j = 1, ..., Mfractions f_i of a suite of source properties $X_{i,j}$. The number of source properties (or endmembers) is here M = 3 or 4, and the associated freshwater sources are indicated as sea ice (j = 1), meteoric (j = 2), seawater (j = 3 for 3EM), or Pacific and Atlantic seawater (j = 3 and 4 for 4EM variants, respectively). Written as a sum:

$$X_i = \sum_{j=1}^M X_{i,j} f_j.$$

Setting all x, X = 1 for i = 1 retrieves the requirement that the sum of all the source fractions f_i accounts for all of the observed seawateroceanic water:

$$1 = \sum_{j=1}^{M} f_j. \tag{1}$$

The measured properties are then $\delta^{18}O$ concentrations (*i* = 2) and salinity (*i* = 3) for all models; in addition the 4EM variants employ P^* for i = 4 (Table 1). The product of this 5 process is a system of M equations describing M unknowns, which is written in matrix form for $(M \times 1)$ column vectors **f** and **x**, and $(M \times M)$ matrix **X**:

$\mathbf{x} = \mathbf{X}\mathbf{f}$.

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This is solved for f by standard (exact) inversion of a square matrix at each water parcel on our ocean boundary grid, to calculate the resulting spatial distributions of the relevant freshwater oceanic water source fractions:

$\mathbf{f} = \mathbf{X}^{-1}\mathbf{x}.$

2.3 End-member values

Previous studies have used different values for the end-member concentrations of salinity, $\delta^{18}O$ and nutrients, which are summarised in Tables 2 and 3. A least-squares linear fit to 15 the $\delta^{18}O$ and salinity data from the three sections likely to contain freshwater of meteoric origin (Davis, Fram and Bering Straits) suggests a $\delta^{18}O$ end-member in the range of -20 ‰ (Bering Strait) to -30 ‰ (Fram Strait), with a mean value of -23.3 ‰, which is within the range of the published values. The

The relationships between salinity and $\delta^{18}O$ for our data and from cited sources are shown in Fig. 3A. This phase diagram is akin to the oceanographer's "mixing diagram", where measured oceanic water properties tend to lie along lines connecting core water mass properties as a result of mixing between those properties. In this case, processes

- that add sea ice melt water or meteoric water cause mixing along the lines joining the three endpoints (seawater, meteoric water, sea ice melt water). The difference here is that there are processes that remove water mass constituents (freezing, evaporation), and this is manifested on the phase diagram as points that "back away" from the relevant endpoints, clearly seen, for example, in Fig. 3A in the Fram Strait data. The Fram Strait data also exhibit
- ¹⁰ the two-layer mixing relationship indicating the likely presence of Greenland ice sheet melt, which has a distinctly lighter $\delta^{18}O$ signature (Cox et al., 2010). The fits to data from the three sections likely to contain Atlantic seawater (Fram and Davis Straits, Barents Sea Opening) suggest an Atlantic seawater salinity endpoint of ≈ 35 . The relationships between salinity and $\delta^{18}O$ for our data and from cited sources are shown in Fig. 3A.
- ¹⁵ Considering the published nitrate-phosphate relationships, the most appropriate to this study are the values used by Jones et al. (2008), Sutherland et al. (2009), and Dodd et al. (2012), because Yamamoto-Kawai et al. (2008) include ammonium, and the nutrient measurements used here are of nitrate plus nitrite (Torres-Valdés et al., 2013). A least-squares best fit to the Bering Strait nutrient data has a slope of 0.0654, which is consistent with
 that of Jones et al. (2008), and an intercept of 0.6766 (Table 3). The relationships between nitrate and phosphate concentrations for our data and from cited sources are shown in Fig.

3B.

2.4 Freshwater flux calculation

We use the approach established by TB12 and developed by Bacon et al. (2015), which recognises that a unique definition of a freshwater flux is given by the net surface exchange between the ocean (including ice) and the adjacent land and atmosphere: i.e. the net of precipitation, evaporation and runoff. Then (using volume transports)the The surface freshwater flux within an enclosed ocean volume is then calculated from its dilution effect on salinity:

$$F= \oint \int \frac{v'S'}{\bar{S}} \, ds dz$$

where the integral is taken around the ocean boundary, from seabed to surface, and including sea ice; the overbar indicates area mean and prime indicates deviation from the mean, i.e. $S = S' + \overline{S}$ and $v = v' + \overline{v}$; and s and z are horizontal and vertical coordinates respectively. TB12 describe the calculation and method in detail, and they also inspect the assumption of stationarity, concluding that, for a quasi-synoptic dataset such as this, it is justified (their section 3.5).

¹⁰ Then in the stationary case the surface freshwater flux F plus is equal and opposite to the ice and ocean boundary volume transport V_O is conserved:

$$F + V_O = \mathbf{0},$$

where

$$V_O = \oiint v(s,z) \ dsdz$$

Lastly, the fraction of the ocean seawater flux per water parcel attributed to each of n sources, δV_O is:

$$\delta V_{O,j}(s,z) = f_i(s,z)v(s,z)\delta s\delta z,$$

where δs , δz describe the horizontal and vertical grid spacing (or water parcel size).

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2.5 End-Member uncertainty

Due to the wide range of plausible end-member values for each of the water types, to give an estimate of the likely uncertainty due to end-member choice, fluxes of the different water types were evaluated using a Monte-Carlo technique. Distributions for the different

- end-member parameters were constructed from the cited values (Table 2) by assuming the parameter variability is normally distributed, with mean equal to the mean of the cited values and standard deviation equal to the range. A sample set of 1000 ensembles was drawn from the set of constructed parameter distributions using a Latin Hypercube sampling strategy (McKay et al., 1979). The distributions of the individual parameters in the ensemble,
- which in all cases encompass the end points in Sect. 2.3 above, are shown in Fig. 4. Seawater salinity for 3EM and 4EM models is fixed at the boundary-mean boundary area-mean salinity for the TB12 model (34.662). A second choice of seawater salinity endpoint (35.0) results from the discussion in Section 4.

For each model approach, fluxes of the different water types were estimated by combining

the velocities from the TB12 model with the calculated water type fractions for the sample ensemble. Mean and standard deviations for the attributed volume fluxes of each water type were calculated as the mean and standard deviation of the results from the sample ensemble.

3 Results

- Here we present the results of the application of the methods and end-members, described in Sect. 2, to generate three and four end-member freshwater source fractions and fluxes. Equation 1 allows for individual fractions to be either < 0 or > 1 as long as the sum of all fractions is equal to one. There is a valid physical interpretation for negative Negative fractions of meteoric and ice-modified waters , where processes remove result from removal of
- ²⁵ freshwater from seawater representing net by evaporation and sea ice formation, respectively. Seawater However, seawater fractions, either total or individual Atlantic and Pacific

water fractions, should be positive. Consequently, Pacific and Atlantic water fractions were made positive-definite by rounding to zero any of the fractions that were less than zero, and setting the remaining seawater fraction so that equation 1 was not invalidated.

3.1 Three end-member model (3EM)

- ⁵ The distribution of 3EM source fractions is shown in Fig. 5. Ice-modified waters are found almost exclusively in the surface / upper waters of the model (depths down to 1000 dbar in the Davis Strait), with highest-magnitude fractions (-0.15) found in sub-surface waters of the western Fram Strait between depths of \sim 50 and 300 dbar. The fractions of ice-modified waters are mostly negative(indicating high salinity from upstream ice formation),
- ¹⁰ indicating brine, with a small fraction (~ 0.05) positive (indicating fresh meltwatermelt water input) in the surface (above 70 dbar) East Greenland Current (EGCEast Greenland Current; between 6.5 and 2° W) of the Fram Strait. Meteoric waters are also found almost exclusively in the surface / upper waters of the model, with high fractions (> 0.08) in the surface / subsurface waters (depths down to 350 dbar) in the Davis Strait and the western side of the
- $_{15}$ Fram Strait. There is also a high fraction of meteoric water in the Bering Strait. Seawater fractions are high (\sim 1) in all deep / intermediate model waters at depths in excess of \sim 350 dbar.

Typical volume fluxes (positive indicating into the Arctic) for the 3EM source fractions are shown in Fig. 6. The strongest fluxes of ice-modified waters occur as brine exports in

- ²⁰ surface waters of the middle of the Davis Strait , and on the western side of the Fram Strait (EGC)and East Greenland Current), and as brine import to the east in the Bering Strait, with fluxes of ~ 0.1 Sv in magnitude(positive fluxes indicating an export of high-salinity waters). The patterns of countervailing fluxes over the Belgica Bank (west of 6.5° W) in the Fram Strait are indicative of indicate recirculation (see TB12). Meteoric water volume fluxes
- follow the same general pattern as for ice-modified waters, with strong export (~ 0.1 Sv) in the middle of the Davis Strait and the EGC. There is a East Greenland Current and strong import (~ 0.1 Sv) of meteoric waters in the Bering Strait. Seawater volume fluxes indicate a strong export mid-Davis Strait (~ 1 resemble the oceanic circulation of TB12 (as expected),

with moderate export in the EGC concentrated exports in Davis Strait (~ 1 Sv)and the East Greenland Current (~ 0.5 Sv)and moderate import, and imports to the east in the Fram Strait in the West Spitsbergen Current (WSC; east of 5° E) and in the Bering Strait. There is also weak export of seawater (~ 0.1) for the deeper waters in the middle of the Fram Strait (between 2° W and 5° E).

For the 3EM model schemaschemes, the net seawater volume flux is effectively zero $(0.002 \pm 0.006 \text{ Sv}, \text{ Table 4}, \text{ Monte Carlo uncertainty quantification})$. The net volume export of meteoric waters $(200 \pm 44 \text{ mSv})$ is consistent with the TB12 surface freshwater input of $187 \pm 44 \text{ mSv}$ (Table 4). The model also indicates a volume of exported high-salinity ice-modified water net brine input export ($60 \pm 50 \text{ mSv}$), which is consistent with similar to the model solid sea ice export of $40 \pm 14 \text{ mSv}$, with the bulk of this the brine export occurring through the Davis Strait (note that this is represented in the model by an apparent net import)

of fresh ice-modified water in opposition to the general circulation, Table 4).

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The 3EM model indicates that the volume export of meteoric water through Fram Strait is concentrated in the Belgica Bank and EGC regions (East Greenland Current regions - 22±6 (mSv) and 83±50 (mSv), respectively),-- with close to zero meteoric flux in the remainder of the strait (Table 5). This is consistent with the picture described in previous studiesDodd et al. (2012); Rabe et al. (2009); Meredith et al. (2001). High-salinity ice-modified water: Dodd et al. (2012); Rabe et al. (2009); Meredith et al. (2001). Brine is exported mainly

- ²⁰ in the EGC East Greenland Current (88 ± 56 mSv), with small (~ 5 mSv) fluxes of icemodified water in the middle and Belgica Bank sections of the strait (Table 5). The import of high-salinity water in the WSC is attributed exclusively to ice-modified water (apparent brine import both in the West Spitsbergen Current and the Barents Sea Opening - 44 ± 36 mSv), reflecting (Table 4) 48 ± 35 mSv (Table 5) respectively - reflects the higher $\delta^{18}O$ values at the surface (= 0.4 %) relative to these for deeper waters (= 0.2 %)) to the east of 5% W
- at the surface (~ 0.4 ‰) relative to those for deeper waters (~ 0.2 ‰)) to the east of 5° W (Fig. 2). This is discussed in Section 4.

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The 4EM scheme extends the 3EM scheme through use of inorganic nutrient (nitrate and phosphate) data, aiming to discriminate between Atlantic and Pacific seawater origin. The 4EM scheme retains single end-points for salinity and $\delta^{18}O$, as in 3EM. In the 4EM+ scheme, distinct salinity and $\delta^{18}O$ end-member properties are attributed to Atlantic and Pacific seawaters, replicating previous practice (Dodd et al., 2012; Jones et al., 2008; Sutherland . The resulting distributions of 4EM and 4EM+ source fractions are shown in Figures 7 and 9, respectively, and characteristic volume fluxes for the source fractions in Figures 8 and 10.

- In common with the 3EM model, both 4EM and 4EM+ models allocate the bulk of the 10 ice-modified water waters, mainly brine with some melt water input, to the surface / upper waters. However, both four end-member schema indicate a schemes indicate small but non-zero fraction fractions (~ 0.01) of ice-modified waters in the deeper waters brine in the east of the Fram Strait and in the Barents Sea Opening. The distribution of meteoric
- waters in both four end-member models is consistent with the 3EM model where meteoric 15 waters also mostly occupy the surface layers. However, differences occur in the Davis Strait, where the 4EM and 4EM+ models indicate lower fractions (~ 0.01) below ~ 350 dbar, in the Bering Strait where meteoric water is confined to the eastern side, and in the deeper waters of the model where the meteoric fraction is non-zero (< 0.01). Both four end-member
- models indicate Pacific water mostly in the surface / near surface waters of the Davis, Fram 20 and Bering Straits, and almost exclusively Atlantic Water water in the deepest waters of the model (~ 0.9). Both models indicate quantities of Pacific Water in the deepest water show small fractions of Pacific water in the deep waters of the Fram Strait and Barents Sea Opening (~ 0.1), and Atlantic water in the Bering Strait (~ 0.1).
- Differences between the 3EM three and four end-member model schema schemes are 25 also reflected in the fluxes of the different fractions. For both four end-member models. there are non-zero fluxes of ice-modified watersbrine, meteoric water (both < 0.005 Sv), and Pacific water (< 0.02 Sv) in the deeper waters of the Fram Strait and Barents Sea

Opening. Consistent with the 3EM model, the 4EM model has a net oceanic volume flux (sum of Pacific and Atlantic contributions) that is effectively zero (4EM 0.002 ± 0.006 Sv, Table 6), while but the net oceanic volume flux for the 4EM+ model is larger and indicates a net outflow non-zero indicating a net export (-0.104 ± 0.051 Sv, Table 8). Net model liquid freshwater export (sum of meteoric and ice-modified fractions) for the 4EM model is the same as for the 3EM model (140 ± 67 mSv), while the 4EM+ export is smaller with a large relative uncertainty (35 ± 51 mSv).

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Net-The net ice-modified water (mainly brine) flux for both the 4EM and 4EM+ schemas schemes is also consistent with the 3EM model and the TB12 solid ice flux, with the 4EM model estimating 60 ± 50 mSv and the 4EM+ 63 ± 64 mSv (Tables 6 and 8). Both 4EM and 4EM+ models show the same flux pattern for ice-modified water as the 3EM model, with the bulk of the high-salinity ice-modified water brine input exiting through the Davis Strait (Tables 4, 6 and 8, Fig. 11).

While the net volume flux of meteoric water for the 4EM model is the same as that of
the 3EM (200 ± 44 mSv), the 4EM+ model estimates a smaller net volume flux (98 ± 46 mSv, Tables 6 and 8). Both 4EM and 4EM+ models show the same flux pattern for meteoric water as the 3EM model, with meteoric water entering the Bering Strait and exiting through the Davis and Fram Straits. However, the net import of meteoric water through the Bering Strait and the net export of meteoric water through the Davis Strait in the 4EM+ model
schema schemes is approximately half the magnitude of the fluxes in the other two schema schemes (Tables 4, 6 and 8, Fig. 11).

Both 4EM and 4EM+ model schemas schemes indicate an imbalance in the net volume fluxes for both Pacific and Atlantic seawater, with both model schemas showing water. They both show a net export of Pacific seawater water (4EM 1.495 ± 0.268 Sv; 4EM+ 1.488 ± 0.263 Sv) that is balanced by a net import of Atlantic seawater water of approx-

imately equal magnitude (4EM 1.497 ± 0.268 Sv; 4EM+ 1.384 ± 0.255 Sv, Tables 6 and 8). Current understanding of Arctic fluxes suggests that Pacific water enters the Bering Strait and exits both through the Davis Strait, after passing through the western Canadian Archipelago, and on the western side of the Fram Strait (Haine et al., 2015). Consis-

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tent with this view, both four end-member schemas schemes indicate that Pacific water, entering the Arctic through the Bering Strait, exits mostly through the Davis Strait with a much ($O(10\times)$) smaller flux through the Fram Strait, mainly across Belgica Bank and in the EGCEast Greenland Current. Export of Pacific water through the Davis Strait is approximately twice the magnitude of the import through the Bering Strait (Tables 6 and 8). Atlantic seawater water circulates in through the Barents Sea Opening and out through the western Fram and Davis StraitStraits, with the import through the Barents Sea Opening approximately twice the magnitude of the export (Tables 6 and 8).

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For the Fram Strait, the pattern of water fluxes described by both the 4EM and 4EM+
 schemas schemes is consistent with the pattern described above for the 3EM model (Tables 7 and 9). In both four end-member schema, Pacific-origin schemes, Pacific water is exported across Belgica Bank and in the EGCEast Greenland Current, accounting for approximately 15% of the Fram Strait oceanic volume flux (Tables 7 and 9). While fluxes of meteoric and ice-modified waters described by the 4EM model are the same as for the 3EM
 model (Table 7), the fluxes from the 4EM+ schema schemes are different (Table 9).

The description of Arctic freshwater fluxes presented by the 4EM+ model is broadly consistent with that from previous studies of fluxes in the Fram Strait using 4EM+ type schemas schemes with distinct Pacific seawater, $\delta^{18}O$, and salinity end-members (Dodd et al., 2012; Azetsu-Scott et al., 2012; Rabe et al., 2013). Analysis of a time series of observations from the Fram Strait suggest a mean freshwater export flux dominated by waters of meteoric origin, mixed with high-salinity ice-modified waters brine to the west of 2° W in the EGC East Greenland Current and over the Greenland shelf (i.e. Belgica Bank), with fluxes of negative meteoric origin waters also noted in the WSC-West Spitsbergen Current (Dodd et al., 2012; Rabe et al., 2013).

The greatest differences between the models are in the fluxes of meteoric, brine and ice melt waters across Belgica Bank and in the EGC East Greenland Current (Fig. 11), with the 4EM+ schema schemes showing less export of meteoric water in the EGC East Greenland Current compared to the the other schemaschemes. In the 4EM+ model, the import of high-salinity water in the WSC West Spitsbergen Current is attributed almost
equally to "negative" meteoric-origin water and high-salinity ice-modified (brine input) water, in contrast to the 4EM and 3EM schemaschemes, which attribute this high-salinity import to high-salinity ice-modified water brine (Tables 7 and 9). Export of ice-modified water Brine export is also lower in the 4EM+ schemes compared to the 3EM and 4EM models (Tables 7 and 9; Fig. 11).

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The estimated distribution of water types across In the Davis Strait in the 4EM+ model is gualitatively consistent with previous studies, where column inventories of the water types source fractions show highest freshwater content in the surface waters on the western side of the strait, where the net freshwater inventory consists of a mixture of "oceanic freshwater"

and high-salinity ice-modified water from Pacific seawater and meteoric fractions, with a 10 contribution from brine (Azetsu-Scott et al., 2012). To the east of the Davis Strait, there is a contribution from fresh ice-modified small contribution from sea ice melt water (Azetsu-Scott et al., 2012).

4 **Discussion and summary**

In this section, we first examine points of consistency, both between the different end-member 15 models and between the models and other evidence; then we consider inconsistencies, and their consequent meaning, between those models; finally, we offer some general perspectives on freshwater calculations in the Arctic.

4.1 **Consistency**

- Within uncertainty, the net seawater flux of the 3EM and 4EM models is zero: 2 ± 6 mSv 20 for 3EM; 2 ± 379 mSv for 4EM (Tables 4 and 6). Furthermore, the 3EM and 4EM model estimates of net Arctic meteoric freshwater volume export flux is 200 ± 44 ; so in this section, we first discuss the "minority" water mass constituents, meaning ice-modified waters (mainly brine), "Pacific" waters and meteoric waters, in terms of implications for net fluxes and fundamental points of interpretation; finally, we offer some general perspectives. 25
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4.1 Ice-modified waters

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The models generate apparent brine imports in the West Spitsbergen Current and the Barents Sea Opening, both of magnitude ~ 45 mSv(Tables 4 and 6), a total of ~ 90 mSv with a large relative uncertainty of ~ 50 mSv. If correct, this is a substantial component of the Arctic Ocean freshwater budget. These (apparent) fluxes are too small to be visible on Fig. 5, but for scale, note that each net (oceanic water) inflow is ~ 3 Sv, which agrees well (again 1 % of which is 30 mSv. These brine fluxes are consequences of weakly positive $\delta^{18}O$ anomalies centred around ~ 300 m depth in both locations, each about 200 m thick and each spanning ~ 200 km. The presence of these features in both Fram Strait and the Barents Sea Opening suggests that they are source water (Atlantic seawater) properties

- Barents Sea Opening suggests that they are source water (Atlantic seawater) properties and not the result of modifications by local processes. Frew et al. (2000) examine the oxygen isotope composition of northern North Atlantic water masses from measurements made in 1991. Considering the waters of interest here – the upper ~ 500 m in the eastern North Atlantic (their stations 10, within uncertainty)with the 24, 26, 72) – we find (broadly) salinities
- and $\delta^{18}O$ values in the ranges 35.0 35.2 and 0.2 0.4 ‰ respectively (their Fig. 2). This combination and range describes the part of the dense cloud of points heading a short distance "north-eastwards" in phase space away from the seawater endpoint (Fig. 3 panel a inset).

A consistent interpretation of the apparent West Spitsbergen Current and Barents Sea Opening brine imports, therefore, is that they are actually manifestations not of local processes but rather of source water variability, in the light of our salinity (34.662) and $\delta^{18}O$ (mean 0.2 ‰) endpoints. As a result, we ran the 3EM model again, now with salinity 35.0 and fixed $\delta^{18}O$ of 0.35 ‰; the results are shown in Tables 10 and 11. There is no change to component totals (seawater, brine, meteoric totals), or to gateway totals (Fram, Davis and

²⁵ Bering Straits, and the Barents Sea Opening), but there are significant component changes between gateways and within Fram Strait. For the Barents Sea Opening, we see 38 mSv removed from the seawater component and added to the meteoric fraction, \sim doubling the meteoric freshwater import from 13 ± 31 to 25 ± 7 mSv, more than halving the ice-modified

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water flux, which we have been interpreting as brine import, from 48 ± 35 to 22 ± 7 mSv, and greatly reducing their uncertainties (1 sd), giving us confidence that this new 3EM run is "better" in this regard. The two freshwater import values are consistent with freshwater entering the Arctic Ocean in the Norwegian Coastal Current as the 14 mSv of TB12surface freshwater input of 187 ± 44 , who use a boundary mean salinity (effective) reference of 34.67, and with the 23 mSv - of Smedsrud et al. (2010), using a salinity reference of 35.0, as

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for our new 3EM run, respectively. The remaining 22 mSv of ice-modified water is, therefore, unlikely to be brine import, given the $\delta^{18}O$ mean endpoint of 0.35 %; it is more likely to be meltwater export south of Svalbard (cf. Gammelsrød et al. (2009)). A similar pattern is seen in the West Spitsbergen Current in the east of Fram Strait, where an apparent brine import

- ¹⁰ In the West Spitsbergen Current in the east of Fram Strait, where an apparent brine import and its uncertainty of 44 ± 36 mSv reduce to 16 ± 4 mSv. For our geochemical approach, we began with a salinity endpoint that replicated the budget method's effective salinity reference value; however, we conclude that the geochemical approach requires a different, geochemical, salinity endpoint, relevant to the source water properties under consideration.
- At the same time, there must be some uncertainty associated with the seawater endpoint properties, even when considering only the Atlantic source, given the measurements of Frew et al. (2000), given also that their measurements were made 14 years before those used here, and given further that we lack more evidence of upstream (source) $\delta^{18}O$ variability.
- Sea ice is A second point concerns the near-total absence of positive ice-modified fractions, representing sea ice melt, anywhere around the boundary (Fig. 5). The actual absence of melted sea ice in late summer in these locations is not credible. However, inspection of the two Arctic export routes west and east of Greenland Davis Strait and the East Greenland Current (in the west of Fram Strait) shows similar features: high brine fractions around 50 m
 depth, decreasing towards the surface. In common with Cox et al. (2010), we interpret this as the result of sea melting back into the oceanic water from which it (partly) originated, resulting in (partial) reduction of the brine signal.

Thirdly, we know that sea ice is frozen out of liquid seawater, leaving and it leaves behind in the seawater a negative $\delta^{18}O$ signal resulting from this distillation-type process (Östlund and Hut, 1984). In the long-term mean, and allowing for trends in net freshwater input and lags between this input at the surface and its manifestation at the boundary, the positive freshwater export flux of the sea ice should be approximately equal to the negative

- freshwater export flux of the freshwater deficit resulting from this sea ice formation(brine) export flux. We find the latter (the deficit flux) to be a surprising coincidence (allowing for uncertainties) between the net brine flux, at 60 ± 50 mSv for both the 3EM and 4EM models, and this is similar to the TB12 sea ice export of 40 ± 14 mSv. The TB12 measurements were
- made in summertime, and we note evidence of seasonal signal "cancellation", where the 10 $\delta^{18}O$ seawater deficit signal is a maximum at depth (\sim 50 ; Figures 5 and 7) and reduces towards the surface, which we interpret as the (seasonal) result of sea ice melting back into the near-surface seawater. More work is needed to understand how representative this balance may be; for example, would wintertime measurements of sea ice and brine fluxes
- show a similar balance? What does this say about local versus non-local freeze-out and 15 melt-back processes on seasonal brine and sea ice export variability?

The previous two paragraphs note that (i) the TB12 net surface freshwater flux is (approximately) the same as our net meteoric freshwater flux, and (ii) our sea ice and ice-modified water fluxes are (approximately) equal and opposite. A further, combined, view arises. The net 3EM and

4.2 "Pacific" water

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The only change in the 4EM liquid freshwater export is the sum of the meteoric and ice-modified freshwater fractions, and equals 140 ± 67 , which is model over 3EM is the inclusion of P^* , intended to distinguish seawater of Atlantic origin from that of Pacific origin. The retention of single salinity and $\delta^{18}O$ endpoints for seawater ensures that all source water fluxes remain the same as the TB12 net liquid freshwater export of 147 ± 42 (the total freshwater flux is then obtained by adding the solid, sea ice, fraction). Fluxes of liguid freshwater from the

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TB12 model also compare well to the for 3EM and 4EM models' net surface volume fluxes of meteoric and ice-modified waters across the four main gateways (Fig. ??).

4.3 Inconsistency

The first inconsistency arises from the inclusion of inorganic nutrient constraints. apart from the separation of seawater into Atlantic- and Pacific-sourced fluxes (Tables 6 and 7). In the 5 4EM model, ~ 1 Sv of Pacific seawater enters the Arctic through Bering Strait, while more than double that $- \sim 2.5$ Sv – of Pacific seawater exits the Arctic, mainly through Davis Strait, indicating the apparent net "creation" of ~ 1.5 Sv of Pacific seawater (Table 6). The quantity of seawater labelled "Pacific" that exits the Arctic (mainly through Davis Strait) is

- more than double the quantity of actual Pacific seawater entering (through Bering Strait). 10 This is mirrored by the origins and fate of Atlantic seawater, with \sim 3.6 Sv entering the Arctic and only ~ 2.1 Sv exiting, which indicates indicating an apparent net "destruction" of ~ 1.5 Sv of Atlantic seawater (Table 6). The magnitude of this apparent "conversion" of Atlantic to Pacific seawater is over five times greater than the uncertainty on the fluxes (~ 0.3 Sv; Table
- 6). In the 4EM model, discrimination between Atlantic and Pacific waters is solely based on 15 P^* , which consequently suggests that the assumption that the nitrate:phosphate (N:P) nutrient ratio is a conservative tracer of seawater origins is flawed. This apparent conversion of 1.5 Sv of Atlantic to Pacific water is outside any plausible uncertainty of the relevant volume and nutrient fluxes; see TB12 and Torres-Valdés et al. (2013). Furthermore, it is similar to TB12's downwards export of 1.9 Sv out of the Atlantic water layer into denser 20

layers.. The N:P ratio (expressed here as P^*) was proposed as a tracer that would be conservative with respect to biological activity (Jones et al., 1998, 2008; Yamamoto-Kawai et al., 2008). However, evidence indicates that the N:P of waters entering the Arctic is further modified along their pathways, most likely by denitrificationalone or in combination with a potential 25 external source of phosphate (Torres-Valdés et al., 2013; ?). This is particularly true for waters of Pacific origin, known to undergo further denitrificationover the Chukchi Shelf, such that the P* signal in Davis Strait is much larger than at the Bering Strait (Torres-Valdés et al., 2013) . Those modification processes thus render the N:P ineffective as a tracer (at least when considering full depth assessments) distribution of the 4EM Pacific fraction around the Arctic Ocean boundary (Fig. 5) show the expected geographical distribution, with the main concentrations in the Bering Strait (import) and Davis Strait (export), and weaker concentrations in the west

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- of Fram Strait (export). Not previously reported, however, are significant concentrations 5 at depth (fractions > 0.1 at depths > 500 m) across Fram Strait. A credible hypothesis to explain all these observations - the doubling of Pacific export over import, the transformation of Atlantic water, and the deep presence of Pacific water - concerns denitrification, the process that occurs in ocean sediments and removes nitrate from the ecosystem by discharging
- N_2 . Chang and Devol (2009) estimate a net pan-Arctic denitrification rate of \sim 13 Tg N 10 yr⁻¹, with much of that expected to occur in the shallow waters of the Barents and Chukchi Seas (6 and 3 Tg N yr⁻¹ respectively). They further note the likelihood that the process is a consequence of sea ice retreat enabling increased primary production through increased shelf-break upwelling, which delivers nutrient-rich waters to upper-ocean waters with greater
- light availability; the resulting increase in export production then fuels higher rates of sedimentary 15 denitrification. In addition, and while the geographical distribution and intensity of circum-Arctic Discussion Paper dense water formation remains an active topic of research, it is known that the winter-time Barents Sea supports significant dense water formation rates, and that the dense product waters exit the Barents Sea via St. Anna Trough (e.g. Aksenov et al., 2010). Thus there
- exists a credible mechanism to denitrify inflowing Atlantic water and then to transmit it into 20 the deep Arctic Ocean.

Additionally, the We acknowledge that much remains unknown about the Arctic Ocean biogeochemical cycle; understanding of denitrification is at an early stage, and understanding of Arctic Ocean sources and sinks of nitrate and phosphate is incomplete (Chang and Devol, 2009)

. The N:P nutrient ratio of river runoff is has been pragmatically assumed to be constant and 25 to match that of Atlantic seawater, in that it has no excess of phosphate (Dodd et al., 2012; Yamam -However, phosphate excess (Dodd et al., 2012; Yamamoto-Kawai et al., 2008; Jones et al., 2008 , and knowledge of the riverine delivery of water constituents such as nutrients, sediment, and carbon nutrients is less well constrained than estimates of freshwater volume (Bring

et al., 2016, 2017), suggesting that there may be other, as yet unquantified, riverine nutrient sources (or sinks) in the Arctic. Denitrification in the bottom sediments of the Laptev Sea continental margin, inferred from nutrient budget estimates over the shelf, has also been suggested to lead to a potential overestimate in the volume of Pacific origin seawater when using nutrient ratios as a tracer (Bauch et al., 2011). Although these factors are already acknowledged as likely sources of error when using N:P ratios as a tracer (Dodd et al., 2012; Yana

- using nutrient ratios as a tracer (Bauch et al., 2011). Although these factors are already acknowledged as likely sources of error when using N:P ratios as a tracer (Dodd et al., 2012; Yama, our results suggest that the influence of such processes is likely to be significantly greater than previously thought. Nevertheless, the N:P ratio (expressed here as P*) was proposed as a tracer that would be conservative with respect to biological activity (Jones et al., 1998, 2008;
- ¹⁰ The results presented here, when combined with those of Bauch et al. (2011) and Alkire et al. (2011), suggest strongly that the N:P ratio is no longer conservative. We suggest, however, that it may still be useful in generating net quantification of denitrification rates, once the question of sources and sinks is resolved. For illustration, using an Atlantic to Pacific nitrate offset of $5 10 \mu$ mol L⁻¹ (Fig. 3) and a water mass conversion rate of 1.5 Sv (as above), we find
- ¹⁵ a net, apparent, pan-Arctic denitrification rate of 3.3 6.6 Tg N yr⁻¹, the same order of magnitude as the 13 Tg N yr⁻¹ of Chang and Devol (2009), but including Baffin Bay, which they do not.

Another inconsistency arises from consideration of results from the 4EM+ model (Tables 8 and 9), when Pacific and Atlantic seawaters are defined as separate categories using both salinity and $\delta^{18}O$. These two seawaters will lie on the mixing line between any single seawater endpoint and pure freshwater (Fig. 3). If Pacific seawater lies on this mixing line and is also defined as a separate category, then these constraints are degenerate. This is reflected in the significant shifts of fluxes between all components - Atlantic, Pacific, meteoric and ice-related.

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4.3 Meteoric water

A primary positive result of this study is the finding that both variants of the 3EM model (and the 4EM model) robustly quantify the net rate of Arctic meteoric freshwater input (the net of

P-E+R within the defined boundary) as $200 \pm 44 \text{ mSv}$ (Tables 4, 6, Table 10), and that this geochemical quantification agrees closely with the TB12 budget method net surface freshwater input rate (within the same boundary) of $187 \pm 44 \text{ mSv}$, providing a degree of cross-validation of both methods.

- An inconsistency arises from consideration of the composition and "labelling" of the waters of Bering Strait. Water entering the Arctic through the Bering Strait should, by definition, be seawater of Pacific origin. However, the Bering Strait inflow is unusually fresh because it contains a significant fraction of meteoric freshwater (Östlund and Hut, 1984, and Table 4). The meteoric water in the Bering Strait originates in , originating in part from the Alaskan
- ¹⁰ Coastal Current on the east side of Bering Strait, and it which preserves the runoff signal from the western North American rivers: (e.g. Woodgate and Aagaard, 2005; Chan et al., 2011). A second important reason for the presence of meteoric freshwater in Bering Strait is the basic fact that the Pacific Ocean experiences a net positive precipitation anomaly: (e.g. Warren, 1983). There are two sets of constraints on the water in Bering Strait, therefore: it must be all Pacific water (defined by P^*), because that is where it comes from; and it must be $\sim 10\%$ meteoric freshwater (defined by $\delta^{18}O$) to generate its low salinity. These

constraints must, therefore, be partially degenerate (Fig. 3).

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A third inconsistency arises when Pacific and Atlantic seawaters are defined as separate categories using salinity and $\delta^{18}O$. These two seawaters will lie on the mixing line between any single seawater category, such as that associated with the TB12 boundary-mean salinity, and pure freshwater (Fig. 3). If Pacific seawater lies on this mixing line and is also defined as a separate category, then these constraints are also degenerate.

The results of using such wholly or at least partially degenerate constraints on the model fluxes are most clearly manifested in the 4EM+ model. In contrast to the models with common seawater properties. The models with single seawater endpoint values (3EM and 4EM), there is a positive net ocean volume export for the 4EM+ model (104 ± 5.1 have near-zero net seawater export (actually 2 ± 6 mSv). The fraction of Pacific origin seawater identified in , while the 4EM+ model is not significantly different from that in the 4EM model (0.806 ± 0.076 , for 4EM; 0.825 ± 0.099 , for 4EM+). However, the volume of meteoric

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water identified shows a positive net seawater export (as the sum of Atlantic and Pacific seawaters) of 104 ± 51 mSv, which mainly occurs in Davis Strait. At the same time, the meteoric water export flux is about half that of the 4EM model (Tables 6 and 8). The TB12 net salinity-based estimate of liquid freshwater export compares well to the $\delta^{18}O$ -derived estimates of meteoric origin waters and high-salinity ice-modified water from the 3EM, with 5 the difference appearing (again) mainly in Davis Strait. The model is balancing reduced meteoric freshwater export with increased salinity export, and 4EM models, which is consistent

with the current paradigm of the Arctic freshwater budget (Haine et al., 2015). However, for With the current paradigm of the Arctic freshwater budget (Haine et al., 2015). However, for the 4EM+ model the picture of Arctic freshwater export being the sum of meteoric and ice-modified water fractions is modified by the inclusion of an "oceanic" origin freshwater component (Fig. **??**). The theoretical underpinning of the definition of a single reference salinity used in the 3EM and 4EM models (Bacon et al., 2015) combined with the constancy of $\delta^{18}O$ in oceanic waters, which is the basis of the use of $\delta^{18}O$ as a tracer (Östlund and Hut, 1984 10 -leads us to the interpretation of the 4EM+ model Pacific water as a mixture of seawater.

- meteoric water and ice-modified water in an undefined ratio. Consequently "oceanic" origin 15 freshwater, in the 4EM+ schema, is likely to be simply a mixture of meteoric water and ice-modified water in undefined ratio. This interpretation of oceanic origin freshwater is consistent with the results for the Fram and Davis Straits, where an increase in oceanic freshwater flux is matched by a decrease in predicted meteoric freshwater flux (Figures
- 11 and ??). it is able to do that because Atlantic seawater, Pacific seawater and meteoric 20 freshwater all lie on the same mixing line: the degeneracy causes unrealistic results.

4.4 Perspectives

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Continuing the point of discussion from the previous section: the use of the N:P inorganic nutrient ratio as a tracer can appropriately distinguish Atlantic and Pacific origin seawater on entry to the Arctic (Jones et al., 1998, and Fig. 3).

Our evidence indicates an apparent ~ 1.5 conversion of inflowing Atlantic water into a water mass ("Polar", perhaps) with the same inorganic nutrient properties as inflowing Pacific water. Geochemically, processes which change the N: P ratio are observed to occur in the shallower shelf regions of the Arctic and in the Chukchi Sea (?Chang and Devol, 2009; Bauc - Consequently, this conversion may have been achieved through further modification of ussion inflowing Pacific water which then mixes with Atlantic water prior to outflow. Alternatively, there may be a process (or processes) that we do not understand modifying Atlantic water

- directly within the Arctic. While the understanding of nutrient sources, sinks, and transformations 5 within the Arctic remains incomplete (e.g. Torres-Valdés et al., 2013, 2016), we cannot ascertain exactly where or how the addition of phosphate and/or the removal of nitrate may be happening. However, we must now regard the employment of the N:P ratio in this context Discussion Paper to be unsafe.
- Turning now to positive results, this is the first demonstration of consistency between 10 the "control volume" approach to quantification of freshwater fluxes (as in TB12) and the deochemical tracer approach, so we describe now how and why this works. The TB12 approach is outlined above in Sect. 2.1, is mathematically generalised in Bacon et al. (2015) - and is further illustrated in (Carmack et al., 2016, Appendix). Traditional ocean (and sea
- ice) freshwater flux calculations have in the past required the use of arbitrary reference 15 salinities. However, in this approach, there is nothing to distinguish freshwater from the salinities. However, in this approach, there is nothing to distinguish freshwater from the pure water component of seawater (cf. **??**). The key perception that enabled the analytical removal of arbitrary reference salinities is that there is only one unique physical (and non-geochem). definition of freshwater in the marine context: the net freshwater flux at the surface (meaning
- the net of precipitation, evaporation and runoff). For this approach to work, an actual (or 20 notional) control volume, plus knowledge around the marine boundary of velocity and salinity, is required. The outcome is that the reference salinity in the freshwater flux calculation is functionally replaced by the ocean (and sea ice) boundary-mean salinity.

The approach here Our geochemical approach to oceanic water flux calculation employs three valid and geochemically distinct categories of water: sea ice (in its various manifes-25 tations), meteoric (surface-origin) freshwater, and seawater (where seawater is the component of the mixture that contains all of the dissolved salt and this contains no significant isotopic distillation signaturesalts). First, we note again that our total sea ice flux, being the sum of the fluxes of solid sea ice, sea ice meltwatermelt-water, and the freshwater deficit Paper

(brine) in the seawater from which the ice was formed, is approximately zero. Second, the TB12 velocity field is constrained to conserve salinity, and this is reflected in our zero net seawater fluxes, which is another statement of salinity conservation, because "seawater" is the category that contains all of the ocean salinity. Third, we note that the same categories (both here and in TB12) of surface-origin freshwater are all meteoric, as the net of P - E + R. This is why our surface (meteoric) freshwater flux agrees with the TB12 results: both are (explicitly or implicitly) meteoric.

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In conclusion, in this work we have both reconciled the (traditionally divergent) perspectives of the Arctic freshwater budget provided by control volume and geochemical approaches,

- and shed light into the causes of their previously conflicting results. Our findings indicate that future applications of geochemical approaches to monitoring the climatic evolution of Arctic freshwater fluxes should avoid tracer-based definitions of distinct oceanic water typesWe find the category "Pacific water", defined from the N:P ratio, to be non-conservative; however, it is very likely to continue to be useful, probably to quantify pan-Arctic denitrification,
- possibly also to help quantify dense water formation rates, where that process happens in denitrifying shelf seas. This continuing albeit different usefulness of the N:P ratio relies on retention of single salinity and δ¹⁸O endpoints to describe seawater, so that the N:P categorisation can then only operate on seawater. Degeneracy intrudes with subdivision of salinity and δ¹⁸O categories, meaning that three would-be "endpoints" (Atlantic, Pacific, meteoric) actually lie on the same salinity–δ¹⁸O mixing line, causing confused results, both
 - for the Atlantic–Pacific contrast and for the Pacific–meteoric contrast. In terms of $\delta^{18}O$ signal, precipitation/evaporation and freezing/melting are manifestations of the same process with opposite signs. Consequently, $\delta^{18}O$ values reflecting only net isotopic fractionation are unable to quantify river runoff without the use of another conservative
- tracer. It was hoped that barium could be used as a tracer of riverine input into the Arctic (Kenison Falkner et al., 1994). However, barium was found to be non-conservative (through biological scavenging) in seawater (Abrahamsen et al., 2009). Nevertheless, other, more exotic species, may prove useful. For instance, Laukert et al. (2017) show that the distribution of neodymium isotopes in Fram Strait bears a considerable resemblance to our "Pacific"

water distribution (our Fig. 9, their Fig. 3), and with a similar interpretion to ours (Section 4.2 above) as to the provenance of the water mass. Furthermore, Wefing et al. (2019) analyse isotopes of iodine and uranium, sourced from UK and French nuclear reprocessing plants, which trace Arctic Ocean circulation pathways and residence times, showing that some fraction of the near-surface freshened oceanic waters in the west of Fram Strait, which appear to be of Pacific origin from the N:P analysis, may actually have originated from the Norwegian Coastal Current.

We envisage that sustained measurement of suitable tracers around the Arctic boundary has the potential to further our quantification and understanding of key processes, variability

and timescales and to help mitigate the scarcity of observations in the Arctic Ocean interior. More (and more reliable) tracers are needed, more observations of more "traditional" tracers are needed through the water column (from surface to sea bed), more of those observations are needed in seasons outside summer-autumn, and we need better understanding of Arctic Ocean biogeochemical processes.

15 Data availability

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All data used in the analysis presented here is available from the original authors. See Sect. 2.1 for details.

Author contribution

AF conducted the analysis and prepared the manuscript. SBand ACNG, ACNG and STV assisted with the analysis and preparation of the manuscript. TT and STV assembled the data usedand assisted with manuscript preparation. STV assisted with manuscript preparation., and TT assisted with the analysis.

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scheme	esConstraints	Fluxes	Comments
3EM	Volume conservation, salinity, $\delta^{18}O$	Seawater, meteoric water, ice melt	Seawater is assigned a fixed salinity regardless of origin.
	Volume	Atlantic seawater,	Atlantic and Pacific
4EM	conservation, salinity, $\delta^{18}O$, P_{*}^{*}	Pacific seawater, meteoric water, ice melt	seawaters are assigned a common salinity and $\delta^{18}O$, but different P^* values.
4€M+	$\begin{array}{c} \underbrace{ \text{Volume}} \\ \underbrace{ \text{conservation,}} \\ \underbrace{ \text{salinity,}} \\ \underbrace{ P^* \\ \end{array} \end{array} \overset{\delta^{18}O}, \end{array}$	Atlantic seawater, Pacific seawater, meteoric water, ice melt	AtlanticandPacificseawatershavedifferentsalinity, $\delta^{18}O$ and P^* values.

 Table
 I. Description of the three model schemes.

	Atlantic	Pacific	mean Met.	Ice Melt	Source
$\delta^{18}O$	0.24 ± 0.03	-0.8 ± 0.1	-20 ± 2	-2 ± 1.0	Yamamoto-Kawai et al. (2008)
(‰) (∞)	$\begin{array}{c} 0.3 \\ 0.3 \\ 0.19 \pm 0.06 \\ 0.35 \pm 0.15 \end{array}$	-1.0 ± 0.5 -1.3 -0.8 ± 0.1 -1 ± 0.1	$-21 \\ -18.4 \\ -18 \pm 2 \\ -21 \pm 2$	$\frac{surf + 2.1}{0.5}$ -2 ± 1 1 ± 0.5	Bauchaet/al. (1995) Dodd et al. (2012) Azetsu-Scott et al. (2012) Sutherland et al. (2009)
Mean	0.28	-0.98	-19.7	<u>-0.6</u>	
Sal. (PSI	J }34.87 ± 0.03	32.5 ± 0.2	0	4 ± 1	Yamamoto-Kawai et al. (2008)
<u>(PSU)</u>	34.92	33	0	3	Bauch et al. (1995)
	34.9	<u>mean</u> 32.0	0	4	Dodd et al. (2012)
	34.75 ± 0.14	32.5 ± 0.2	0	4 ± 1	Azetsu-Scott et al. (2012)
	35 ± 0.15	32.7 ± 1	0	4 ± 1	Sutherland et al. (2009)
Mean	34.89	32.54	0	3.75	

Table 2. End-member values for salinity and $\delta^{18}O$ (‰) from the literature. Note Bauch et al. (1995) calculate ice melt $\delta^{18}O$ by multiplying measured surface seawater $\delta^{18}O$ (*sur f*) by a "fractionation factor" of 1.0021.

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	Slope	Intercept	Source
Atlantic	0.0545	0.1915	Jones et al. (2008)
	0.053	0.170	Dodd et al. (2012)
	0.048 ± 0.003	0.130 ± 0.04	Sutherland et al. (2009)
Mean	0.052	0.164	
Pacific	0.0653	0.94	Jones et al. (2008)
	0.08 ± 0.015	$\textbf{0.85}\pm\textbf{0.13}$	Sutherland et al. (2009)
	0.0654	0.6766	Calculated for this study from observations
Mean	0.070	0.822	

Table 3. P:N relationships, where $PO_4 = Slope * NO_3 + Intercept \ (\mu \text{ mol kg}^{-1})$

	Oceanic	Met.	Ice Melt	Sum
Davis	-3.035 ± 0.008	-0.209 \pm 0.055	0.100 ± 0.062	-3.144
Fram	-1.566 \pm 0.004	-0.104 \pm 0.027	0.038 ± 0.030	-1.632
Barents	3.671 ± 0.004	$\textbf{0.013} \pm \textbf{0.031}$	$\textbf{-0.048} \pm \textbf{0.035}$	3.636
Bering	0.931 ± 0.003	0.099 ± 0.023	-0.029 \pm 0.026	1.001
Liquid	0.002 ± 0.006	-0.200 ± 0.044	0.060 ± 0.050	-0.139
Solid			$\textbf{-0.040} \pm \textbf{0.014}$	-0.04

Table 4. Mean volume fluxes (Sv \pm standard deviation) for the three end-member (3EM) model. Positive values indicate fluxes into the Arctic. Values of solid freshwater flux from Tsubouchi et al. (2012).

	Oceanic	Met.	Ice Melt	Sum
BB	-0.350 ± 0.001	-0.022 \pm 0.006	-0.002 \pm 0.006	-0.373
EGC	-5.364 \pm 0.007	$\textbf{-0.083} \pm \textbf{0.050}$	0.088 ± 0.056	-5.359
Mid.	0.303 ± 0.000	$\textbf{-0.000} \pm \textbf{0.003}$	$\textbf{-0.005} \pm \textbf{0.003}$	0.298
WSC	$\textbf{3.845} \pm \textbf{0.004}$	0.001 ± 0.032	$\textbf{-0.044} \pm \textbf{0.036}$	3.803
Liquid	-1.566 ± 0.004	-0.104 ± 0.027	0.038 ± 0.030	-1.632

Table 5. Mean volume fluxes (Sv \pm standard deviation) for the components of the Fram Strait flux(Belgica Bank, BB; East Greenland Current, EGC; Mid-strait, Mid.; West Spitsbergen Current, WSC)from the three end-member (3EM) model. Positive values indicate fluxes into the Arctic.

	Atlantic	Pacific	Met.	Ice Melt	Sum
Davis	$\textbf{-0.815} \pm \textbf{0.346}$	$\textbf{-2.219} \pm \textbf{0.346}$	-0.209 \pm 0.055	0.100 ± 0.062	-3.144
Fram	$\textbf{-1.333} \pm \textbf{0.088}$	$\textbf{-0.233} \pm \textbf{0.088}$	-0.104 \pm 0.027	$\textbf{0.038} \pm \textbf{0.030}$	-1.632
Barents	$\textbf{3.520} \pm \textbf{0.184}$	0.151 ± 0.184	$\textbf{0.013} \pm \textbf{0.031}$	$\textbf{-0.048} \pm \textbf{0.035}$	3.636
Bering	0.126 ± 0.076	0.806 ± 0.076	0.099 ± 0.023	-0.029 \pm 0.026	1.001
Liquid	1.497 ± 0.268	$\textbf{-1.495} \pm \textbf{0.268}$	$\textbf{-0.200} \pm \textbf{0.044}$	0.060 ± 0.050	-0.139
Solid				$\textbf{-0.040} \pm \textbf{0.014}$	-0.04

Table 6. Mean volume fluxes (Sv \pm standard deviation) for the four end-member (4EM) model. Positive values indicate fluxes into the Arctic. Values of solid freshwater flux from Tsubouchi et al. (2012).

	Atlantic	Pacific	Met.	Ice Melt	Sum	
BB	$\textbf{-0.182} \pm 0.035$	-0.167 \pm 0.035	$\textbf{-0.022}\pm0.006$	-0.002 \pm 0.006	-0.373	
EGC	$\textbf{-4.948} \pm \textbf{0.376}$	-0.416 \pm 0.377	$\textbf{-0.083} \pm \textbf{0.050}$	$\textbf{0.088} \pm \textbf{0.056}$	-5.359	
Mid.	0.226 ± 0.058	0.077 ± 0.058	$\textbf{-0.000} \pm \textbf{0.003}$	$\textbf{-0.005} \pm \textbf{0.003}$	0.298	
WSC	$\textbf{3.571} \pm \textbf{0.274}$	$\textbf{0.274} \pm \textbf{0.275}$	0.001 ± 0.032	$\textbf{-0.044} \pm \textbf{0.036}$	3.803	
Liquid	-1.333 ± 0.088	-0.233 ± 0.088	-0.104 ± 0.027	0.038 ± 0.030	-1.632	_

Table 7. Mean volume fluxes (Sv \pm standard deviation) for the components of the Fram Strait flux (Belgica Bank, BB; East Greenland Current, EGC; Mid-strait, Mid.; West Spitsbergen Current, WSC) from the four end-member (4EM) model. Positive values indicate fluxes into the Arctic.

	Atlantic	Pacific	Met.	Ice Melt	Sum
Davis	-0.934 \pm 0.343	-2.231 ± 0.367	$\textbf{-0.060} \pm \textbf{0.057}$	0.080 ± 0.084	-3.144
Fram	$\textbf{-1.333} \pm \textbf{0.079}$	$\textbf{-0.234} \pm \textbf{0.086}$	-0.091 \pm 0.025	0.026 ± 0.030	-1.632
Barents	$\textbf{3.493} \pm \textbf{0.168}$	0.151 ± 0.185	0.011 ± 0.037	$\textbf{-0.019} \pm \textbf{0.050}$	3.636
Bering	$\textbf{0.158} \pm \textbf{0.089}$	$\textbf{0.825} \pm \textbf{0.099}$	0.041 ± 0.030	$\textbf{-0.023} \pm \textbf{0.034}$	1.001
Liquid	1.384 ± 0.255	$\textbf{-1.488} \pm \textbf{0.263}$	$\textbf{-0.098} \pm \textbf{0.046}$	0.063 ± 0.064	-0.139
Solid				$\textbf{-0.040} \pm \textbf{0.014}$	-0.04

Table 8. Mean volume fluxes (Sv \pm standard deviation) for the four end-member (4EM+) model. Positive values indicate fluxes into the Arctic. Values of solid freshwater flux from Tsubouchi et al. (2012).

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	Atlantic	Pacific	Met.	Ice Melt	Sum
BB	-0.191 \pm 0.034	-0.167 \pm 0.035	-0.011 \pm 0.005	-0.004 \pm 0.007	-0.373
EGC	-4.929 \pm 0.345	-0.416 \pm 0.376	-0.060 \pm 0.057	0.046 ± 0.073	-5.359
Mid.	0.231 ± 0.053	0.076 ± 0.056	$\textbf{-0.007} \pm \textbf{0.004}$	-0.003 \pm 0.005	0.298
WSC	$\textbf{3.556} \pm \textbf{0.251}$	0.274 ± 0.273	$\textbf{-0.013} \pm \textbf{0.040}$	$\textbf{-0.014} \pm \textbf{0.051}$	3.803
Liquid	-1.333 ± 0.079	-0.234 ± 0.086	-0.091 ± 0.025	0.026 ± 0.030	-1.632

Table 9. Mean volume fluxes (Sv \pm standard deviation) for the components of the Fram Strait flux (Belgica Bank, BB; East Greenland Current, EGC; Mid-strait, Mid.; West Spitsbergen Current, WSC) from the four end member (4EM+) model. Positive values indicate fluxes into the Arctic.

	Oceanic	Met.	Ice Melt	Sum
Davis	-3.003 ± 0.007	-0.219 ± 0.049	$\underline{0.078 \pm 0.055}$	-3.144
Fram	-1.550 ± 0.003	$\textbf{-0.109} \pm \textbf{0.024}$	$\underline{0.026 \pm 0.027}$	-1.632
Barents	3.633 ± 0.001	0.025 ± 0.007	$\textbf{-0.022} \pm \textbf{0.007}$	3.636
Bering	$\underline{0.921 \pm 0.003}$	$\underline{0.102\pm0.022}$	-0.023 ± 0.025	1.001
Liquid	0.002 ± 0.006	-0.200 ± 0.044	$\underline{0.060\pm0.050}$	-0.139
Solid			$\textbf{-0.040} \pm \textbf{0.014}$	-0.04

Table 10. Mean volume fluxes (Sv \pm standard deviation) for a three end-member model with seawater salinity and $\delta^{18}O$ fixed at 35.0 and 0.35 ‰, respectively. Positive values indicate fluxes into the Arctic. Values of solid freshwater flux from Tsubouchi et al. (2012).

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	Oceanic	Met.	Ice Melt	Sum
BB	-0.346 ± 0.001	-0.023 ± 0.005	-0.004 ± 0.006	-0.373
EGC	$\textbf{-5.309} \pm \textbf{0.003}$	-0.100 ± 0.023	0.050 ± 0.026	-5.359
Mid.	0.300 ± 0.000	0.001 ± 0.000	$\textbf{-0.003} \pm \textbf{0.001}$	0.298
WSC	3.805 ± 0.001	0.014 ± 0.004	-0.016 ± 0.004	3.803
Liquid	-1.550 ± 0.003	-0.109 ± 0.024	0.026 ± 0.027	-1.632

Table 11. Mean volume fluxes (Sv \pm standard deviation) for the components of the Fram Strait flux (Belgica Bank, BB; East Greenland Current, EGC; Mid-strait, Mid.; West Spitsbergen Current, WSC) for a three end-member model with seawater salinity and $\delta^{18}O$ fixed at 35.0 and 0.35 ‰, respectively. Positive values indicate fluxes into the Arctic.

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Figure 1. Map of the Arctic Ocean, showing the four main gateways. The position of the $\delta^{18}O$ and nutrient sample locations is indicated by green diamonds, and the Tsubouchi et al. (2012) CTD station positions by red crosses.



Figure 2. Sections of $\delta^{18}O$ (panel a), salinity (panel b)and P_{*} , P^* (panel c) , and volume flux from Tsubouchi et al. (2012) (panel d) after optimal interpolation onto the Tsubouchi et al. (2012) CTD station positions, clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal potential density (σ) surfaces separating the main Arctic water masses ; grouped as described in follows, surface water ($\sigma_0 < 26.0$), subsurface water ($26.0 < \sigma_0 < 27.1$), upper Atlantic water ($27.1 < \sigma_0 < 27.5$), Atlantic water ($\sigma_0 = 27.5$ to $\sigma_{0.5} = 30.28$), intermediate water ($\sigma_{0.5} = 30.28$ to $\sigma_1 = 32.75$), and deep water ($\sigma_1 > 32.75$); definitions from Tsubouchi et al. (2012). Note the broken scaling of the y-axis.



Figure 3. Panel a: Salinity - $\delta^{18}O$ relationship for all samples used in this manuscript; mean literature end-points (\pm standard deviation) are marked. The Red crosses indicate the mean values of literature end-points and black dashed lines in the inset indicate a linear best fit to the datamixing lines between them. Panel b: Nutrient data for all samples used in this manuscript compared to the published P:N:P relationships of Jones et al. (2008), Dodd et al. (2012), Sutherland et al. (2009). Dashes thick black lines are for Jones et al. (2008), and thin black lines for Sutherland et al. (2009) and Dodd et al. (2012). The dashed red line indicates a best fit to the Bering Strait nutrient data presented here. Symbols denoting the data from each section are common to both panels. Note Dodd et al. (2012) uses the same Pacific relationship as Jones et al. (2008).

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Figure 4. Parameter space for the Monte-Carlo simulations. Solid red line indicates the mean of the published values for the parameter; dashed red lines indicate maximum and minimum of published values.



Figure 5. Sections of ice-modified fraction (panel a), meteoric fraction (panel b), and seawater fraction (panel c), for the 3EM model, clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal surfaces separating the main Arctic water masses as described in Tsubouchi et al. (2012). End-members used were the mean of the literature values (see textTables 2 and 3). Note different color scales for each panel.



Figure 6. Sections of ice-modified water flux (panel a), meteoric water flux (panel b), and seawater flux (panel c), for the 3EM model (mSv), clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal surfaces separating the main Arctic water masses as described in Tsubouchi et al. (2012). End-members used were the mean of the literature values (see textTables 2 and 3). Note different color scales for each panel. Positive values indicate flux into the Arctic.



Figure 7. Sections of ice-modified fraction (panel a), meteoric fraction (panel b), Pacific fraction (panel c), and Atlantic fraction (panel d), for the 4EM model, clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal surfaces separating the main Arctic water masses as described in Tsubouchi et al. (2012). End-members used were the mean of the literature values (see textTables 2 and 3). Note different color scales for each panel.



Figure 8. Sections of ice-modified water flux (panel a), meteoric water flux (panel b), Pacific water flux (panel c), and Atlantic water flux (panel d), for the 4EM model (mSv), clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal surfaces separating the main Arctic water masses as described in Tsubouchi et al. (2012). End-members used were the mean of the literature values (see textTables 2 and 3). Note different color scales for each panel. Positive values indicate flux into the Arctic.



Figure 9. Sections of ice-modified fraction (panel a), meteoric fraction (panel b), Pacific fraction (panel c), and Atlantic fraction (panel d), for the 4EM+ model, clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal surfaces separating the main Arctic water masses as described in Tsubouchi et al. (2012). End-members used were the mean of the literature values (see textTables 2 and 3). Note different color scales for each panel.



Figure 10. Sections of ice-modified water flux (panel a), meteoric water flux (panel b), Pacific water flux (panel c), and Atlantic water flux (panel d), for the 4EM+ model (mSv), clockwise around the four gateways from Davis to Bering Straits. Solid black lines indicate the isopycnal surfaces separating the main Arctic water masses as described in Tsubouchi et al. (2012). End-members used were the mean of the literature values (see textTables 2 and 3). Note different color scales for each panel. Positive values indicate flux into the Arctic



Figure 11. Meteoric and ice water volume fluxes. Top row (panels a and d) shows histograms of the total attributed volume fluxes (Sv) for all model schemasschemes. Middle row (panels b and e) shows mean volume fluxes (Sv \pm standard deviation) for each gateway. Bottom row (panels c and f) shows volume fluxes (Sv \pm standard deviation) for the components of the Fram Strait (Belgica Bank, BB; East Greenland Current, EGC; Mid-strait, Mid.; West Spitsbergen Current, WSC). The 3EM model is in blue, the 4EM model in green, and the 4EM+ model in red. Positive values indicate fluxes into the Arctic.

Net per-station mean depth-integrated volume fluxes of freshwater from Tsubouchi et al. (2012) meteoric, and ice-modified water components for the three model schemas (panel a 3EM; anel b 4EM panel c 4EM+), clockwise around the four gateways from Davis to Bering traits. Thick black line shows freshwater flux (), red line meteoric volume flux (± standard deviation), and blue line ice-modified water volume flux (± standard deviation). The dashed reen line is the difference between the freshwater flux and the sum of the meteoric and , meteoric, and ice-modified water components for the three model schemas (panel a 3EM; panel b 4EM panel c 4EM+), clockwise around the four gateways from Davis to Bering Straits. Thick black line shows freshwater flux (), red line meteoric volume flux (\pm standard deviation), and blue line ice-modified water volume flux (\pm standard deviation). The dashed green line is the difference between the freshwater flux and the sum of the meteoric and ice-modified water fluxes, which is the assumed oceanic freshwater contribution. Positive values indicate fluxes into the Arctic. Net per-station mean depth-integrated volume fluxes Discussion Paper of freshwater from Tsubouchi et al. (2012), meteoric, and ice-modified water components

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- for the three model schemas for the Fram Strait (panel a 3EM; panel b 4EM panel c 10 4EM+). Thick black line shows freshwater flux (), red line meteoric volume flux (± standard deviation), and blue line ice-modified water volume flux (± standard deviation). The dashed areen line is the difference between the freshwater flux and the sum of the meteoric and ice-modified water fluxes, which is the assumed oceanic freshwater contribution. Positive values indicate fluxes into the Arctic. Positions of the components of the Fram Strait flux 15
- (Belgica Bank, BB; East Greenland Current, EGC; Mid-strait, Mid.; West Spitsbergen Current, WSC) are indicated.
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