

Interactive comment on “Arctic freshwater fluxes: sources, tracer budgets and inconsistencies” by Alexander Forryan et al.

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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

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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 $\sim 10 \mu\text{mol-N} / \text{kg}$.

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 $14\text{--}66 \text{ kmol-N} / \text{s}$. 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 $10 \mu\text{mol} / \text{kg}$. Take (for scale) 1 Sv of Atlantic water; that is $106 \text{ m}^3 / \text{s}$, or $109 \text{ kg} / \text{s}$. Then the required nitrate removal rate is $10 \mu\text{mol} / \text{kg} \times 109 \text{ kg} / \text{s} = 10 \text{ kmol} / \text{s}$, 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 denitrifica-

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tion 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 end-member 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

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"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 relative 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

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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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