Seasonal variability of the net water-mass transport among the four major basins

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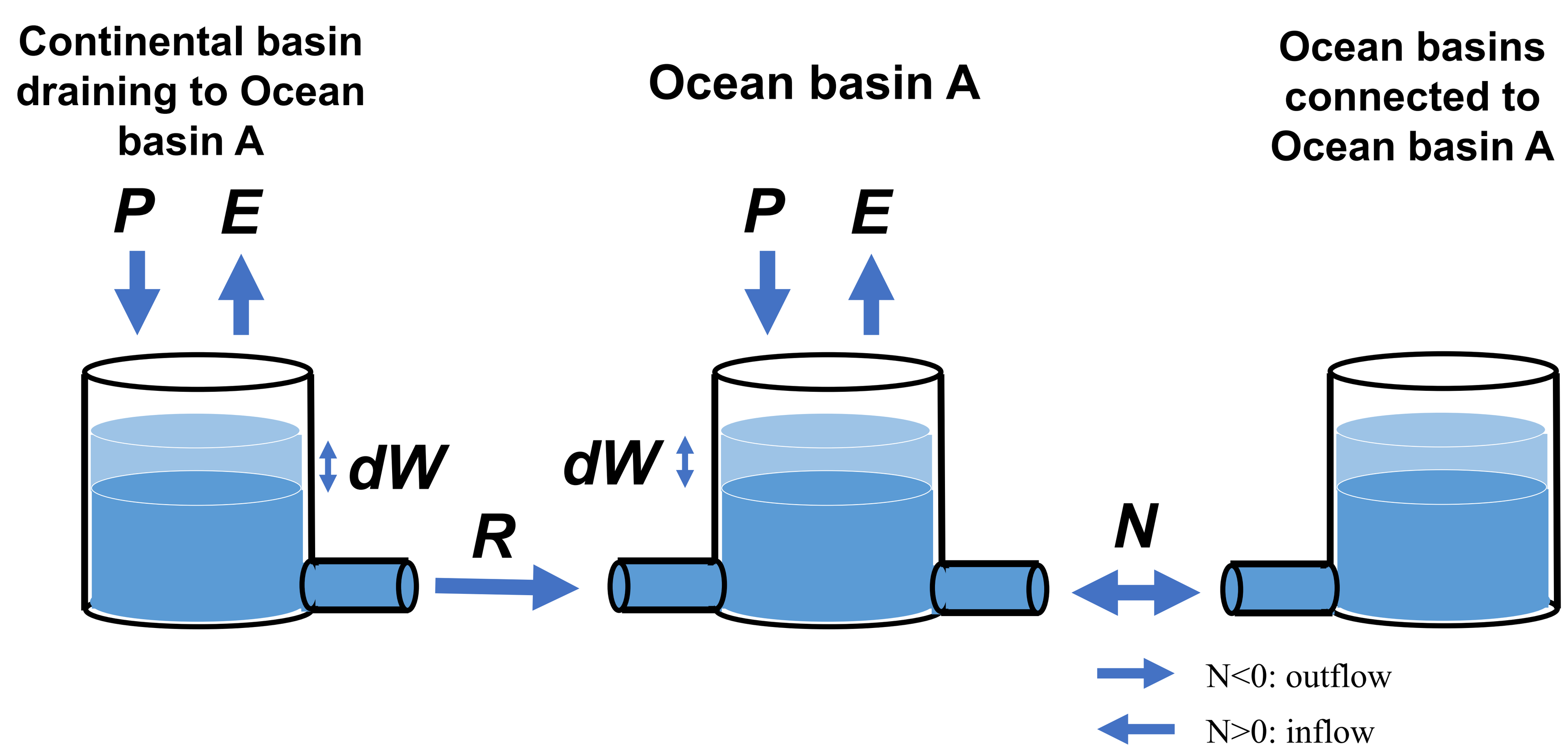
Abstract. Global water cycle involves water-mass transport on land, atmosphere, ocean, and among them. Quantification of such transport, and especially its time evolution, is essential to identify footprints of the climate change and helps to constrain and improve climatic models. In the ocean, net water-mass transport among the ocean basins is a key, but poorly estimated parameter presently. We propose a new methodology that incorporates the time-variable gravity observations from the GRACE satellite (2003-2016) to estimate the change of water content, and that overcomes some fundamental limitations of existing approaches. We show that the Pacific and Arctic Oceans receive an average of 1916 (95% confidence interval [1812, 2021]) Gt/month (~0.72 ± 0.02 Sv) of excess freshwater from the atmosphere and the continents that gets discharged into the Atlantic and Indian Oceans, where net evaporation minus precipitation returns the water to complete the cycle. This salty water-mass transport from the Pacific and Arctic Oceans to the Atlantic and Indian Oceans show a clear seasonal variability, with a maximum transport of 3000 Gt/month during boreal summer, a minimum of 1000 Gt/month or less on February, Mars, and November.

1. Methodology and datasets

- *W*: Water budget → **GRACE RL06 mascon**, Center of Space Research (CSR), University of Texas
- *dW*: Change of water budget → Discrete derivative as difference of consecutive months
- *P*: Precipitation → **ERA5 reanalysis**
- *E*: Evaporation → **ERA5 reanalysis**
- *R*: River runoff → Residual from Equation 1
- *N*: Net water exchange between neighbouring ocean regions through the ocean boundaries → Residual from Equation 2



Equation 1 (**for land**):

$$dW = P - E - R$$

Equation 2 (**for ocean**):

$$dW = P - E + R + N$$

2. Results

Equations 1 and 2 are applied to estimate N in 4 ocean regions for the **2003-2016** period.

Ocean regions: Pacific, Atlantic, Indian, and Arctic oceans.

Associated drainage basins: Estimated from the global continental runoff pathways scheme of Oki and Sud (1998). There are no direct water exchanges in the form of R among land drainages (see Figure 1).

Results are given in **Gt/month** (1 Sv ≈ 2600 Gt/month; 1 Gt = 10^{12} kg, the weight of 1 km³ of freshwater)

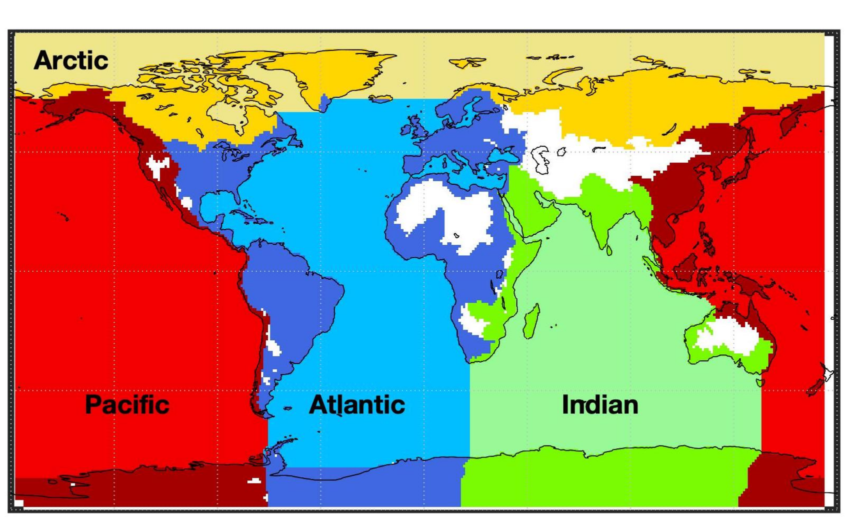


Figure 1. Pacific, Atlantic, Indian, and Arctic Ocean basins and their associated continental drainage basins according to the global continental runoff pathways scheme of Oki and Sud (1998). Within each basin, darker colour represents the continental basin, lighter colour the ocean basin. White regions represent endorheic basins.

2.1 Oceanic net water transport in the Pacific and AIA oceans

Averaged over the studied 14 years, the Pacific Ocean loses water through the atmospheric *P−E* at the average rate of 142 Gt/month (CI95=[48, 243]), which is greatly over-compensated by inflow *R* from land of 1403 Gt/month (CI95=[1370, 1436]). From this surplus, a minor (if any) amount of 67 Gt/month (CI95=[25, 108]) stays (and accumulates) in the Pacific, while 1194 Gt/month (CI95=[1096,1291]) is transported horizontally to the "non-Pacific" Atlantic/Indian/Artic (AIA) oceans, which will be called the "Pacific outflow" hereafter. The time variability of the Pacific outflow can be seen in Figure 2.

In the AIA Oceans, the situation is found to be markedly distinct, given the fact that the AIA oceans together have surface area comparable to the Pacific (177x10⁶ m2). The AIA oceans collectively lose 3484 Gt/month (CI95=[3406, 3560]) through the atmospheric *P−E*, that is ~25 times more than does the Pacific. This water deficit is only ~68% compensated by land *R* inflow of 2378 Gt/month (CI95=[2337, 2419]). With the nominal minor amount of water accumulation at 87 Gt/month (CI95=[44, 130]), the AIA oceans thus presents an average inflow of 1194 Gt/month (CI95=[1102, 1284]) from the Pacific, which will be called the "AIA inflow". The time variability of the AIA inflow can be seen in Figure 2.

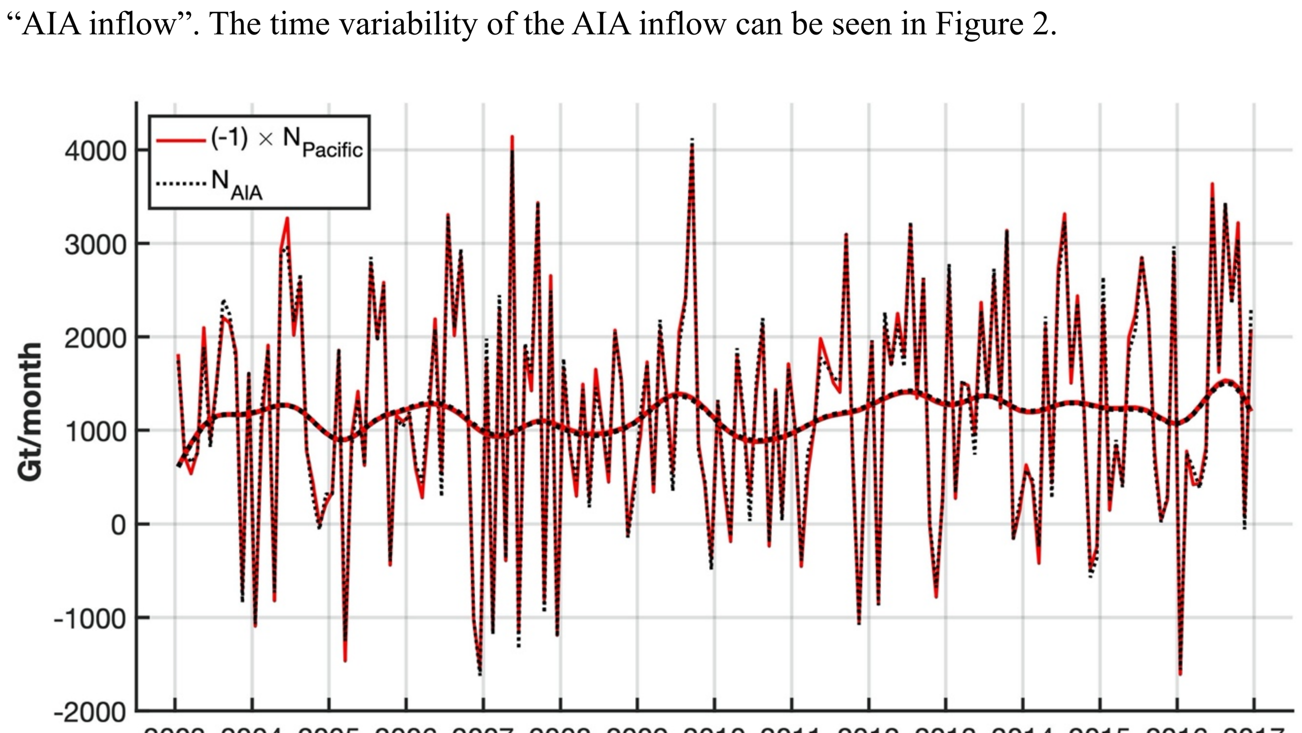


Figure 2. Monthly time series of WT flux from the Pacific to the AIA Oceans. Red curve is (the opposite of) the Pacific outflow, and black curve is the AIA inflow. Thick lines are the low pass filtered signal by a Hann function of 24 months.

2.2 Oceanic net water transport in the Atlantic, Indian, and Arctic oceans

Corresponding analyses have been performed for the Atlantic, Indian, and Arctic Oceans separately. A diagram of the mean water-mass fluxes is shown in Figure 3. On average, the Atlantic Ocean receives 926 Gt/month (CI95=[876, 980]; or 0.36 Sv) of salty water, and loses to the atmosphere 879 Gt/month (CI95=[828, 930]) via *P−E+R*. The latter is equivalent to a freshwater deficit of 0.34 Sv, which increases the near-surface salt concentration and enables water to sink in North Atlantic producing deep water. These values are close to the 0.13-0.32 Sv estimated from ocean models, as needed to keep salinity balance in the Atlantic Ocean (Zaucker et al., 1994). Similarly, the Indian Ocean loses 957 Gt/month (CI95=[894, 1022]) of freshwater that is restored by 991 Gt/month (CI95=[907, 1073]) of salty water. The freshwater lost via *P−E+R* by the Atlantic and Indian Oceans goes to the Pacific (1261 Gt/month, CI95=[1171, 1347]) and Arctic (730 Gt/month, CI95=[712, 747]) Oceans, which return 1194 (CI95=[1096, 1291]) and 723 (CI95=[708, 739]) Gt/month of salty water through the ocean, respectively. Then, the Pacific presents a surplus of freshwater that reduces near-surface salt concentration, which prevents the formation of deep water. Together, the Pacific and Arctic Oceans supply 1917 Gt/month (CI95=[1812, 2021]) of water to the Atlantic and Indian Oceans, where it is reincorporated into the water cycle via net *E−P*.

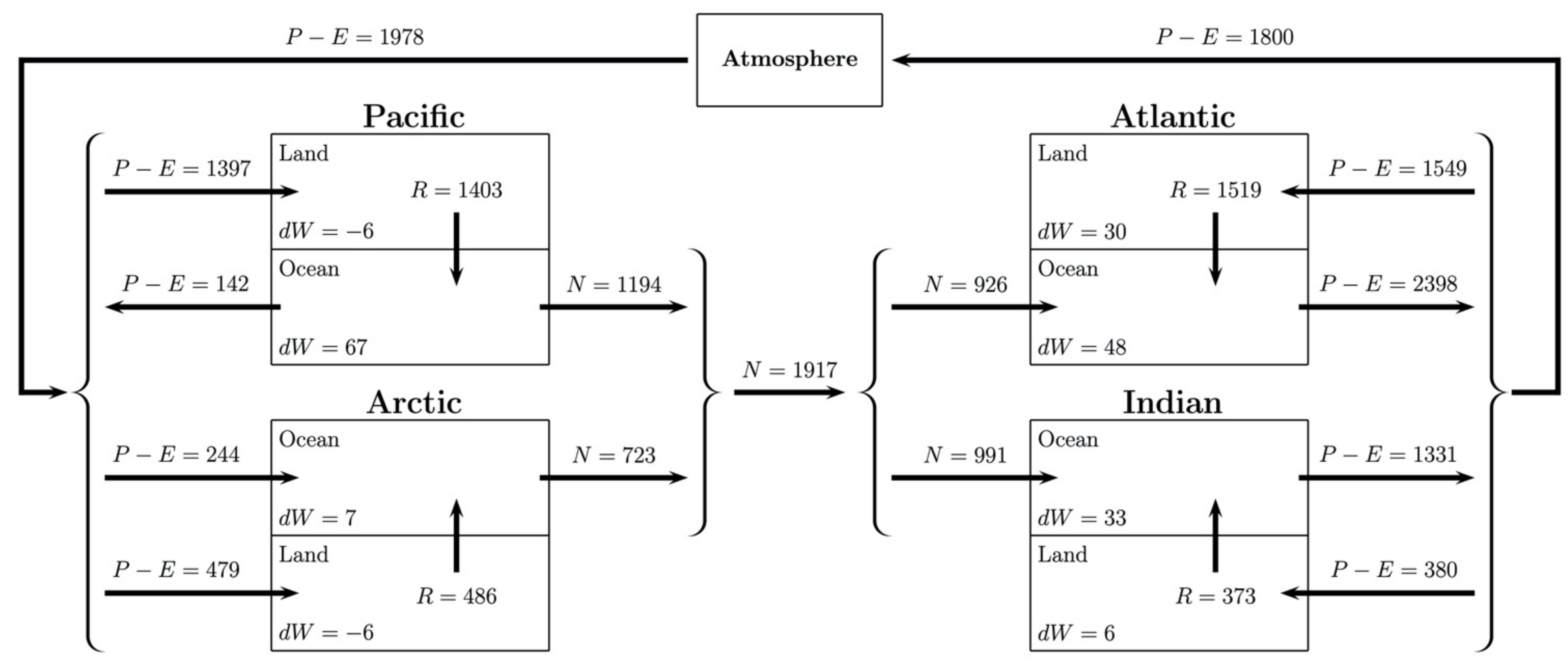


Figure 3. Diagram of the mean values of the water-mass transport of the studied regions. Units are Gt/month .

2.3 Annual climatology

The Pacific and Arctic Oceans show an overall outflow throughout the year, unlike the Atlantic and Indian Oceans, which show an inflow for every month. The Pacific outflow shows a prominent seasonal undulation peaked around August 3 and a peak-to-peak WT variation of ~2000 Gt/month from boreal summer to November, when a near-zero minimum occurs. The Arctic Ocean show half of the Pacific variability and a less pronounced seasonal undulation. A minimum outflow of ~320 Gt/month is reached in March and April, and a maximum ~1300 Gt/month in July. Together, the Pacific and Arctic Oceans send ~3000 Gt/month of seawater to the Atlantic and Indian Oceans during boreal summer, and a minimum amount five times lower, around 600 Gt/month, in November. The annual maximum is reached on August 8th. The Atlantic/Arctic inflow mirrors this behaviour. Separately, the Atlantic and Indian inflows show a similar peak-to-peak variation of ~2000 Gt/month, reaching the maxima in August and May, respectively. The Indian maximum seems to be related to a local maximum of the Pacific outflow. The annual maxima of net WT of the four basins are reached between August 3rd and September 9th, although the annual signals of the Pacific and Indian Oceans almost triple those from Arctic and Atlantic Oceans (Figure 4).

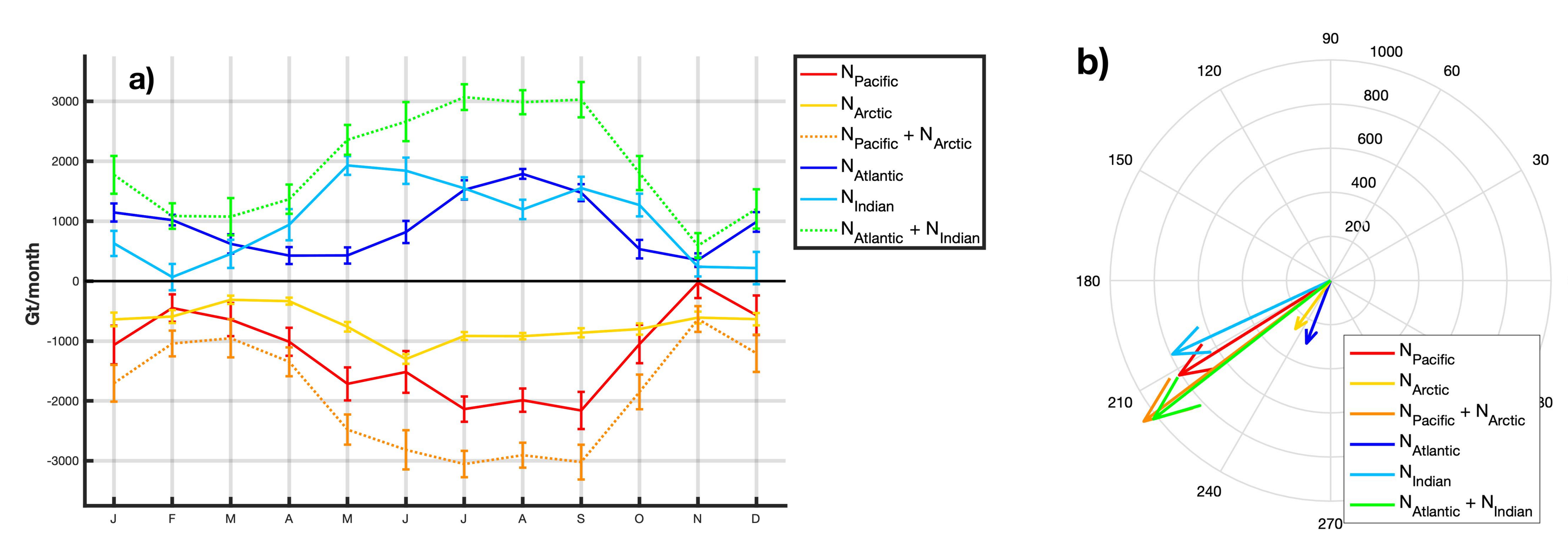


Figure 4. (a) Annual climatology time series (error bar is one standard deviation), and (b) phasor diagram (amplitude in unit of Gt/month, a degree of the phase angle approximately corresponds to a day of the year starting in January) of the inflow/outflow WT of the ocean basins.

3. Discussion and conclusions

In this work we present a new methodology that combines GRACE data with the general hydrologic budget equation to estimate the horizontal water-mass convergence/divergence for any oceanic region. We use the proposed methodology to estimate the net WT and exchanges among the Pacific, Atlantic, Indian, and Arctic Oceans, for the period of 2003 – 2016. Our main finding is that **the Pacific and Arctic Oceans, while replenished with precipitation and land runoff, are nearly continuously losing water to the Atlantic and Indian Oceans**. In particular, the WT climatology is such that the Pacific Ocean loses water at a rate from near zero to up to the peak of 2000 Gt/month during the boreal summer, which coincides with the maximum of the global atmosphere water content. On top of the climatology, the interannual Pacific water loss varies significantly between ~950 to ~1450 Gt/month annual means during the studied period.

The results presented here are consistent with the well-known salinity asymmetry between the Pacific and Atlantic Oceans. However, they are in contrast to previous GRACE-based studies where a simple seesaw WT between the Pacific and the Atlantic/Indian oceans was reported (Chambers and Willis, 2009; Wouters et al., 2014). In those studies, the *P−E+R* term in Equation 2 in both Pacific and Atlantic/Indian Oceans was approximated by that from the global ocean mean. However, the mean freshwater flux in the Pacific (1261 Gt/month) quite mis-matches that in the Atlantic/Indian Oceans (−1837 Gt/month), meaning that the approximation was quite poor and hence the *N* term was not properly estimated in these studies.

Acknowledgements and References

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