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# D2.6.3 Freshwater flux time series grids for the Arctic Ocean

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## *SUMMARY*

An assessment of the fresh water budget is provided, built on observations on sea ice and freshwater observations provided in Monarch-A.

The error of the annual mean fresh water budget is of similar order as the interannual variability of runoff and fresh water transports, i.e. 50 mSv. The estimates of mean sea level change and interannual variability of steric sea level variations are of a much smaller magnitude, i.e. 4.6 and 9.0 mSv, respectively. The mass changes as observed by GRACE are consistent with the seasonal runoff pulses, i.e. a runoff increase (decrease) leads to a lowering (rise) of the sea level.

## *MONARCH-A CONSORTIUM*

| **Participant no.** | **Participant organisation name** | **Short name** | **Country** |
|---|---|---|---|
| 1 (Coordinator) | Nansen Environmental and Remote Sensing Center | NERSC | NO |
| 2 | The University of Sheffield | USFD | UK |
| 3 | Universität Hamburg | UHAM | NO |
| 4 | Centre National de la Recherche Scientifique | CNRS | FR |
| 5 | Scientific foundation Nansen International Environmental and Remote Sensing Center | NIERSC | RU |
| 6 | Universitetet i Bergen | UiB | NO |
| 7 | Danmarks Tekniske Universitet | DTU | DK |
| 8 | Institut Francais de Recherche pour l'Exploitation de la Mer | IFREMER | FR |

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# 1 Introduction

Sea ice thickness is a major limitation in the measurement of mean sea surface heights, and thus the derivation of realistic mean dynamic topography, and thus providing independent remote sensing constraints on Arctic Ocean circulation models. The changes in sea ice motion and transport, especially in and out of the Arctic straits, can be assessed using satellite data, together with gridded fields of ice thickness and mean sea level anomalies. The total volume of sea ice, its seasonal melting and freezing, the regional variability and the fluxes through the straits can be estimated from a combination of satellite observations, model simulations and in-situ data (upward looking sonar)

The following assessment builds on observations on sea ice and freshwater observations provided in WP 2.1, independent in-situ data, and on the estimates provided in Workpackage (WP) 2. 4. The fresh water fluxes are compared to the Arctic Ocean part of the Greenland ice sheet melt, the river discharges using the input of WP 2.4 and compared to the sea level time series of WP 2.2. The direct measurements of the freshwater pulse by satellite gravity (GRACE) are qualitatively compared to the flux estimates.

# 2 Data

## 2.1 Sea ice flux

The Fram Strait accounts for the major part of sea ice export from the Arctic (Serreze et al., 2006). Hence, improved estimates of the sea ice volume flux and its variability through the Fram Strait is an important constraint in closing the sea ice and fresh water budgets of the region. NERSC(2012) combined ICEsat ice thickness with microwave ice concentration and ice area flux one obtains sea ice volume flux (Figure 1), computed along 79° N. As expected the flux is maximum in the center, and tapering off to zero at the sides due to fast ice in the west or no ice to the east. The flux values are found to be comparable to Spreen et al., 2009, although somewhat on the high side and with considerable interannual variability. High values near the edge could indicate compaction by surface waves or a contamination of the signal of the same waves. Hence, the results for the outer 5-6 data points should be interpreted with caution.

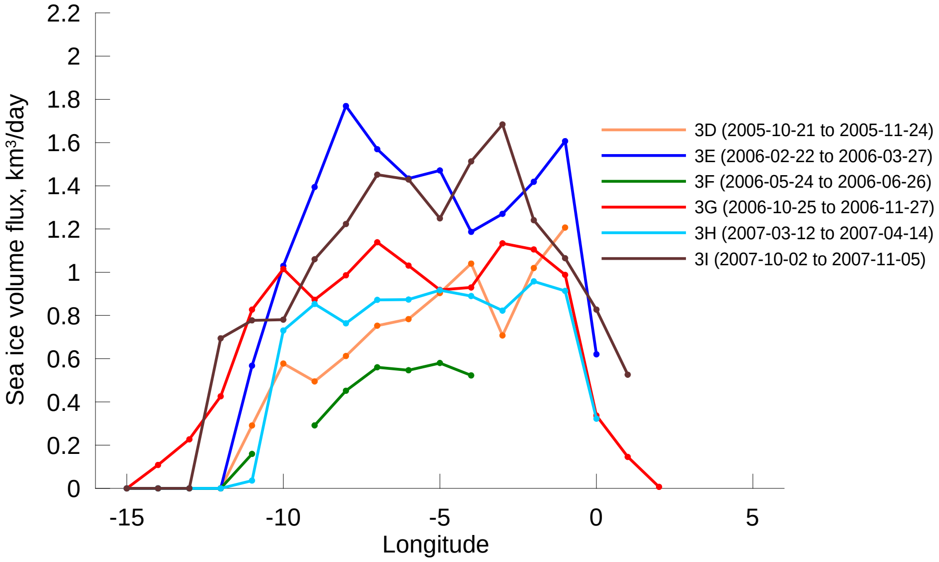

*Figure 1. Sea ice volume flux [km$^3$/day] southward across 79°N for six different ICESat campaigns. The quantity is derived from thickness data from ICESat, ice concentration from passive microwave observations and area flux data from Kloster et al, (2009)*

Taking the curve for 2006-10-25 (red) as representative, one obtains a transport of about 140 mSv when integrating across the strait (1 mSv = 1000m$^3$s$^{-1}$). This is again somewhat higher than Spreen et al. (2009), but within the range of empirical studies compiled by Koenigk et al. (2008).

## 2.2 Liquid fresh water

UHAM (2013) applied data assimilation in an ocean model to derive the mean and variability of the fresh water fluxes through the major straits of the boundary of the Arctic Ocean. The flow through the Bering Strait is prescribed, and thus excluded from the analysis, i.e. considering the Fram Strait, were warm salty Atlantic Water coming in to the Arctic along eastern flank of the strait and cold and fresher Arctic waters flow southward with the East Greenland Current; the Davis Strait (integrating the entire outflow through Canadian Archipelago; the Barents Sea Opening (BSO; entrance for warm Atlantic waters to the Arctic; the St. Anna Trough through which Atlantic Waters modified in the Barents Sea transported further to the Arctic Ocean. The Bering Strait provides a positive fresh water contribution to the Arctic and has been observed to increase from about 2000 to 3000 km$^3$y$^{-1}$ from 2001 to 2011, with strong interannual variability (Woodgate et al., 2012)

Whereas there is a strong seasonality in fresh water (FW) transport through Fram Strait and BSO, it is very hard to see any seasonal signal in Davis Strait and St. Anna Trough. The largest differences between runs with and without assimilation that reach about 60 mSv are in the Fram Strait during the year 2006. It might be associated with decrease in ice melting to the north of the Fram Strait during this period.

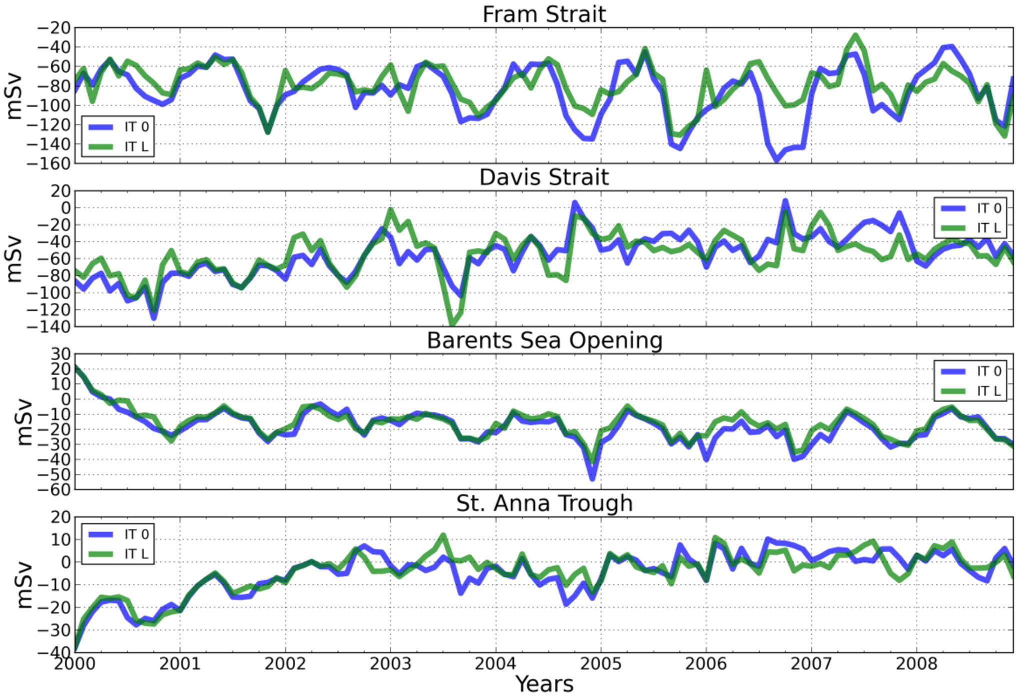
Fram Strait
Davis Strait
Barents Sea Opening
St. Anna Trough

*Figure 2 Fresh water (relative to 35psu) transport through Arctic Ocean strait, take from the model studies by UHAM (2013). Blue curve: model before data assimilation; green curve: model after data assimilation.*

The mean values of different transports are summarized in the Table 1, where also estimates for P-E, runoff and Bering Strait import are included. The runoff from melting of the Greenland ice sheet is estimated preliminarily by V. Barletta and coworkers to be 145 Gt/y, corresponding to only 4.6 mSv.

In the net there is a remaining imbalance of about 60 mSv out of the basin, which is within the error bars of the underlying estimates.

| | Fram Strait Ice | Fram Strait | Davis Strait | Barents Sea Opening | St. Anna Trough | Runoff | P-E | Bering Strait |
|---|---|---|---|---|---|---|---|---|
| Fresh water flux (mSv) | -140.00 | -79.16 | -55.38 | -15.60 | -4.27 | 100.00 | 29.00 | 100.00 |

*Table 1: Mean values of fresh water transport. Liquid fresh water values are from run with data assimilation by UHAM 2013. Fram Strait ice is from this study; runoff and P-E are from Aagaard and Carmack (1989; Bering Strait from the upper estimate of Woodgate et al., 2012*

## 2.3 P-E and runoff

Estimates of P-E (precipitation minus evaporation) and runoff are taken from Aagaard and Carmack (1989) to be 29.0 and 100.0 mSv, respectively. The various runoff estimates by USFD (2013) yield typically an interannual variability of typically 20% of the mean and up to 50% for single years. Hence, a large part of the uncertainty of the fresh water budget may be due to the runoff estimates. In the time series there is no apparent correlation with the fresh water transports or with the sea level variations (below), although a quantitative correlation analysis has not been performed.

The runoff will comprise a major component of gridded time series of fresh water fluxes.

## 2.4 Sea level change

O. Henry and co-workers (Monarch-A partners, 2013) computed the steric sea level (thermosteric plus halosteric components) based on hydrographic data since 1970, comparing them to 11 Norwegian tide gauge sites (Figure 3) The steric and coastal mean sea level (CMSL) curves correlate well between 1970 and 2006 (correlation of 0.65), while as of 2006, the steric sea level curves show a downward trend not seen in the CMSL curve. This suggests that over the time span 1970-2006 observed CMSL rise along the Norwegian coast has a steric origin. However the interannual variability in steric sea level and Norwegian CMSL are not well correlated, suggesting that the latter is influenced by other factors on such time scales, e.g., wind stress-driven ocean circulation and ocean mass changes. The magnitude of the interannual variability can be obtained from the change of about 80 mm over the 4 years from 1987-1991, i. e. 9 mSv

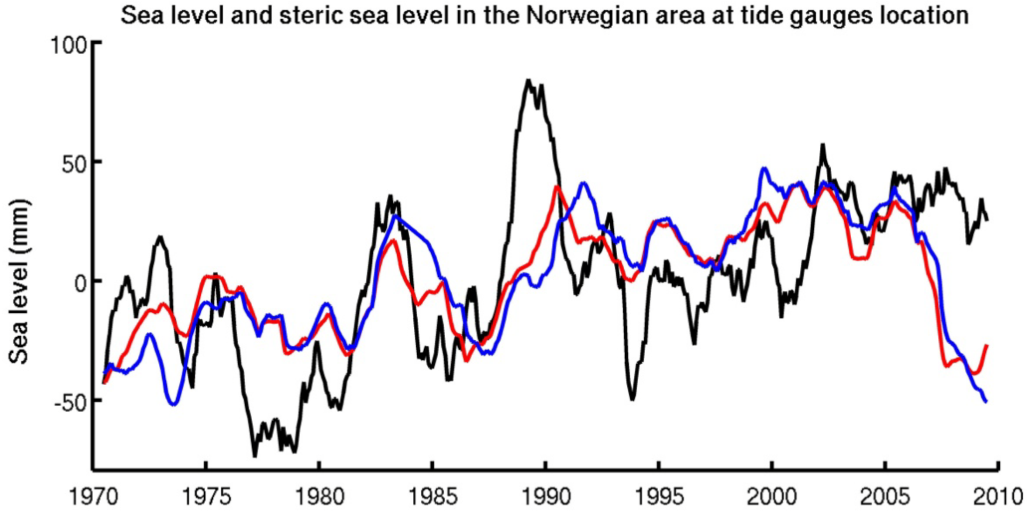

Figure 3. Coastal mean sea level from Norwegian tide gauge records (11 stations, black curve), steric sea level computed from EN3 (blue curve) and IK09 (red curve) database (interpolated at each tide gauge sites).

## 2.5 GRACE signals from freshwater flux pulses

Barletta and Forsberg (2013) used GRACE data to investigate the seasonal changes of the Arctic Ocean mass signals, with an ultimate aim to detect the flow from the Siberian rivers across the Arctic to the Beaufort Gyre**.** The results indicate a seasonal signal north of Siberia, associated with the outflow of freshwater from the Siberian rivers. This signal was consistent with Russian tide gauge sea level data as well as the order of magnitude of the outflow of the Siberian rivers. An important finding is that the inflow of freshwater, which initially implies an increase in sea level, also displace more salty, heavier waters, the net result of which is a mass loss in spring (May) of up to -300mm/y, compared to a mass gain in winter (January) up to +150mm/y. If multiplying with the area of 14,056,000 km2 for the Arctic Ocean, the corresponding volume fluxes read -134 mSv and 167 mSv, respectively. These figures are in the same order of magnitude as the transports in Table 1, although their corresponding local areas should be used and the regional mass variations affect more the internal mass redistributions of the Arctic, rather than the integrated fresh water budget.

# 3 Conclusion

In Monarch-A all the major components of the fresh water budget have been observed and analysed (i.e. runoff from land, liquid fresh water transports through the major straits and the ice transport out of Fram Strait). The error of the annual mean fresh water budget is of similar order as the interannual variability of runoff and fresh water transports, i.e. 50 mSv. The estimates of mean sea level change and interannual variability of steric sea level variations are of a much smaller magnitude, i.e. 4.6 and 9.0 mSv, respectively. A complicating factor is the propagation of fresh water signals in the Arctic Ocean. The mass changes as observed by GRACE are consistent with the seasonal runoff pulses, whereas the direct connection is not clear, as immediately the volume is affected, whereas the dominant effect picked up by GRACE is on the salinity (steric), i.e. a runoff increase leads to a lowering of the sea level.

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