The Role of Siberian River Discharge in Arctic Freshwater Balance

(Роль стока сибирских рек в формировании баланса пресной воды в Арктике)

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Model and Data uncertainties that change FW balance in numerical experiments

1. **Precipitation rate** (in summer (10%) and in winter (80-120%), Yang et al 2005)
2. **River runoff** (ungauged volume is 30%, increasing trend of 2.9 ± 0.4 $km^3 a^{-1}$ Shiklomanov 2010)
3. **Pacific waters** (since 2001 Bering Strait freshwater variability is ~ 25% of the total annual Arctic river run-off (Woodgate et al 2006))
4. **Ice model** (Radiation and Cloudiness)
5. **Evap+Rivers-Precipit. balance**
6. **Vertical and horizontal diffusion**

Coupled Ice-Ocean Model

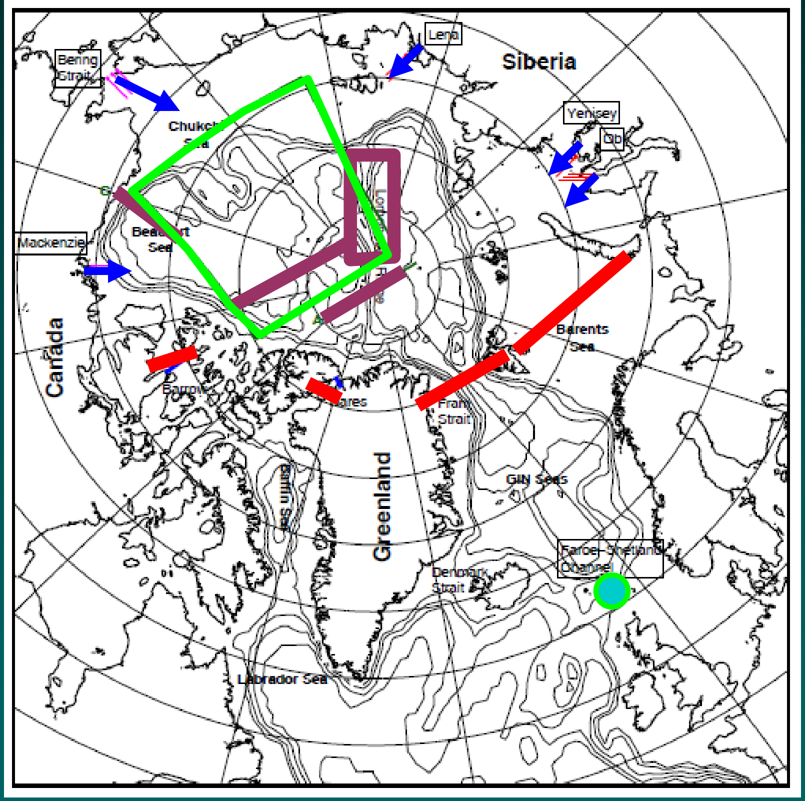
3D Ocean Circulation Model of ICMMG based on z-level vertical coordinate approach

Kuzin1982, Golubeva at al.,1992, Golubeva,[2001], Golubeva and Platov,[2007]

Ice model-CICE 3.14 (elastic-viscous-plastic)

W.D.Hibler ,1979, E.C.Hunke, J.K.Dukowicz,1997, G.A.Maykut 1971
C.M.Bitz, W.H.Lipscomb 1999,J.K.Dukowicz, J.R.Baumgardner 2000,
W.H.Lipscomb, E.C.Hunke 2004

Domain configuration



- Ob, Yenisey and Lena river discharge
- Mackenzie river discharge and Bering Strait transport
- Water export or import from/to Arctic
- River freshwater in the area if the Lomonosov Ridge
- Transpolar Drift and Alaskan sections
- Canadian basin (Beaufort Gyre) water properties
- Faroe-Shetland Channel

Floats modeling

- The float is considered as passive lagrangian particle floating down the stream

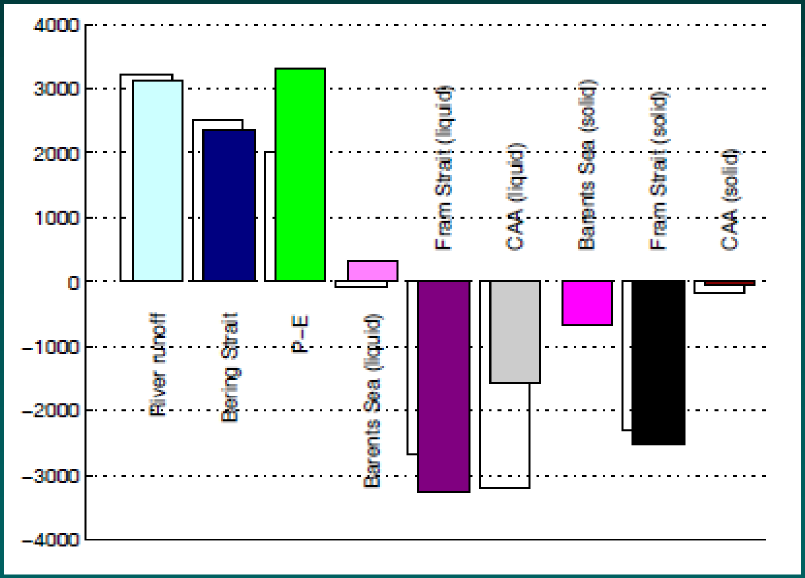
$$\vec{\mathbf{r}} = \vec{\mathbf{r}}_{\mathbf{0}} + \vec{\mathbf{v}}_{\mathbf{0}} \cdot dt$$

- We could consider diffusion as a stochastic process with normal distribution centered at advective position of the particle with r. m. s. proportional to $(A \cdot dt)^{1/2}$, where A is diffusion coefficient.

$$x_{dif} = x_{adv} + \sigma_x \Phi^{-1}(\text{"rand"} - 0.5)$$

$$\sigma_x = \alpha \sqrt{A \cdot dt}$$

Freshwater balance

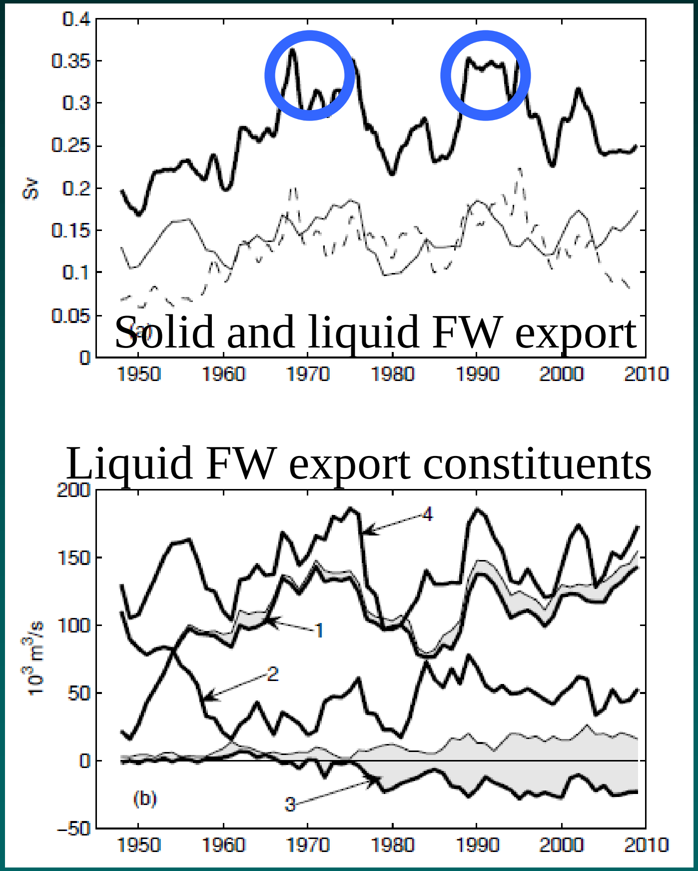


Exp. vs *Serreze et al.* [2006]

km^3/year

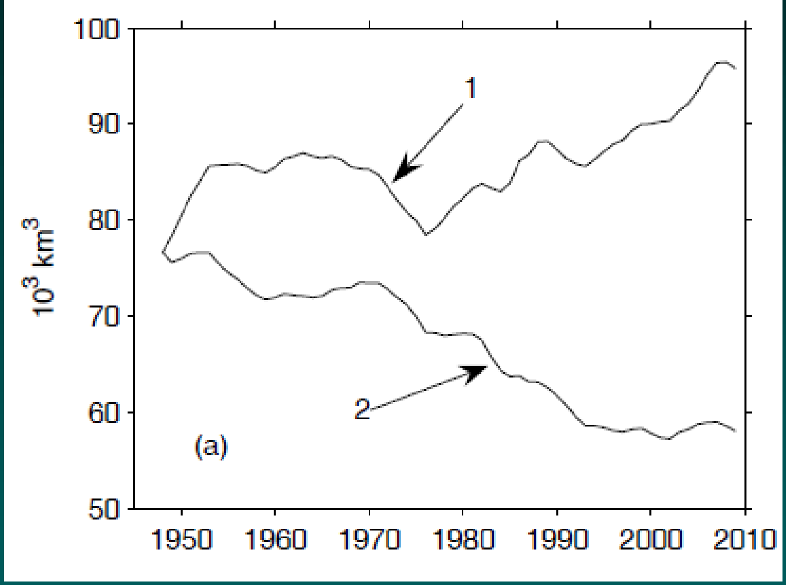
- River runoff and Bering strait import are approx. equal to data estimations
- Precipitation rate is about 1.5 higher (Xie and Arkin [1997], Yang [1999])
- Barents Sea import is opposite to observed export, but both are small
- Fram Strait export about 20% higher
- Canadian Arctic Archipelago export 2 times lower
- Sea ice export is approx. at corresponding level

Freshwater transport to the North Atlantic



- Liquid and Solid components are at the same level
- Most of FW is exported through Fram Strait (1) (approx. 100,000 m^3/s)
- Canadian straits (2) are at the second place (50,000 m^3/s)
- 10,000 m^3/s of FW is exported through the Barents Sea (3), but then 20,000 m^3/s is returned back to Arctic
- The most intensive export of freshwater was in late 60s, which starts the Great Salinity Anomaly of 1970s (GSA70)
- The same intensification is seen in early 90s, which could start the GSA2000

The Total Arctic FW Volume



Arctic (>65ºN) freshwater volume calculated relative to S_0=34.8 psu

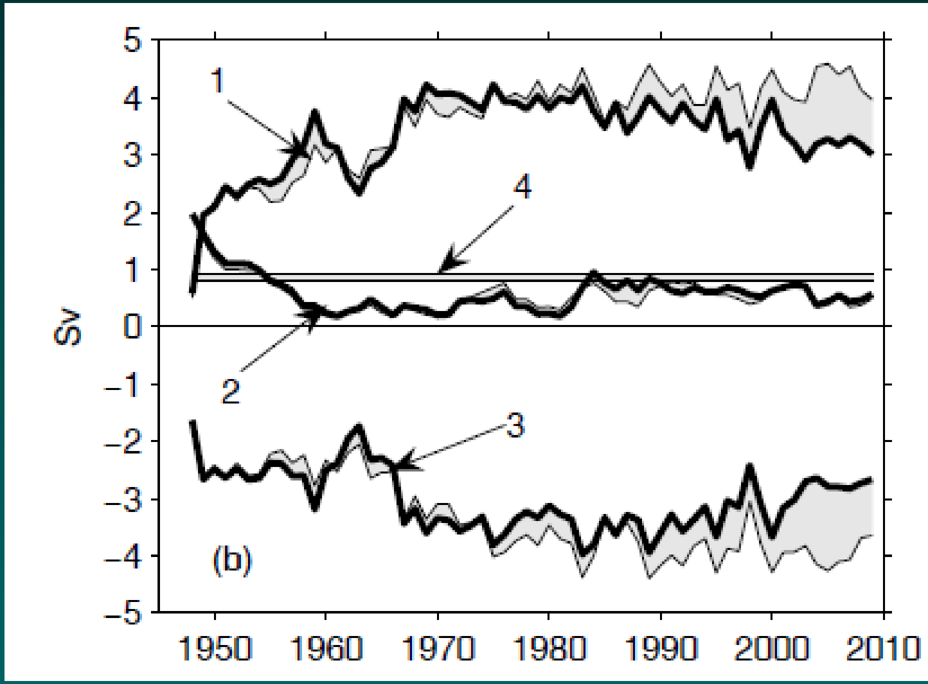
$$\text{FW Volume} = \int_{\text{Arctic}} \int_0^h \frac{S_0 - S}{S_0}\, dz\, d\Omega$$

h: $S(z<h)<S_0$

Experiments with and without Arctic river discharges

- The averaged volume of Arctic FW is about 85,000 km^3;
- When rivers are switched off it falls down to 60,000 in 60 years;
- Even when rivers are switched off and Bering Strait inflow is constant (0.8 Sv) there are still some periods of FW volume growth

The Total Export of Arctic Water through Straits

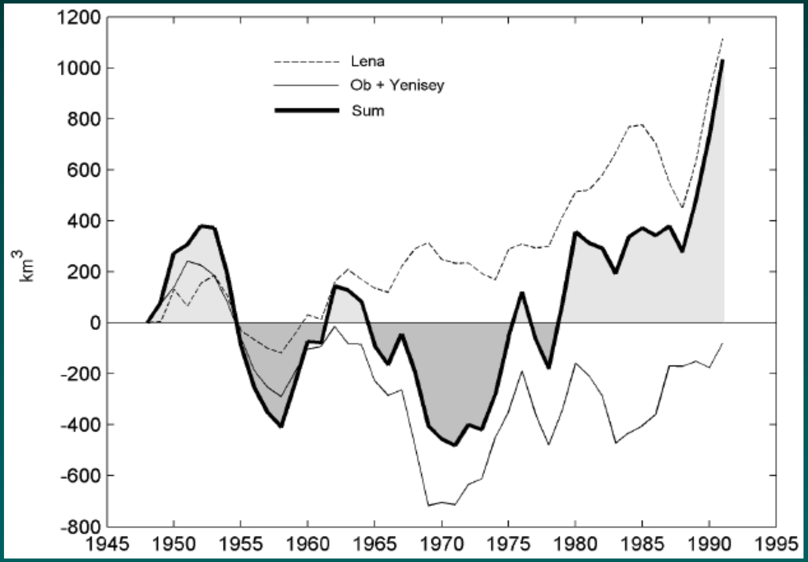


Experiments with and without Arctic river discharges

- The switching off the river discharge is small compared to the Arctic water export/import balance (4);
- The export through Fram Strait (1) is increased by 1 Sv;
- The CAA transport is not changed significantly;
- The import through the Barents Sea is increased by 1 Sv;
- The total effect is that Arctic ventilation by Atlantic water is increased by 1 Sv, which is disagreeing with the estuary approach ⇨
- At this point, Arctic cannot be considered as an Atlantic estuary

Accumulated Siberian river discharge

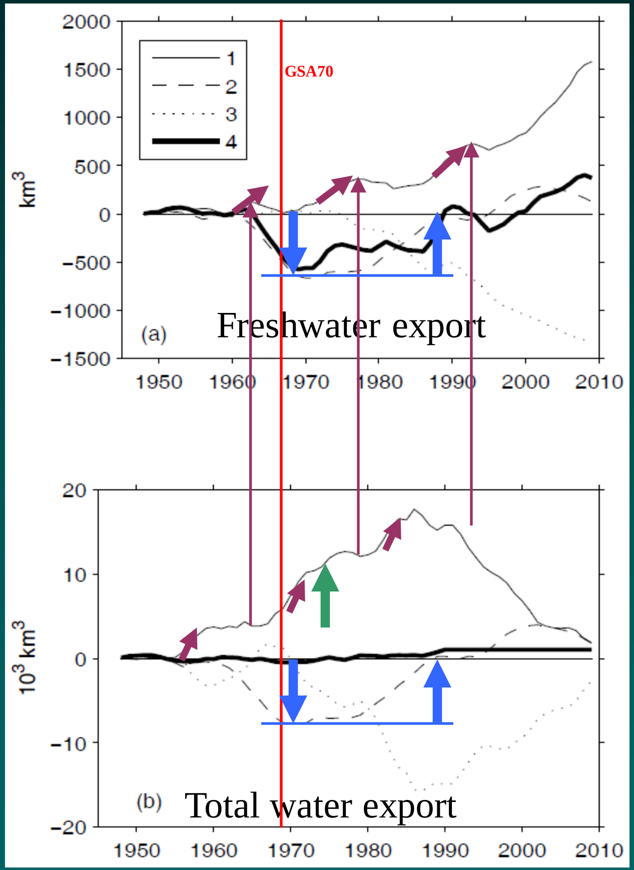
Experiments with observed and climatic Arctic river discharges



Time accumulated difference between the observed and climatic river discharge for Ob, Yenisey and Lena

- River discharge deficit from 1954 to 1978 with an exception of 1962-64
- River discharge excess from 1978 to 1990
- Lena accumulated runoff increases from 1957
- Ob and Yenisey accumulated runoff decreased before 1968 then starts to increase

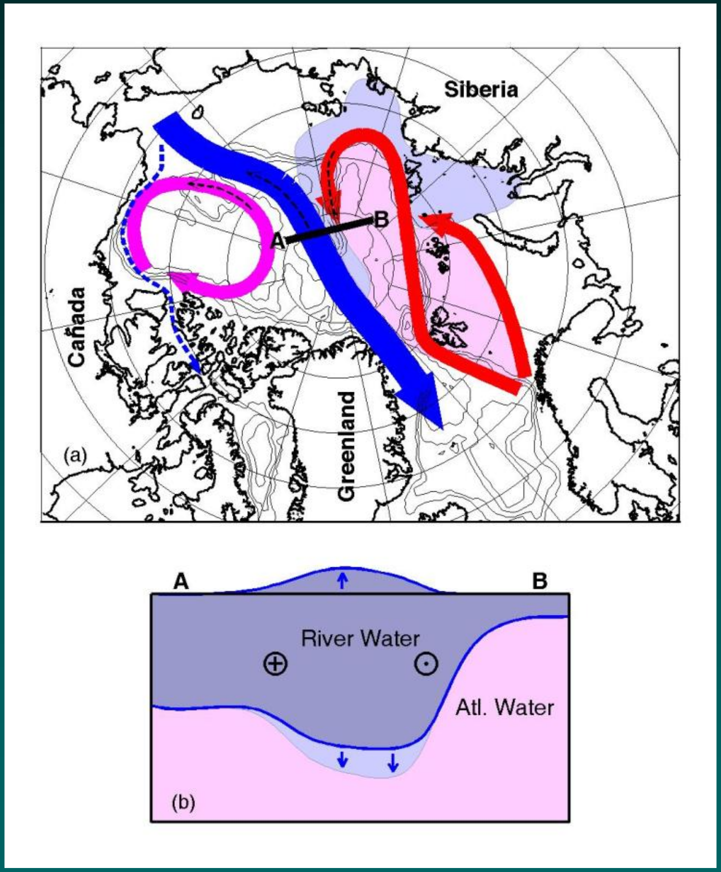
Accumulated difference between numerical tests



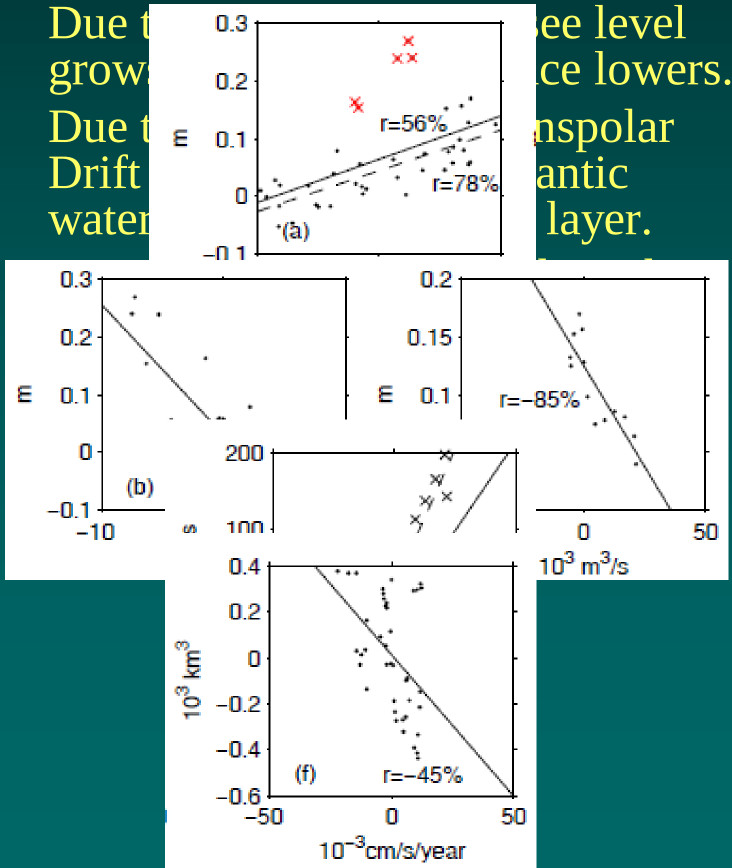
1 – Fram Strait, 2 – CAA, 3 – Barents Sea, 4 – total export

- Three pulses of Fram Strait outflow (~5,000 km^3 each);
- The last phase of each of these pulses was accompanied by the growth of FW export;
- The first growth contributed additional 100 km^3 in 1963 and it preconditioned the GSA70;
- In 1960-1970 the CAA throughflow had contributed less Arctic waters into the Baffin and Labrador Seas by 7000 km^3, compensated shortly by the Fram Strait transport, while in 1990 exactly this volume was restored. It led to a 20 years prevention of about 600 km^3 of FW from being exported to Atlantic through the Canadian Straits

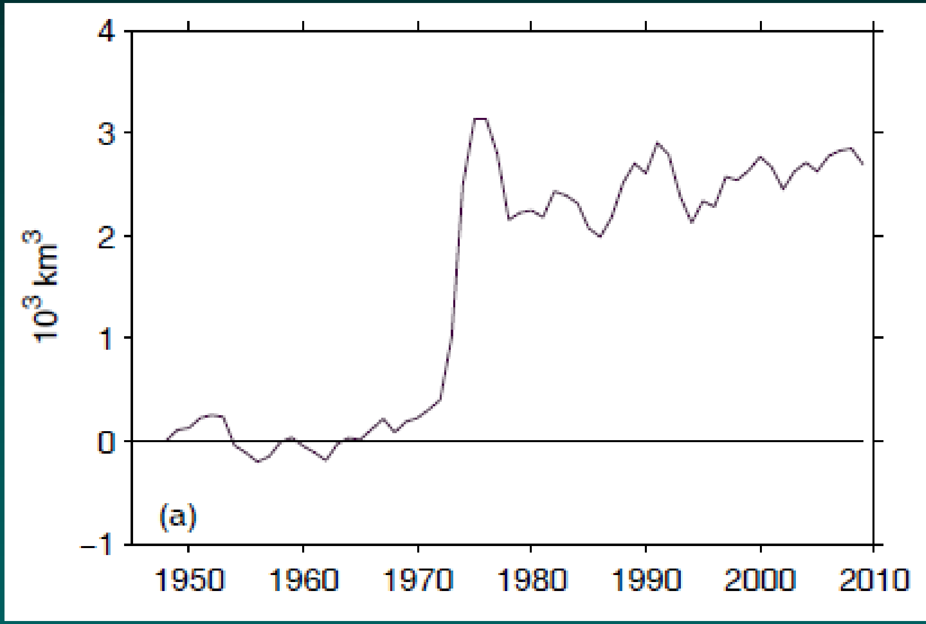
The role of Siberian river discharge in controlling Arctic water export distribution



- River discharge excess produces a positive freshwater anomaly along the Lomonosov ridge (2 years lag).
- Due t… see level grow… ce lowers.
- Due t… nspolar Drift … antic water … layer.
- …
- …



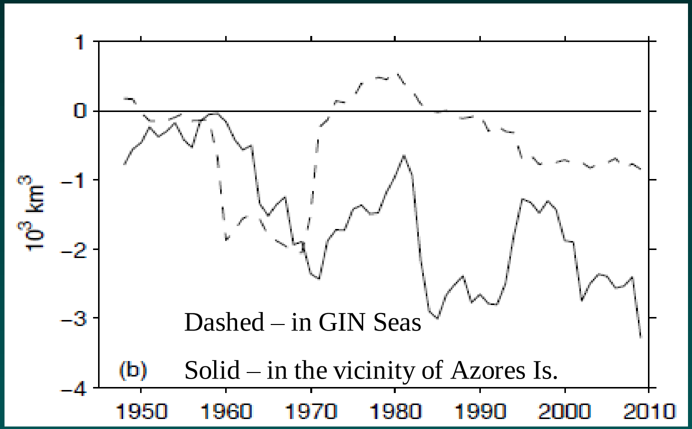
FW volume of Arctic and North Atlantic referenced to 34.8 psu. Difference between tests



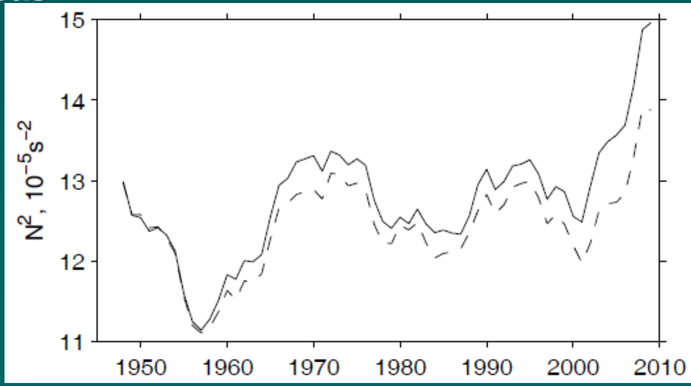
- The most signficant discrepancy appears in 1975 and amounts a value of more than 3000 km^3 of FW;
- The mapping reveals that this anomaly of the FW located in the vicinity of Azores Islands;
- How could the FWC disturbance reach such a distant location from river mouthes?
- How could 400 km^3 variations in river supplement cause 3000 km^3 anomaly there?

Mixed layer activity

Volume difference of water involved into vertical mixing

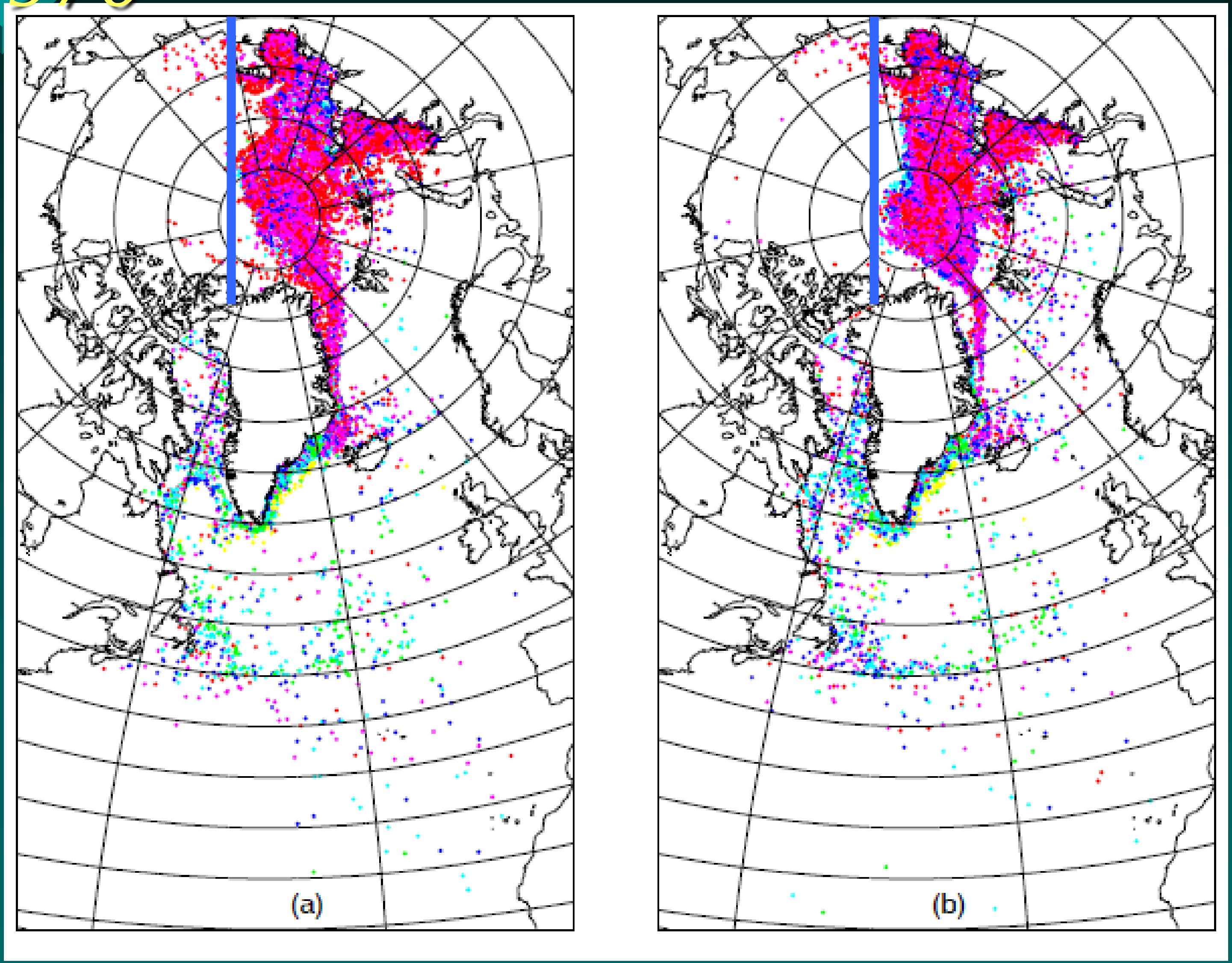


Mean Brunt-Väisälä frequensy of upper 100 m in GIN Seas

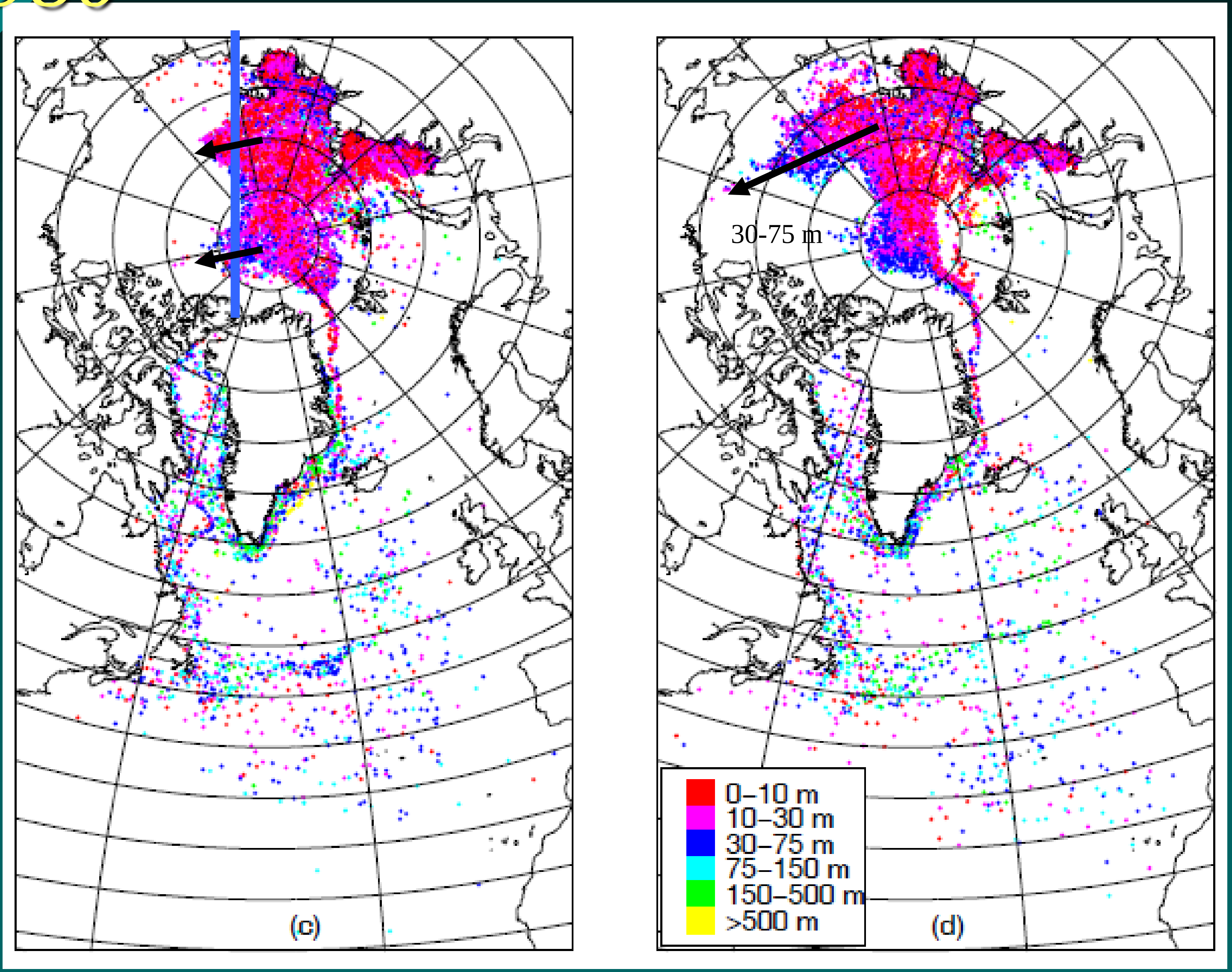


- The reduction of FW volume could result from any mixture of water masses, such as convection or diffusion.
- In case of climatic river discharge experiment the stability of the upper layer in North Atlantic is lower, therefore more water is involved into vertical mixing.
- In case of observed river discharge experiment less water is involved into vertical mixing thus more freshwater content is preserved from vertical mixing

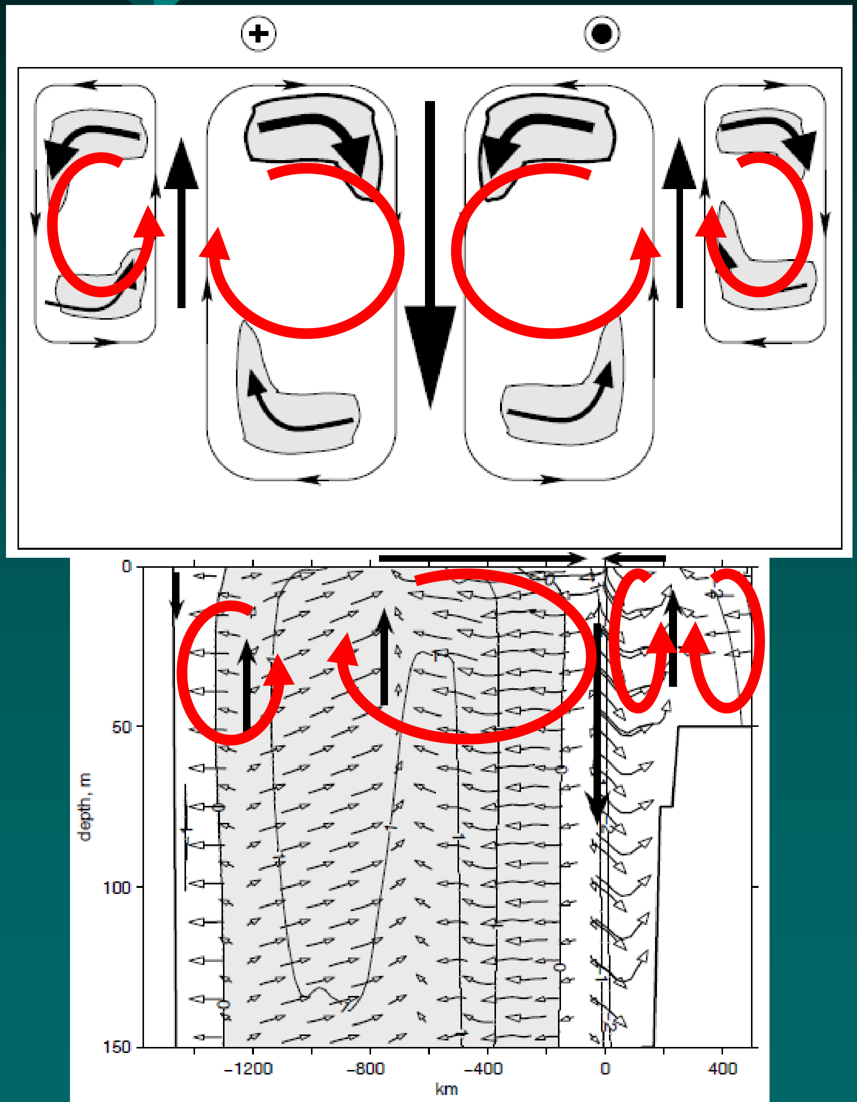
The position of floats in 1965 and in 1970



The position of floats in 1975 and in 1980

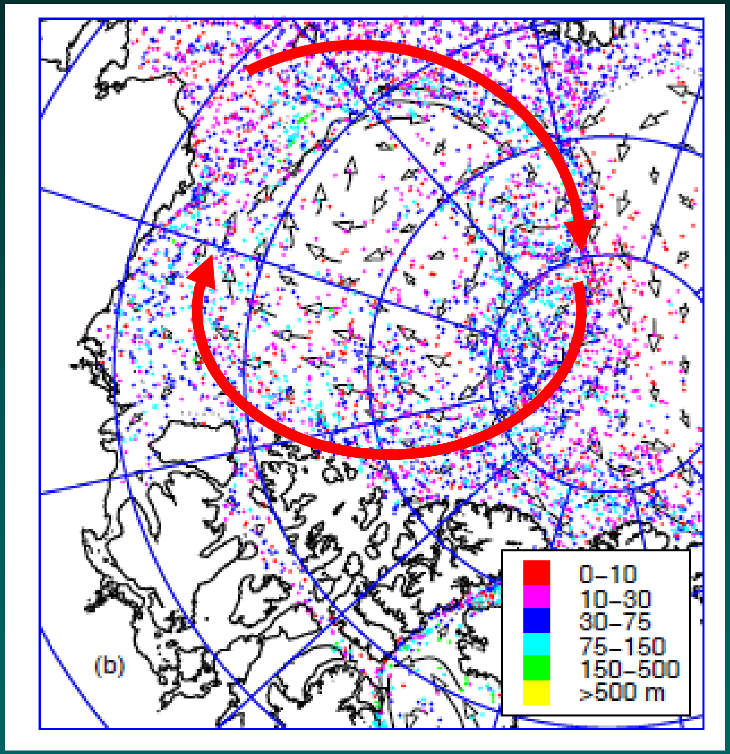


Vertical circulation scheme in the Beaufort Gyre



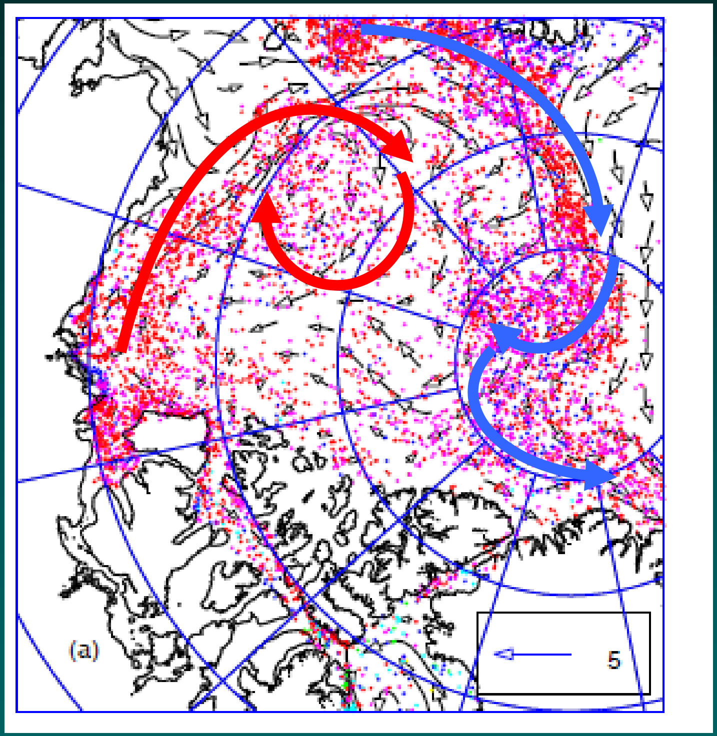
- The Siberian river water cannot enter the gyre circulation cell because it is three-dimensionally closed

Pacific floats in 1965



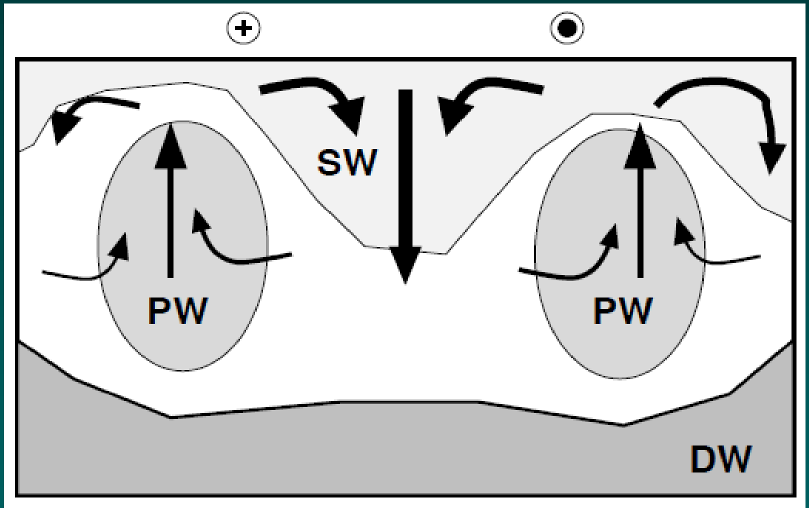
- Pacific water layer is placed mostly in the subsurface layer. About 60% of all Pacific floats are in 30-150 m layer.
- BG core region is almost free from Pacific floats, only few of them, but in the upper layer, are present here.
- They concentrate at the outer boundary of the BG.

Mackenzie river floats in 1965



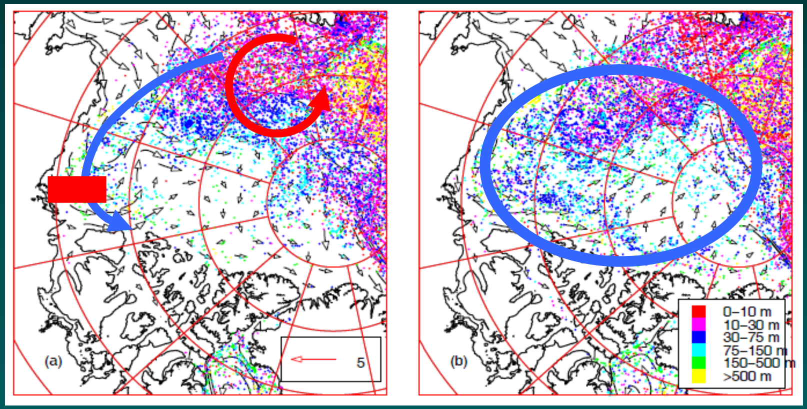
- Mackenzie floats are placed inside the area of negative wind circulation. In this situation they are more likely to get caught by BG Ekman pumping
- Kolyma and Khatanga floats circulate around BG center and finally pass through Fram Strait.

The vertical scheme of the freshwater storage in the Beaufort Gyre



- Surface water (SW), situated inside the BG, concentrates in its center.
- Surface water, situated outside the BG, cannot reach its interior region.
- Pacific water (PW), situated both inside or outside the BG, concentrates at its outer boundary.

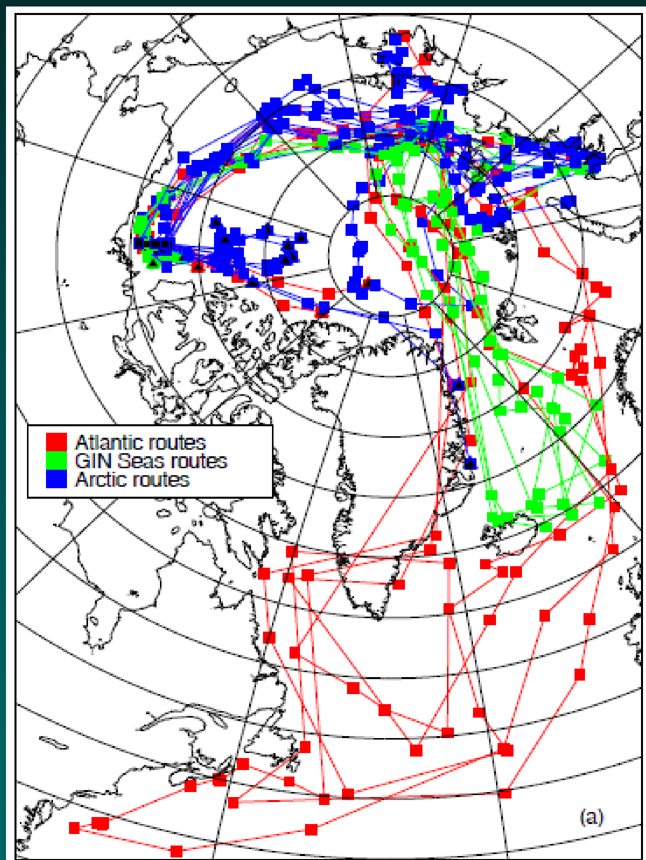
Siberian river floats in 1981 and in 1985 in the Beaufort Gyre



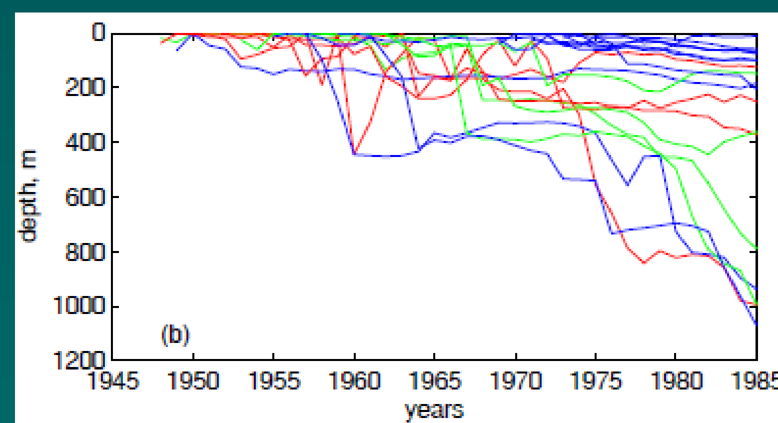
Tracing back the position of the floats cought in specified area we can see …

- In 1981 those floats positioned in top layers (0-30 m) are circulating in Chukchi Sea and hardly can penetrate into the BG
- A deeper layers have more expansive floats, but they propagates along the shelf break, staying aside from BG core.
- In 1985 the number of floats in BG increases. If the circulation index were happened to turn back to negative values then a new BG would incorporate most of Siberian river floats situated here.

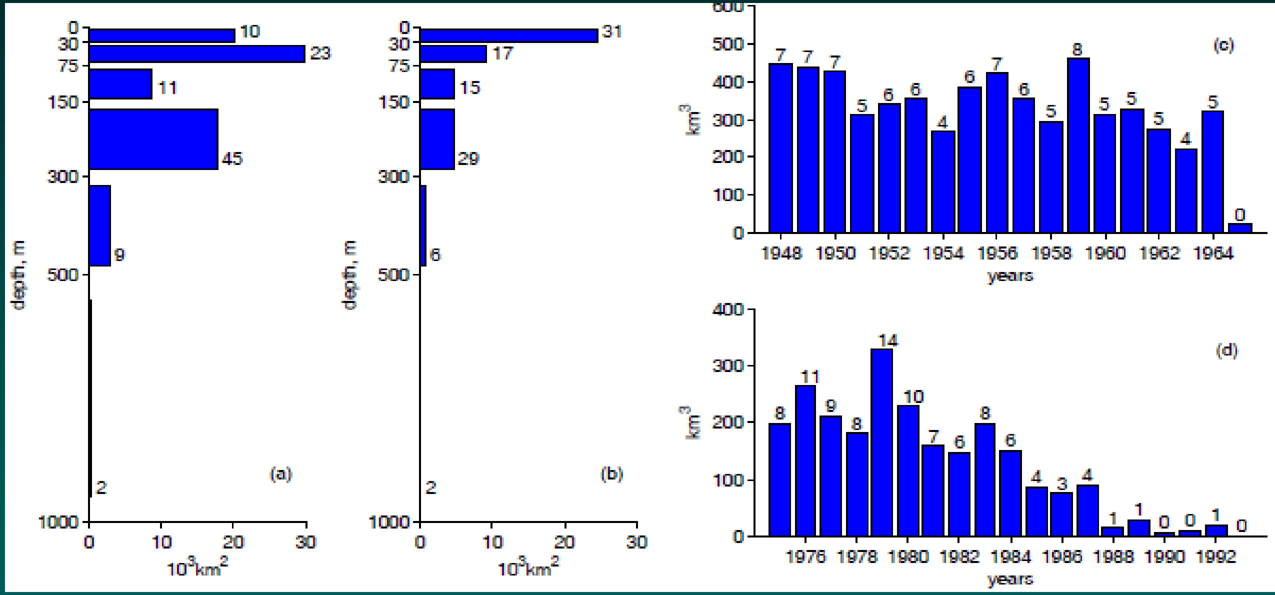
Tracks of Siberian river floats caught in the Beaufort Gyre in 1981



- Among 19 floats situated in specified rectangle
  - 8 had a very long trip before they were caught in BG. Starting at the river mouthes they drifted through the Fram Strait into the GIN Seas,
  - 4 of them passed the Denmark Strait and reached the Gulf Stream near USA coast.
  - One of these floats recirculated here even twice.
  - In a long run all these 8 floats returned back into Arctic through the Fram Strait and Barents Sea and finally were caught in Beaufort area.
- During this trip they were several time involved into vertical mixing, therefore they moved up and down, some of them ended up as high as at 100 m level the other went deeper to 1000 m.

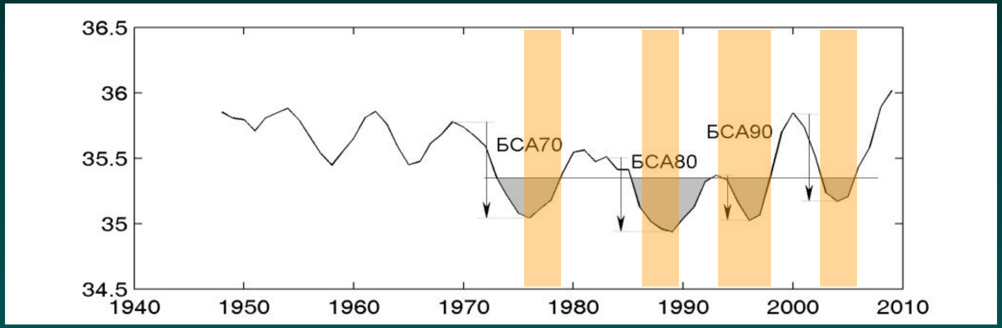


Distribution of Siberian river floats in the GIN seas in 1968 and in 1995



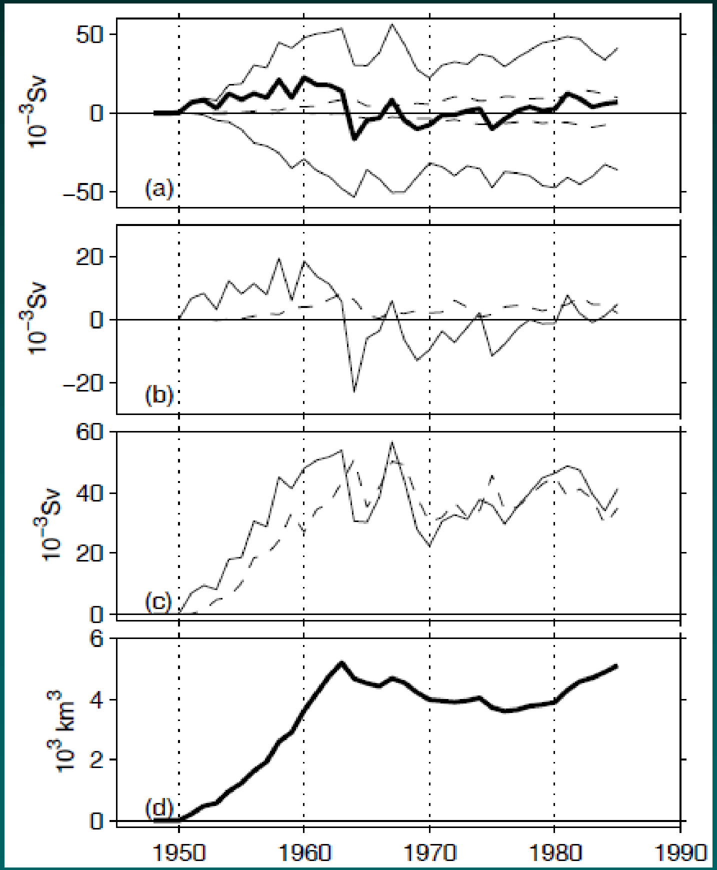
- In 1968 45% of Siberian river floats were in 150-300 m layer and only 10% in the upper 30 m layer
- In 1995 150-300 m layer had only 20% of floats, while the upper 30 m layer had 31%
- In 1968 the preceding 20 years made approx. equal contributions
- In 1995 most of the GIN Seas floats were contributed 10-20 years ago

GSA signal in the North Atlantic



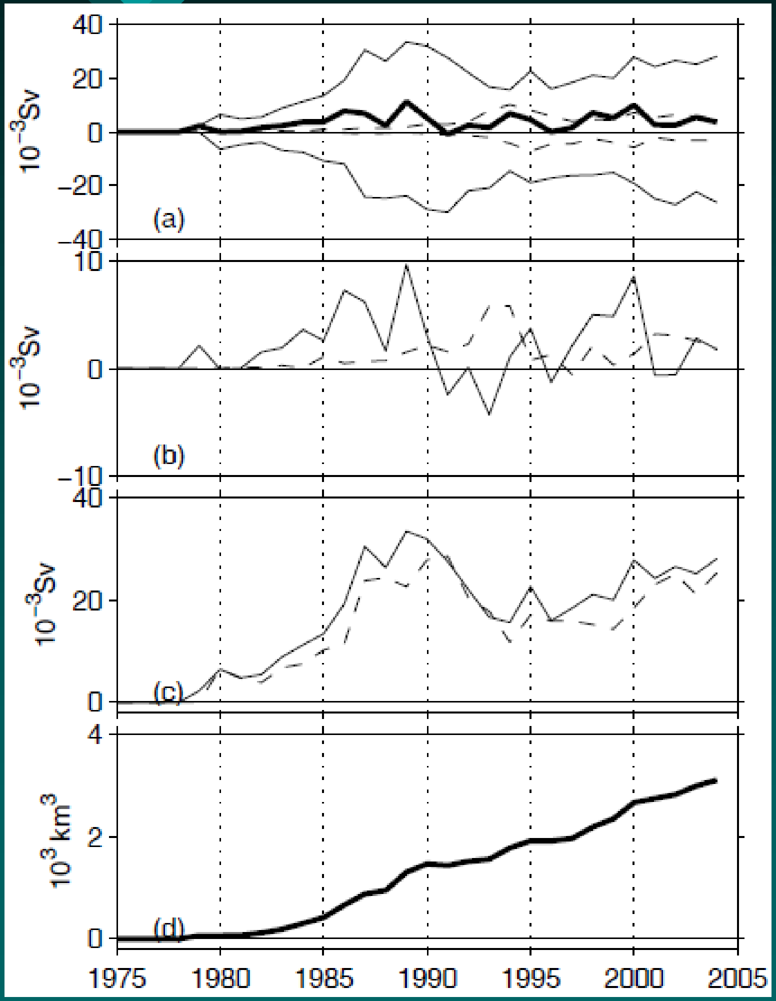
- In a review of salinity anomalies Sundby and Drinkwater [2007] summarized the hydrographic observation by Turrell [1995] in the Faroe-Shetland Channel section and highlighted three distinct signals
  - GSA70 – 1976-1979,
  - GSA80 – 1987-1989,
  - GSA90 – 1993-1998.
- The similar signal is seen in 2000s, which could be assigned to
  - GSA2000 – 2003-2006.

Transport of Siberian river water through the borders of the GIN seas in 1948-1985



- Most river waters were passing with the East Greenland Current (a,b).
  - Its balance of imported and exported waters was positive in 1950-1964, because time was needed for the floats to come into some equilibrium and because of the start of the GSA in 60s.
  - After that period the East Greenland Current balance was mostly negative, that is more river volume was driven out than that flowed in.
  - In 1968 and in 1974 there was two positive picks.
  - Also the start of the new anomaly can be seen, as in 80s the balance returned back to positive values.
- The balance of Norwegian Current on the contrary always remained positive (b). It means that some of its floats were used to compensate the East Greenland Current mismatch. But these floats, driven back by Gulf Stream and North Atlantic Current are hardly can be associated with Siberian rivers anymore.
- Fig. (c) shows the balance of the GIN Seas imported and exported Siberian river waters after subtracting Norwegian Current content in case it is treated as a non-river water floats.
- The total volume of Siberian river waters (d) in the area of GIN Seas.
  - During the formation of the GSA it reached its maximum of about 5200 km^3.
  - After minimum of 3600 km^3 in 1976 it starts recovering in support of the new salinity anomaly, which we will be discussed later.

Transport of Siberian river water through the borders of the GIN seas in 1975-2004



- Most river floats were passing through the GIN Seas with the East Greenland Current (a,b),
  - but its balance of imported and exported waters was always positive except 1991-1994 period, when new formed salinity anomaly starts its way southward.
- The Norwegian Current provides certain amount of floats to East Greenland Current which basically makes no difference to its balance (b),
  - but in 1991-1994 because of this contribution the total income remains positive, despite the East Greenland Current slowing.
- The total volume of Siberian river waters staying in the area of GIN Seas (d) steadily grows the whole period showing no maxima nor minima.
- The rate of growing is quite small about 3000 km^3 in 20 years, which corresponds to only 5000 m^3/s.

Conclusions

- The first GSA was in 1960-1974 and is attributed to the Great Salinity Anomaly of 70s. Another GSA of the GIN Seas origin was found according to model results in 1989-1995 produced the salinity anomaly propagating around northern North Atlantic in 2000s. The role of Siberian rivers in both of them may be evaluated as 36% and 25% of the initial anomaly freshwater volume. The GSA80 and GSA90 are also present in our model results but having smaller impact on the North Atlantic thermohaline structure.

- Besides the direct contribution in water volume, there is indirect reorganization of Arctic exchange of water masses with North Atlantic. The switching off the river runoff resulted in an increase of the Fram Strait export of cold and less saline water to the North Atlantic and corresponding the Barents Sea import of warm and salty Atlantic water. Thus the overall Arctic-North Atlantic exchange accelerates. The acceleration Arctic-North Atlantic exchange during river discharge deficit in a long run will lead to a continuous Arctic warming and to a degradation of Atlantic meridional overturning circulation. The question which arises from this result: "does the increasing of river discharge, observed in last decades, really serve to Arctic warming or, the contrary, serve to prevent Arctic from it?"

- Even a small amount of freshwater excess or deficit could result in a distant and multi-folded response in FWC as we found it in case of appearing a freshwater anomaly in the vicinity of Azores Islands which was 10 times larger than the original river discharge disturbance.

- The most part of Siberian river discharges contribute to the North Atlantic via Fram Strait and play a minor role in BG accumulation of Arctic freshwater.

Thank you