# Beaufort Gyre dynamics and implications for North-Atlantic-Arctic exchange

Andrey Proshutinsky, WHOI

The 2014 OCB Summer Science Workshop
The Coupled North Atlantic-Arctic System: Processes and Dynamics
(Mon. July 21)
Woods Hole Oceanographic Institution
Quissett Campus, Clark 507, Woods Hole, MA.

# Collaborators, Projects and funding agencies

**Collaborators:**

*R. Krishfield and J. Toole, Woods Hole Oceanographic Institution*
*M-L. Timmermans, Yale University*
*D. Dukhovskoy, Florida State University.*

**Projects:**

*Beaufort Gyre Explorations studies*
*Ice-Tethered profilers to monitor the Arctic Ocean conditions*
*Arctic Ocean Model Intercomparison Project*
*Manifestations and consequences of Arctic climate change*

**Sources of funding: NSF, WHOI**

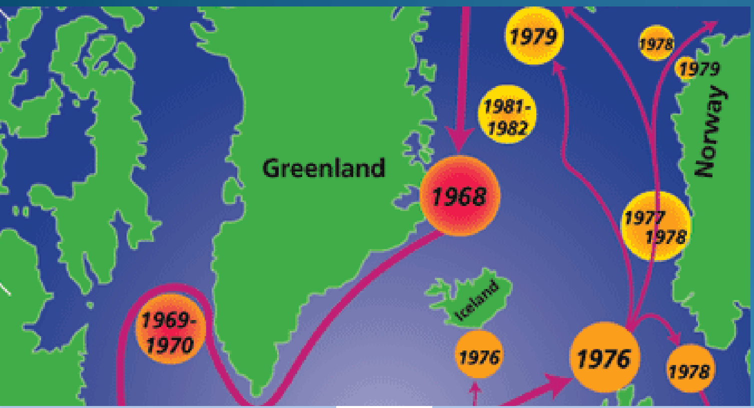
# Instead of introduction:

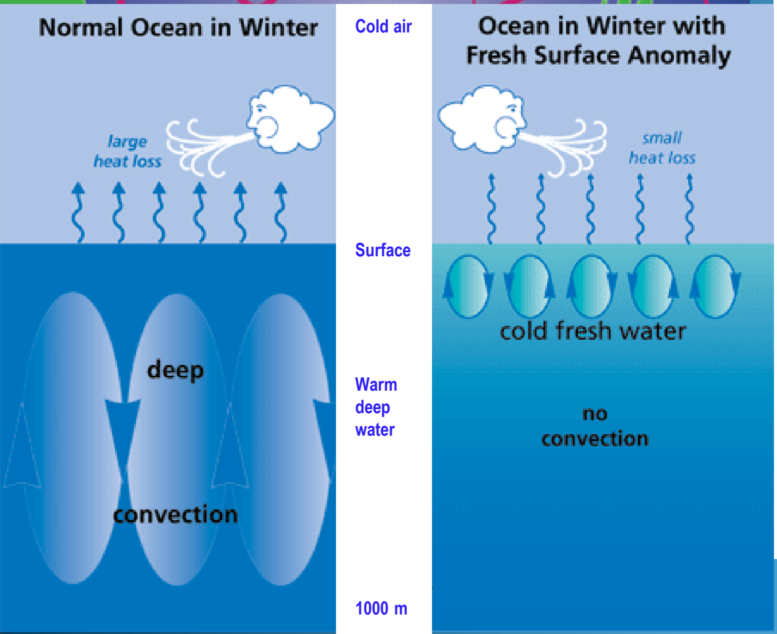
NBC News Learn program in partnership with the National Science Foundation prepared a 5-minute film describing our Beaufort Gyre exploration project hypothesis, objectives, tasks and preliminary results.

This film is located at the Beauofort Gyre website www.whoi.edu/beaufortgyre.

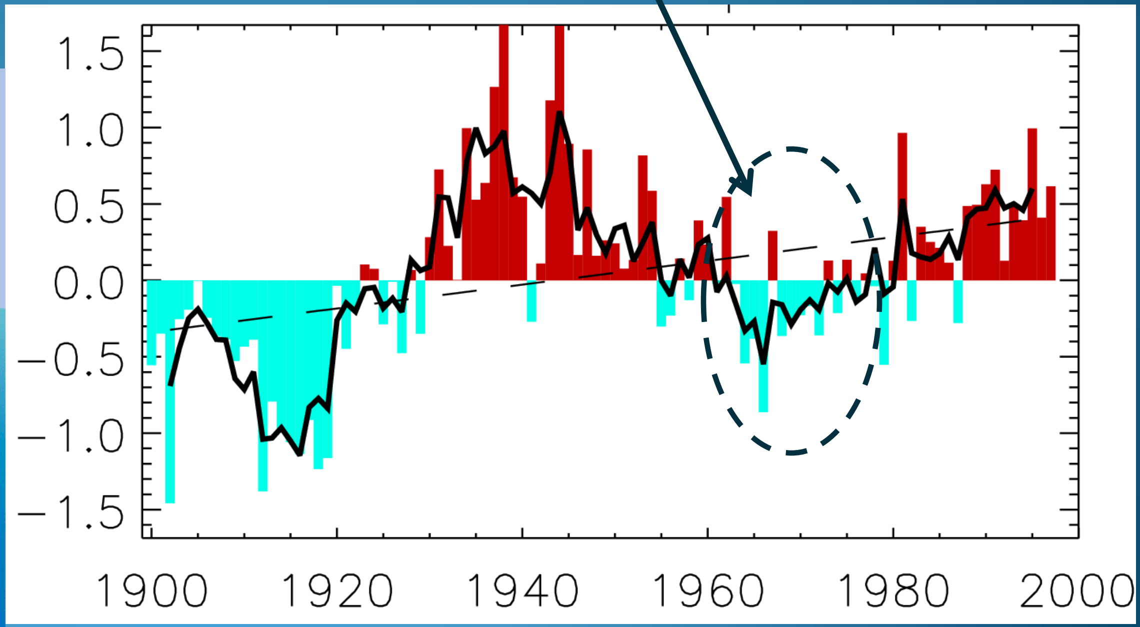
# Great salinity anomalies of the 1970s, 1980s, 1990s (Dickson et al., 1988; Belkin et al., 1988)

**The Great Salinity Anomaly, a large, near-surface pool of fresher-than-usual water, was tracked as it traveled in the sub-polar gyre currents from 1968 to 1982.**

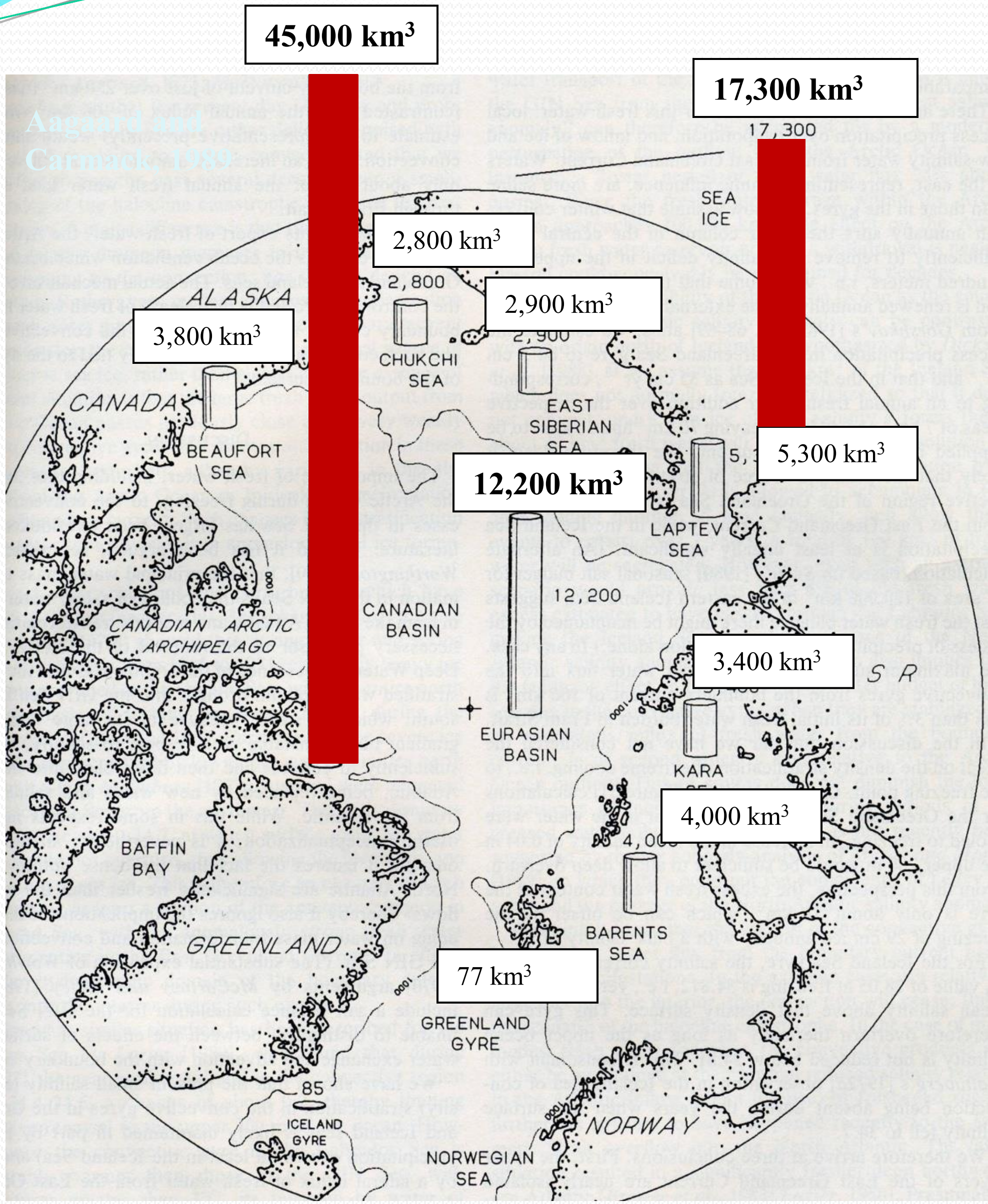



**This surface freshening of the North Atlantic coincided very well with Arctic cooling of the 1970s. At this time warm cyclone trajectories were shifted south and heat advection to the Arctic by atmosphere was shutdown.**

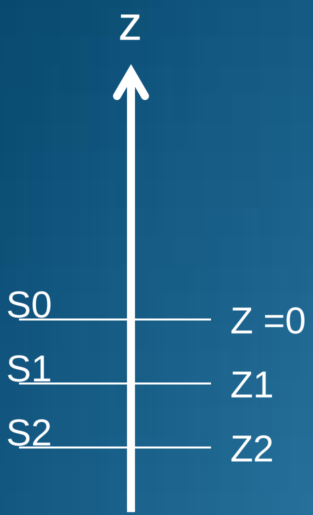


# Arctic Ocean  - largest freshwater reservoir




**And the oceanic Beaufort Gyre (BG) of the Canadian Basin is the largest freshwater reservoir in the Arctic Ocean (*Aagaard and Carmack*, 1989).** Freshwater content: calculated relative to salinity 34.80 according to Aagaard K. and E. Carmack, JGR, vol. 94, C10, 14,495-14,498,1989. The total freshwater content of the Arctic Ocean based on the data from the 1970s is about 80,000 cubic km.

# Freshwater content (liquid) (FWCL) (m) in the ocean is calculated as




$$\mathrm{FWCL} = \int_{z2}^{z1} \frac{[Sref - S(z)]}{Sref}\, dz,$$

where the *z* axis is defined as positive up with the surface *z* = 0. The reference salinity, *Sref* is taken as 34.8; *S*(*z*) is the salinity of the water at depth *z*. We take *z*2 as the depth level where *S*(*z*) = *Sref* while *z*1 defines the upper level of the FWCL integrations. For total water column FWCL, *z*1 = 0. Change in FWCL is thus a measure of how much liquid freshwater has accumulated or been lost from the ocean column bounded by the 34.8 isohaline and z = *z*1.

# Annual Freshwater (FW) budget of the Arctic.

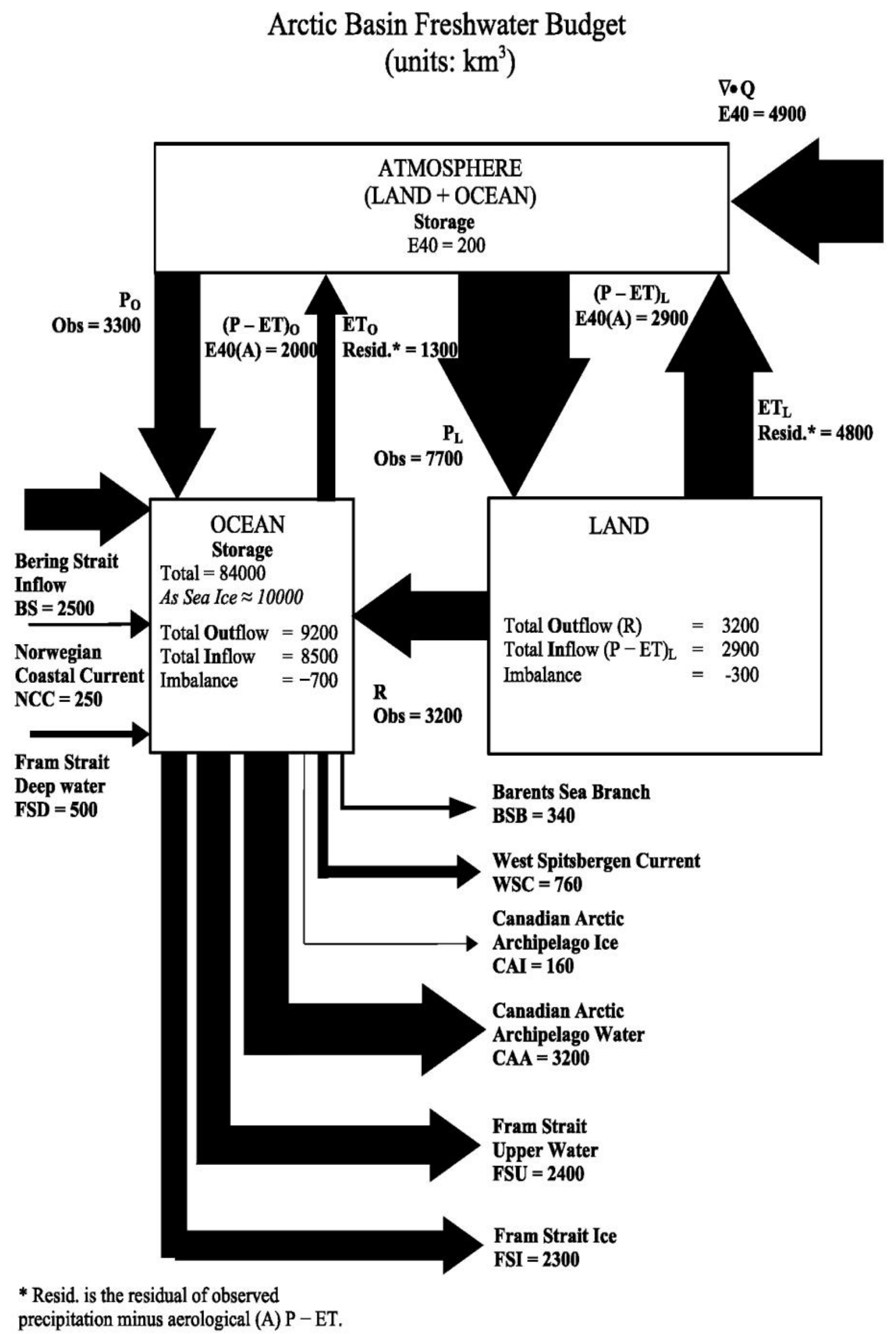
The atmospheric box combines the land and ocean domains. The boxes for land and ocean are sized proportional to their areas.

All transports are in units of $km^3$ per year. Stores are in $km^3$. The width of the arrows is proportional to the size of the transports.
Subscripts "L" and "O" denote land and ocean, respectively (from Serreze et al., 2006).

E40 (ERA-40) shows results obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis.

P and ET depict precipitation and evapotranspiration, respectively. The net precipitation (P-ET) represents water available for runoff (R).
$\nabla \cdot Q$ is the divergence of the horizontal water vapor flux Q integrated from the surface to the top of the atmospheric column.

**According to Serreze et al., 2006, the total storage of freshwater in the Arctic Ocean is around 84,000 cubic km. But due to Serreze, the freshwater content component due to sea ice has reduced by ~ 7,300 cubic km because of sea ice melt.**



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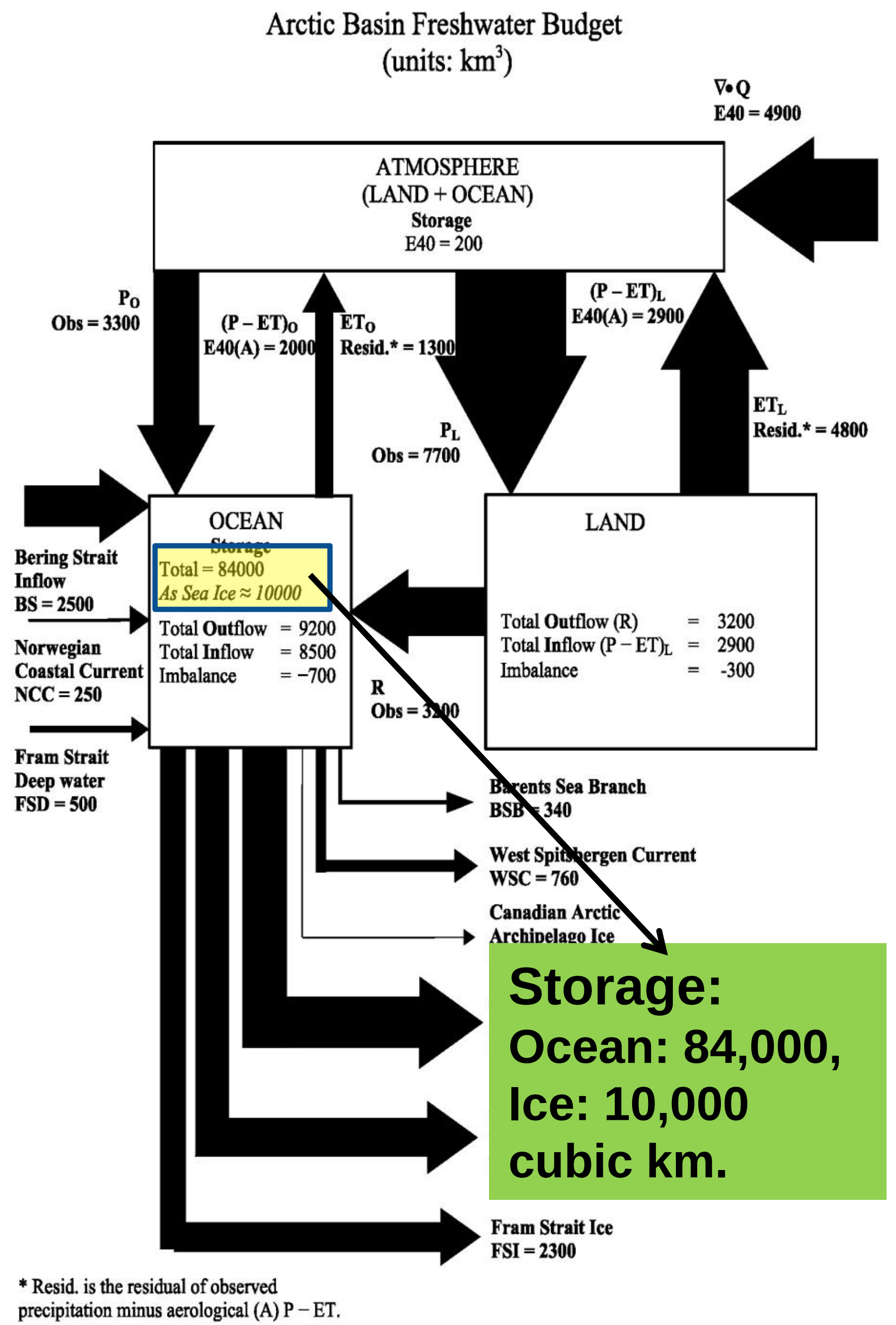

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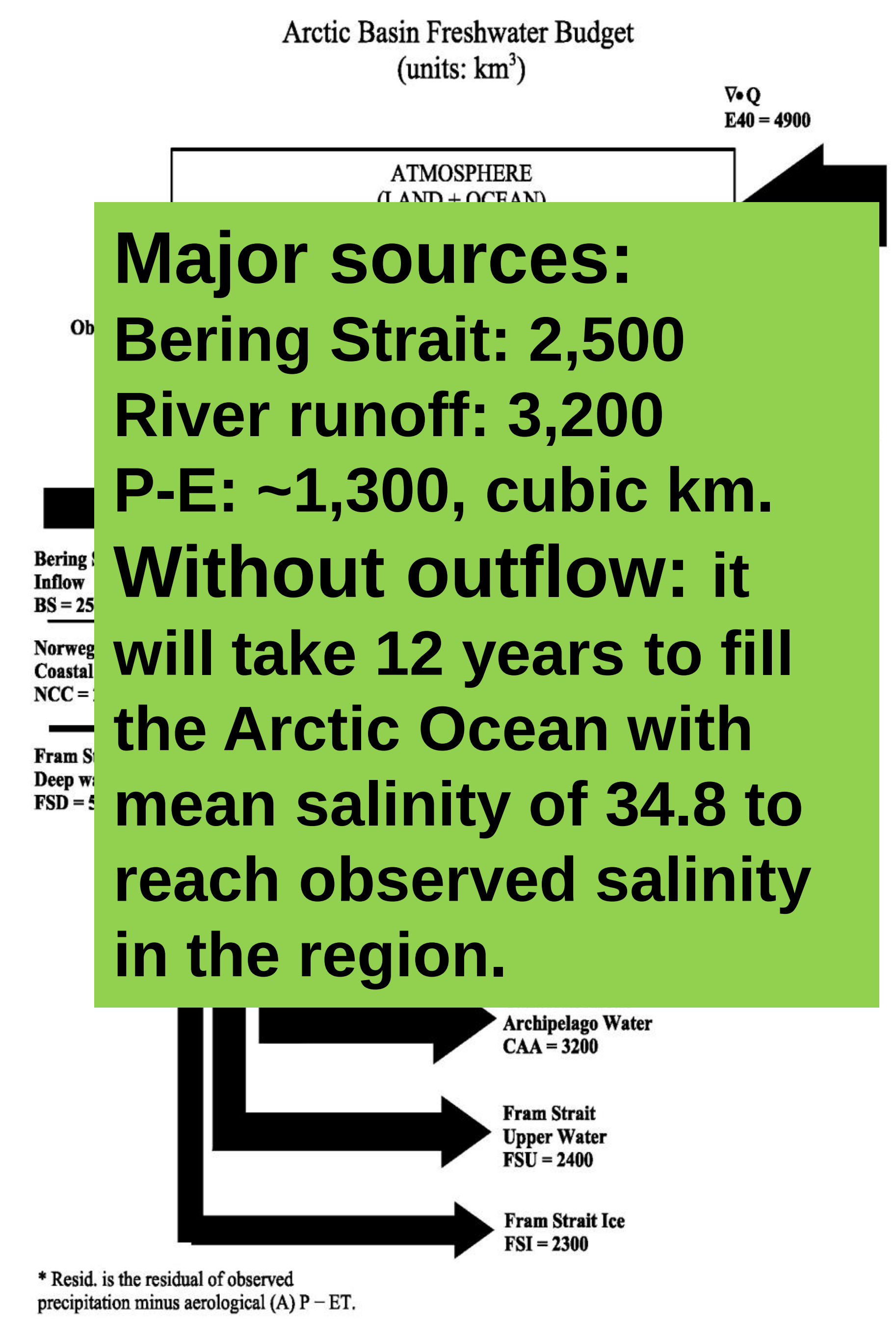
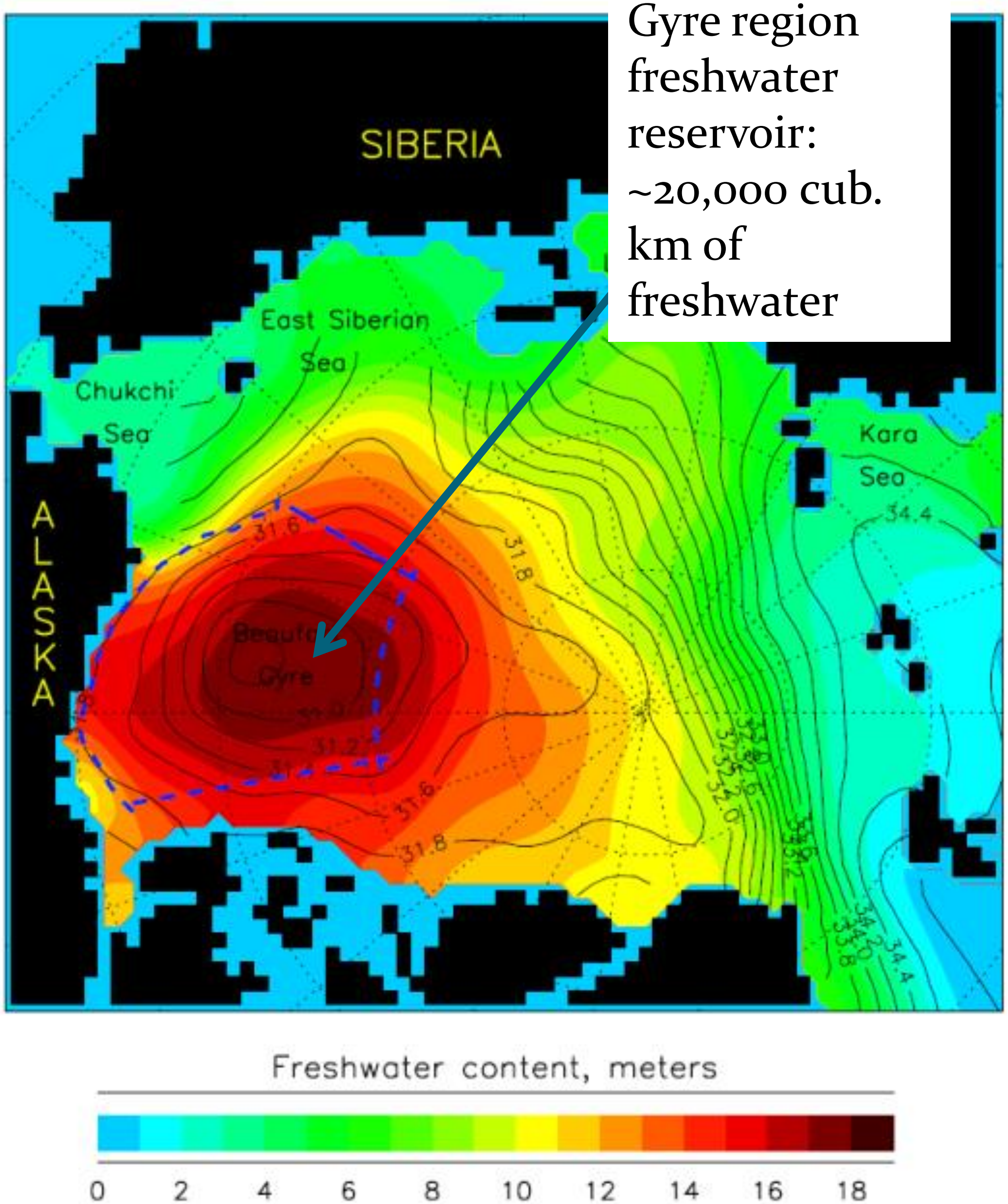



**Major sources:**
**Bering Strait: 2,500**
**River runoff: 3,200**
**P-E: ~1,300, cubic km.**
**Without outflow: it will take 12 years to fill the Arctic Ocean with mean salinity of 34.8 to reach observed salinity in the region.**




The Beaufort Gyre region freshwater reservoir: ~20,000 cub. km of freshwater

**1. What is the origin of the salinity minimum in the BGR?**

**2. What is the role of the BG system in Arctic climate change?**

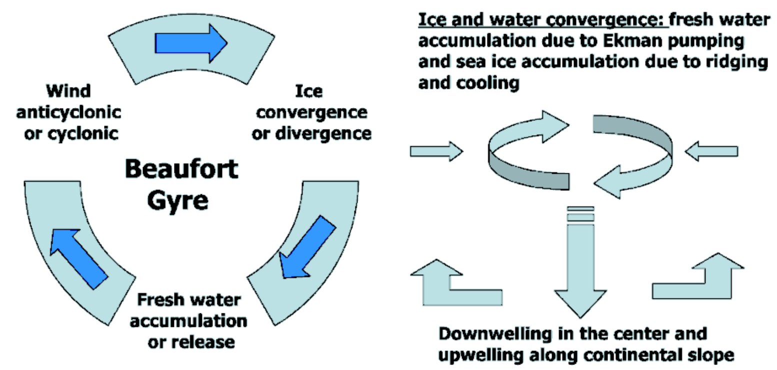
**What are the driving forces of the BG circulation and how stable is the BG system?**

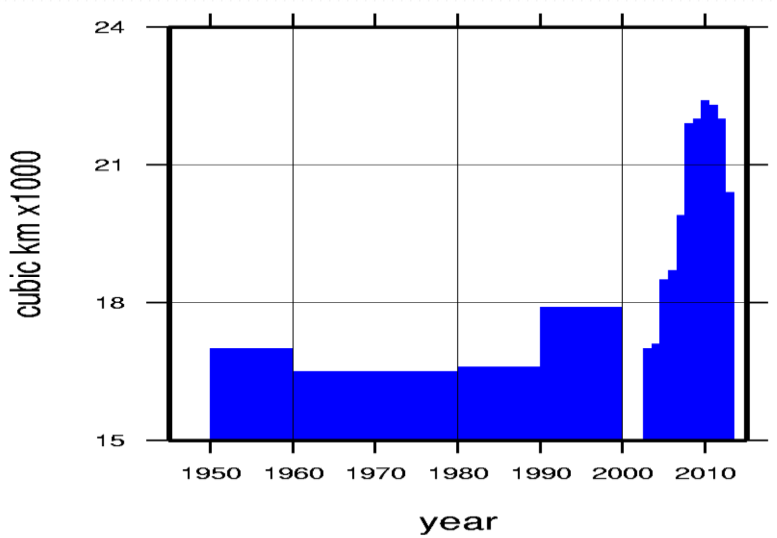
**What is the current state of the BG system?**

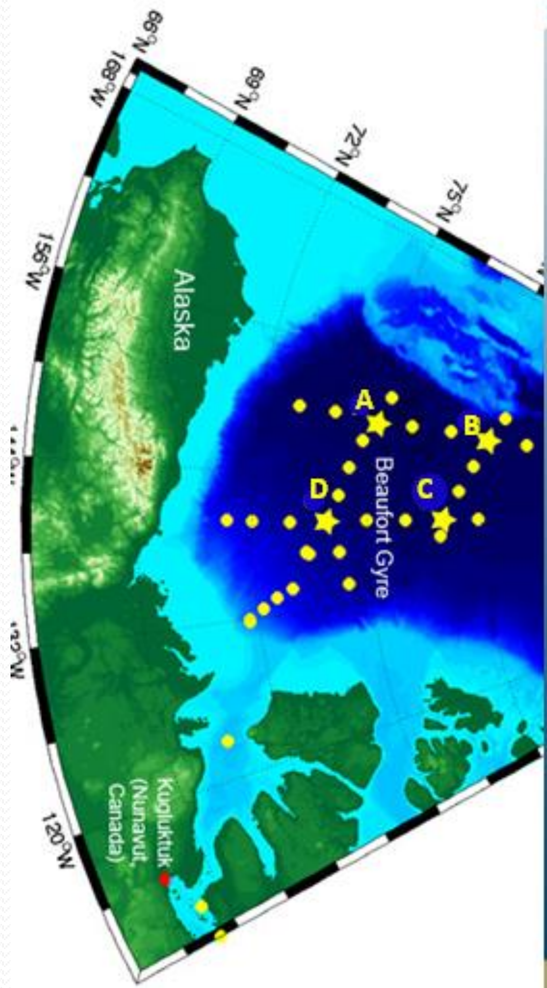
**How does the BG system change in time and what is the range of its seasonal inter-annual and decadal variability?**

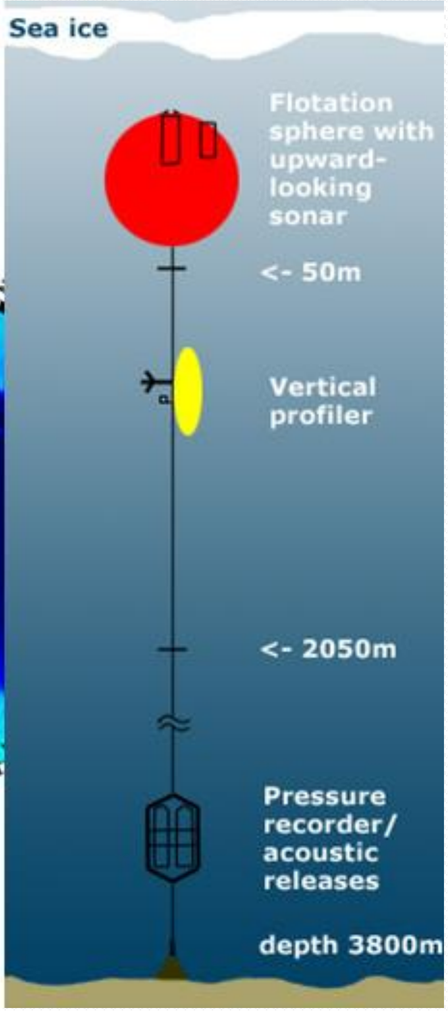
# Historical Data Analysis
# Modeling Studies
# Field Program (2003-2017)

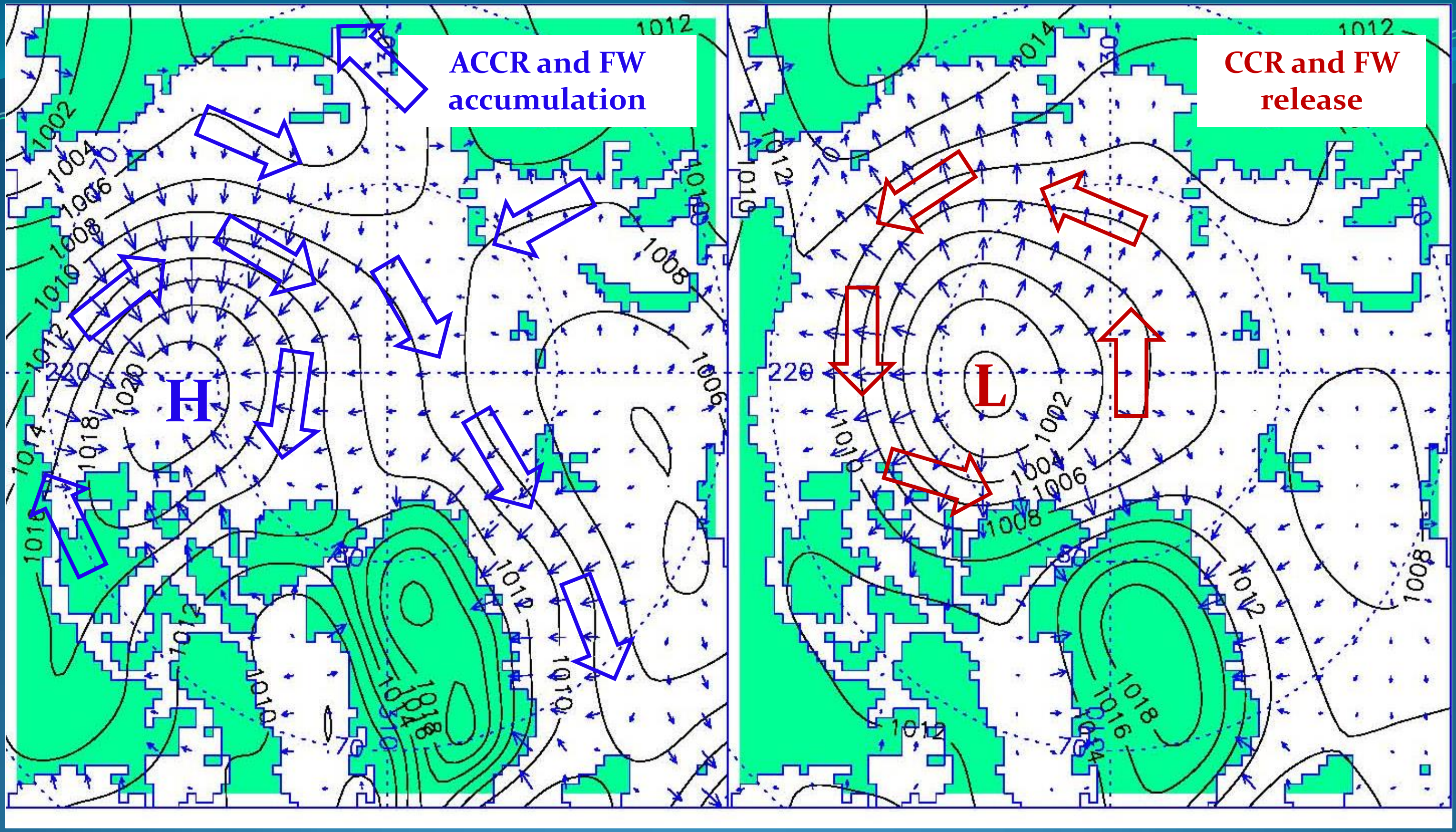
**Hypothesis: The BG accumulates freshwater under anticyclonic (CW) wind forcing then releases freshwater during cyclonic (ACW) forcing.**



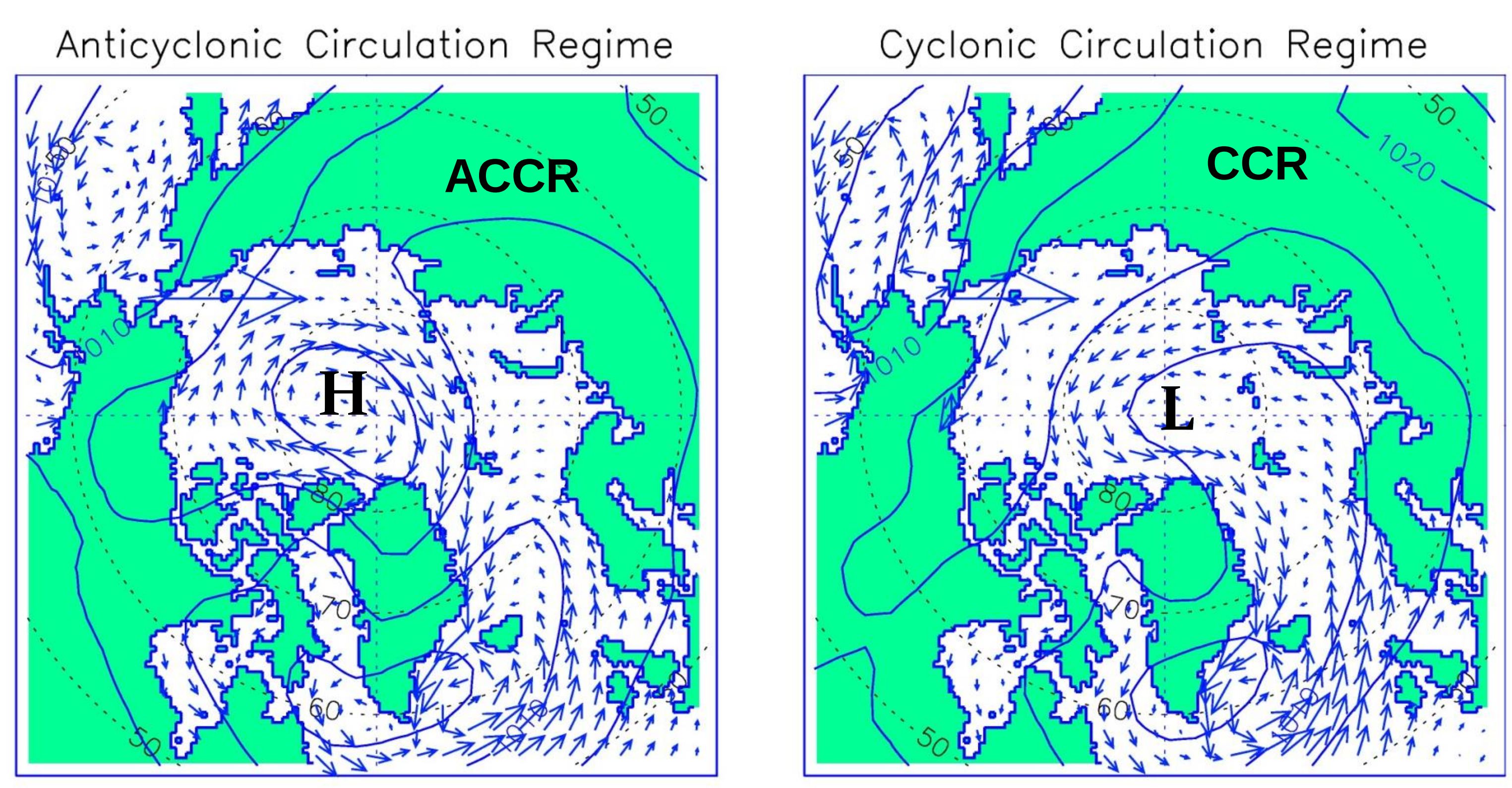






**Panels shows SLP (black lines, hPa) wind directions (large arrows) and Ekman transport (blue small arrows) typical for ACCRs (left) with Ekman transport converging; and CCRs (right) with Ekman transport diverging.**

# Arctic Ocean Oscillation Index (AOO)

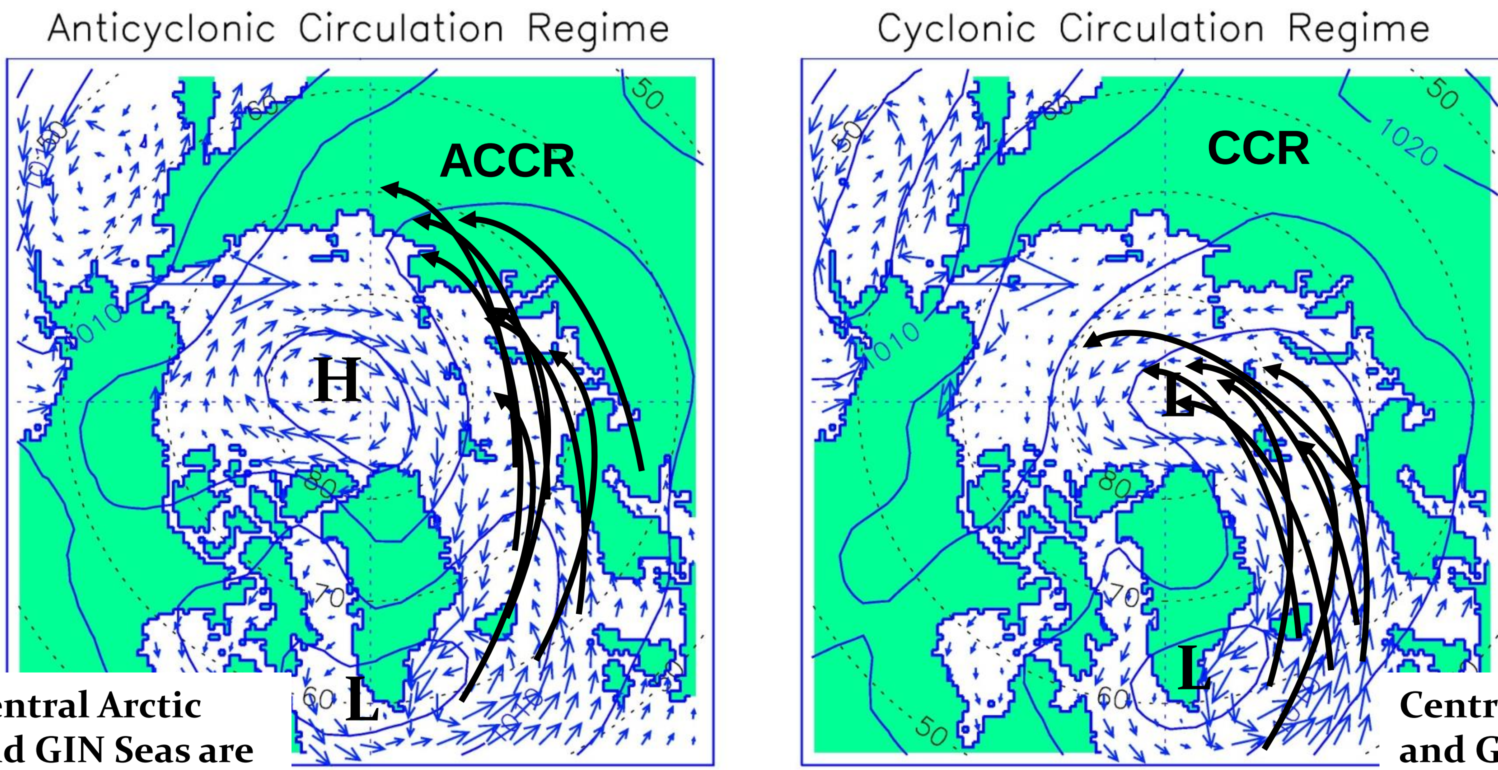
**Analyzing simulated annual sea ice motion and ocean circulation in the Arctic Ocean, Proshutinsky and Johnson [1997] revealed two circulation regimes: cyclonic (CCR) and anticyclonic (ACCR)alternating at intervals of 5-7 years with a period of 10-15 years.**




**Proshutinsky, A., Johnson, M., 1997. Two circulation regimes of the wind-driven Arctic Ocean. Journal of Geophysical Research 102, 12493–12512.**

- During **Anti-Cyclonic Circulation Regime** (**ACCR**) high atmospheric pressure dominates over the central Arctic Ocean Basin and cyclone trajectories are shifted toward Siberia

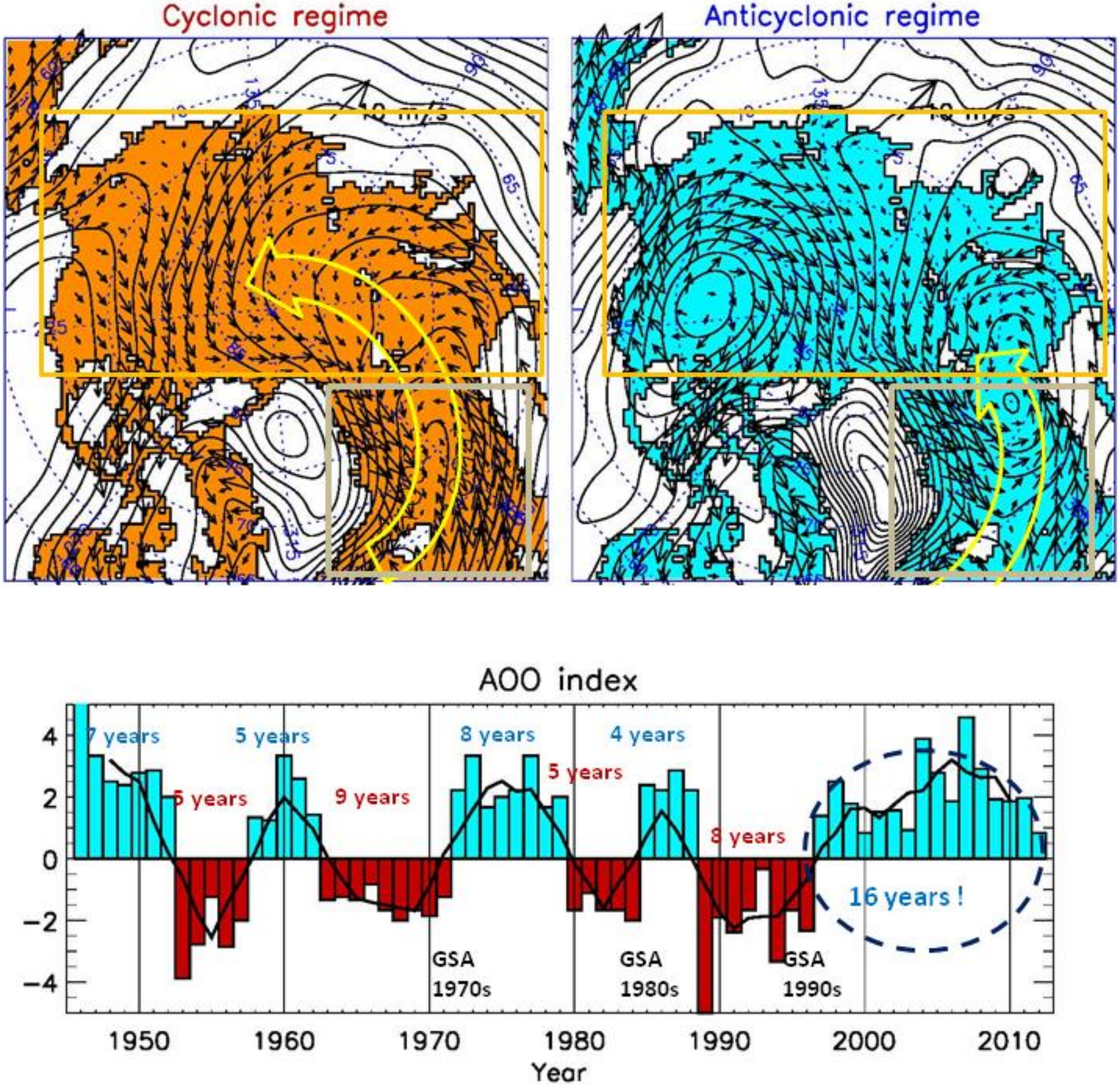
- During **Cyclonic Circulation Regime** (**CCR**) cyclones penetrate into the central Arctic Ocean Basin and atmospheric circulation becomes cyclonic




**Central Arctic and GIN Seas are separated**

**Central Arctic and GIN Seas are one system**

***Proshutinsky, A., Johnson, M., 1997. Two circulation regimes of the wind-driven Arctic Ocean. Journal of Geophysical Research 102, 12493–12512.***


Cyclonic regime
Anticyclonic regime
AOO index
7 years
5 years
8 years
4 years
5 years
9 years
5 years
8 years
16 years !
GSA
1970s
GSA
1980s
GSA
1990s
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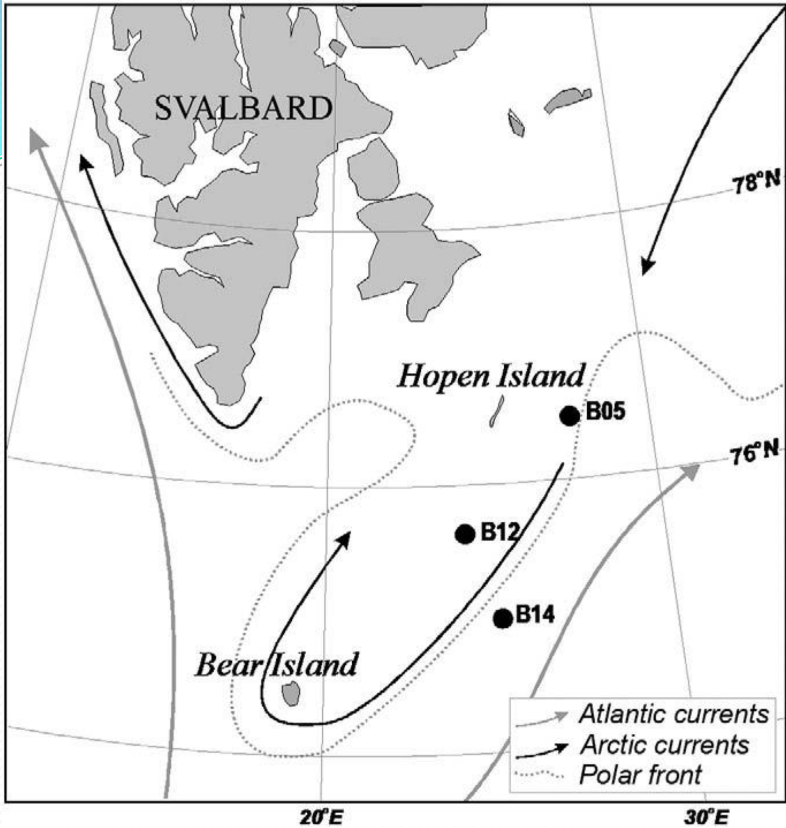
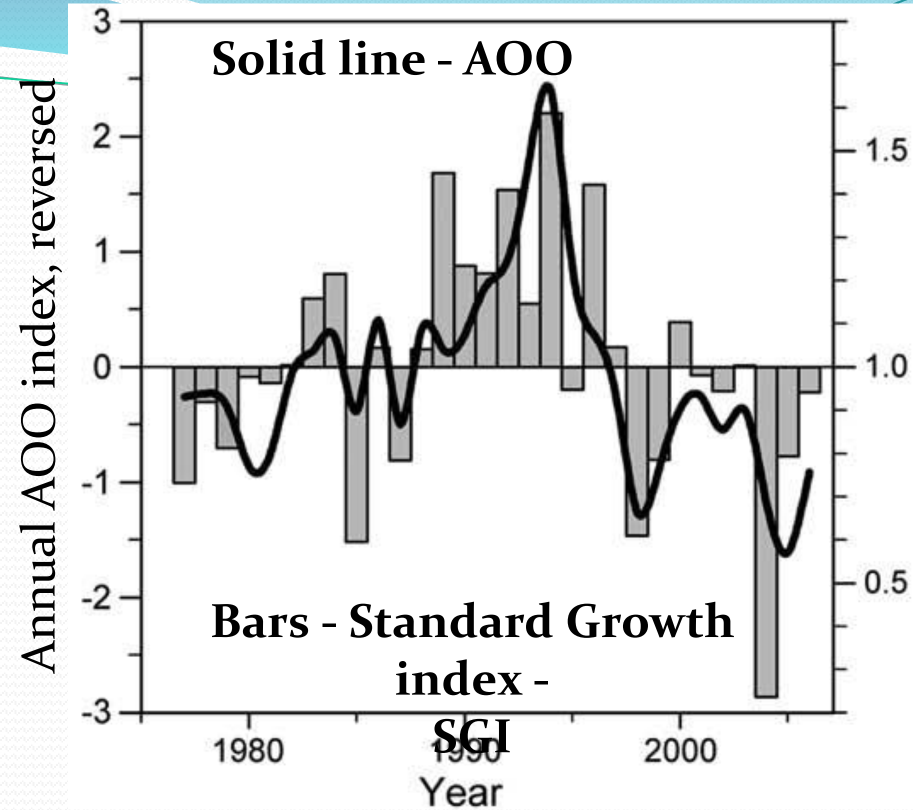
Year

# Correlations between wind circulation regimes and environmental parameters

| Parameters | Anomaly during ACCR | CCR | Source |
|---|---|---|---|
| Vorticity over polar cap | N | P | Tanaka et al., 1995 |
| SLP | P | N | Proshutinsky and Johnson, 1996, 1997 |
| Surface air temperature | N | P | Martin and Munoz, 1997 |
| Duration of ice melt season | N | P | Smith, 1998 |
| Sea ice extent | P | N | Maslanik et al, 1996 |
| Ice drift speed | N | P | Hakkinen and Proshutinsky, |
| Siberian river runoff | P | N | Proshutinsky and Johnson, 1997 |
| Beaufort Gyre Freshwater content | P | N | Proshutinsky et al., 2002, 2009 |
| Ice extent in the Bering Sea | P | N | Niebauer, 1988 |
| Ice extent in Davis Strait | P | N | Agnew, 1991 |
| Sea level along Siberia | N | P | Proshutinsky et al, 2004 |
| Atlantic water temperature | N | P | EWG atlas, 1997, 1998 |




Map of the study region showing the western Barents Sea and part of the Spitsbergen Archipelago. Collection locations of *Clinocardium ciliatum* are indicated, as are general current patterns and the assumed location of the Polar Front, which coincides with the limit of maximum ice cover in late winter.




**There is very good correlation between SGI –standard growth index of bivalve shells in the Barents Sea and AOO showing the influence of climatic forcing on ecological processes over decadal scales**

**From: Carroll, M.L., et al., Climatic regulation of Clinocardium ciliatum (bivalvia) growth in the northwestern Barents Sea, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2010)**

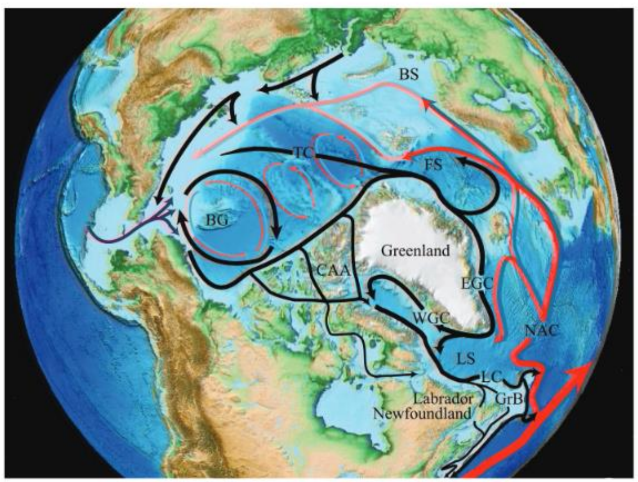
*Limnol. Oceanogr.*, 58(3), 2013, 803–816

doi:10.4319/lo.2013.58.3.0803

# Remote climate forcing of decadal-scale regime shifts in Northwest Atlantic shelf ecosystems

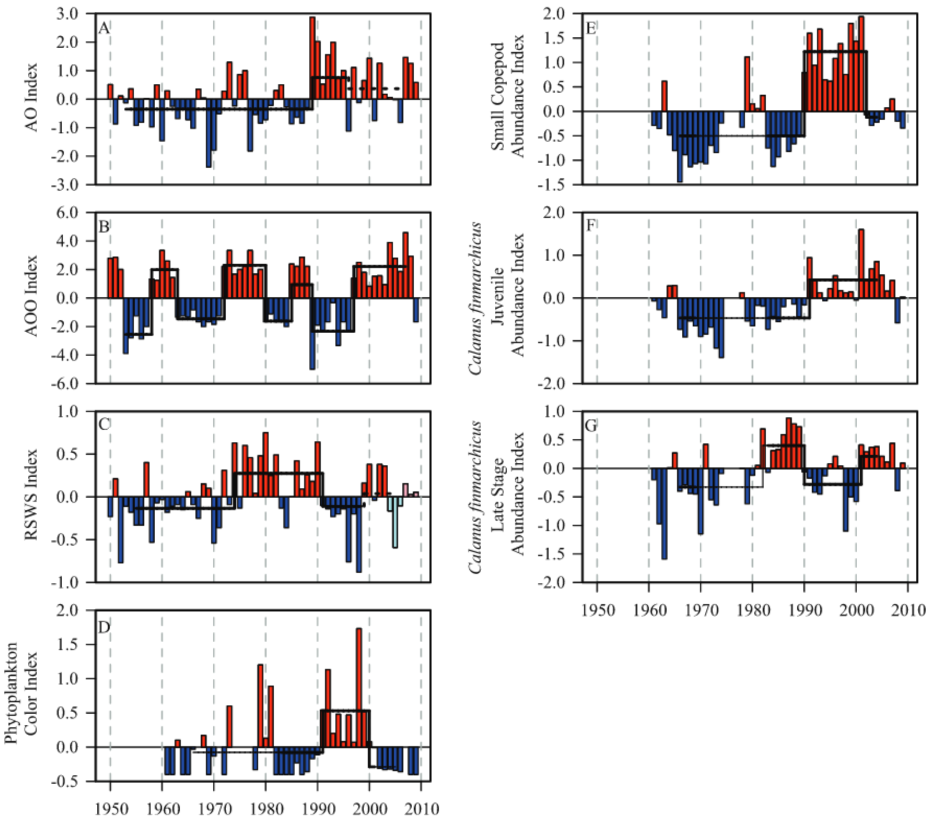
Charles H. Greene,[a,*] Erin Meyer-Gutbrod,[a] Bruce C. Monger,[a] Louise P. McGarry,[a] Andrew J. Pershing,[b,c] Igor M. Belkin,[d] Paula S. Fratantoni,[e] David G. Mountain,[f] Robert S. Pickart,[g] Andrey Proshutinsky,[g] Rubao Ji,[h] James J. Bisagni,[i] Sirpa M. A. Hakkinen,[j] Dale B. Haidvogel,[k] Jia Wang,[l] Erica Head,[m] Peter Smith,[m] Philip C. Reid,[l,n] and Alessandra Conversi [n,o,p]



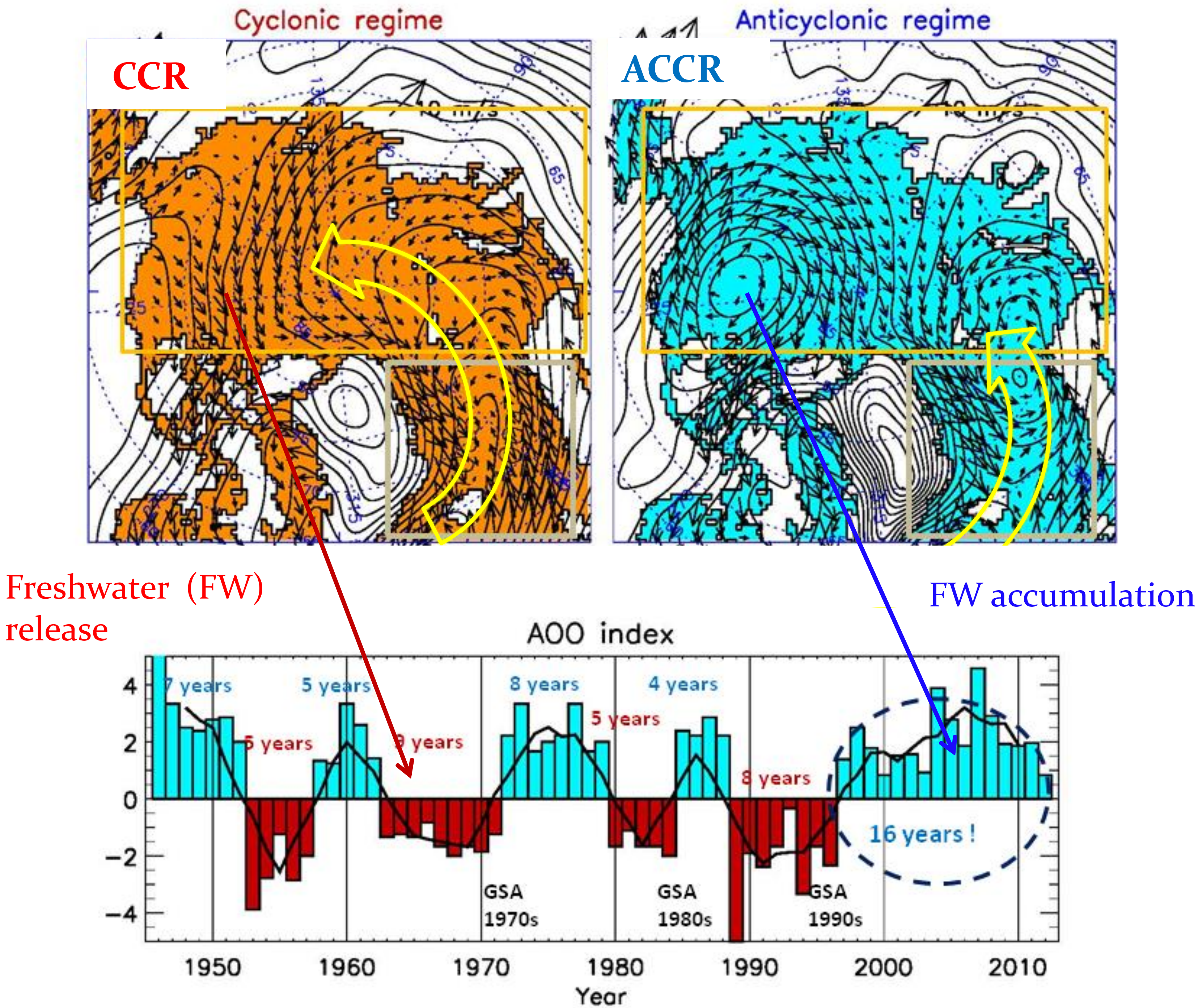



BG Beaufort Gyre
BS Barents Sea
CAA Canadian Arctic Archipela
EGC East Greenland Current
FS Fram Strait
GrB Grand Banks
LC Labrador Current
LS Labrador Sea
NAC North Atlantic Current
TC Transpolar Current
WGC West Greenland Current

Fig. 4. Circulation patterns for the Arctic Ocean, emphasizing upper ocean inflows and outflows with North Pacific an Atlantic Oceans. Acronyms for geographic features and currents are listed beside the figure panel. Illustration is copied with pe from MERCINA (2012).




**Recently this index was used in several studies to explain decadal-scale regime shifts in Northwest Atlantic shelf ecosystems.**



Cyclonic regime
CCR
Anticyclonic regime
ACCR
Freshwater (FW) release
FW accumulation
AOO index
7 years
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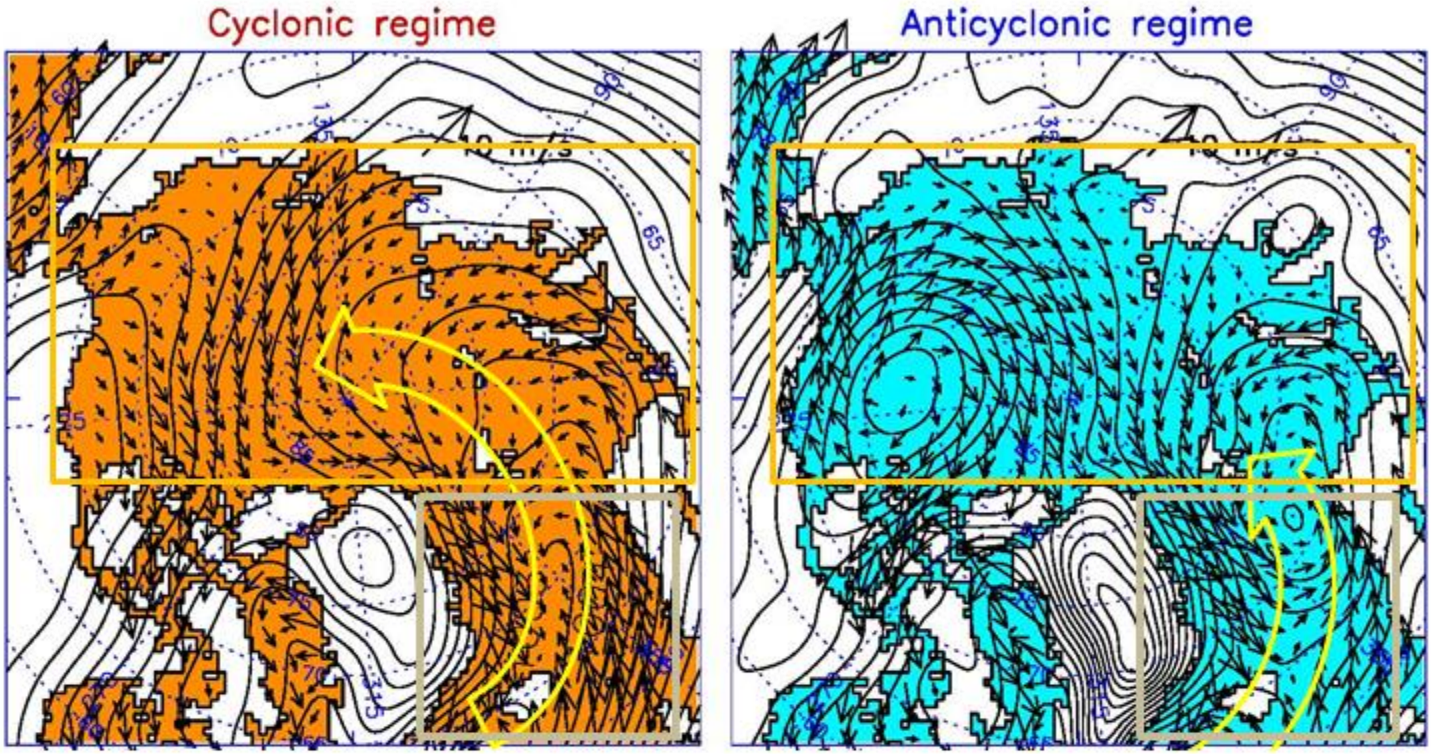
16 years !
GSA 1970s
GSA 1980s
GSA 1990s
Year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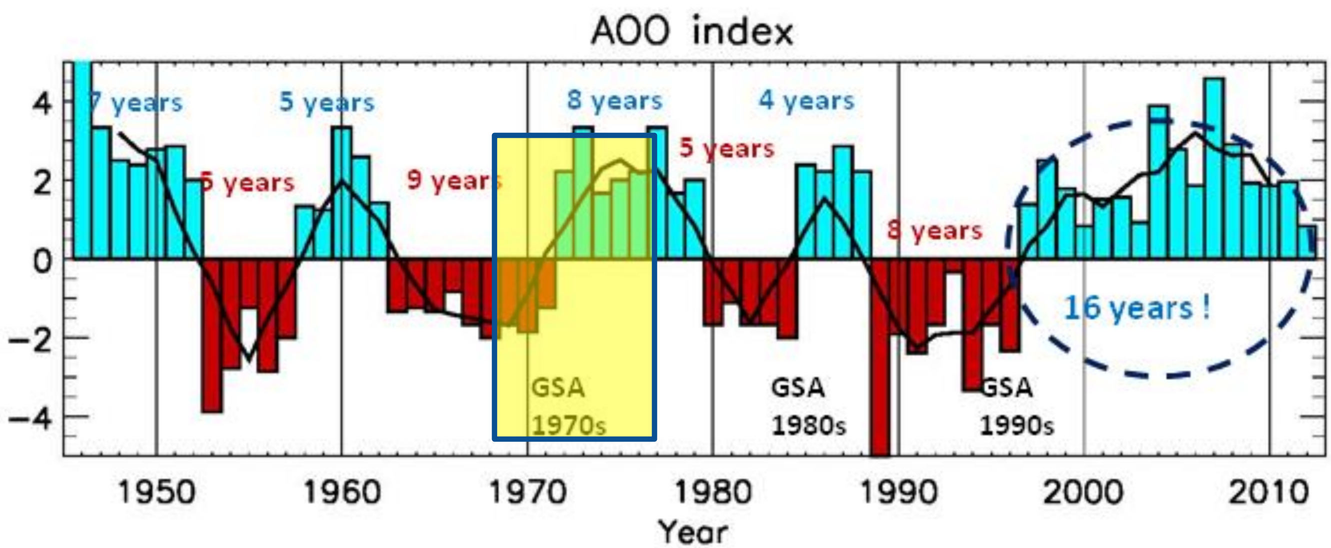
Anticyclonic regime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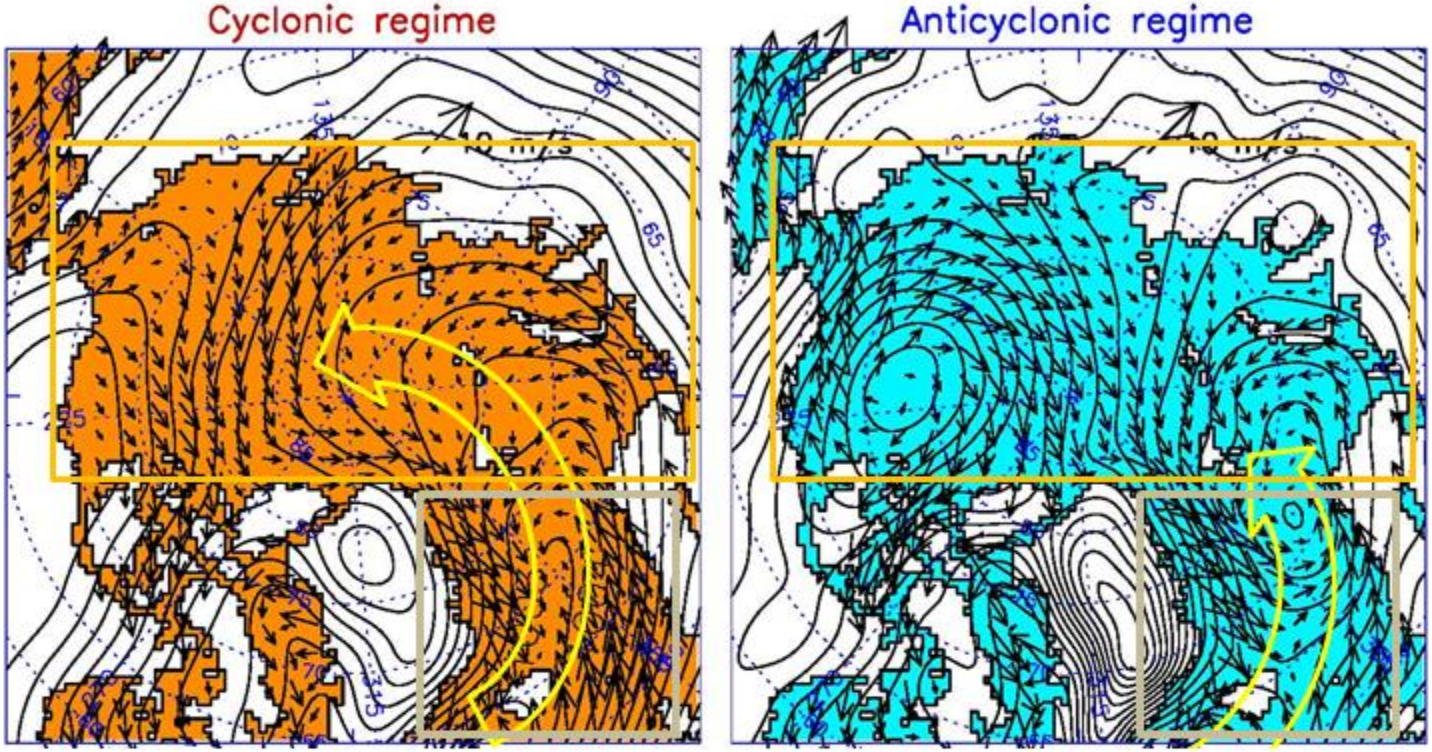
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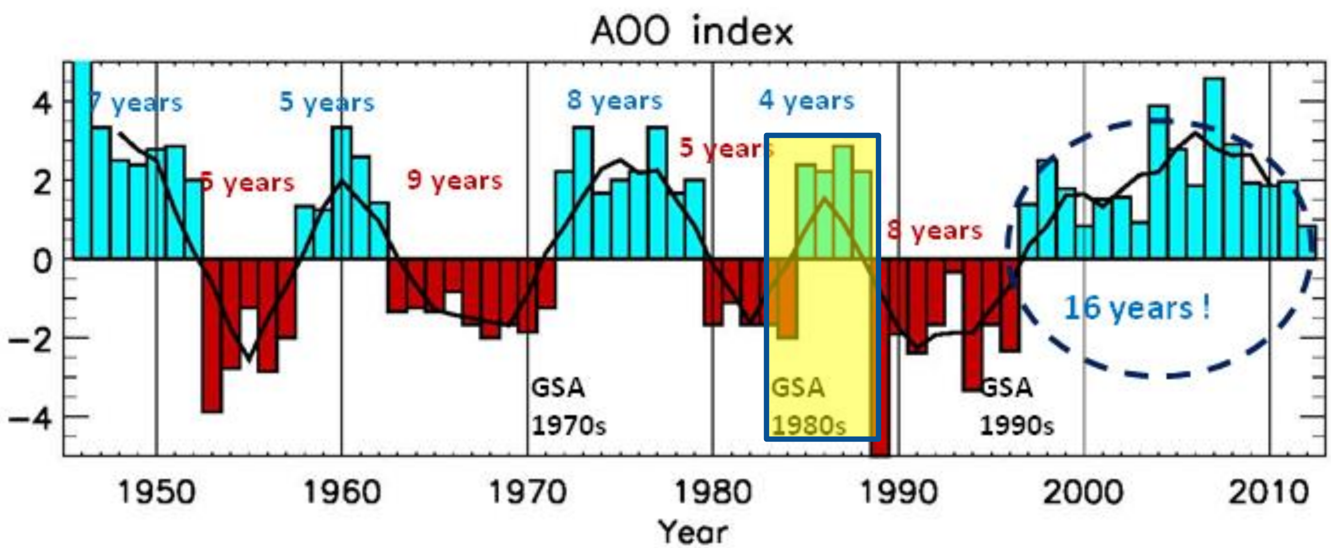
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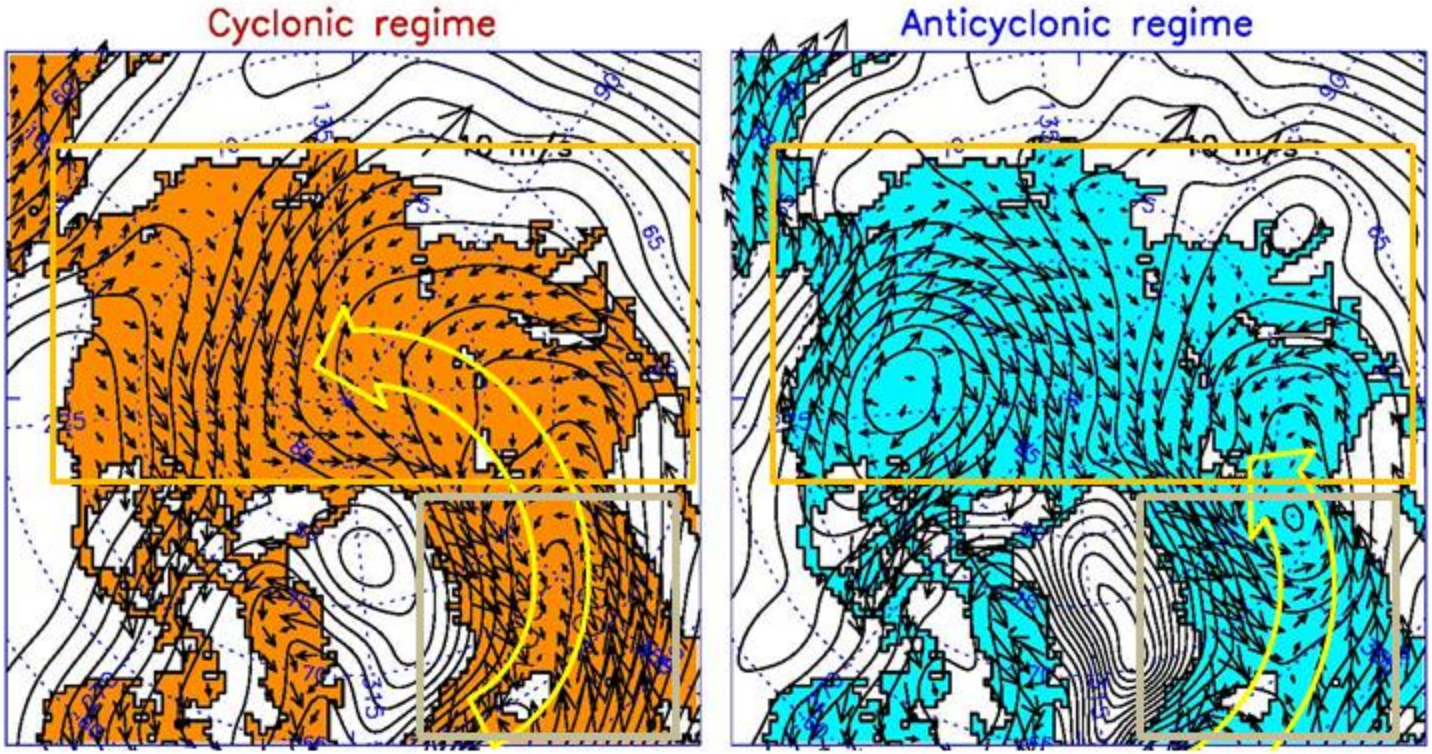
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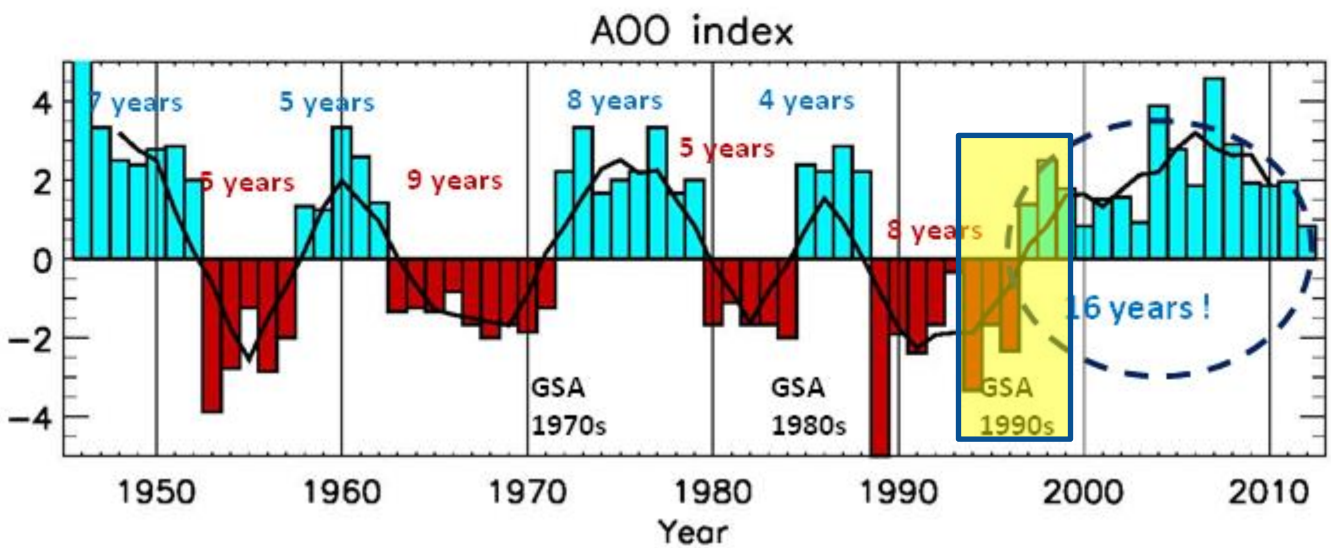
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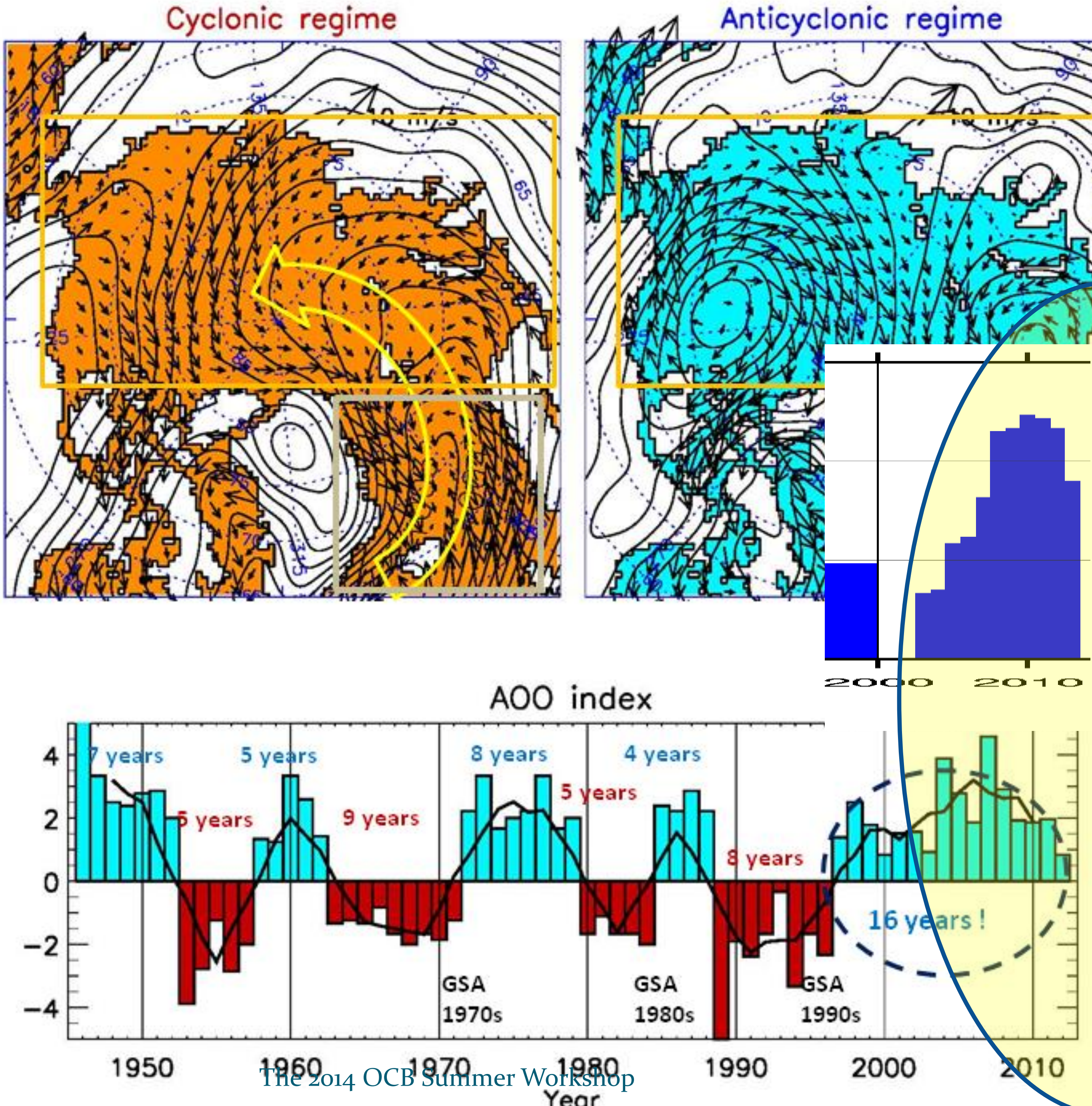
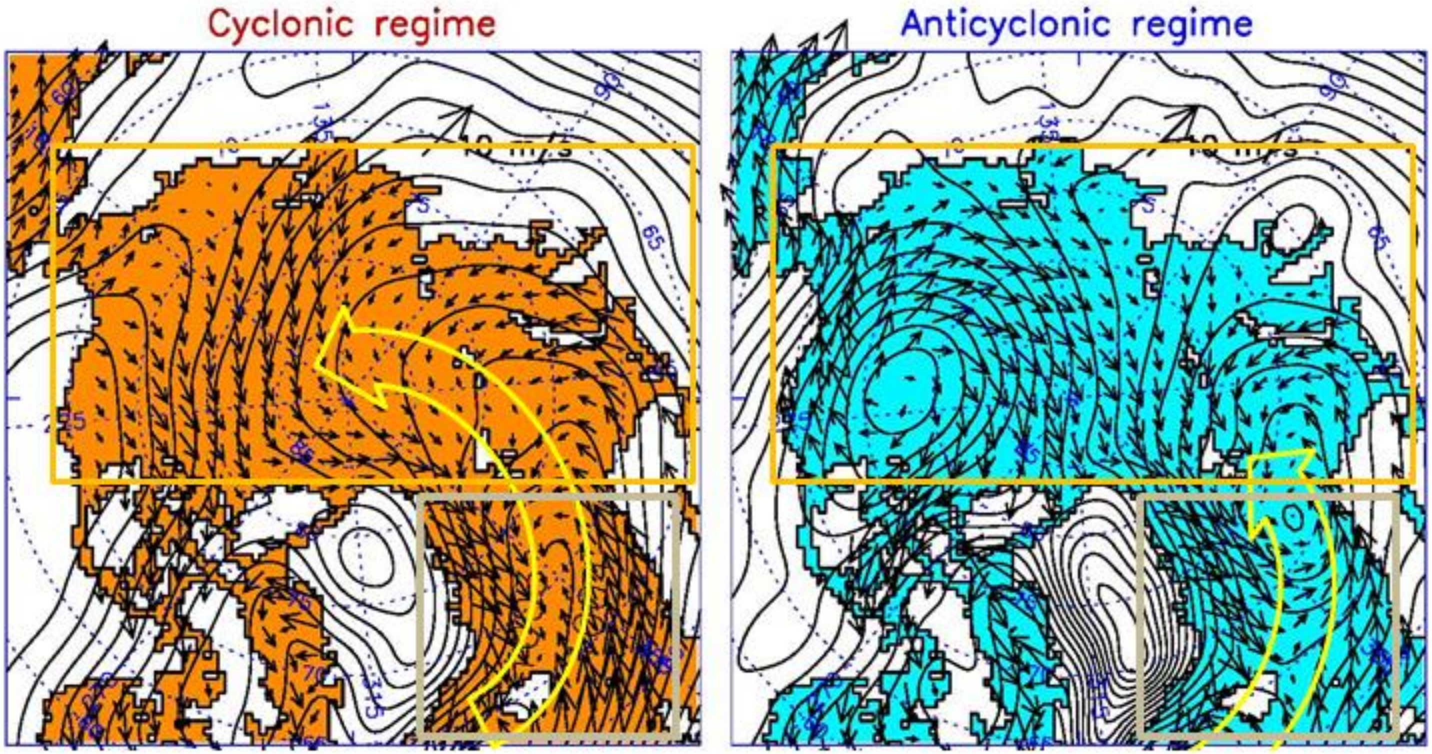



**Observed FW content in the BG region in 2003-2013**

- Our observations show that in the period 2003-2013 the BG region accumulated more than 5000 cubic km of freshwater, an increase of approximately 25% relative to the climatology of the 1970s.

- A possible FW release from the Arctic of this magnitude is enough to cause a salinity anomaly in the North Atlantic with magnitude comparable to the Great Salinity Anomaly (GSA) of the 1970s. GSAs can influence global climate by inhibiting deep wintertime convection that in turn may reduce the ocean meridional overturning circulation. In this sense, the BG FW reservoir is a "ticking time bomb" for climate.

- However, it is unclear whether the Arctic climate may have exceeded a "tipping point" where the freshwater will continue to accumulate and exceed anything observed in the past.

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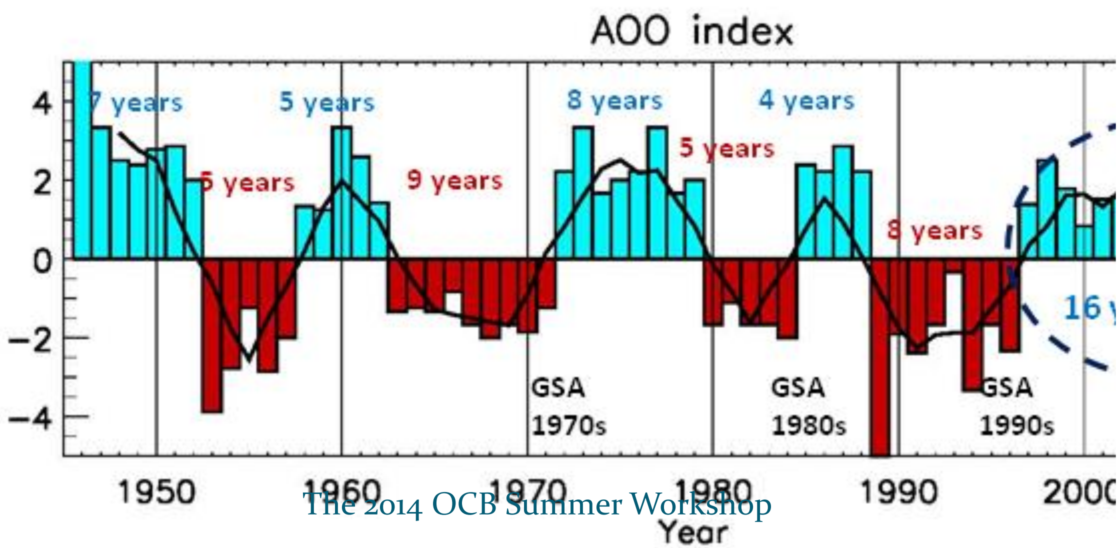


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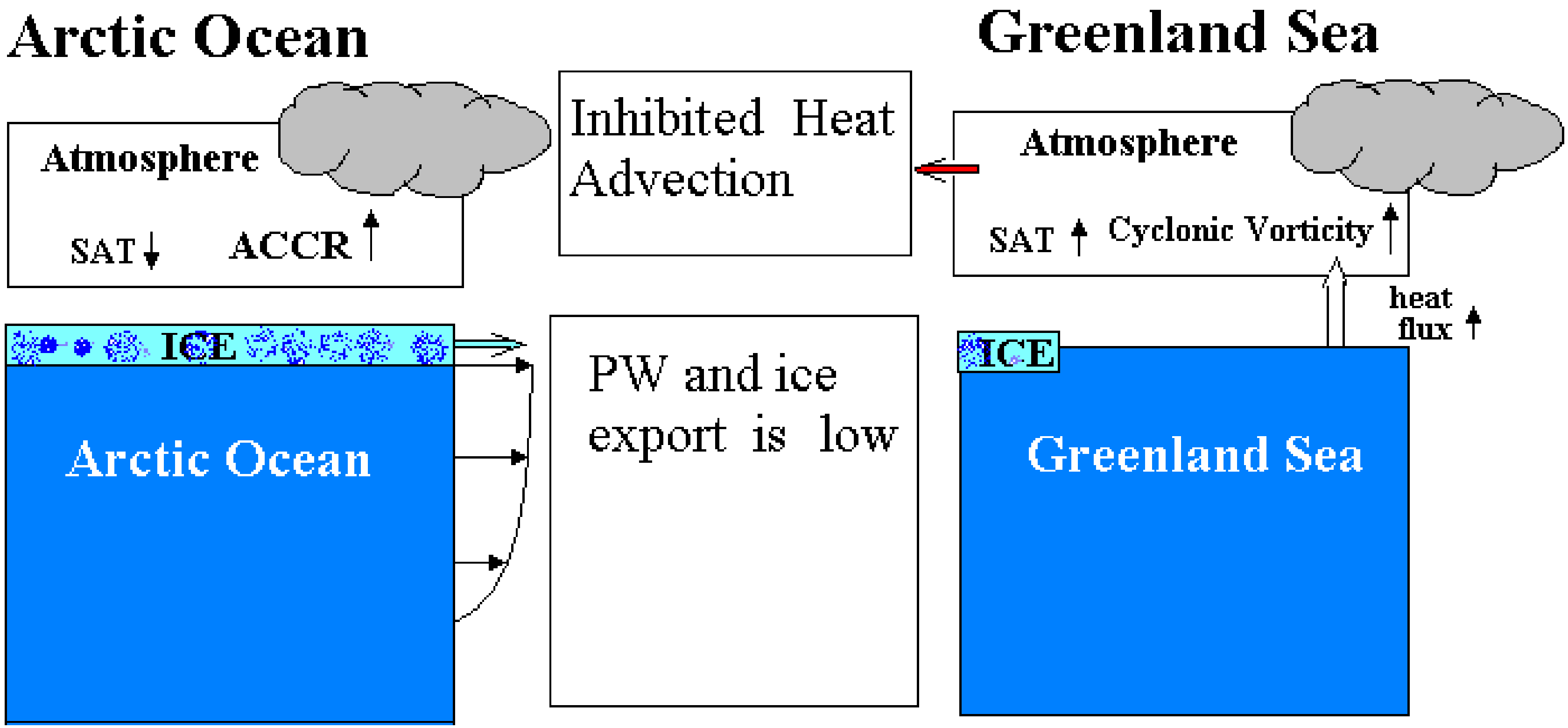
# Hypothesis

- Arctic Ocean – Greenland Sea form closed atmosphere-ice-ocean climatic system with auto-oscillatory behavior between two climate states with quasi-decadal periodicity
- The system is characterized by two opposite states: (1) ACCR - a cold Arctic and warm Greenland Sea region; (2) CCR - a warm Arctic and cold Greenland Sea region.
- Freshwater and heat fluxes regulate the regime shift in the system

# State 1: Cold Arctic Ocean/ Warm Greenland Sea (ACCR)




**Arctic Ocean:**

* Freshwater content is increasing
* SAT is dropping
* Anticyconic vorticity is intensifying

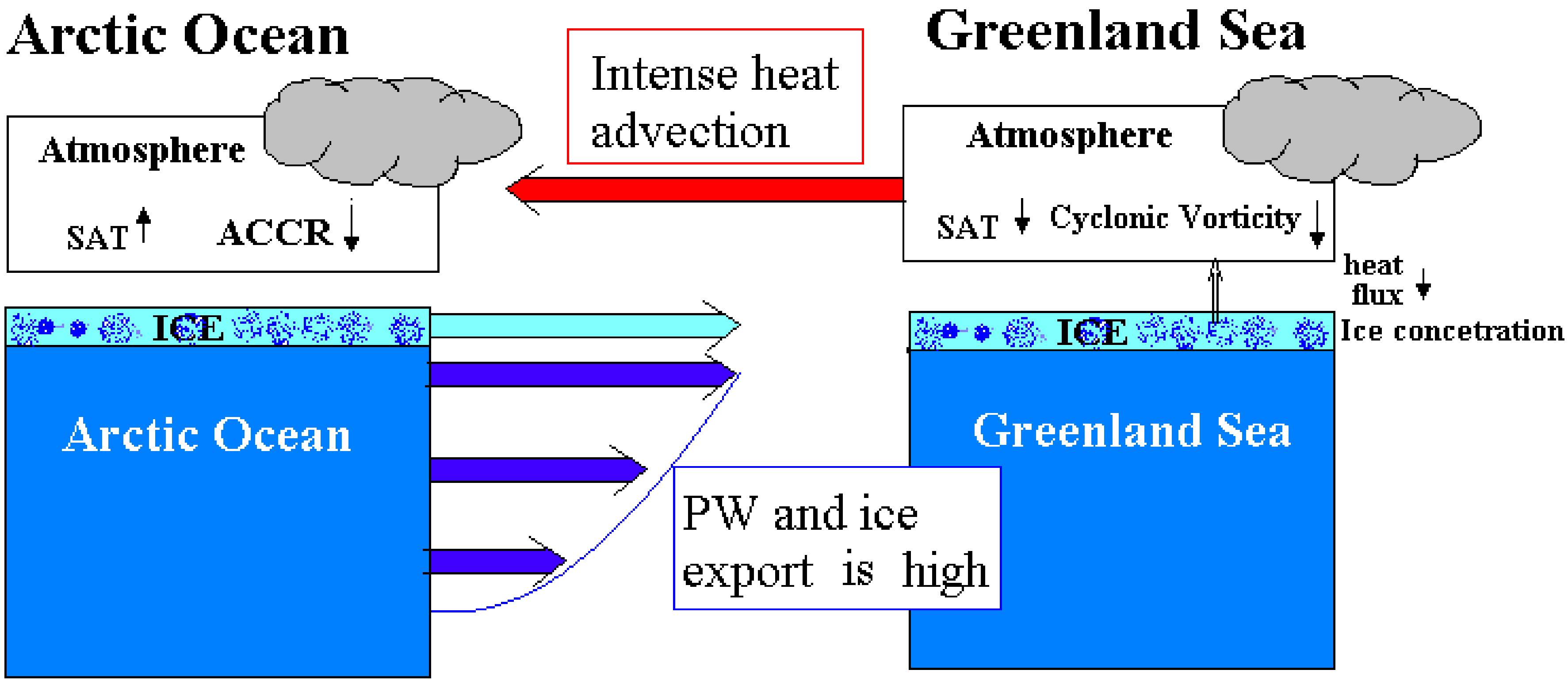
**Greenland Sea:**

* Freshwater import is suppressed
* Deep convection
* Heat flux to the atmosphere is intesified
* SAT is increasing

**Arctic Ocean - Greenland Sea:**

* SAT gradient is increasing
* Dynamic heights gradient is increasing

# State 2: Warm Arctic Ocean/ Cold Greenland Sea (CCR)




## Arctic Ocean:

* Freshwater content is decreasing
* Positive SAT anomalies
* Anticyclonic vorticity is inhibitted and partly changed to cyclonic

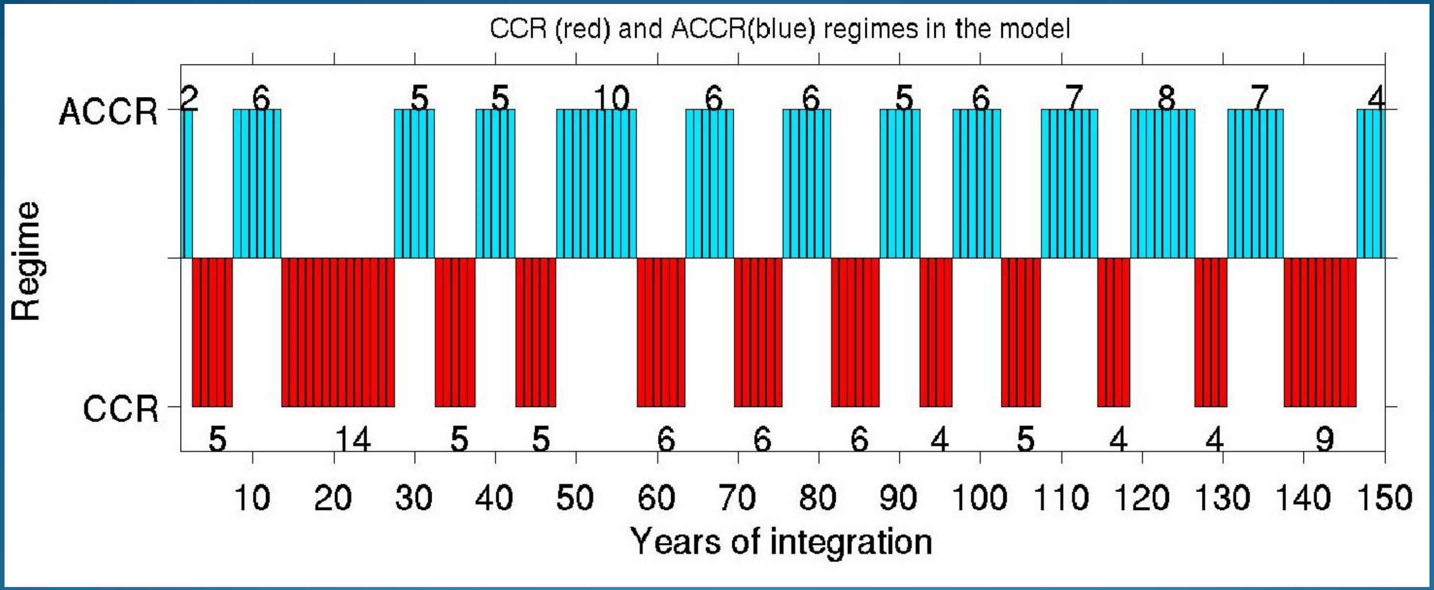
## Greenland Sea:

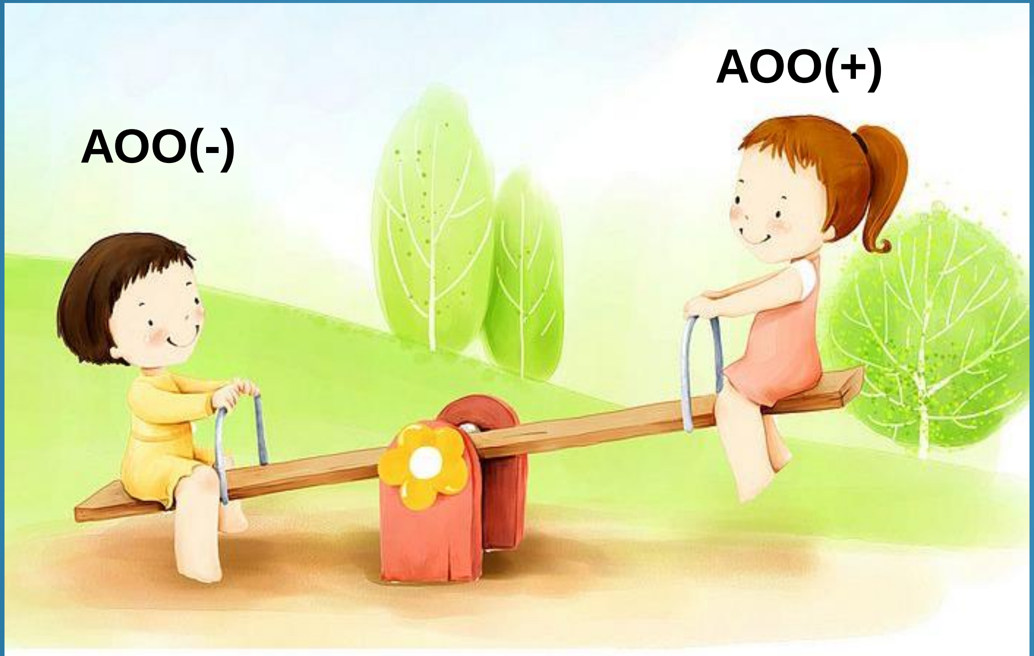
* Intense freshwater import
* No deep convection
* Damped heat flux to the atmosphere
* SAT drops

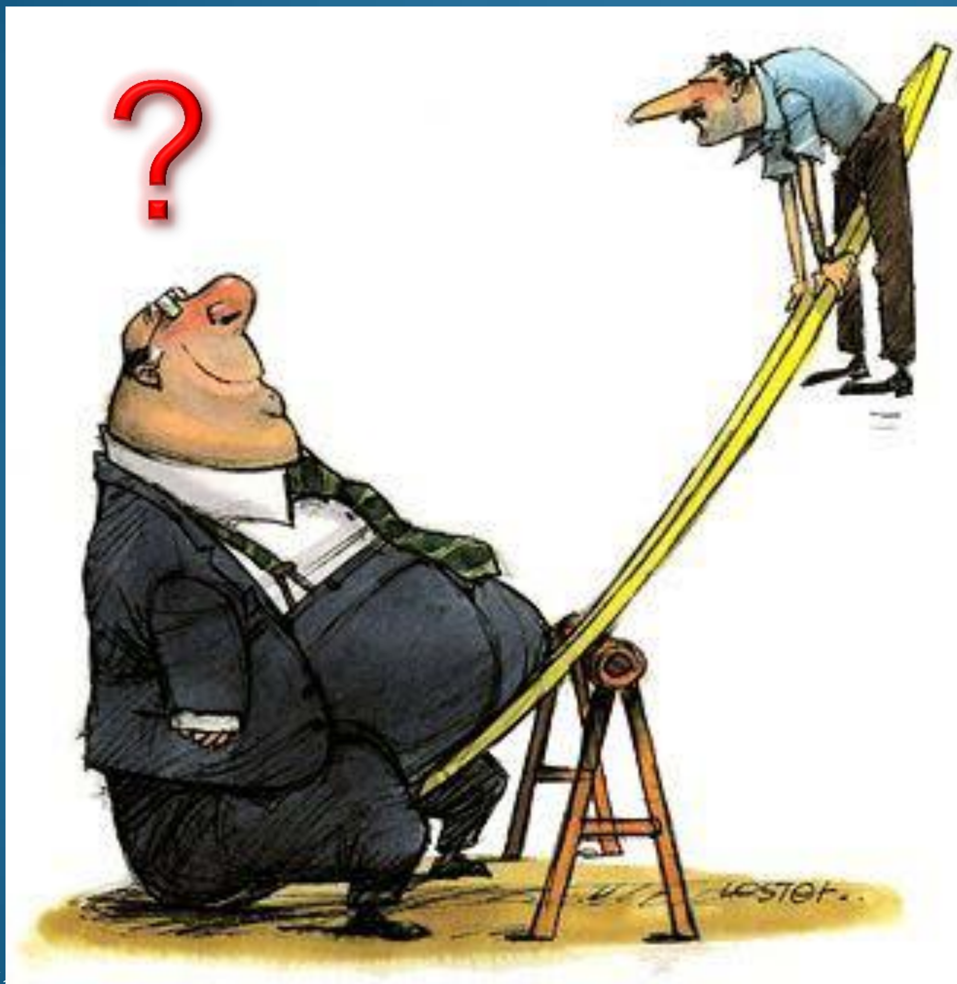
## Arctic Ocean - Greenland Sea:

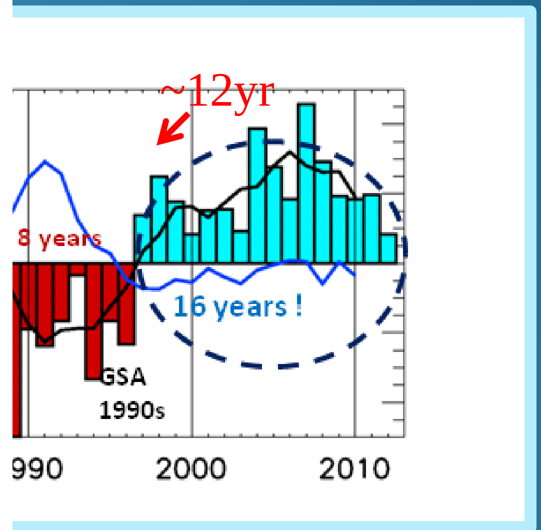
* SAT gradient is decreasing
* Dynamic heights grdaient is decreasing

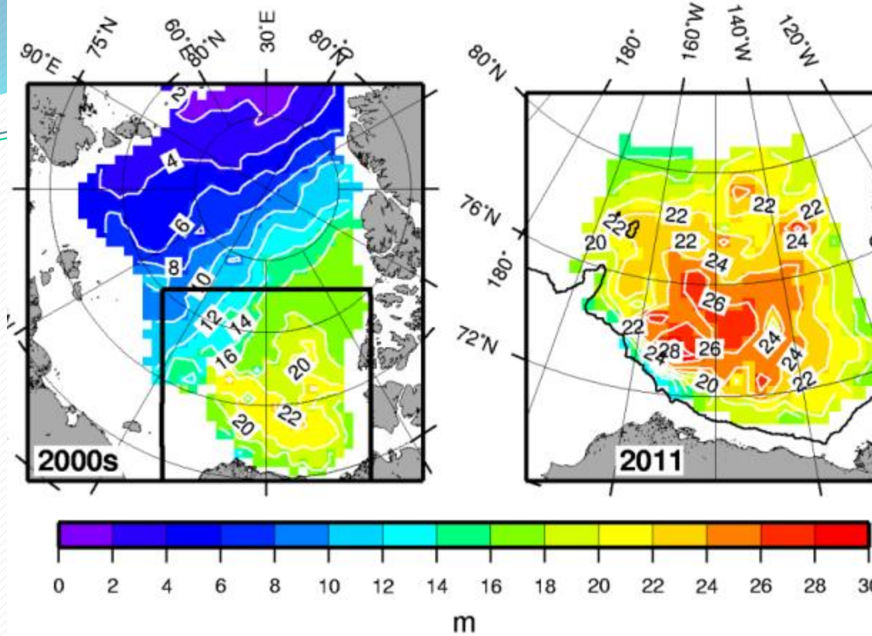
# Arctic Climate Variability (before the 2000s)

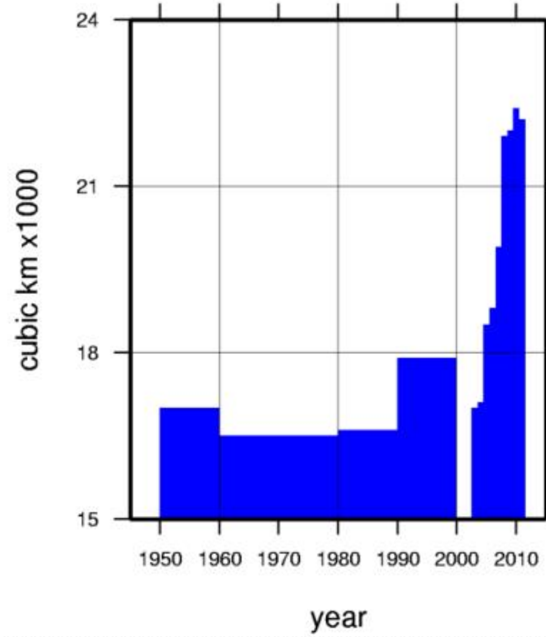


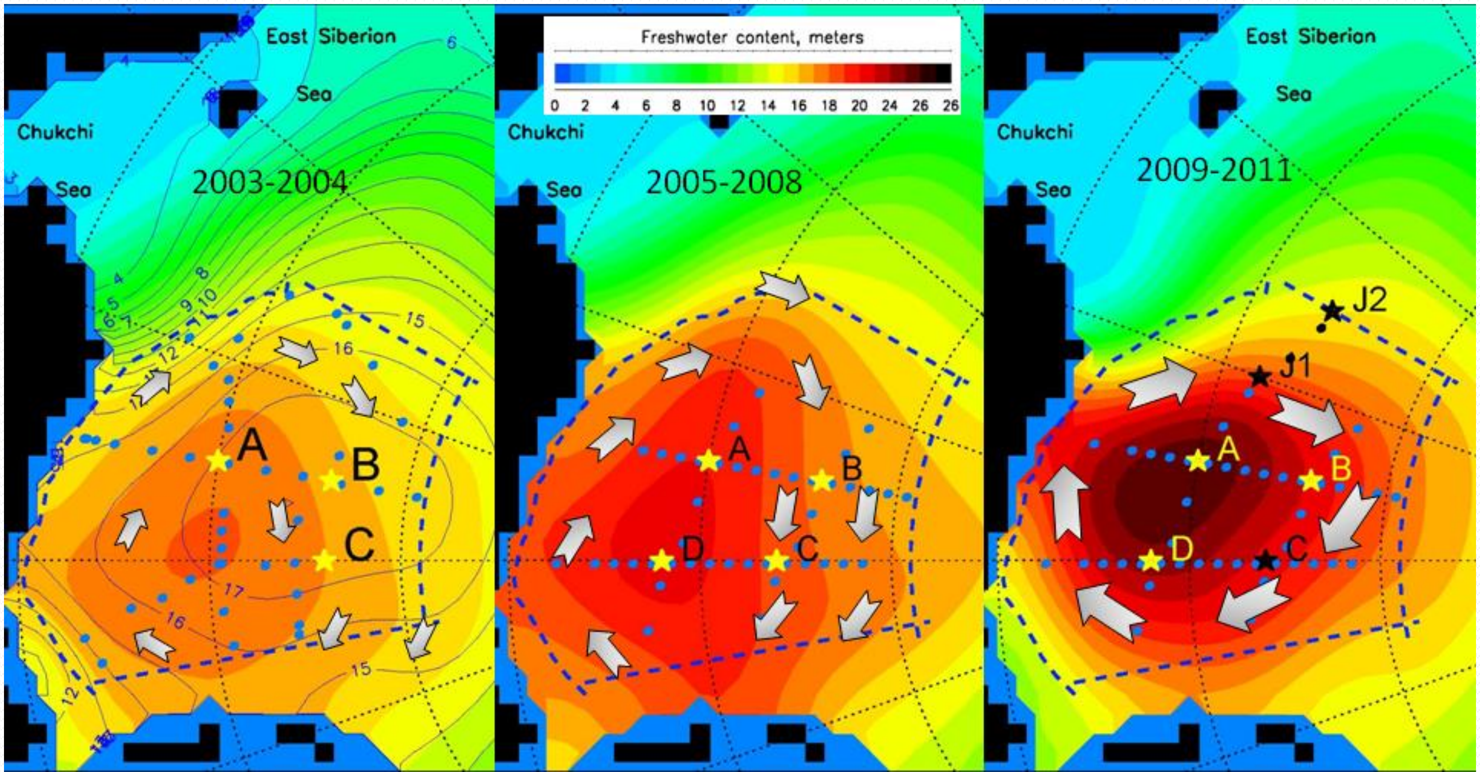






~12yr
8 years
16 years !
GSA
1990s
990
2000
2010

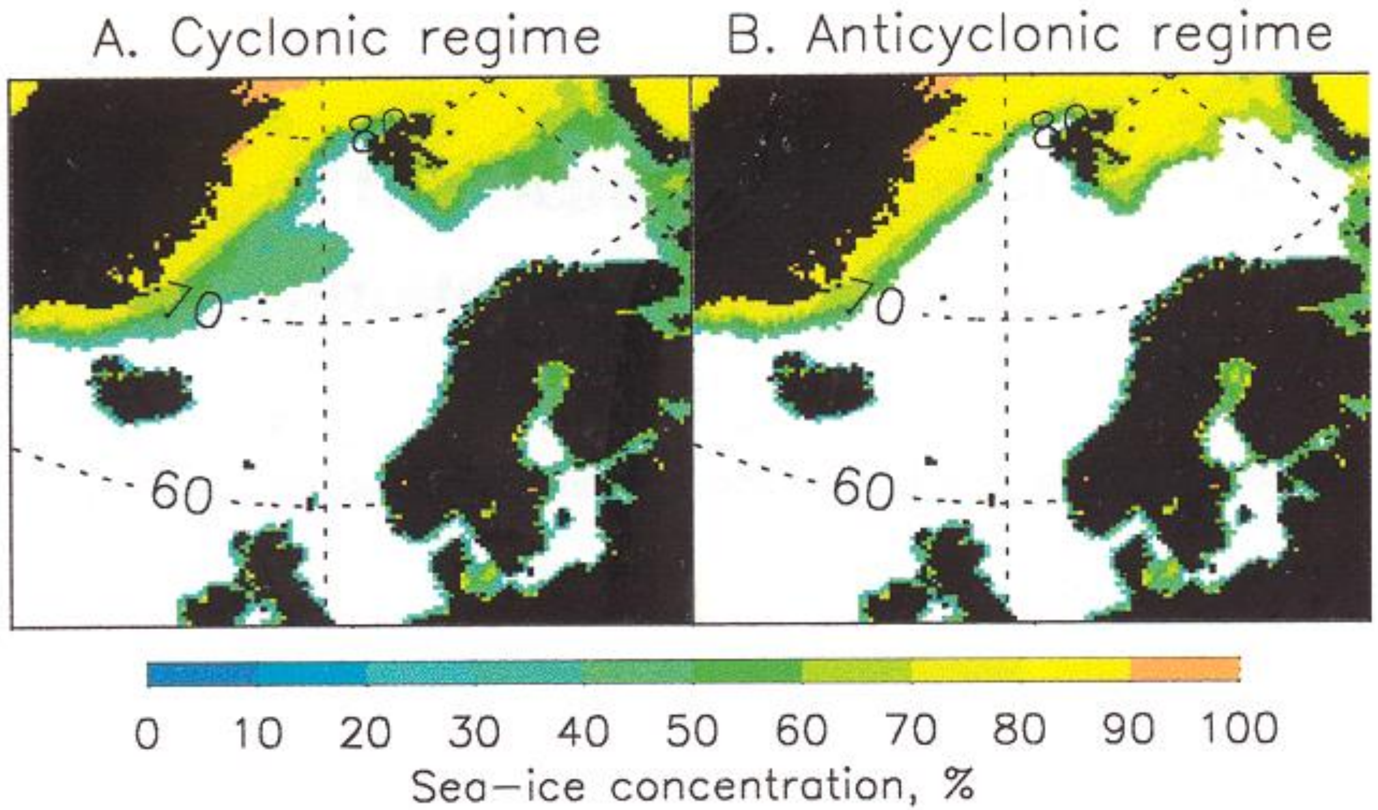

2000s
2011
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
m


cubic km x1000
15
18
21
24
1950 1960 1970 1980 1990 2000 2010
year

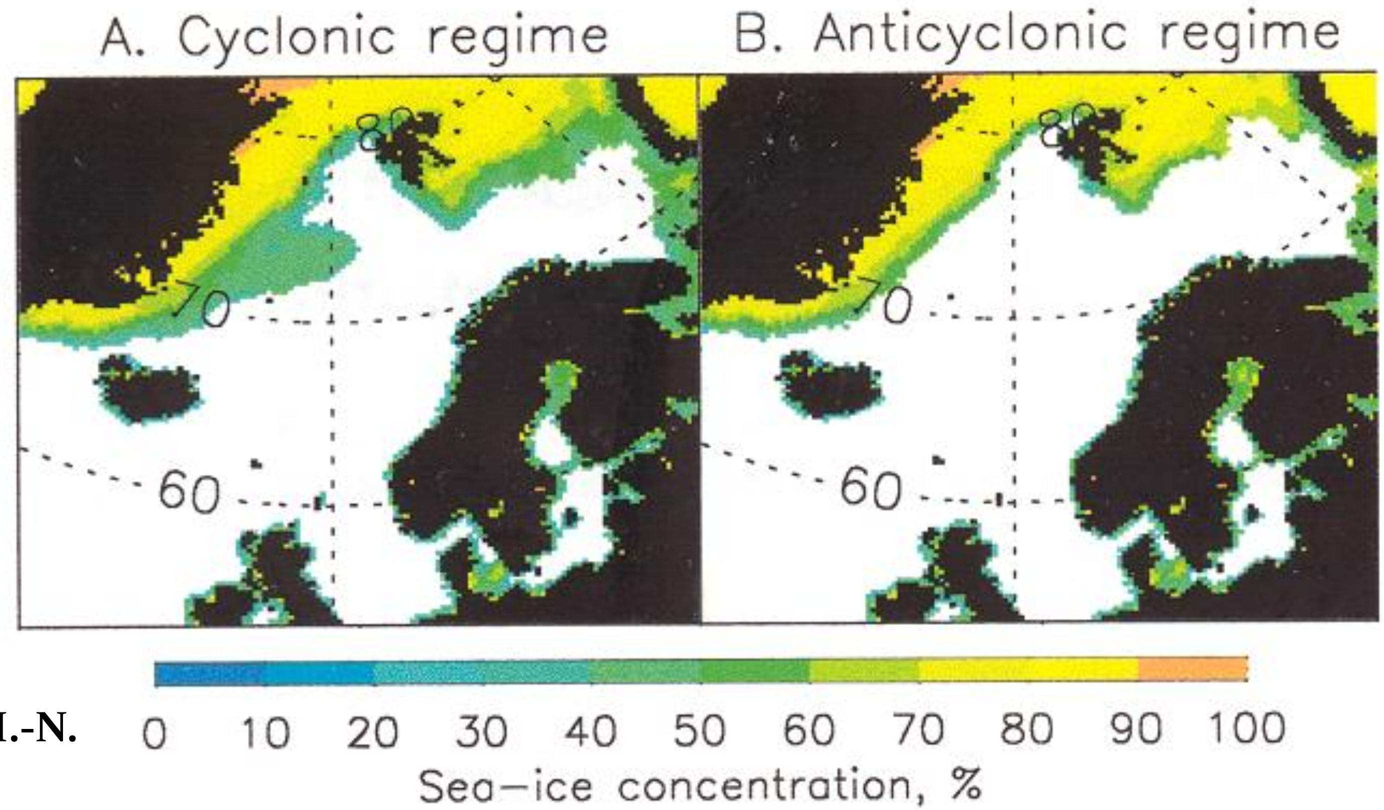

East Siberian Sea
Chukchi Sea
2003-2004
Freshwater content, meters
0 2 4 6 8 10 12 14 16 18 20 24 26 26
2005-2008
2009-2011
A
B
C
D
J1
J2

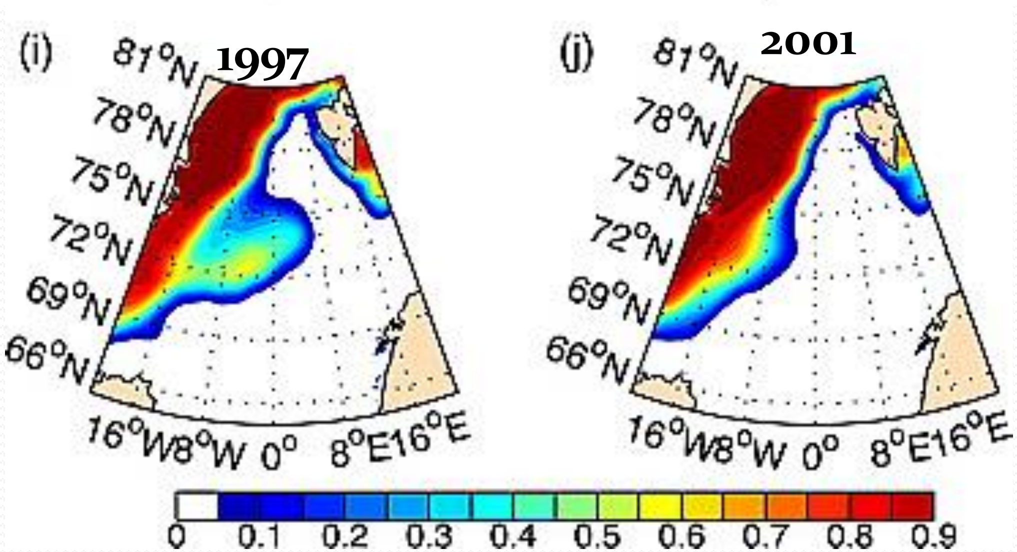
# Sea Ice Variability in the Greenland Sea and Circulation Regimes in the Arctic

Sea ice concentration in the central Greenland Sea is high during the CCR and low during the ACCR



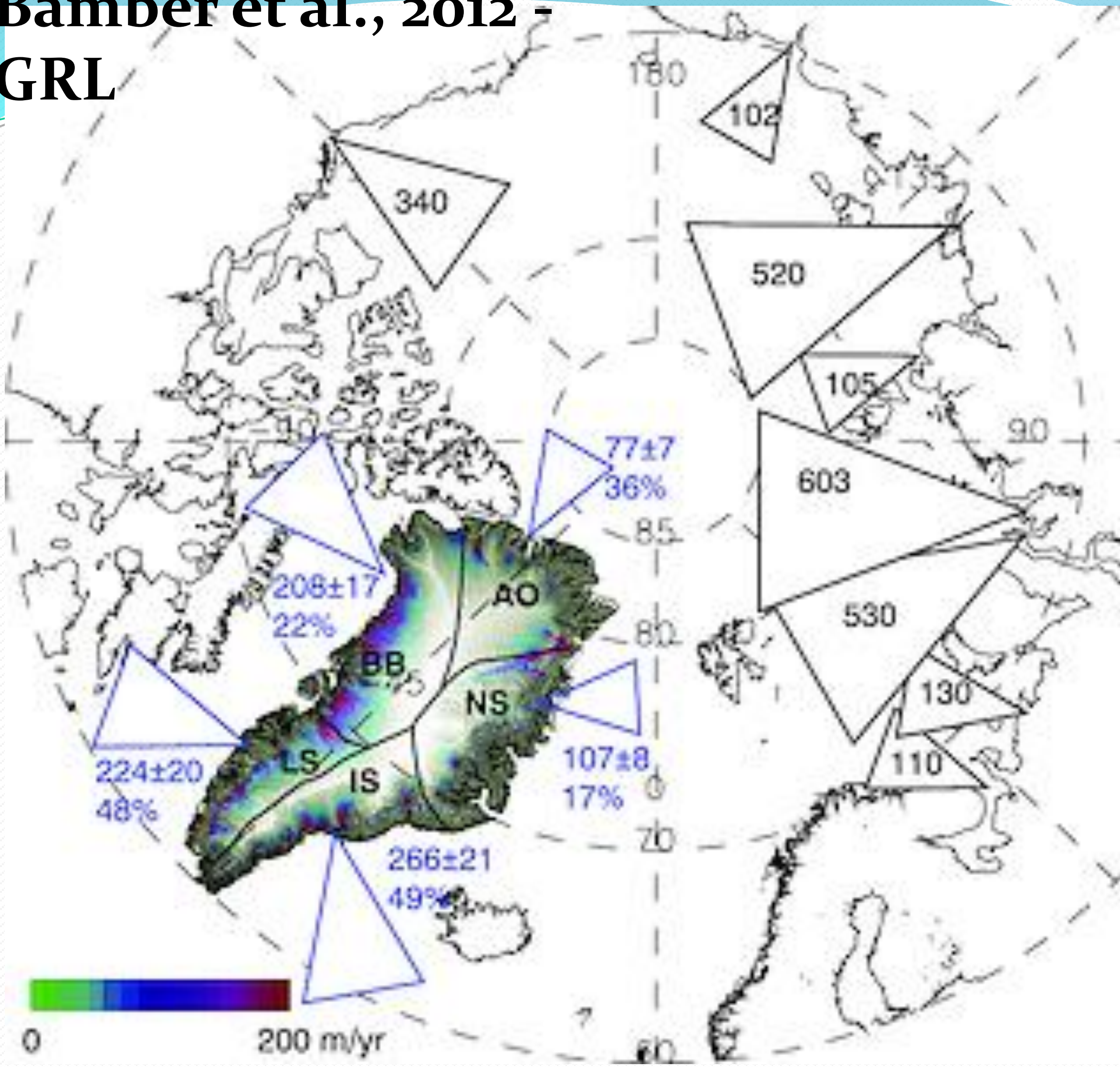

*Proshutinsky et al.*, 2002



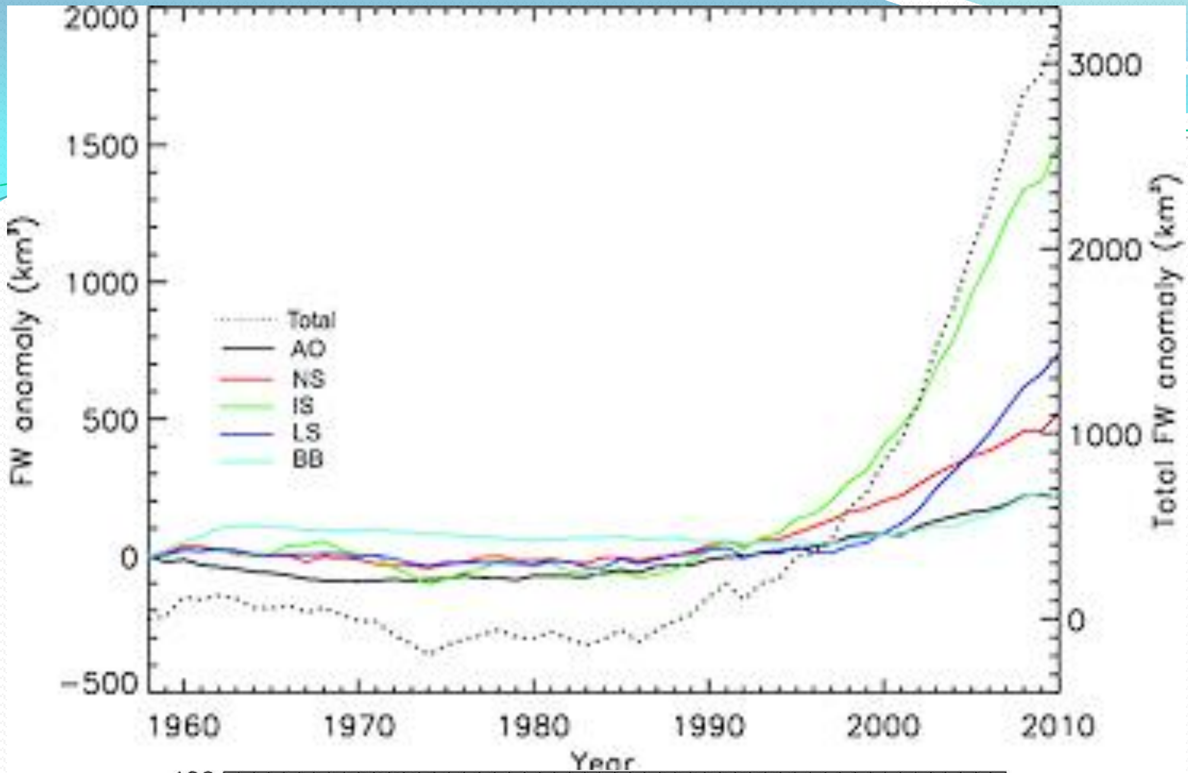

**Germe, A., M.-N. Houssais, C. Herbaut, and C. Cassou (2011), Greenland Sea sea ice variability over 1979–2007 and its link to the surface atmosphere, J. Geophys. Res., 116, C10034, doi:10.1029/2011JC006960.**

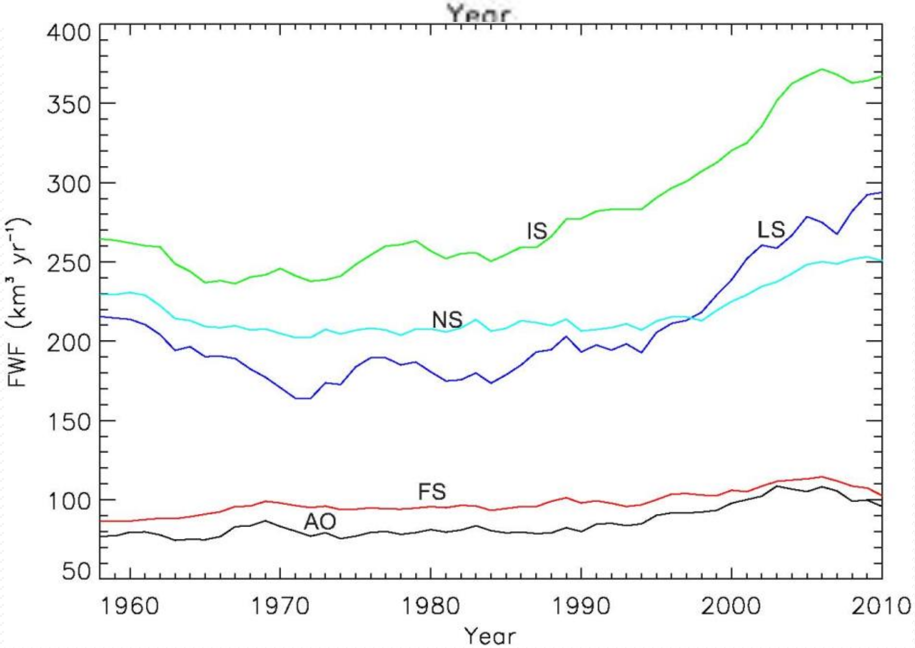
**Bamber et al., 2012 - GRL**




**Map showing the scaled magnitude of FW flux (the area of each triangle is proportional to the flux) for the five oceanographic units described in the text and the eight largest rivers into the Arctic Ocean. The numbers indicate the mean FW flux in $km^3 yr^{-1}$ for the reference period 1961–1990 for each region and the percentages refer to the relative increase in flux for the period 1992–2010, based on a linear trend.**

**The solid lines delineate the five drainage basins: AO = Arctic Ocean, NS = Nordic Seas, IS = Irminger Sea, LS = Labrador Sea, BB = Baffin Bay.**

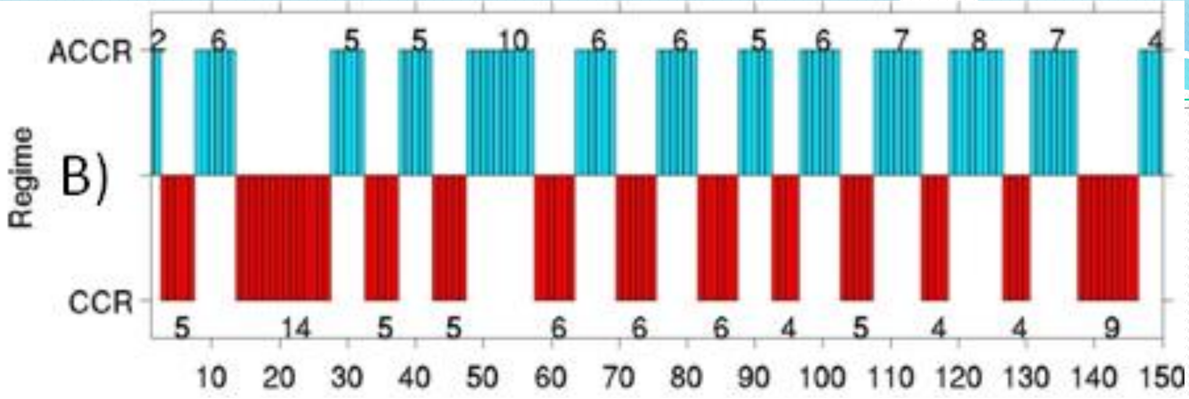


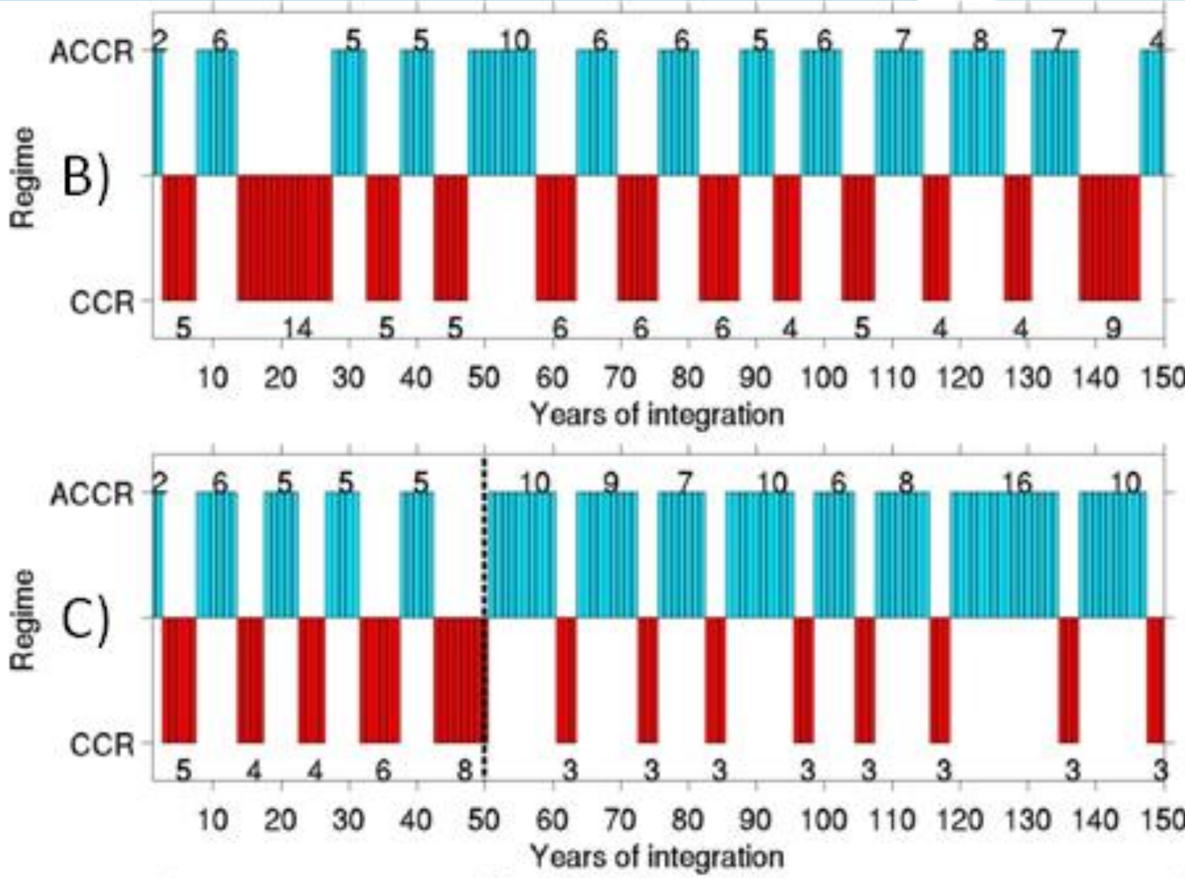

AO –FW flux to the Arctic Ocean

NS – FW flux to the Nordic Seas

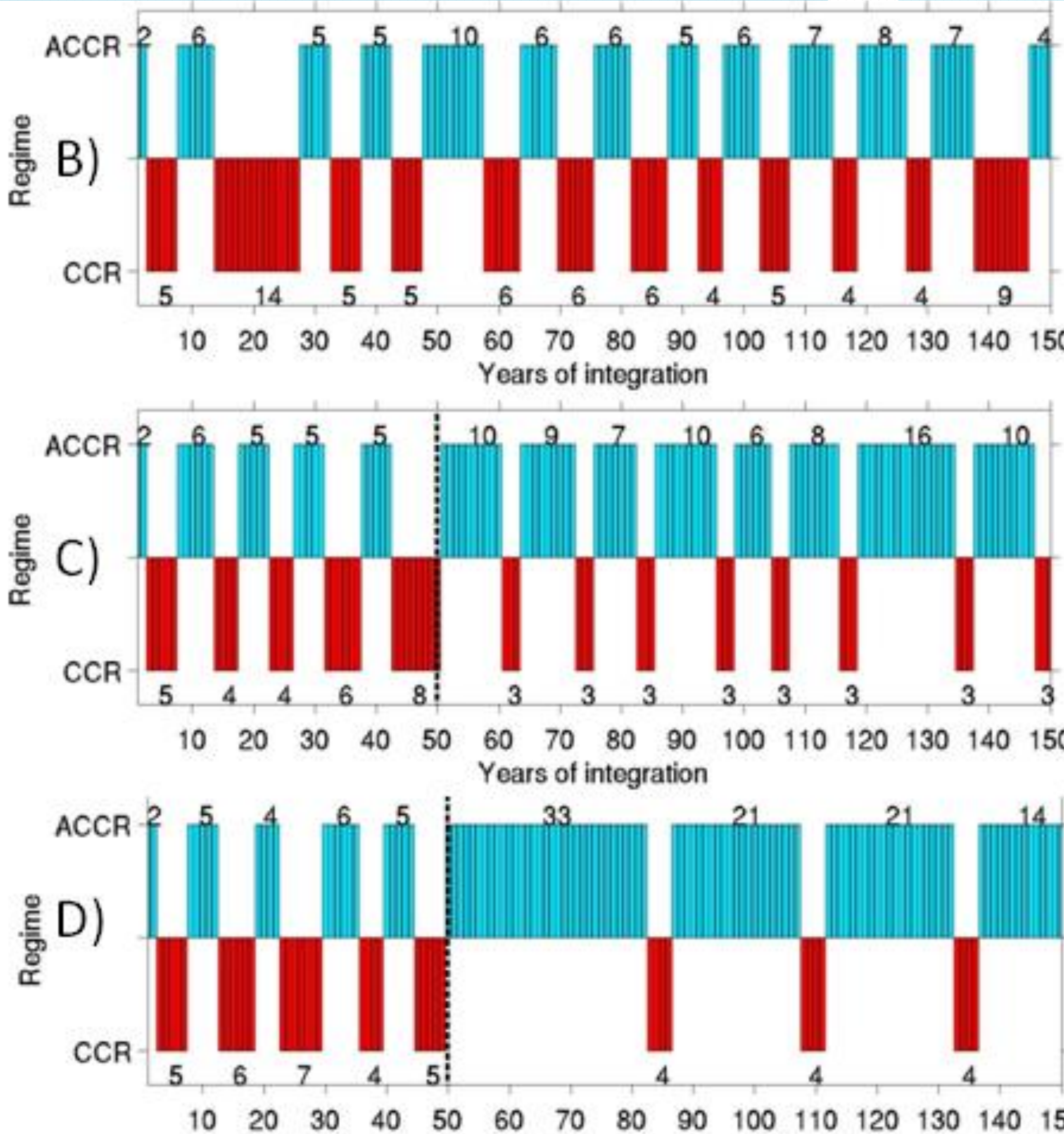
IS – FW flux to the Irminger Sea



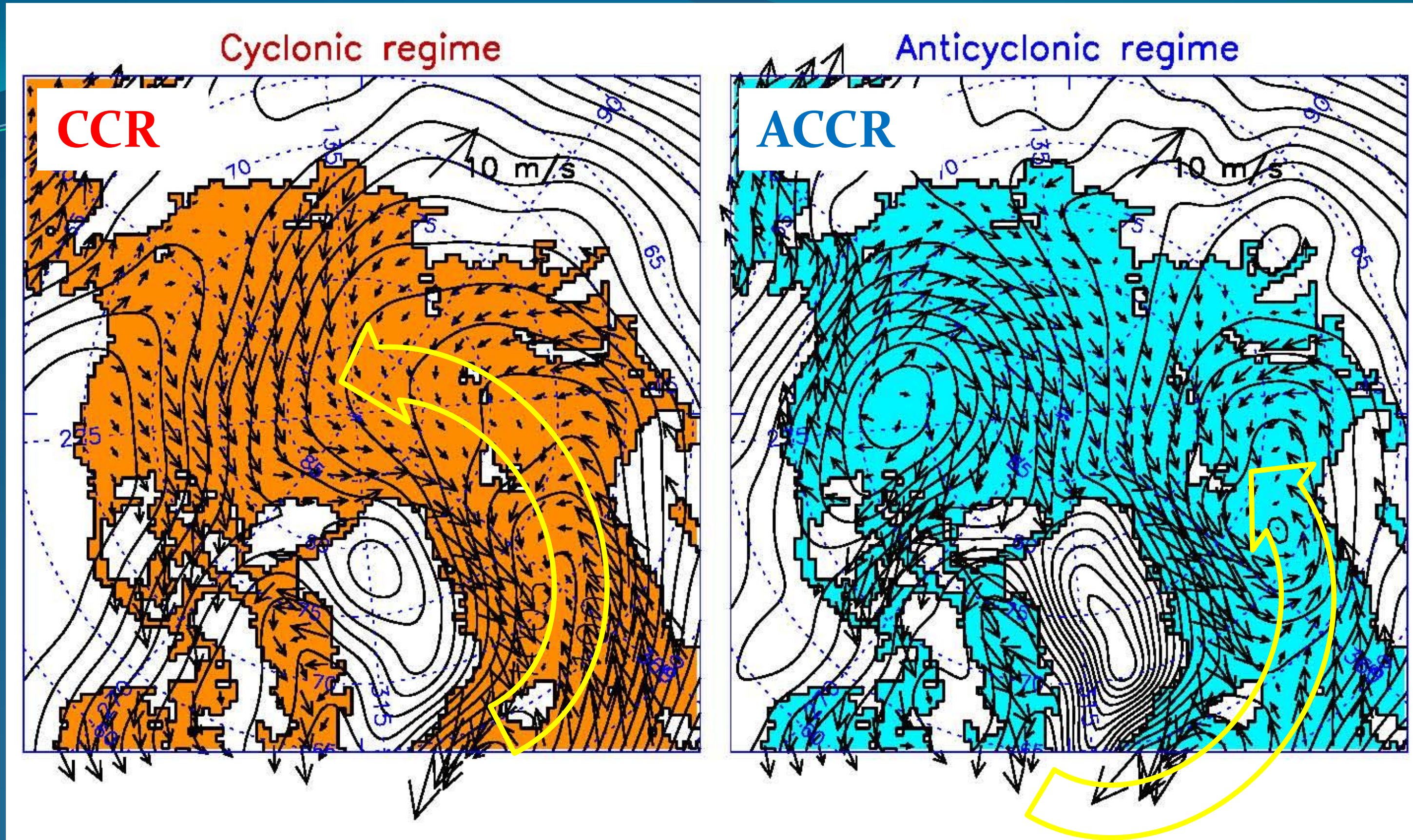

***B)*** *Time series of CCRs (red bars) and ACCRs (blue bars) simulated by our box model nealectina FW flux from*

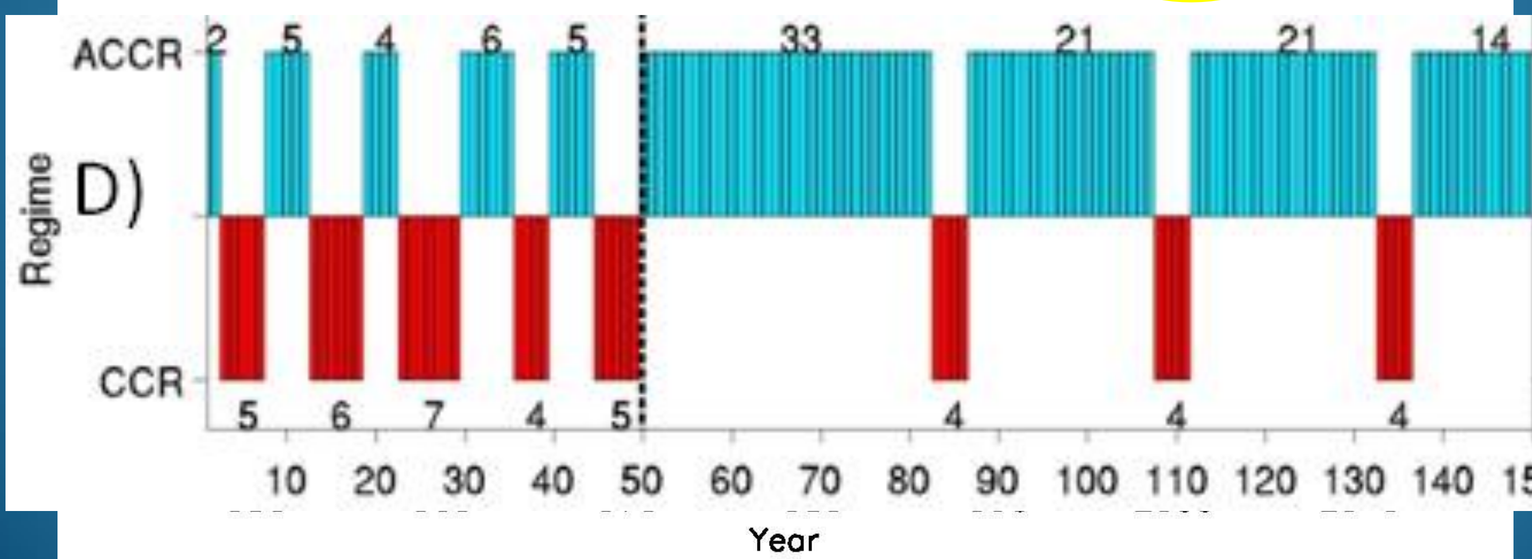



***B)*** *Time series of CCRs (red bars) and ACCRs (blue bars) simulated by our box model neglecting FW flux from Greenland;* ***C)*** *same as in (B) but with FW fluxes from Greenland introduced after 50 years in the model simulation;*




***B)** Time series of CCRs (red bars) and ACCRs (blue bars) simulated by our box model neglecting FW flux from Greenland; **C)** same as in (B) but with FW fluxes from Greenland introduced after 50 years in the model simulation; **D)** same as in (C) but with a doubling of FW fluxes from Greenland. Numbers by the bars indicate the regime duration in years.*


Cyclonic regime
CCR
10 m/s
Anticyclonic regime
ACCR
10 m/s


ACCR
2
5
4
6
5
33
21
21
14
D)
Regime
CCR
5
6
7
4
5
4
4
4
10
20
30
40
50
60
70
80
90
100
110
120
130
140
15
Year

# Concluding remarks:

Based on the analysis presented here we speculate that:

- Ocean-atmosphere heat fluxes in the GIN Sea vary with circulation regimes and regulate interactions between the Arctic Ocean and GIN Sea. Ocean to atmosphere heat fluxes are larger during ACCRs (compared to CCRs) supporting cyclogenesis and ultimately a regime shift to a CCR;
- The duration of ACCRs and CCRs in a changing climate will be different from those in the 20st century; a new mode of variability in the Arctic may consist of long-duration ACCRs, separated by relatively short duration CCRs.
- The major cause of cessation of decadal variability is the monotonically increasing FW flux anomaly from Greenland that began in the mid 1990s, coincident with a shift to a positive AOO.

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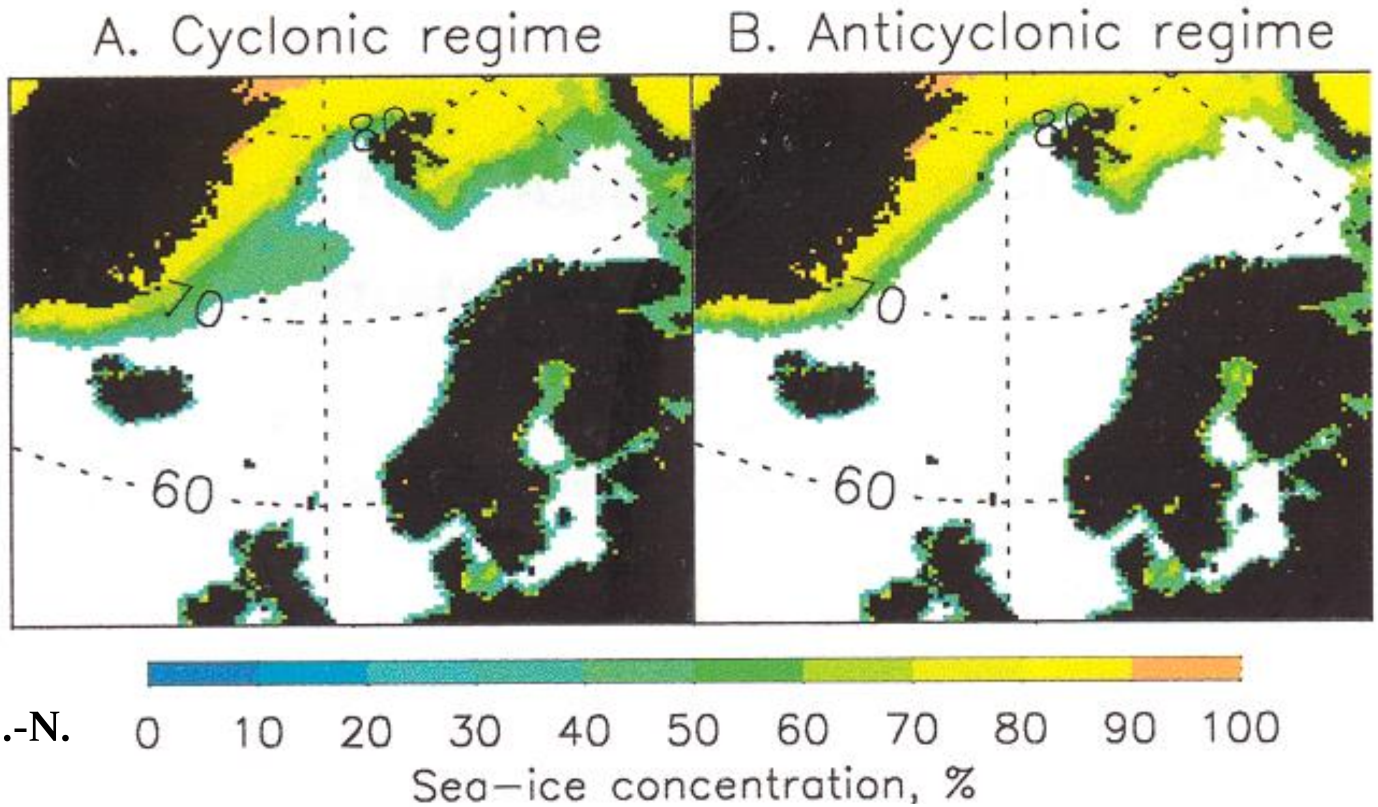
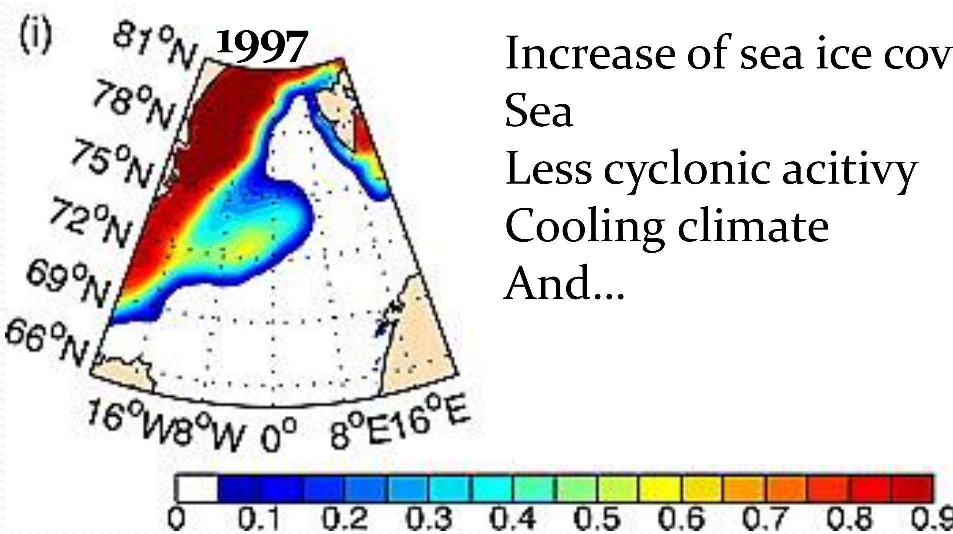
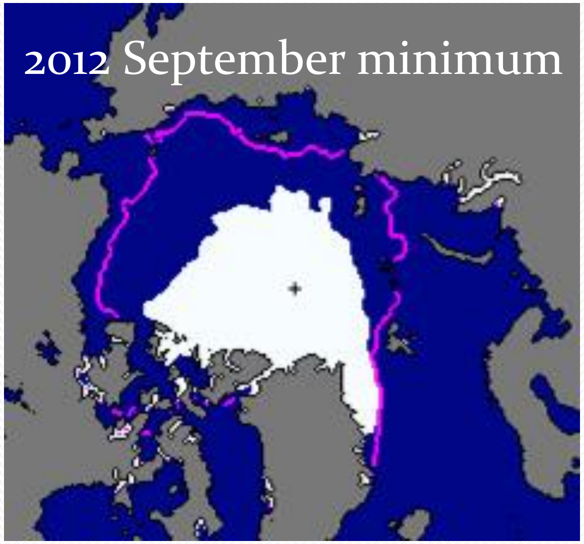
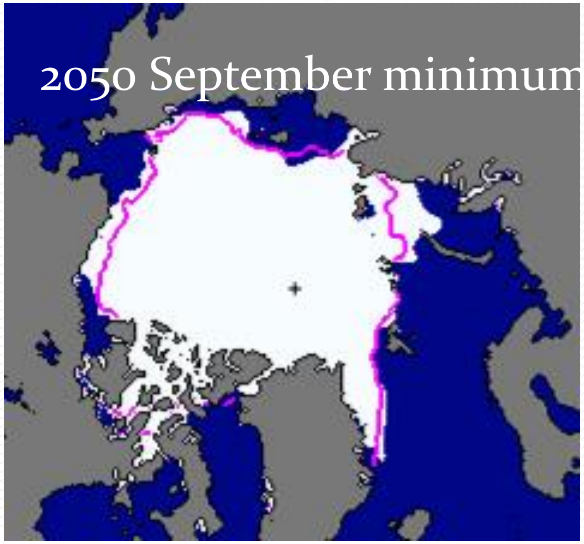


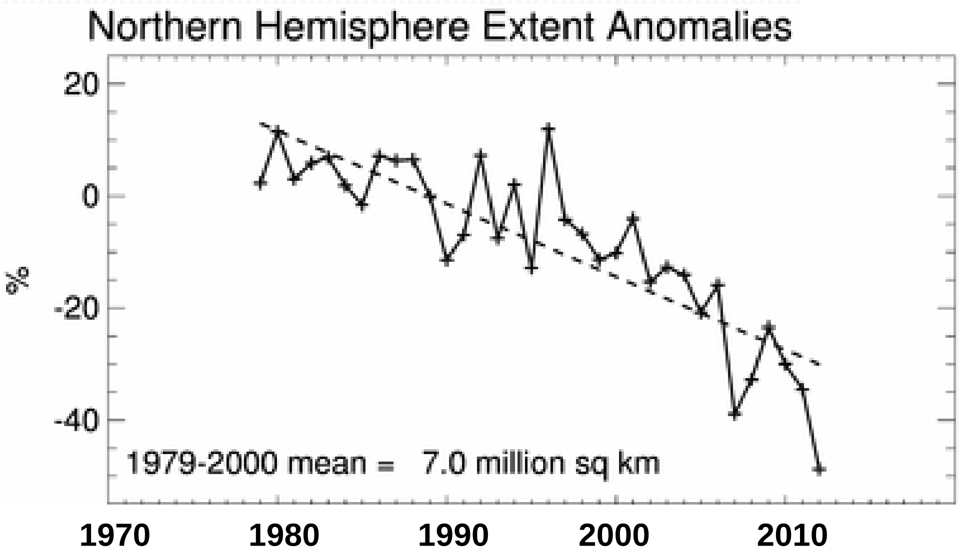

**Germe, A., M.-N. Houssais, C. Herbaut, and C. Cassou (2011), Greenland Sea sea ice variability over 1979–2007 and its link to the surface atmosphere, J. Geophys. Res., 116, C10034, doi:10.1029/2011JC006960.**

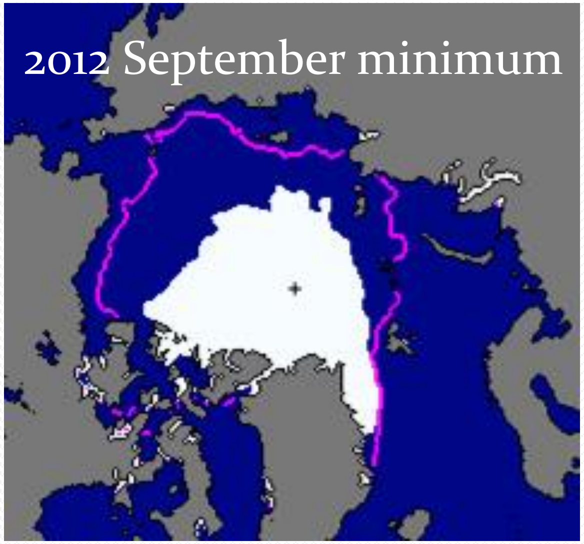


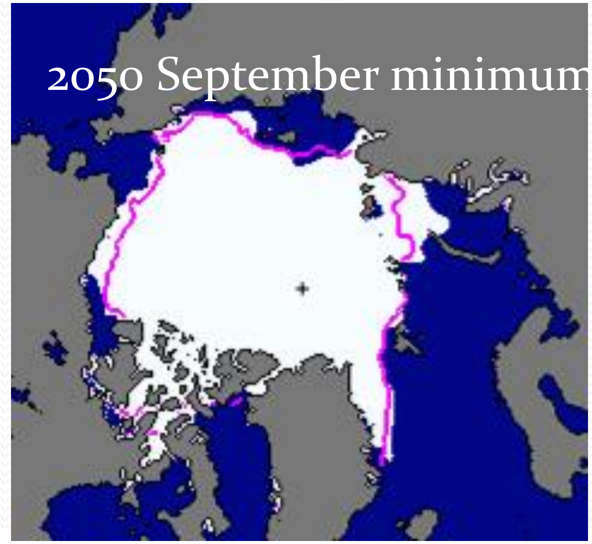

Increase of sea ice coverage in the GIN Sea
Less cyclonic acitivy
Cooling climate
And…

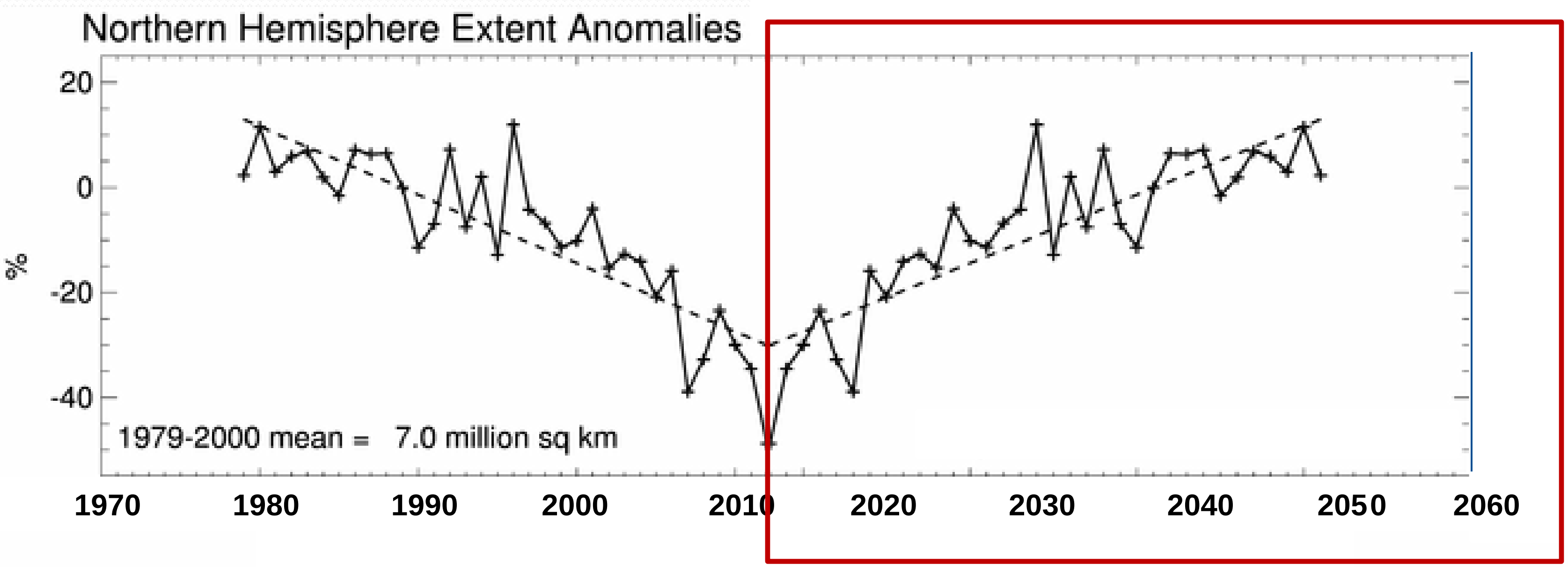

2012 September minimum


2050 September minimum


Northern Hemisphere Extent Anomalies
20
0
-20
-40
%
1979-2000 mean = 7.0 million sq km
1970
1980
1990
2000
2010


2012 September minimum


2050 September minimum


Northern Hemisphere Extent Anomalies
%
20
0
-20
-40
1979-2000 mean = 7.0 million sq km
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060



- **Finally, we can conclude that this scenario can be reinforced toward climate cooling in the case of continuing Greenland ice sheet melt and at the same time freshwater release from the Arctic Ocean.**

- **Under condition of global warming the processes of exchange between the Arctic (including Greenland) and the North Atlantic will be intensifying.**