Increase in acidifying water in the Western Arctic Ocean

Di Qi[1]

Liqi Chen[1] *, Wei-Jun Cai*[2]*, Basshan Chen*[1], et al.

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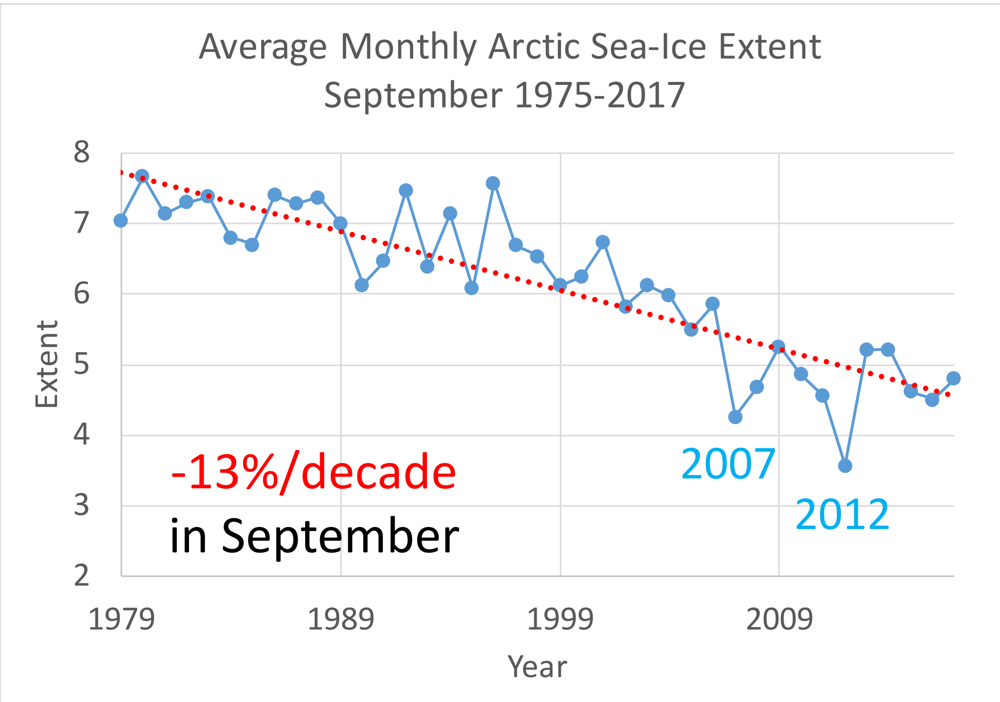
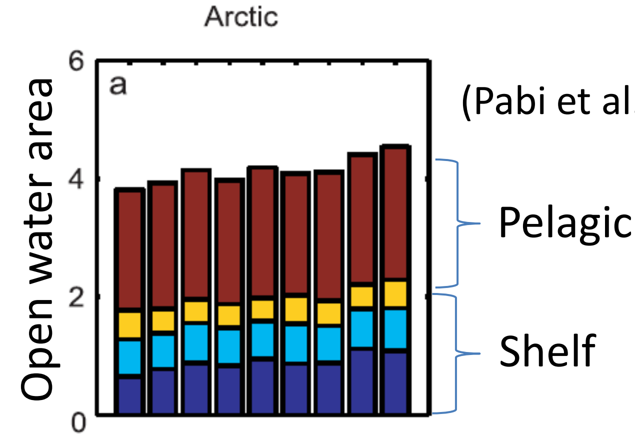
Outline

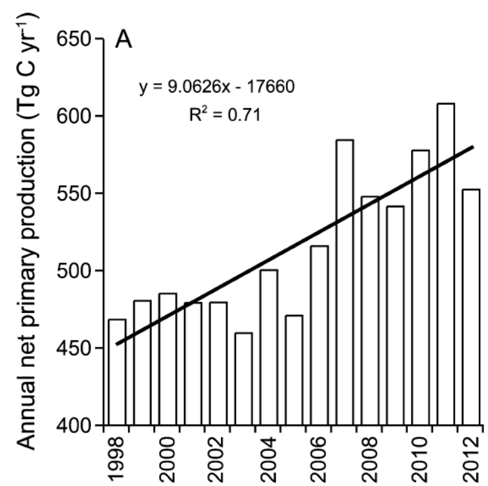
- Background
- Upper ocean Ω_{arag} observations in the Arctic basin
- Link Ω_{arag} to the anomalous circulation pattern and sea-ice retreat
- Conclusions

A reduction of sea ice extent in summer

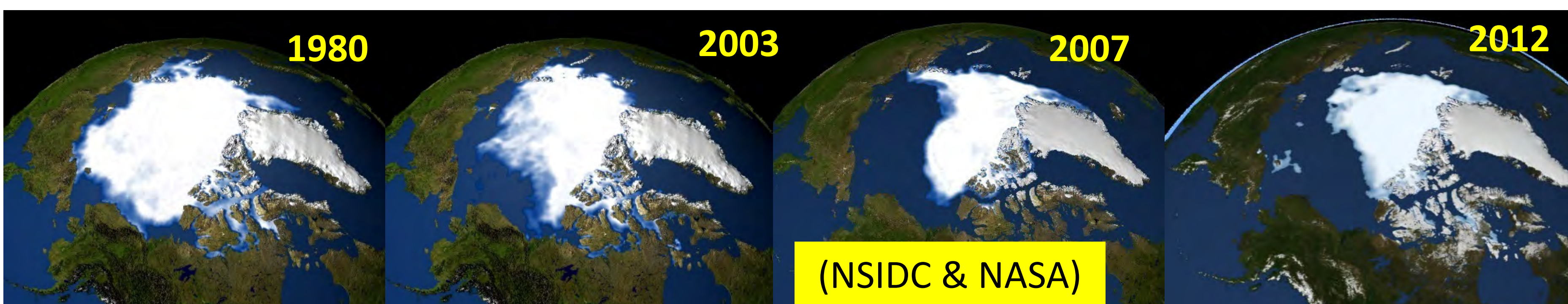




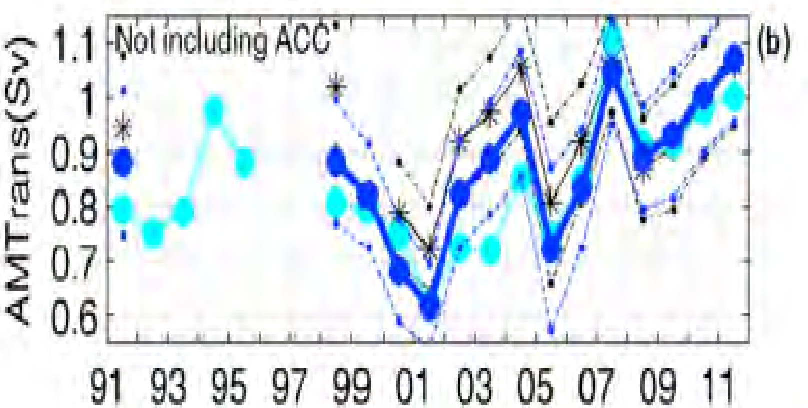
(Pabi et al., 2008)



(Arrigo and van Dijken, 2015)

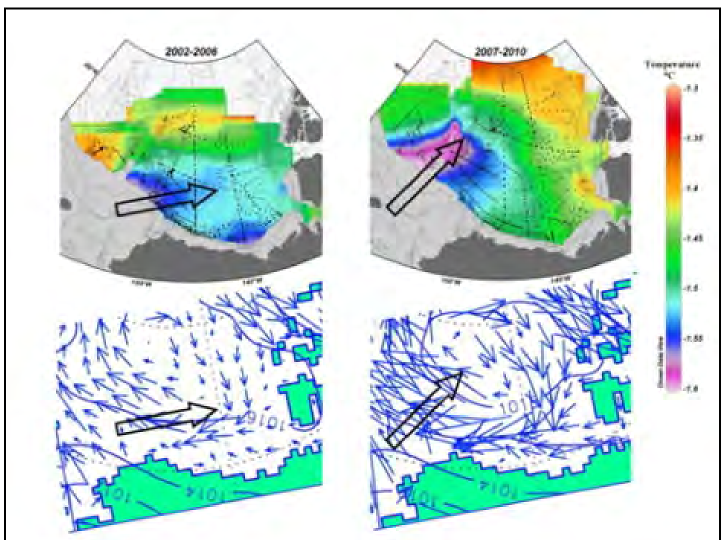


Physical environmental changes in the Pacific Arctic region



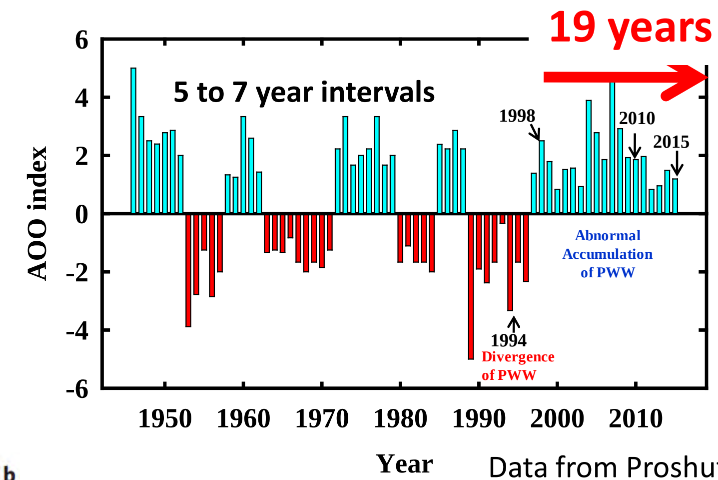
Woodgate et al., 2012

- **Bering Strait throughflow has increased by ~50%**

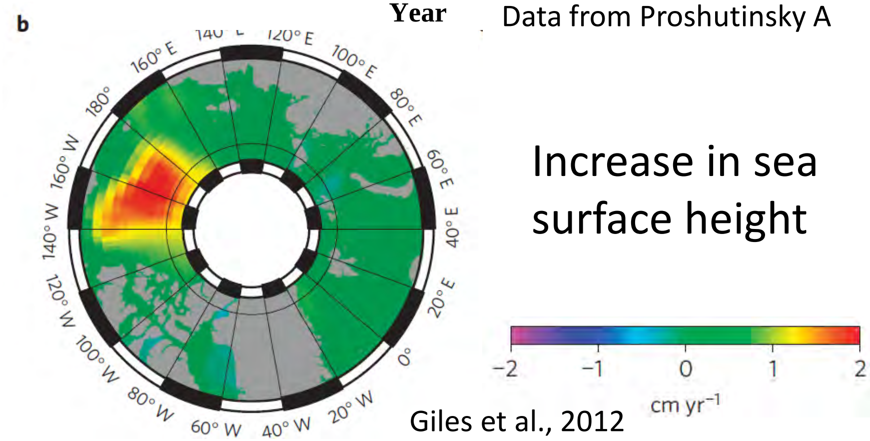


[NOAA, Arctic report card: update for 2011]

- **More PWW advected directly into the interior basin**



Data from Proshutinsky A



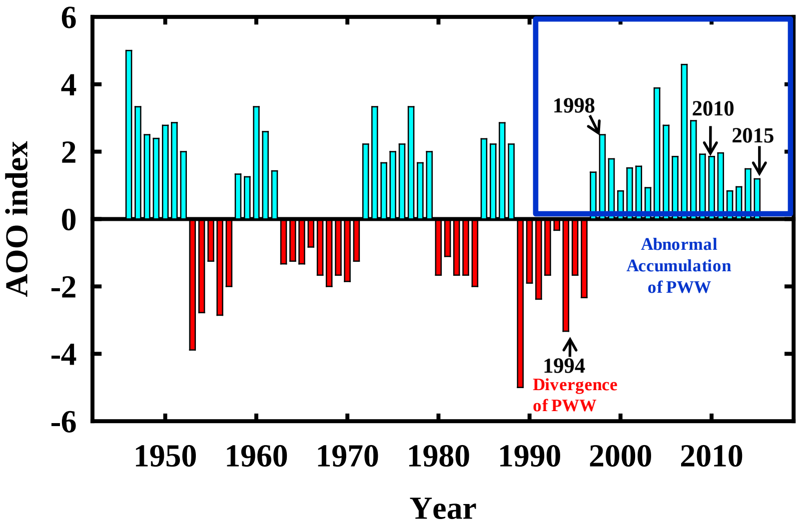
Giles et al., 2012

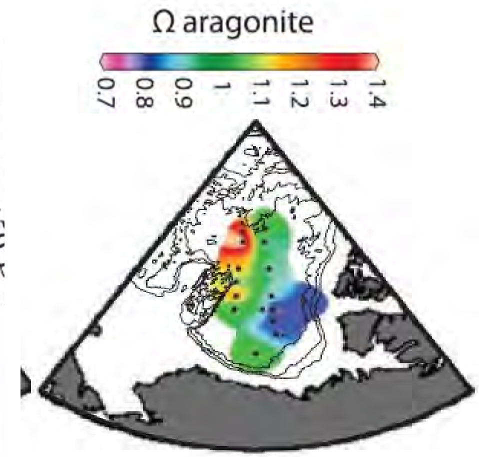
- The anticyclonic circulation (ACCRs) has strengthened the Beaufort Gyre (+AOO index) , accumulation of freshwater, and downwelling (Ekman Pumping) in the Canada Basin, all resulting in an expansion and deepening of the PWW area

Summary the environmental changes in the Pacific Arctic region

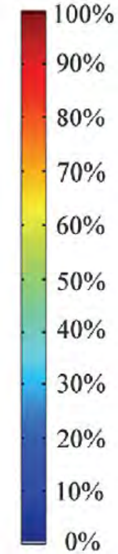
- Increase in sea surface temperatures (Steele et al., 2008)
- **Rapid sea-ice retreat (Perovich et al., 2009)**
- A freshening of surface waters (Yamamoto-Kawai et al., 2009)
- **An increase in Pacific water inflow into the Arctic (Woodgate et al., 2012)**
- An increase in surface carbon CO_2 concentrations (Cai et al., 2010)
- Increased rates of primary production (Arrigo and van Dijken, 2012)
- **An increased freshwater storage** (Giles et al., 2012)

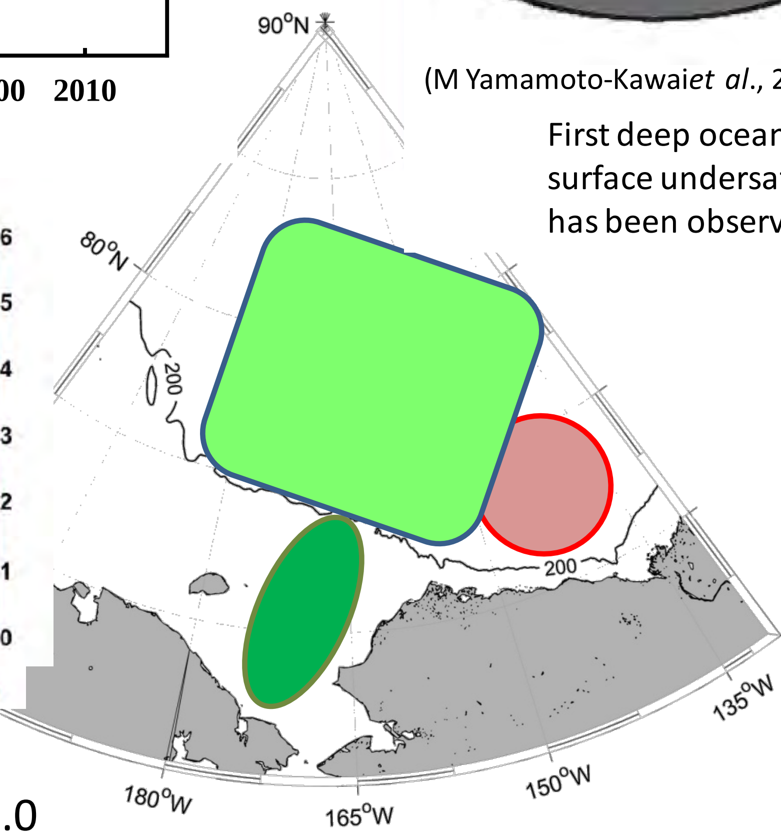
Complexity of OA study in the Arctic





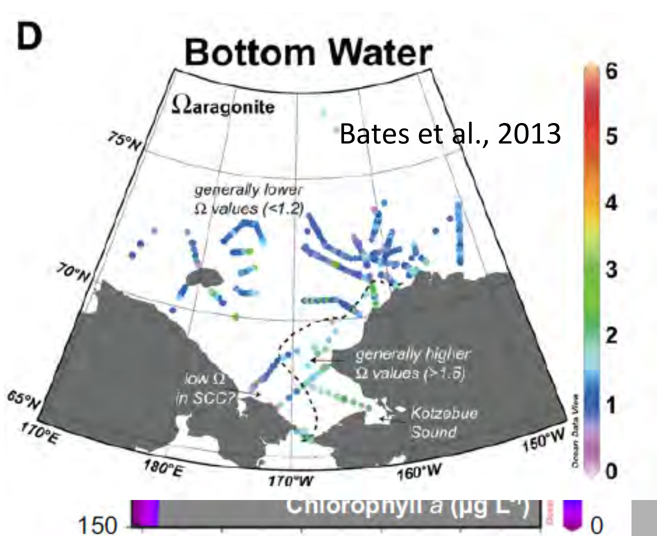
(M Yamamoto-Kawai*et al.*, 2010)





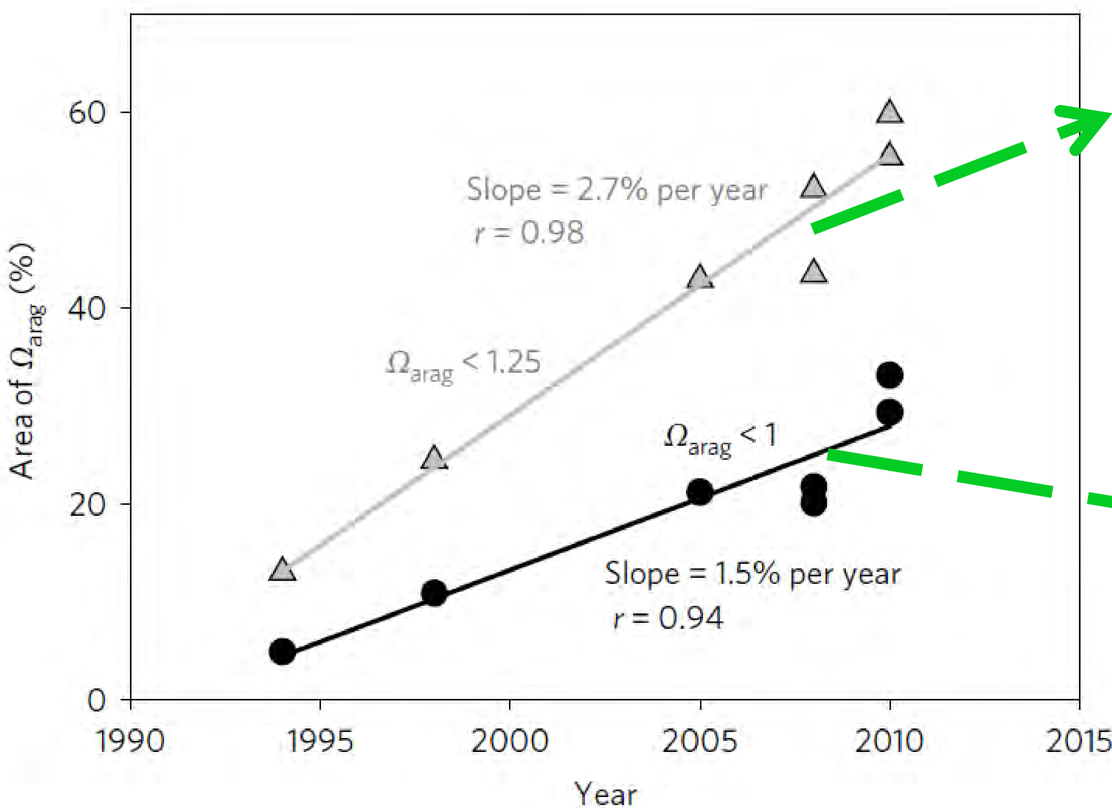
First deep ocean where such surface undersaturation has been observed

)10



(Arrigo et al., 2014)

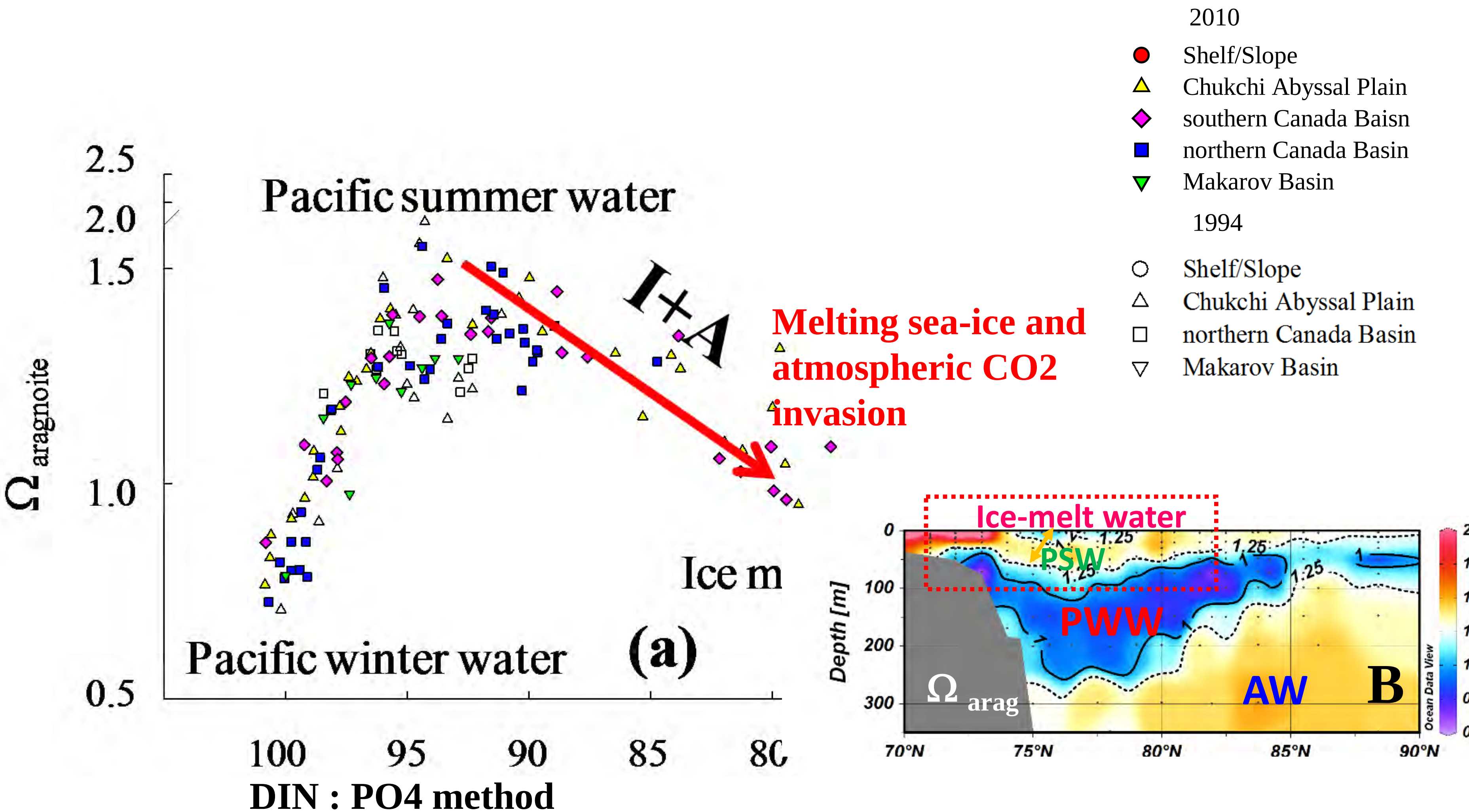
40% of samples had Ω_{arag} of <1.0



if we define a critical state of Ω_{arag} <1.25, where the growth of carbonate mineral-bearing organisms could be threatened (see Methods), **it expanded at a rate of 2.7% per year**

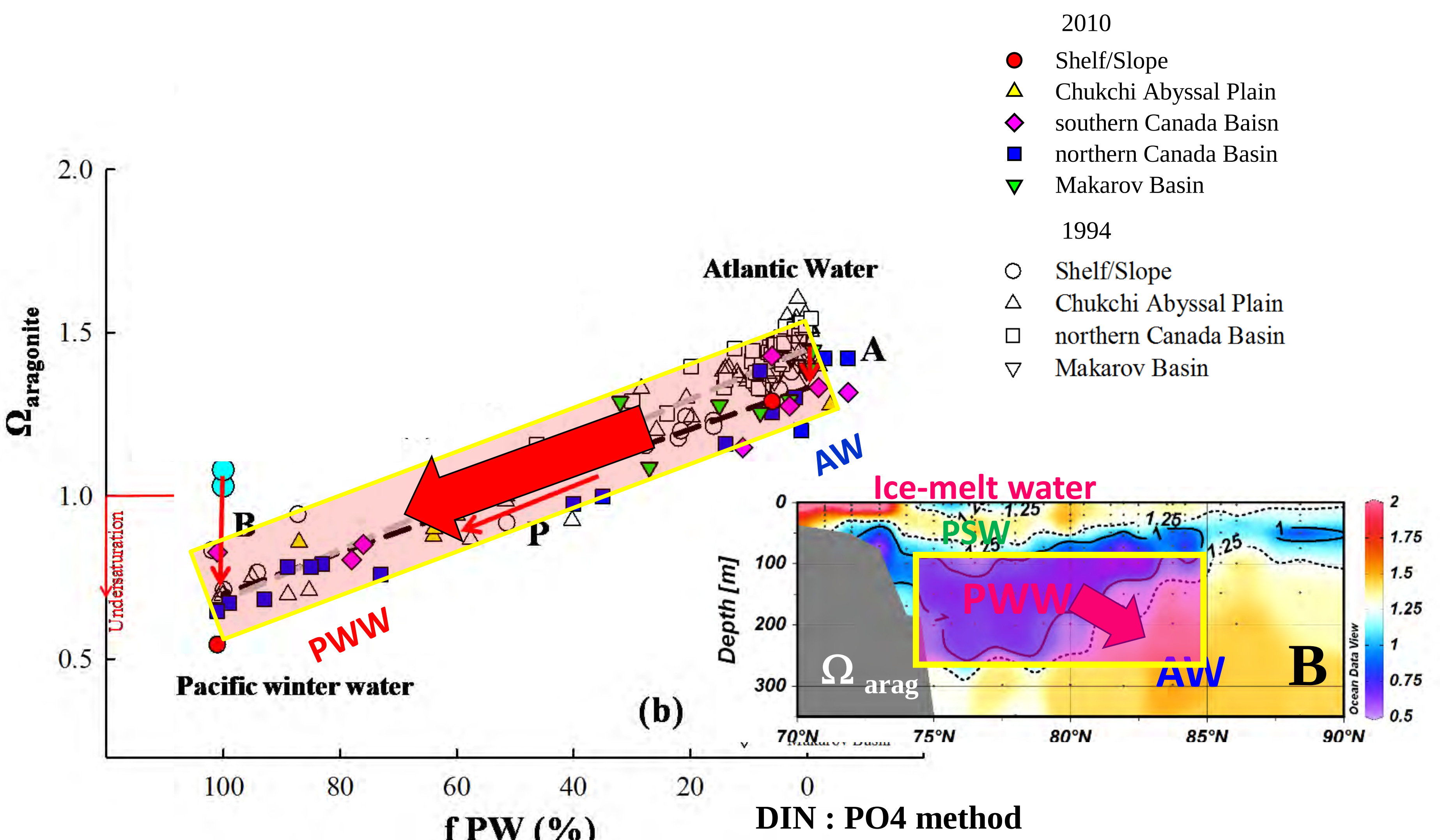
The vertical extent of the undersaturated water has increased by about six-fold with a rate of increase of 1.5% per year.

Surface-Melting sea-ice and atmospheric CO_2 invasion



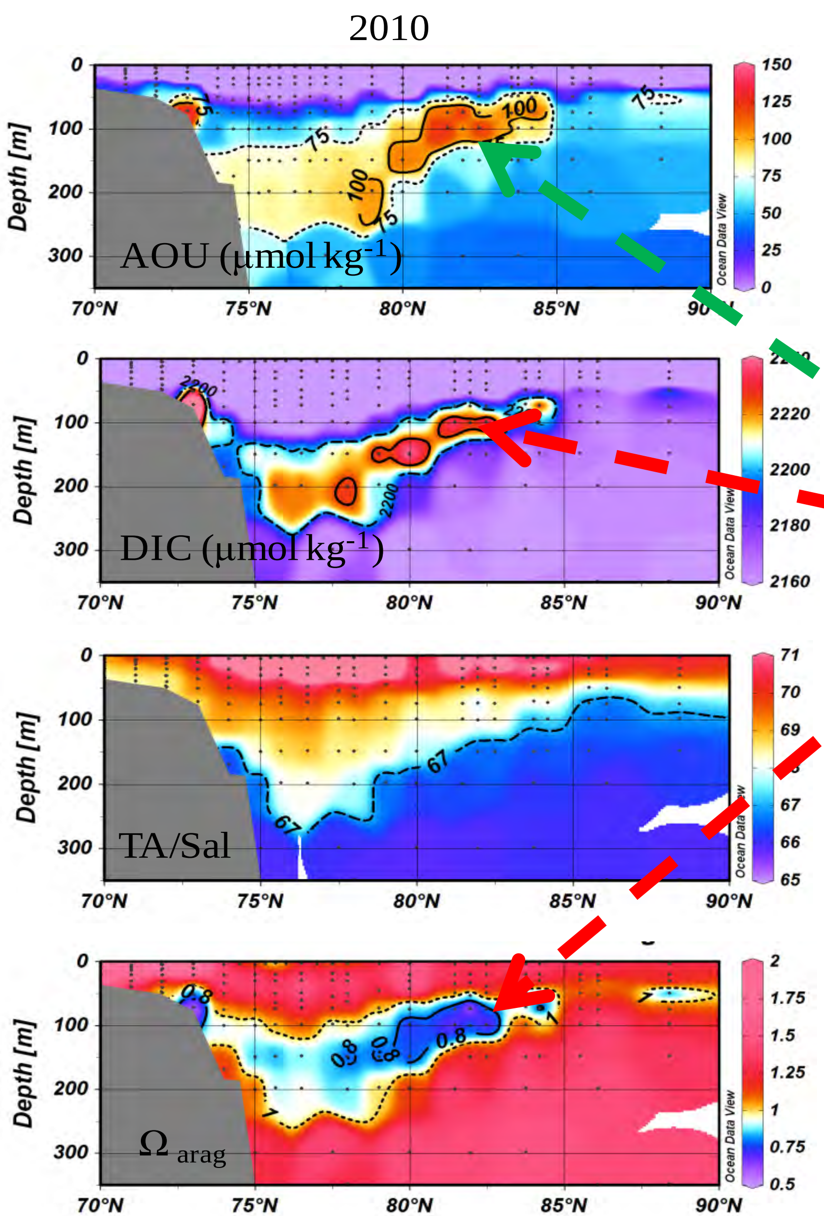
- ➢ **Mixing of seawater with low-Ω aragonite meltwater** would **reduce Ω aragonite by ~0.24;**
- ➢ **Rapid CO_2 uptake from the atmosphere reduce Ω aragonite by ~0.30 .**

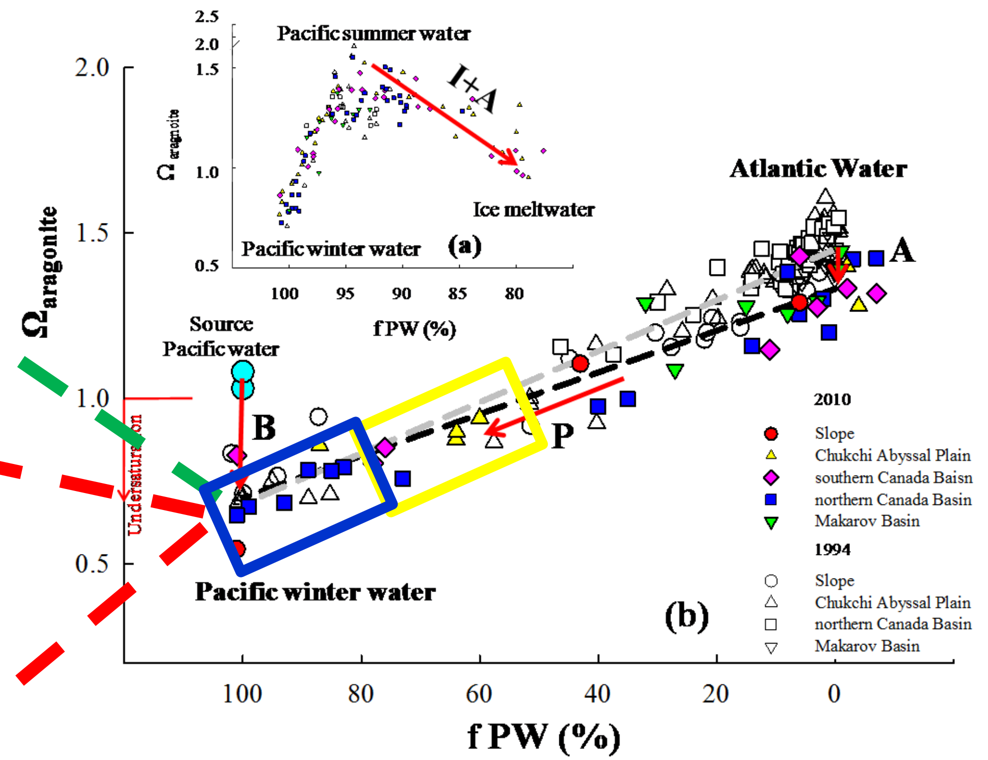
Subsurface 50-250 m (-Increase in PWW intrusion(Major)



Recent significant **increases in Pacific winter waters (PWW)** intrusion have contributed to the widespread ***"corrosive acidified" waters*** in Arctic Ocean.

●Subsurface-Increase in decomposition of organic matter in the northern basin

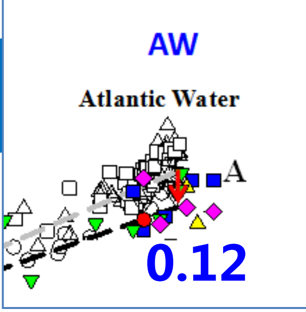


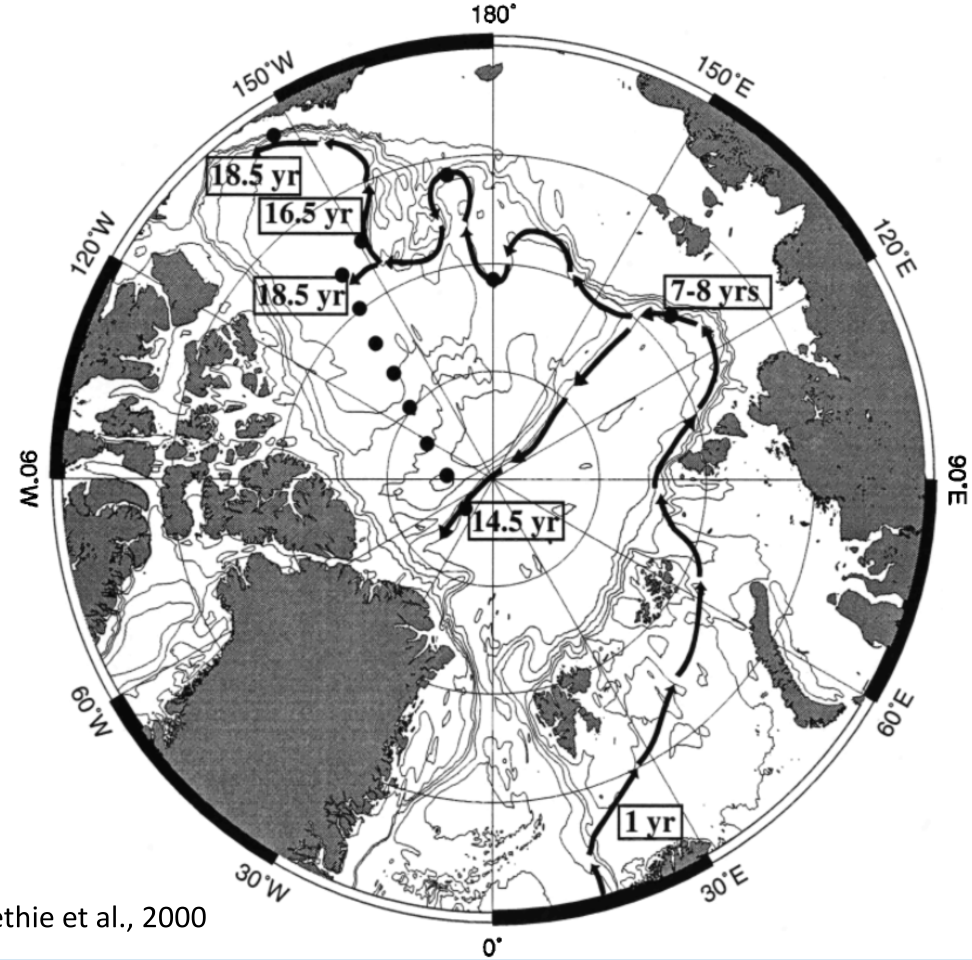


- Ω_{arag} was lower in the northern basin than in the Chukchi abyssal plain and the southern basin

- The result of increased microbial respiration of organic matter originating locally from the surface production enhanced by recent sea-ice melt in the northern basin

Middle layer (AW, 250-800 m)-Ant. CO_2& increase in respiration





Smethie et al., 2000

The transit time for North Atlantic surface water to reach the Canada Basin **16±2**

***p*CO_2 +24 µatm**

Anthropogenic CO_2 uptake from the atmosphere

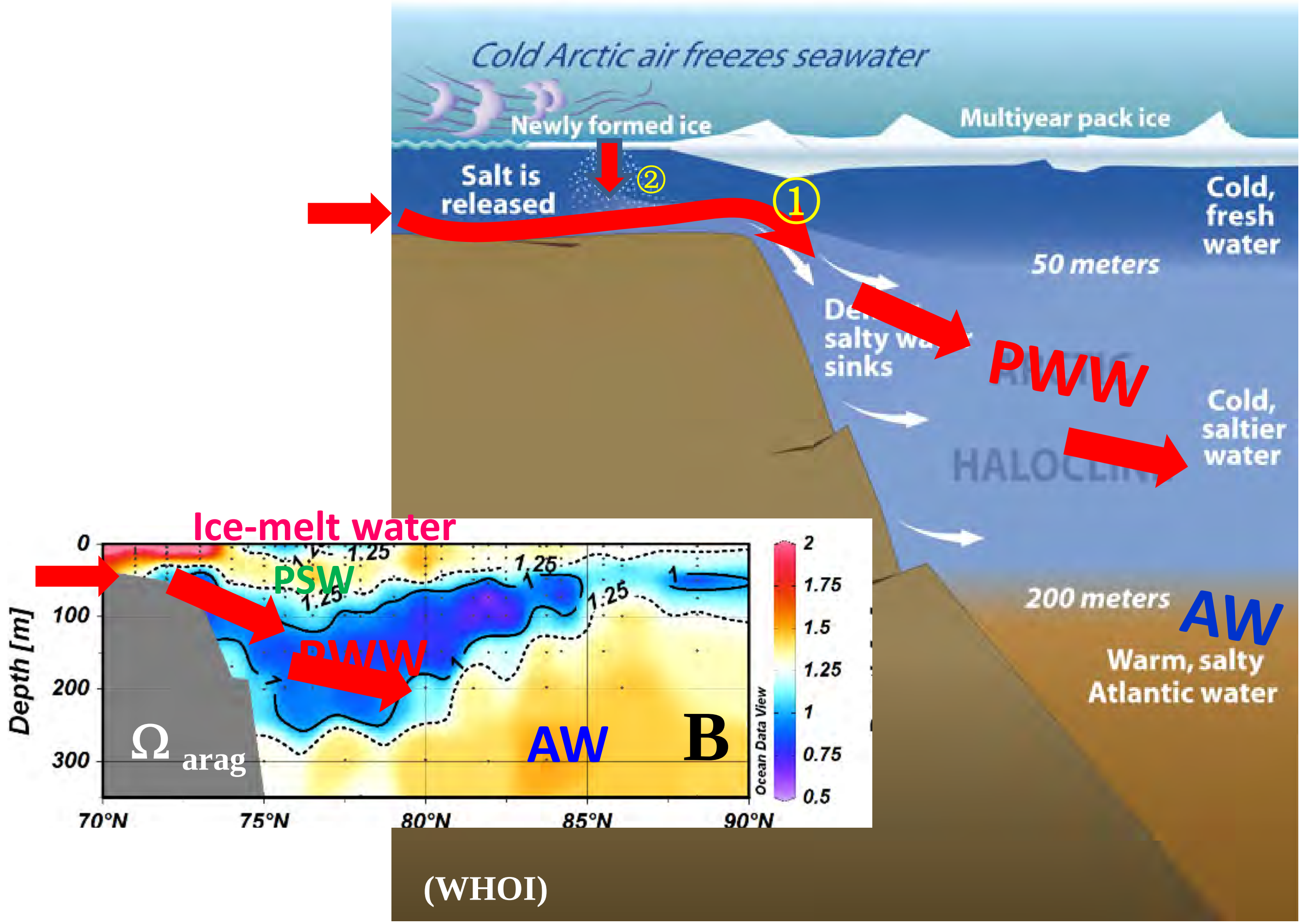
Ω_{arag} -(0.09)

[NO3+NO2]+AOU
+0.7 and +10 µmol kg^{-1}

O/C/N (138/106/16)

The respiration-induced DIC increase would lead to a decrease

Ω_{arag}
-(0.03-0.06)



Two water sources supporting the Arctic PWW.

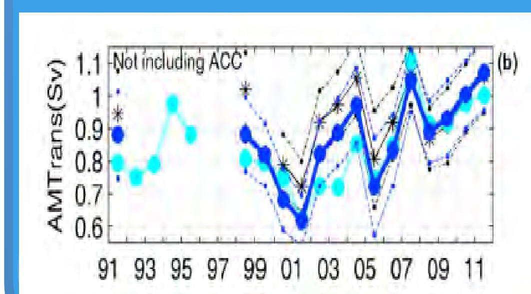
First is the **northward flowing of the Bering Sea water into the Arctic Ocean in winter**, which compensates the loss of surface water under the influence of north wind (Pickart et al.)

Second is the **brine rejection produced dense water in the polynyas** of the Chukchi Sea, Beaufort Sea, and along the Alaskan Coast .

There are several physical processes influencing the expansion of PWW

1

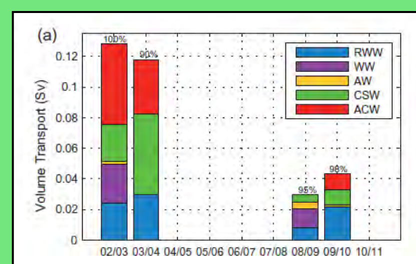
Bering Strait throughflow has increased by ~50%

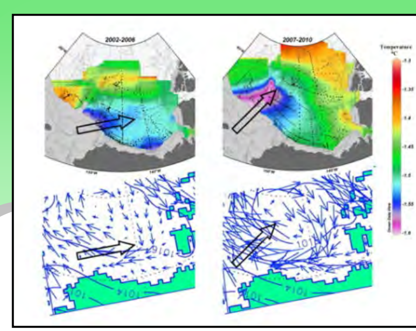


Woodgate et al., 2012 GRL

2

More PWW advected directly into the interior basin





Brugler et al., 2014 PO
Proshutinsky et al., 2011 (NOVAA)

3

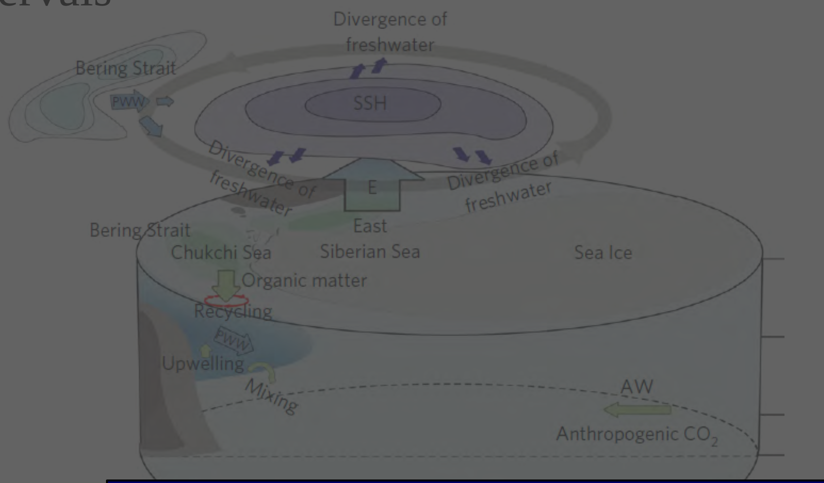
More ice-free/open water in the summer season followed by grow more of PWW in the fall/winter

Weingartner et al., 2005 DSRII

In addition, inflowing PWW is further modulated by the Beaufort Gyre (BG)

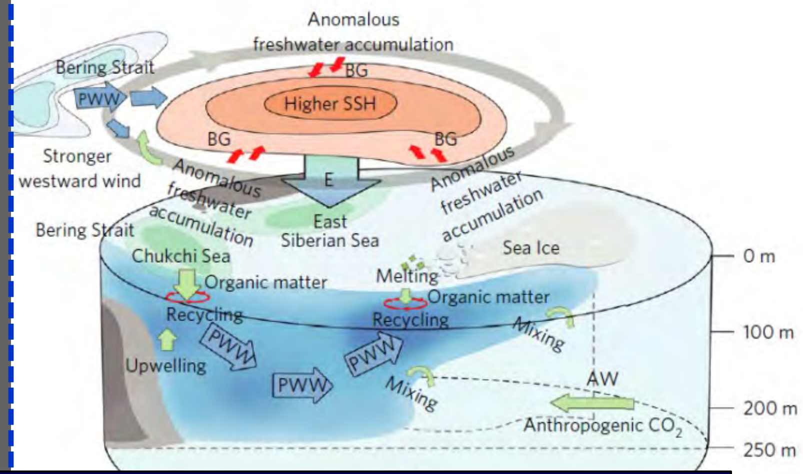
Before 1997

(Before 1997): alternating pattern of cyclonic and anticyclonic regime **for 5 to 7 year** intervals

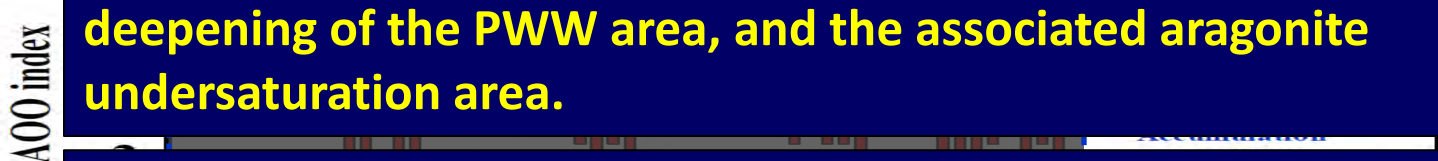


2008, 2010

(1997-2015)： Anticyclonic circulation ; 19 years



- The anticyclonic circulation has **strengthened the Beaufort Gyre**, accumulation of freshwater, and downwelling (Ekman Pumping) in the Canada Basin, all resulting in an **expansion and deepening of the PWW area, and the associated aragonite undersaturation area.**



- **Thus, we conclude that the expansion of PWW, modulated by the larger climate change pattern, is the main process that enhanced ocean acidification.**

Conclusion

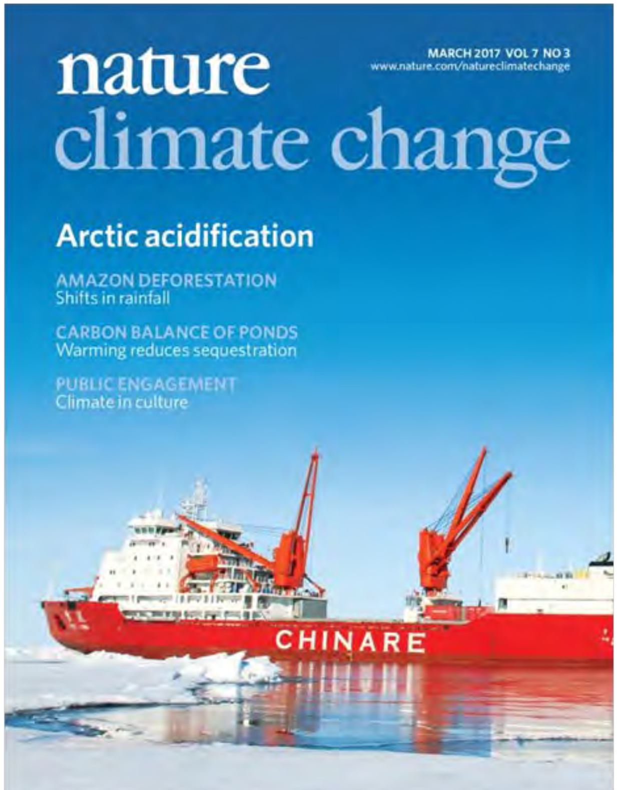
- Over the period of record (**from 1994 to 2010**), the fraction of under- **saturated water** in the Arctic ocean **increased every year,** The vertical extent of the undersaturated water has increased by about **six-fold** with a rate of change at **1.5%** per year.

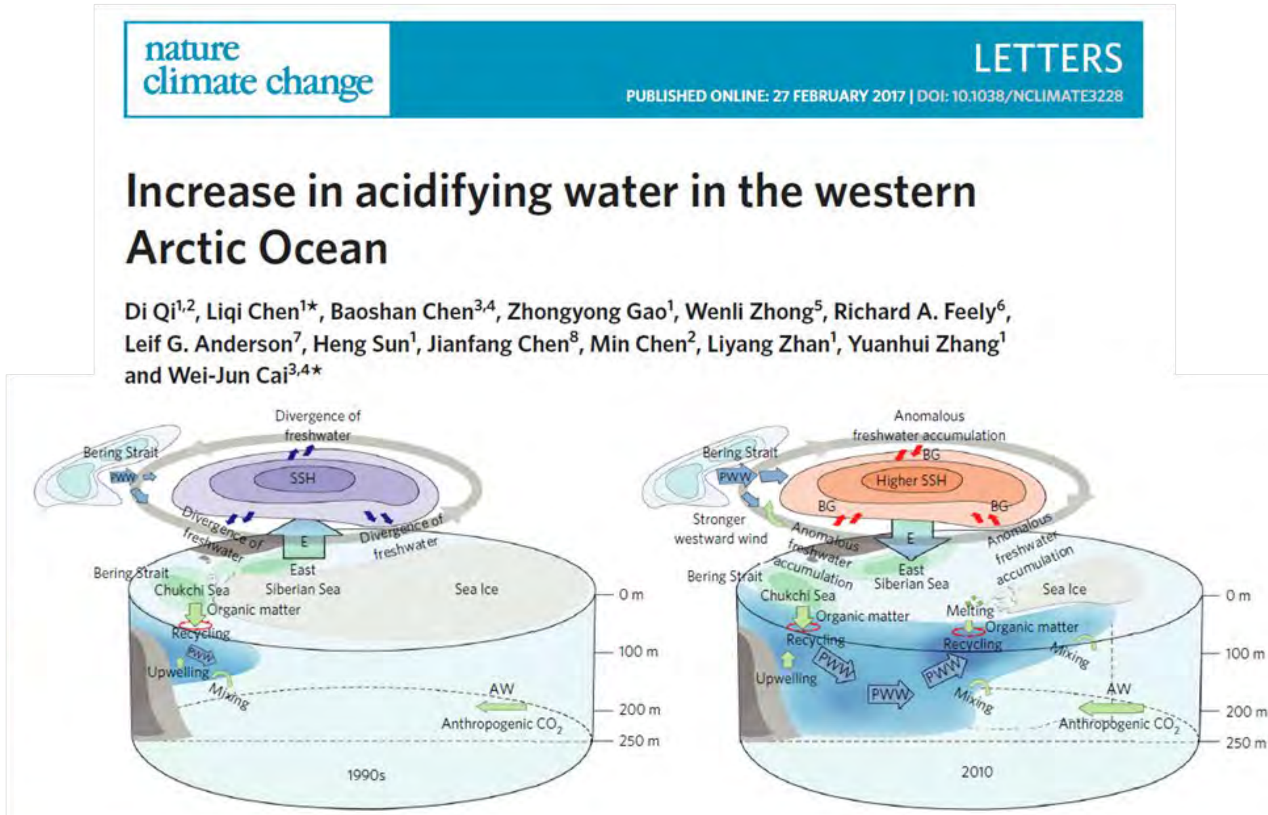
- Tracer data and model simulations suggest that the recent **increase in Pacific winter water (PWW) invasion** driven by **an anomalous circulation pattern and sea-ice retreat** is primarily responsible for the rapid expansion of the **"acidifiying"** water in the Arctic Ocean basins.

- **Local biological recycling** and **anthropogenic carbon dioxide (CO_2) uptake** have also played roles in increasing the extent of the affected area.

Increase in acidifying water in the western Arctic Ocean

http://www.nature.com/nclimate/journal/v7/n3/full/nclimate3228.html

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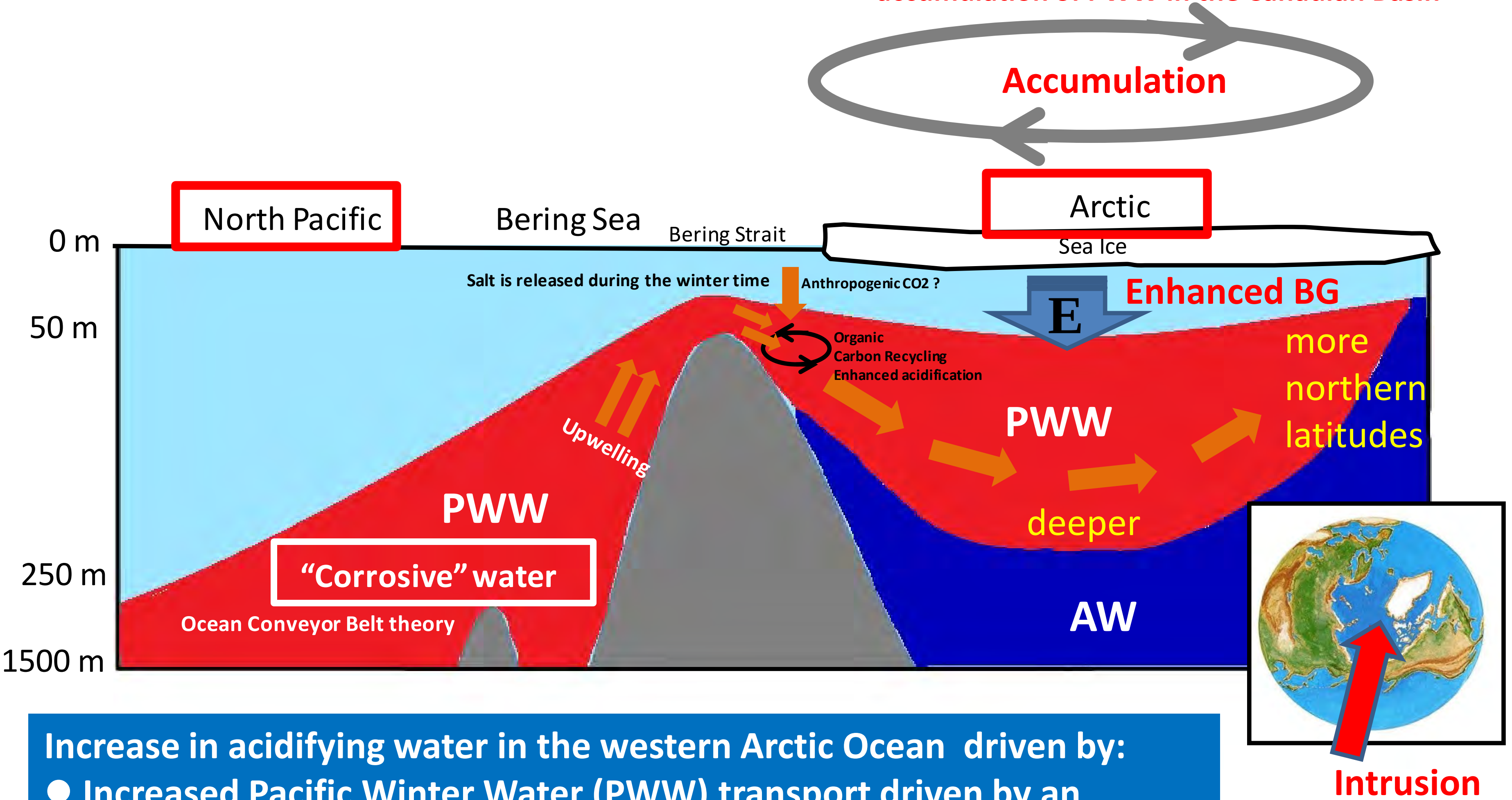
Increase in acidifying water in the western Arctic Ocean

Di Qi[1,2], Liqi Chen[1*], Baoshan Chen[3,4], Zhongyong Gao[1], Wenli Zhong[5], Richard A. Feely[6], Leif G. Anderson[7], Heng Sun[1], Jianfang Chen[8], Min Chen[2], Liyang Zhan[1], Yuanhui Zhang[1] and Wei-Jun Cai[3,4*]

The cover shows the Chinese icebreaker “Xuelong” works on the Arctic during the Chinese national Arctic research expedition (CHINARE)

The summary of this story

Anomalous ACCR started in 1997 has dominated in the Arctic over the last 19 years (1997-2015) that favours the accumulation of PWW in the Canadian Basin



Increase in acidifying water in the western Arctic Ocean driven by:

- Increased Pacific Winter Water (PWW) transport driven by an anomalous circulation pattern and sea-ice retreat (Major)
- Local carbon recycling and anthropogenic CO_2 uptake (Minor)

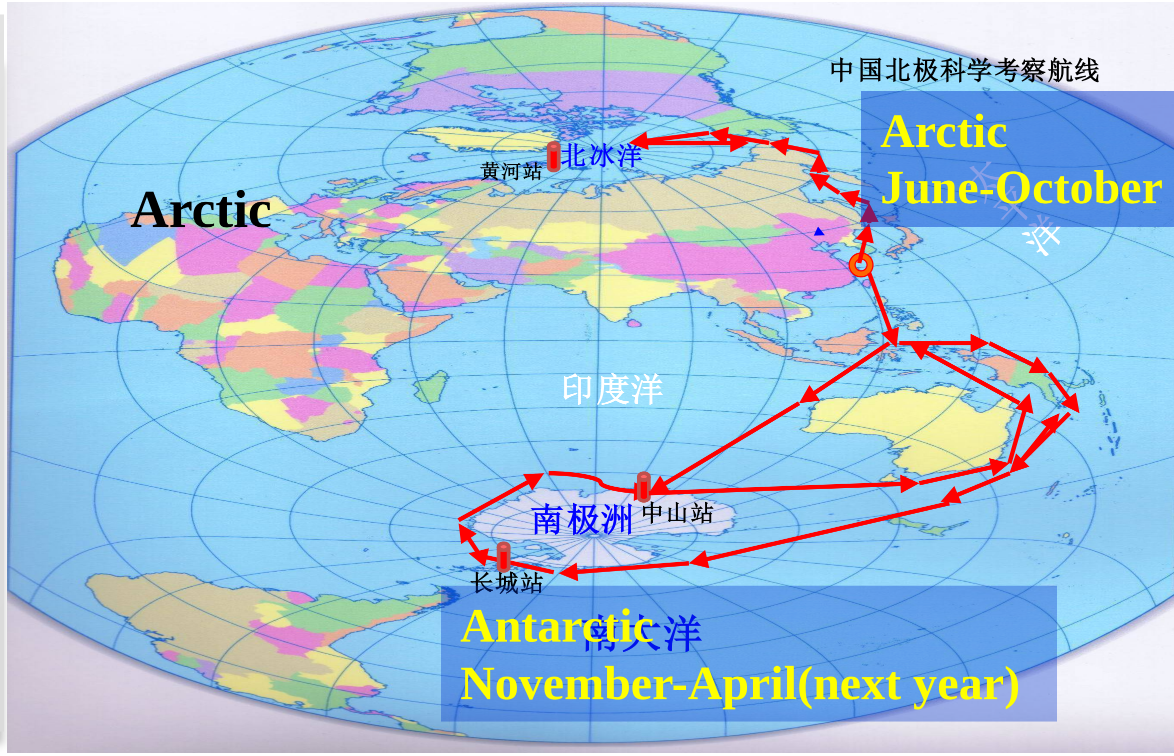
Note:
The corrosive water (PWW) observed in the shallow depths of North Pacific can be explained by the **global thermohaline circulation** (or **Ocean Conveyor Belt**) theory [Broecker,1991].

China's Contribution to the Researches of Carbon Cycle and Ocean Acidification in the Arctic Ocean and Southern Ocean

China's 13th Five-Year plan (2016-2021)

"Xuelong" CHINARE

A new Icebreaker



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Arctic and Antarctic

CHINARE 2016-2021

Arctic Ocean Carbon Cycle and Ocean Acidification

Decrease in the CO2 Uptake Capacity in an Ice-Free Arctic Ocean Basin
Wei-Jun Cai, *et al.*
Science **329**, 556 (2010);
DOI: 10.1126/science.1189338

Decrease in the CO_2 Uptake Capacity in an Ice-Free Arctic Ocean Basin

Wei-Jun Cai,[1]* Liqi Chen,[2] Baoshan Chen,[1] Zhongyong Gao,[2] Sang H. Lee,[3] Jianfang Chen,[4] Denis Pierrot,[5,6] Kevin Sullivan,[5,6] Yongchen Wang,[1] Xinping Hu,[1] Wei-Jen Huang,[1] Yuanhui Zhang,[2] Suqing Xu,[2] Akihiko Murata,[7] Jacqueline M. Grebmeier,[8] E. Peter Jones,[9] Haisheng Zhang[4]

It has been predicted that the Arctic Ocean will sequester much greater amounts of carbon dioxide (CO_2) from the atmosphere as a result of sea ice melt and increasing primary productivity. However, this prediction was made on the basis of observations from either highly productive ocean margins or ice-covered basins before the recent major ice retreat. We report here a high-resolution survey of sea-surface CO_2 concentration across the Canada Basin, showing a great increase relative to earlier observations. Rapid CO_2 invasion from the atmosphere and low biological CO_2 drawdown are the main causes for the higher CO_2, which also acts as a barrier to further CO_2 invasion. Contrary to the current view, we predict that the Arctic Ocean basin will not become a large atmospheric CO_2 sink under ice-free conditions.

The CO_2 concentration in the atmosphere has increased greatly since the industrial revolution, and ~30% of the CO_2 released has been taken up by the ocean. This process slows the increase of this greenhouse gas in the atmosphere and thus global warming (*1*), but will likely affect ocean ecosystems via acidification (*2*, *3*). The Arctic Ocean has great potential for taking up atmospheric CO_2 owing to high biological production in the large ocean margin areas and low temperature (*4*, *5*). A recent synthesis suggested that the Arctic Ocean, though constituting only 3% of the world's ocean surface area and mostly ice-covered, accounts for 5 to 14% of the total ocean CO_2 uptake (*6*). This value is highly uncertain, however, owing to relatively few observations and rapid climate changes. The Arctic is widely viewed as the area on Earth most sensitive to climate changes (*1*), with acidification more pronounced than that of any other ocean (*2*). Sea ice melt in the Arctic Ocean has

In the summer of 2008, we conducted a high-resolution underway survey of partial pressure of CO_2 (pco_2) across the Canada Basin in the western Arctic Ocean where substantial melting of ice had occurred (Fig. 1 and fig. S1). Surface-water temperature was as high as 0° to 5°C in the central Canada Basin (Fig. 2A). Extensive ice melt in this region resulted in salinity values as low as 24 parts per thousand (‰) (Fig. 2B) and ice concentration less than 15% (Fig. 1). Compared to an earlier underway survey in summer 1999, temperatures had increased by 3°C and salinities decreased by ~2‰ (Fig. 2, D and E). During the Arctic Ocean Section (AOS) study in summer 1994, all areas north of 72°N were under ice cover (Fig. 1) with surface seawater temperatures below −1.5°C and salinities above 30‰ (Fig. 2, D and E).

During the summer of 2008, surface-water pco_2 was below the atmospheric level (~375 μatm) in the entire survey area (Fig. 2C). The lowest pco_2 (150 to 250 μatm) occurred in marginal sea areas, in agreement with earlier observations (*4*, *10*–*13*). In the ice-free region of the Canada Basin to the northeast, however, there was a large area of relatively high pco_2 (320 to 365 μatm) that had not been observed before. It contrasted sharply with pco_2 values of 260 to 300 μatm in the summer of 1999 and the very low pco_2 (<260 μatm) from the summer of 1994 (Fig. 2F). Further north (≥77°N), where melting of ice in 2008 was less extensive, pco_2 dropped quickly to below 280 μatm (Fig. 2C). Surface pco_2 also decreased from the central Canada Basin to areas west of 120°W, where ice cover was relatively heavy, temperature was lower,

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The uptake of anthropogenic CO_2 by the ocean decreases seawater pH and carbonate mineral aragonite saturation state (Ω_{arg}), a process known as Ocean Acidification (OA). This can be detrimental to marine organisms and ecosystems[1,2]. The Arctic Ocean is particularly sensitive to climate change[3] and aragonite is expected to become undersaturated (Ω_{arg} < 1) there sooner than in other oceans[4]. However, the extent and expansion rate of OA in this region are still unknown. Here we show that, between the 1990s and 2010, low Ω_{arg} waters have expanded northwards at least 5°, to 85° N, and deepened 100 m, to 250 m depth. Data from trans-western Arctic Ocean cruises show that Ω_{arg} < 1 water has increased in the upper 250 m from 5% to 31% of the total area north of 70° N. Tracer data and model simulations suggest that increased Pacific Winter Water transport, driven by an anomalous circulation pattern and sea-ice retreat, is primarily responsible for the expansion, although local carbon recycling and anthropogenic CO_2 uptake have also contributed. These results indicate more rapid acidification is occurring in the Arctic Ocean than the Pacific and Atlantic oceans[5–8], with the western Arctic Ocean the first open-ocean region with large-scale expansion of 'acidified' water directly observed in the upper water column.

Over the past two decades, global warming and climate change have caused rapid changes in the Arctic, especially in the western Arctic Ocean. These changes include rapid sea-ice retreat[9] and increases in sea surface temperatures[7], Pacific water inflow[10], freshwater storage[11], primary production[12], and surface CO_2 concentrations[13]. Projected climate change processes are thought to amplify OA in the Arctic Ocean, making it more vulnerable to rapid chemical changes than any other ocean basin[4]. Recent OA field and modelling studies in the Arctic Ocean suggest that surface acidification due to CO_2 uptake, sea-ice melt and upwelling of subsurface water[14–17] and subsurface acidification due to Pacific Winter Water (PWW) export[4,18] will affect the timing of future large-scale OA changes in the region[4]. The studies that report proposed mechanisms are based on limited data collected from only the slope and southern basins, two cruises, or the sea surface. The current status and historical changes of OA are unknown. Here we use Ω_{arg} estimates derived from various cruises to identify an unprecedented rate and scale of ocean acidification in the western Arctic Ocean and evaluate links to environmental and climate change over the past two decades.

In this study we report the upper ocean (top 300 m) seawater Ω_{arg} from marginal seas to the basins as far north as 88° N from our summer 2010 cruise as well as four other trans-western Arctic Ocean programs during 1994–2008 (Fig. 1c). We calculated Ω_{arg} from total alkalinity (TA) and dissolved inorganic carbon (DIC) after a careful data quality assessment of all available historical data and a correction to common deep-water values (Methods and Supplementary Fig. 1 and Supplementary Tables 1 and 2). Our results show that the vertical section of aragonite undersaturation (Ω_{arg} < 1) in the western Arctic Ocean expanded substantially, becoming deeper and extending into higher latitudes from 1994 to 2010 (Fig. 1a,b,d–h). During the 1994 survey along the 170° W transect the undersaturated Ω_{arg} occurred only on the Chukchi slope and abyssal plain (approximately 55–125 m depth), with its northern boundary stopping at 78° N and never reaching 80° N where the 1994 stations were still within the Canada Basin (Fig. 1a). This conclusion is further supported by a 1998 survey between 160° W and 170° W where the undersaturated Ω_{arg} waters extended to a depth of ~75–175 m at ~75° N, but quickly narrowed northwards, with its northern boundary stopping at 80° N (Fig. 1b). In summary, the undersaturated water was largely limited to within 50–150 m and its northern boundary was limited to south of 80° N in the 1990s. In contrast, large-scale aragonite undersaturation occurred in the Canadian Basin in 2008 and 2010. Along the western transect (~170° W) the undersaturated region includes waters at depths of approximately 0–30 m on the southern slope and in the basin, 50–250 m between 75° and 80° N within the Chukchi abyssal plain and the southern Canada Basin, 50–200 m between 80° and 85° N in the northern Canada Basin, and a slight expansion to the 50 m depth north of 85° N in the Makarov Basin (Fig. 1e,g). A similar Ω_{arg} distribution pattern also exists along the eastern transect (160° W) (Fig. 1f,h). Overall, the percentage of aragonite undersaturated vertical area of the water column (0–250 m and between 70° and 90° N) increased by a factor of six from 5% in 1994 to 31% in 2010, with an average rate of increase of 1.5% per year (Fig. 2 and Methods). Furthermore, if we define a critical state of Ω_{arg} < 1.25, where the growth of carbonate mineral-bearing organisms could be threatened (see Methods), it expanded at a rate of 2.7% per year (Fig. 2).

We now examine the factors responsible for the rapid expansion of the 'acidified' water in this region. In the sea surface our analysis (Fig. 3a) confirms previous reports that air–sea CO_2 exchange (A) and sea-ice melt (I) are the two main processes for acidification

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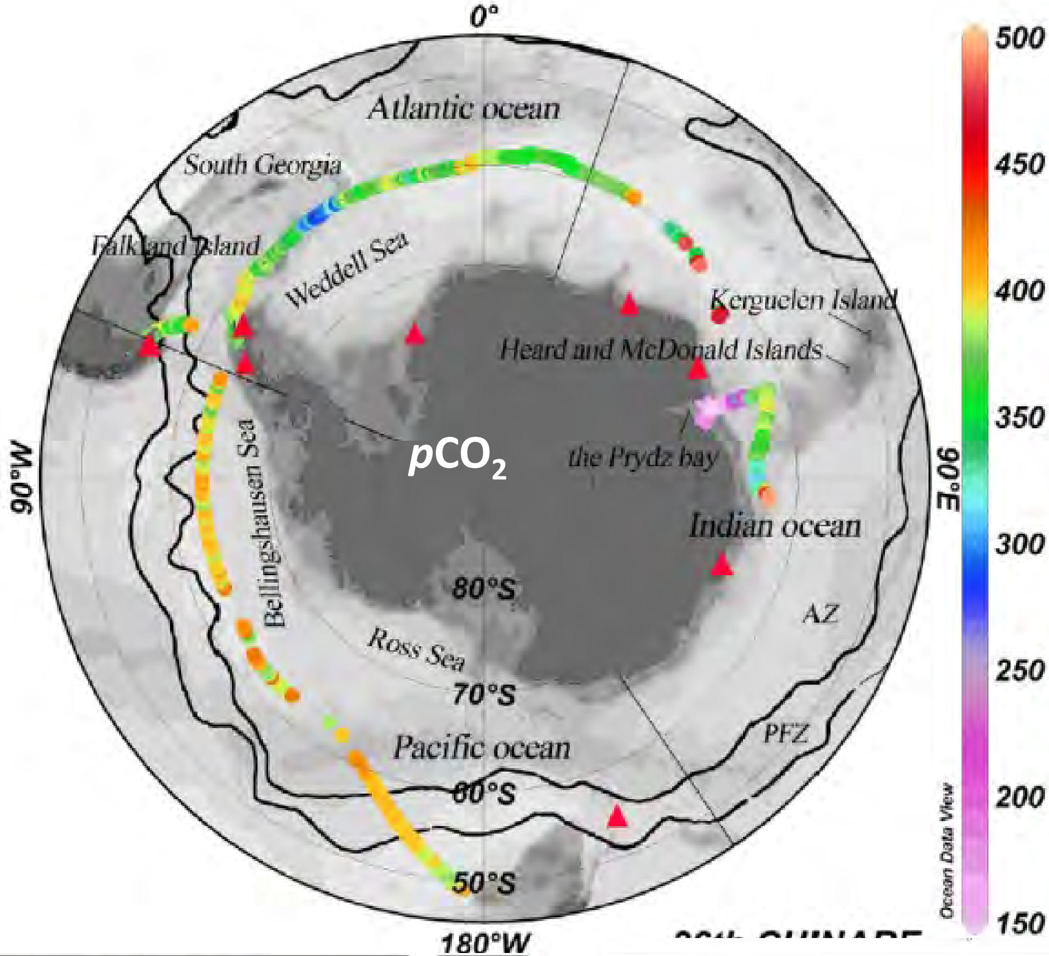
Southern Ocean Carbon Cycle and Ocean Acidification



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Sea–air CO_2 fluxes in the Southern Ocean for the late spring and early summer in 2009

Suqing Xu [a,b,*], Liqi Chen [a], Haiying Chen [c], Jonathan Li [d,e], Wuhui Lin [a,f], Di Qi [a]

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Estimation of monthly air-sea CO_2 flux in the southern Atlantic and Indian Ocean using in-situ and remotely sensed data

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We warmly welcome international cooperation, in order to better understand the carbon cycle and OA in the Polar regions

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Thank you