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**Krill distribution in relation to warming as evidenced from loss of Ice  
Shelf (1972 to 2003) in Amundsen Sea and Threats to krill egg  
development by changing carbonate chemistry of Southern Ocean.**

#### ABSTRACT

Using *Landsat* image data from NASA satellite, dating back to 1972, Hayden and LeCompte et al. (2013) established grounding line, a boundary between disintegrating floating ice shelf and the ground ice that feeds it in Amundsen Sea. This project improved significantly our knowledge of cryospheric processes by comparing 30 years of record from 1972 to 2003. Pine Island located south of Larsen, equivalent to the size of two-thirds of UK, is a key study site of Elizabeth City State University's Center of Excellence for Remote Sensing Education and Research (CERSER). This study proved the break-up of Larsen A ice-shelf in 1995 and Larsen B ice-shelf in 2002. The warming of the waters off Western Antarctic Peninsula (WAP) has influenced density and distribution of the Antarctic Krill *Euphausia superba*. Fevolden and George (1984) established the size frequency patterns of *E. superba* in WAP in the austral summer of 1983. In 2009-2010, Bernard et al (2011) provided evidence to conclude WAP is a region of rapid climate change that altered plankton community structure, suggesting ecosystem-evolution in some parts of Southern Ocean. While *E. superba* is a major grazer in the coastal regions of WAP, *Salpa thomsoni* dominated grazing offshore. *E. superba* will likely become less dominant if pteropod *Limacina helicina* and *Salpa thomsoni* expand their ranges in WAP region. Krill distribution and abundance also depends on primary production in the preceding years. George (1984 and 2016) reported that krill egg development is influenced by temperature, pressure and pH. Potential collapse of Antarctic krill *E. superba* may not occur in 2100 with atmospheric CO<sub>2</sub> at 770 ppm, as hypothesized by Kawaguchi et al (2013) but eggs of pteropod *Limacina helicina antarctica* may become far more susceptible with atmospheric CO<sub>2</sub> reaching 770 ppm since 80% of pteropod eggs failed to undergo organogenesis (Manno et al., 2016).

## INTRODUCTION

Our knowledge on interannual variation of sea ice in Southern Ocean is meager and also we have not understood how the sea ice reduction impacted krill density in Scotia Sea and areas around South Georgia. However we have some new data from remote sensing in the Amundsen Sea over a period of three decades and this new information is the main focus of this paper. This paper also discusses: (1) Warming of WAP region and its influence on krill distribution, (2) Some new information from NSF-LTER study, (3) A discussion of Sir George Deacon's original elucidation of thermal stratification around Antarctica, (4) Discussion on krill and its predators from NOAA-AMLR studies in WAP region, (5) Some high light of krill fisheries from new data from BAS (British Antarctic Survey) and finally (6) Resilience to Ocean Acidification: Krill Vs Pteropods in Southern Ocean.

### LANDSAT SATELLITE IMAGES ON REDUCTION AND LOSS OF ICESHELF IN AMUNDSEN SEA

Pine Island Bay in Amundsen Sea in Western Antarctica, located southeast of Bellingshausen Sea in the Pacific Sector of the Southern Ocean covers a vast area (Fig. 1) off Pine Island Glacier Ice Shelf. West of this Ice-Shelf is 'Elizabeth City State University Bay' that was created because of the warming in the recent decades. Using *Landsat* image data from NASA satellites, the reduction and loss of the Ice Shelf was monitored by the "Remote Sensing" team of scientists from Elizabeth City State University from 1972 to 2003 (LeCompte, 2013).

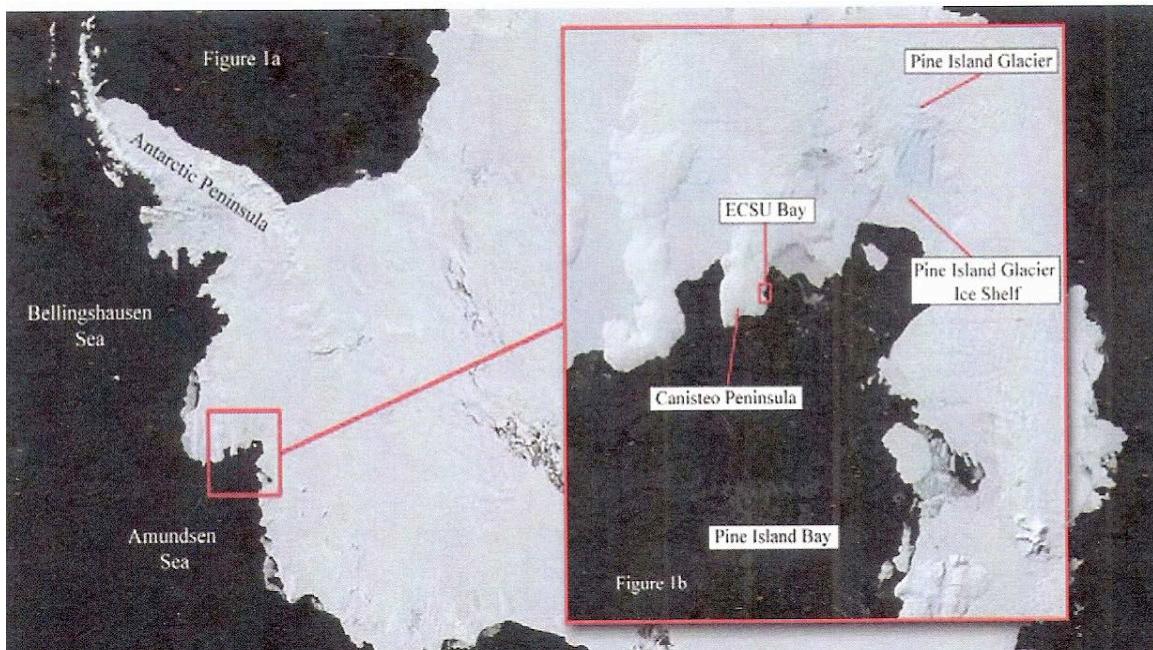


Fig. 1. Pine Island Bay Area in Amundsen Sea, enlarged to show the location of Elizabeth City University Bay and Pine Island Glacier Ice Shelf.

From 1972 to 1986, the Pine Island Ice Shelf expanded from 6.19 square kilometers to 6.82 square kilometers and from then on the Ice Shelf exhibited reduction in area and on January 17, 2003 the ice shelf virtually disappeared to make the ECSU Bay. Although the specific cause of this disappearance of the Ice Shelf is unknown, we believe that this is definitely related to increased basal melting event caused by warmer waters reaching Pine Island Bay. This implies that there is evidence for warmer ocean water causing intrusion of warm “Circumpolar Deep Water” (CDW). Thinning of the ice shelf and outlet glacier is also reported throughout Amundsen Sea since 1986. We have no clear indication of this ice shelf disappearance of krill distribution and location of hot spots of Adelie penguin colonies but Emslie et al., (2007) reported on abandoning of Adelie penguin colonies in Antarctic Peninsular areas and relocation in Ross Sea where the warming is not seen in recent decades as in the Peninsular region.

The precise positions of the Ice Sheet, Ice Shelf and Sea Ice is shown below for 1986 in Fig2 a. In 17 years from 1986 to 2003 the Sea Ice and Ice Shelf retreated significantly opening up an open ocean bay in Fig 2 b and c.

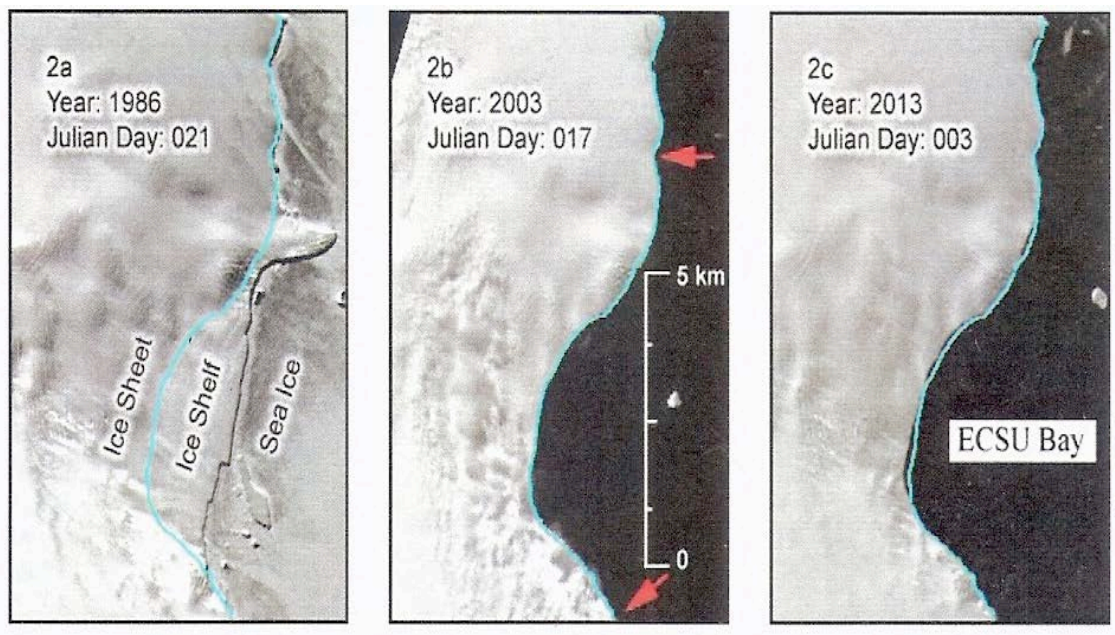


Fig 2. Birth of the New Elizabeth City University Bay in Antarctica.

Interannual variation in the extent of sea ice, particularly in the Scotia Sea region in the Atlantic Sector of the Southern Ocean elicited significant interest amongst krill biologists in recent years because of its relationship to primary production and krill density. We have presented below ‘Cropped Landsat images’ in sequence from 1972 onwards, with the red area being the Ice-Shelf extent. The position of Ice-shelf extent is shown in Fig. 3. for the years, 1981, 1986, 1991, 1997, 2000, 2001 and 2013.

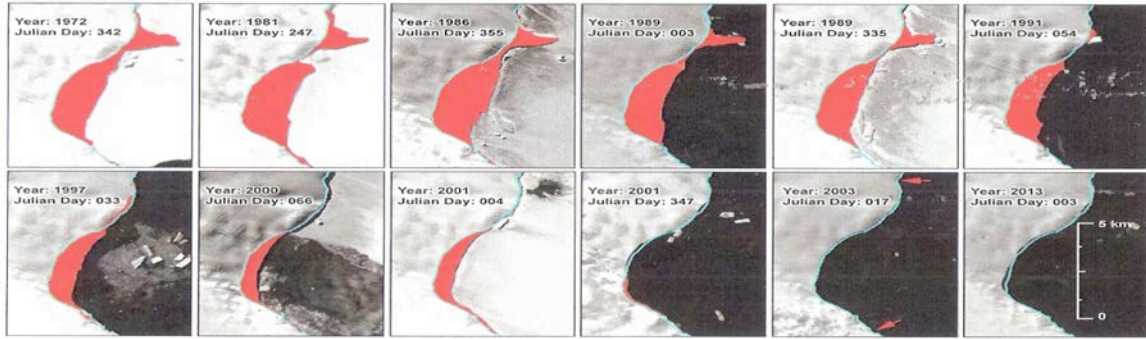


Fig. 3 Progression in the loss of Ice-Shelf from 1981 to 2013.

Scheutchel et al (2016) also reported on ice-retreat in Pope, Smith and Kohler Glaciers in the Western Antarctic Peninsula. Fuentes et al (2016) reported on mass stranding of dead krill as a consequence of glacial melt water in Potter's Cove, Antarctica. Lithogenic particles were found in the gut of stranded krill and evidently these particles interfered with feeding activities of krill. As shown in Fig 4 below, there is clear evidence of sea-ice reduction and glacier melting more common in recent years along the Western Antarctic Peninsula. Fig 4 shows the historically lowest sea ice extent on Nov. 1, 2016.

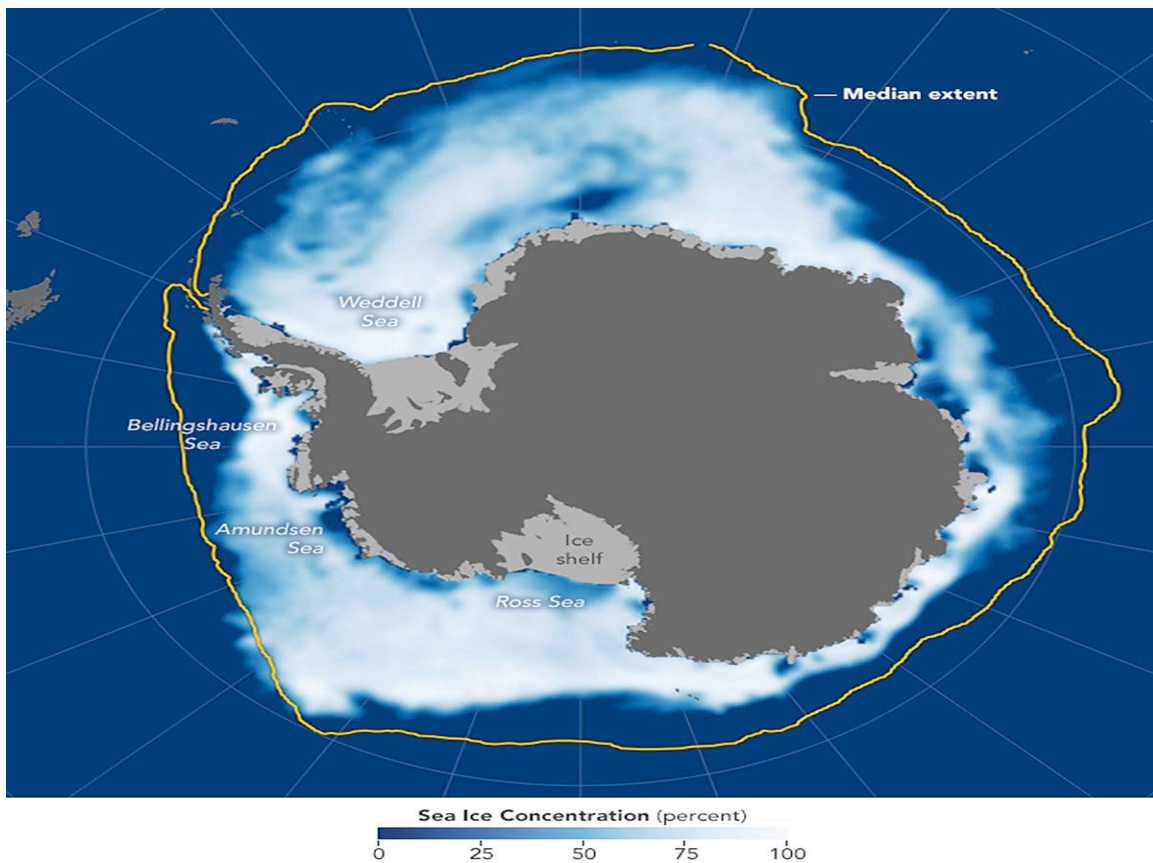


Fig. 4. Sea Ice around Antarctica in Nov. 2016



George (1983) discovered that as a reflection of high feeding rate and elevated metabolism, krill exhibit enhanced catabolic activity under favorable feeding condition when primary production attains peak levels. In other words, it looks as though the diatoms triggered by ammonium-based nitrogenous excretion by krill serve as a stimulus for primary production. Since 1986, this area at the tip of Western Antarctic Peninsula (WAP) experienced significant warming and loss of sea ice.

The Palmer Long-Term Ecological Research (LTER) (Fig. 5) study area was established by US National Science Foundation to the west of the Antarctic Peninsula extending South and North of the Palmer Basin from onshore to several hundred kilometers off shore. Palmer Station is on Anvers Island midway down the Antarctic Peninsula at latitude 64.7 South, longitude 64.0 West.

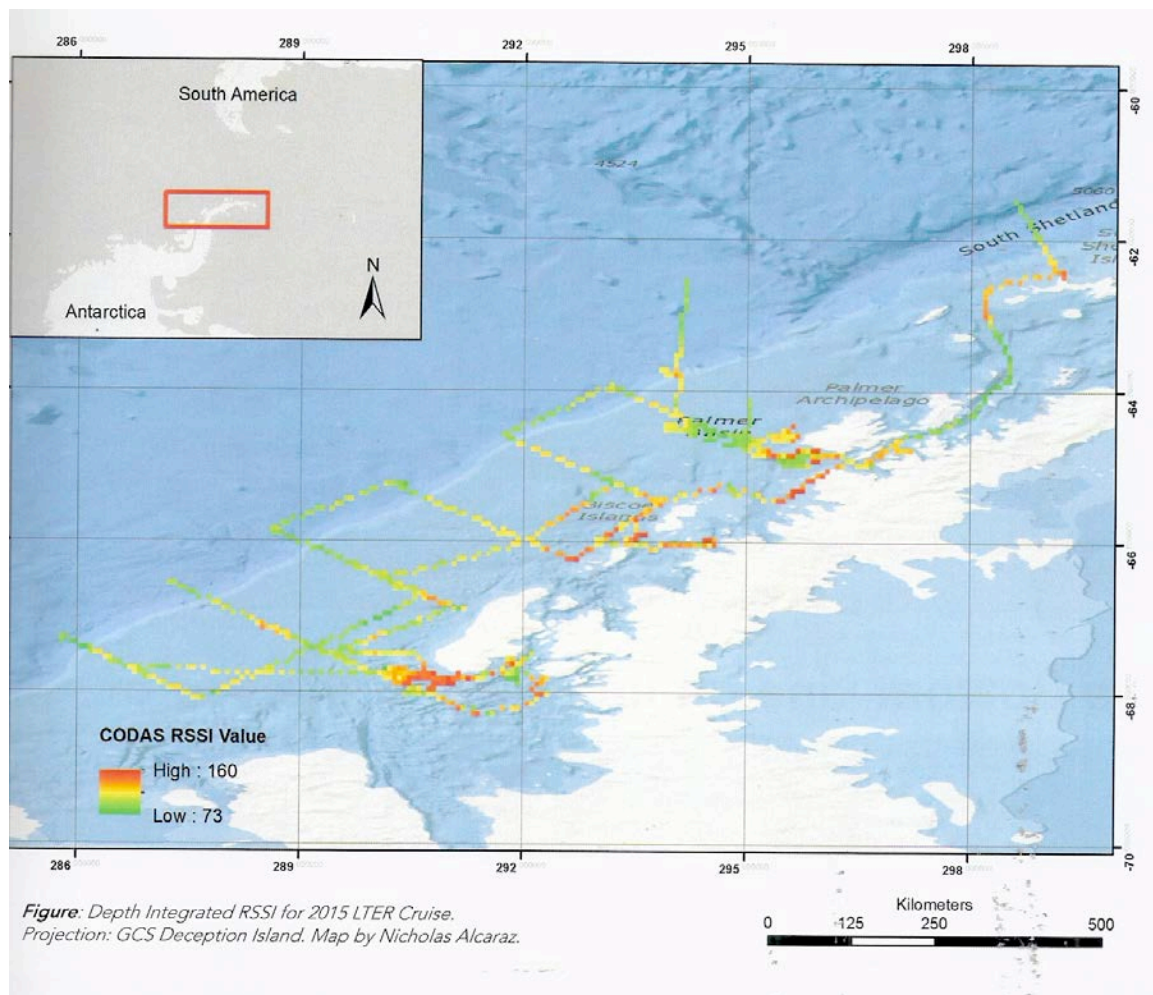


Fig. 6 Palmer LTER (Long Term Experimental Research)

George (2017) evaluated the outcome of this long-term NSF-supported research for nearly 2 decades (LTER) and arrived at three fundamental findings, on the basis of recent report by Steinberg et al. (2015).

1. It appears as though there is now an increase in the euphausiid species *Thyasnoessa macrura* over *E. superba* in 5 years abundance peaks, coinciding nicely with multivariate *El Nino* Southern Ocean Index. Also emerging is a clear association profoundly influenced by primary production two years prior. This LTER study definitely confirmed higher abundance of krill higher ice conditions and concurrently emerging is another important long-term trend with higher abundance of thecosome pteropod *Limacina helicina antarctica* in lower ice conditions. In this paper I am also positing a new hypothesis that pCO<sub>2</sub> increase in the coming decades may pose more threats to pteropods with aragonite skeleton than to euphausiid crustaceans that have calcified exoskeleton.
2. There emerges another significant discovery in LTER studies from Bernard et al (2012) who investigated macro zooplankton abundance off Western Antarctic Peninsula (WAP) in relation to rapid warming in recent years in the Southern Ocean, more so in northern WAP region. There is enough evidence that in the austral summers of 2009 and 2010 large blooms of the soft-bodied planktonic tunicate *Salpa thomsoni* offshore while *E. superba* was the major grazer near shore. This study reveals that in LTER region there are clear shifts in food chain dynamics with dominance of *Salpa thomsoni* and pteropod *Limacina helicina*.
3. Another new discovery in LTER studies includes the relationship between tidal Cycles and krill biomass and aggregations in this penguin foraging WAP region. Bernard and Steinberg (2013) found that tidal phase played a significant role in penguin foraging distance and krill aggregations exhibited an increase in diurnal cycles. Saba et al. (2014) also discovered that krill abundance in the austral summer is simply a reflection of winter and spring controls.

The “KRILLBASE”, a metadata base, developed by Atkinson et al (2017) at the Plymouth Marine Lab in UK provides as temporal-spatial data resource to support a variety of research such as biogeochemistry, autecology, higher predator foraging and food web modeling in addition to krill in CCAMLR region where substantial progress has been made for prudent fisheries management and conservation, culminating in the creation of the new ROSS SEA MPA. However, we are still not sure how long krill lives and our understanding of krill life span is clouded by a spectrum of conflicting views. At the 1982 ‘First International Krill Symposium (George, 1984), the question of age of krill was addressed by Ettershank (1984) who reported that population size structure of krill revealed two length-classes and the larger size class was far more abundant than smaller size class. Ettershank (1983) indicated that the problem of Antarctic krill shrinking during winter prompted investigations into the use of fluorescent age pigment accumulation as indicator of age. However, today we have not yet resolved the longevity of krill although there is promise by studying the krill eye stock banding as a mark of age (Dr. Christian Reiss, personal communication). Nicol (2000) discussed alternative methods for measuring age and longevity in krill but thus far we have not confirmed

whether krill lives for 5 to years or longer but the mere fact that *E. superba* has a much longer life span than sympatric species such as *E. pacifica* that lives not more than two years.

### DEACON'S MODEL ON TEMPERATURE AROUND ANTARCTICA

Deacon (1977) explained circumpolar circulation in the Southern Ocean by saying that water that is cooled and diluted in high latitudes spreads outward at the surface and bottom of the ocean. While warm water which replenishes the salt as well as heat, moves inward in the intervening deep layer. We call this water mass as the Circumpolar Deep-Water (CDW) that is responsible for the massive ice melting and its implications to krill and krill-dependent predators like penguins. As a physical oceanographer, Deacon (1977) was able to define and describe: (A) Antarctic Surface Water (ASW), (B) warm Circumpolar Deep Water (CDW), (C) Antarctic Bottom Water (ABW), (D) Antarctic Circumpolar Current (ACC), (E) Antarctic Coastal Current (ACC), (F) Weddel Sea Gyre (WSG), (G) Meridional Transport, (H) The Antarctic Divergence (AD), Antarctic Convergence (AC) and Antarctic Intermediate Water (AIW). In Fig. 7 below, Deacon illustrated the maximum temperature of the Warm Deep water (CDW) that clearly shows warmer waters closer to coast off Western Antarctic Penguins.

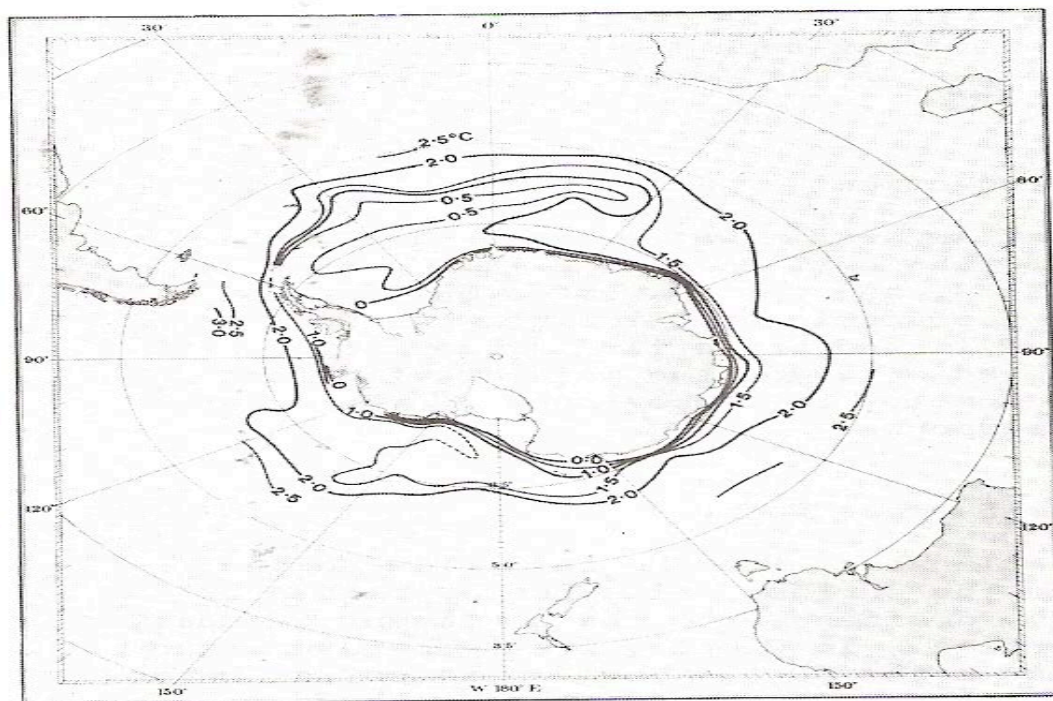


Fig.7. Maximum Temperature of the Warm Deep Water in Celsius

### TEMPERATURE AND CARBONATE CHEMISTRY CHANGE ON KRILL WITH FOCUS ON EMBRYOGENESIS



More than 4.5 decades ago, George (1971) pointed out in a paper presented in the Joint Oceanographic Assembly held in Tokyo, Japan that Antarctic marine poikilotherms (Crustaceans) exhibit thermal sensitivity, with incipient upper lethal temperature at 4 C whereas arctic crustacean species tends to survive with zero mortality when gradually acclimated to temperature as high as 4 C. The wide thermal tolerance of Arctic krill *Meganyctiphanes norvegica* and the ability of this arctic krill species to low dissolved oxygen conditions, as low as 30% saturation, was also reported in a paper by Thillart, George and Stromberg (1999). The wide thermal tolerance of the Arctic and the stenothermal nature of the Antarctic krill *Euphausia superba* are elucidated in the light of dissimilar marine climate evolution in the two polar regions and consequent genetic adaptation. Furthermore, Antarctic krill exhibited a wide metabolic scope at 3 C (George, 1984) in comparison with five other Euphausiid species from temperate and subtropical latitudes, as shown in Table 1. This unique ability of Antarctic krill *E. superba* to exhibit a fairly wide metabolic scope underpins the physiological plasticity of this Southern Ocean species that occurs from the coast as far north as Antarctic Convergence and also commonly found off South Georgia. There is no other euphausiid species in the Southern Ocean that occupies such a vast geographic area around Antarctica. Nevertheless, from we have seen thus far in krill mortality by “stranding”, *E. superba* faces more and more stress with the warmer “Circumpolar Deep Water” approaching close to the coast.

Euphausiid Species	Temperature Acclimated	Minimum Metabolic Rate (microliters/gm/hr)	Maximum Metabolic Rate (microliters/gm/hr)	Metabolic Scope
1. <i>Euphausia superba</i>	3 C	22	806	Wide
2. <i>Euphausia crystallorophias</i>	2 C	42	212	Moderate
3. <i>Euphausia lucens</i>	8 C	218	410	Moderate
4. <i>Euphausia lucens</i>	17 C	360	610	Moderate
5. <i>Euphausia tricantha</i>	19 C	300	320	Narrow
6. <i>Euphausia recurva</i>	21 C	310	520	Moderate
7. <i>Euphausia pargibba</i>	21 C	400	620	Moderate

Table 1. Metabolic Rate and Metabolic Scope of different species of *Euphausia*

Potential threat to Krill is imminent if the warm temperature of the CDW (Circumpolar Deep Water) exceeds 4 or 5 C which is possibly the incipient upper lethal level of the stenothermal *Euphausia superba*. This is why the Paris Climate Accord is very relevant to avoid a catastrophe in climate change by 2100. International Panel on Climate Change (IPCC), based on ocean temperature change from 1958 to 1998, estimated that at the current rate of greenhouse gas emissions and global warming, an increase of 0.04 C per

year is inevitable and this means 0.4 C per decade and 4 C per century and hence, with business as usual will put WAP region at 6 C by 2117. Therefore, it is essential we make rapid reduction in carbon emission by shifting from fossil fuel to renewable energy by 2050 as a conservation paradigm shift to save krill from thermal threat.

George (1984) reported that krill egg development is speeded up (Fig. with an increase of 2.5 C (from 0.5 to 2.) C) and thereby the eggs hatch as naupli not at 800 –1000 m but at 500 to 600 m where pH is lower and pCO<sub>2</sub> is higher. For example, developing eggs reach gastrulation at 2.0 C in 58 hours, much earlier than at –0.5 C. WAP region is warming up in recent years and unless, green house gas emissions are reduce, the current warming trend is bound to transform waters of the Western Antarctic Peninsula, especially the Circumpolar Deep Water (CDW) to a thermal level that may be greater than the upper lethal temperature of *Euphausia superba*. This hypothesis call for more careful experiments on krill egg development, simulating potential future scenario. However, evidence from research on temperate crustaceans suggests that pH sensitivity is definitely seen more in gametes and embryonic stages also in reproductive processes (Mayor et al, 2012)

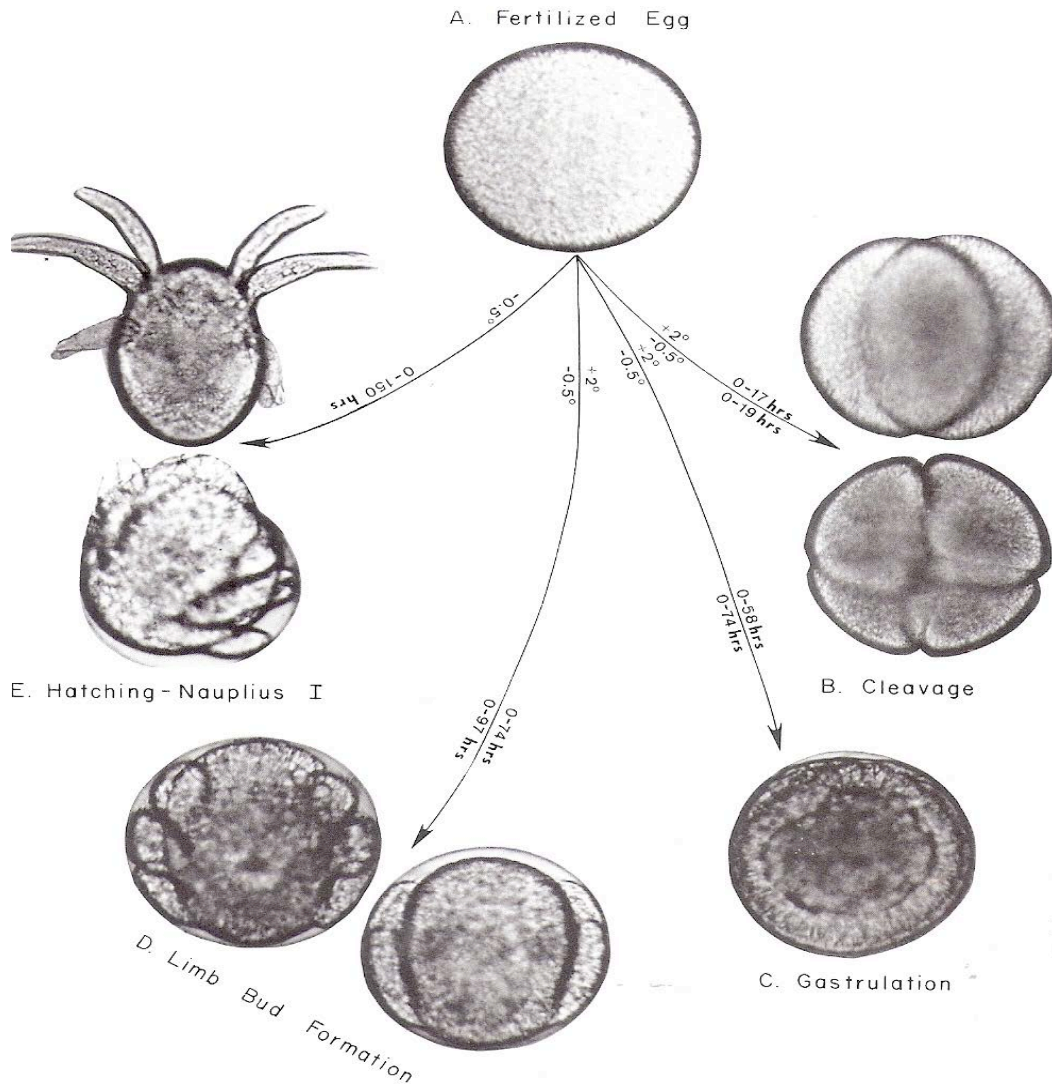


Fig 8. Enhanced rate of krill egg development with an increase of 2.5 C

Furthermore, there is likely to be increase in pCO<sub>2</sub> conditions in the midwater depths (200 to 600 m) with ongoing increase in absorption of atmospheric CO<sub>2</sub>, thus causing decrease in pH. Fig. 9 shows the profile of pH in the Palmer LTER region

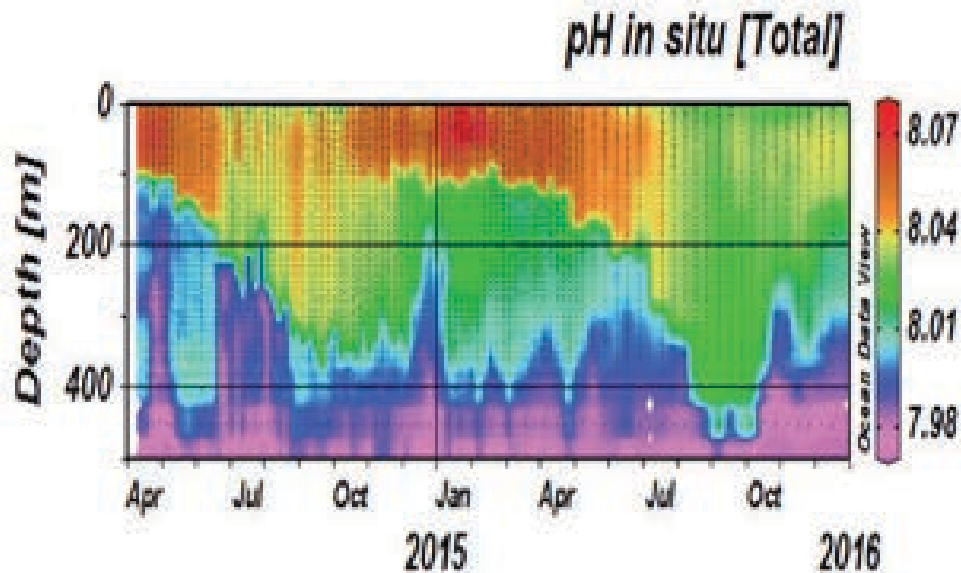


Fig. 9. The pH profile in the LTER region off Western Antarctic Peninsula

It is obvious from Fig.9 above that developing krill eggs, as it sinks deeper, will encounter ocean acidification stress as these eggs go through the water column from 200 to 450 m. Because egg development is accelerated by ongoing climate change, as described above, it is possible that we will witness reduced pH or increase pCO<sub>2</sub> condition, that may interfere with hatching success.

Kawaguchi (2013) also projected pCO<sub>2</sub> condition in the water column of the Southern Ocean between 55 and 76 S latitude as follows:

Depth (meters)	pCO <sub>2</sub> (ppm)
Surface	600
200	800
400	1600
600	1600
800	1600
1000	800
1200	800

Ericson et al, (2017), at the 3<sup>rd</sup> KRILL symposium also presented the influence of ocean acidification on krill physiology and lipid biochemistry on the basis of long term experiments lasting for 11 months. These authors monitored the effects of decreased pCO<sub>2</sub> levels at 400, 1000, 1500, 2000 and 5000 ppm) on adult krill that are now known to dwell at depths as great as 2500 m (Brierley, 2008). Clark and Tyler (2008) argued that the adult krill at abyssal depths are not just unhealthy individuals that will be succumbed to extreme pressure effects but they found evidence of exoskeletons of adult krill, proving that the krill molted and therefore are healthy and barotolerant. George (1981) defined barophilism in deep-sea animals that are adapted in live in pressure greater than 200 atm with unique protein to cope with pressure without getting depolymerized. In the opinion of this author, we must develop high-pressure chambers for testing the adaptation of krill in barophyllic conditions.

The simulation of ambient conditions in the experiment so Eriksson et al (2017) took into account only decreased pH) increased pCO<sub>2</sub> but not ambient hydrostatic pressure as high as 250 atm that adult krill encounters on the deep-sea floor. George and Stromberg (1985) examined the pressure effects on developing fertilized eggs to nauplius state and found that pressure actually accelerated embryogenesis. Ericson et al (2017) also predicted that increased in PCO<sub>2</sub> in the Southern Ocean may also impact Krill fisheries with potential changes in the composition of krill lipids in an acidified Southern Ocean.

#### CONNECTIVITY BETWEEN SCOTIA SEA AND WAP REGION

From scientific data on krill fisheries thus far, we can conclude without any hesitation that there is no threat from harvesting of krill that occurs predominantly in the Atlantic sector of the Southern Ocean. Therefore, it is apparent that threat to krill *E. superba* comes from thermal increase and pH decrease rather than krill fisheries. The total catch of krill in 2016 was 260.151 metric tons. This krill biomass is less than 1% of the total quantity of krill in the Southern Ocean. Krill fisheries in the Southern Ocean is wisely managed by the 'Commission on Antarctic Marine Living Resources' (CCAMLR) and this fisheries is by and large confined to CCAMLR Subarea 48.1, 48.2 and 48.3. The question arises, in the light of recent interannual sea-ice variations and cycles in primary production in Scotia Sea (including areas surrounding South Georgia) and the WAP regions, whether warming western Antarctic regions more so than east Antarctic regions in the entire Southern Ocean may impact krill density.

Piones et al (2013) modeled the remote and local connectivity of *E. superba* populations along the western Antarctic Peninsula (wAP) region to explain the input of krill from upstream sources via advection of individuals that originated in the Bellinghausen Sea, in addition to local and remote spawning and retention by investigations using Lagrangian particle tracks experimentally. It took 120 days (4 months from December Spawning to feeding Calytopis larval stages in April) for particles to reach WAP region from Bellinghausen Sea. This established that 23 % larvae originating from intrusion of Circumpolar Deep Water (CDW); 33 % from Antarctic Circumpolar Current (ACC) and 54 % from outer to inner shelf regions of high biological production. This study focused on krill populations in Marques Bay region

with discovery of local vs. remote input of larvae. We propose similar investigations in the future in both Ross Sea MPA areas and in Elizabeth City State University Bay in the Amundsen Sea.

The figures given below deals with krill fisheries in CCAMLT subareas in the Atlantic sector of the Southern Ocean from WAP region to Scotia Sea and also krill densities around Antarctica.

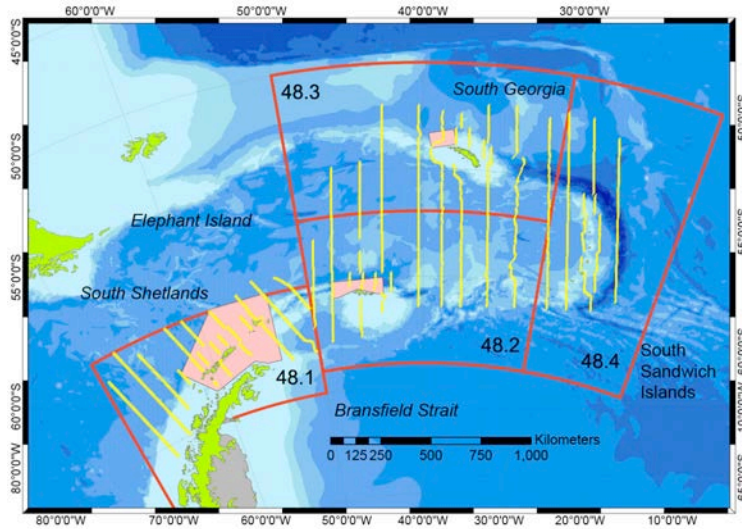


Fig. 10. Mean Krill Fisheries in CCAMLR subareas (after Hill, 2016)

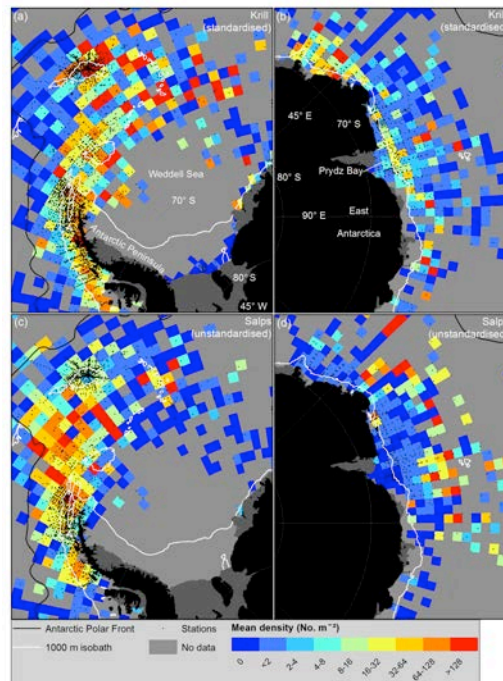


Fig. 11. Krill Density (After Atkinson et al, 2017)

Hill et al. (2016) summarized the status of current krill stock. Atkinson et al (2017) illustrated krill density around Antarctica. Krill fisheries are now permitted in an area about 3.5 million-kilometer square that is divided into four subareas. The trigger level (catch limit) was established as early as 1991 at .62 million tons per year, equivalent to less than 1 % total biomass. Obviously there was a decline krill biomass in the mid-80s but there is no data to establish any decline in krill abundance in recent decades, despite interannual variations caused by previous austral summer primary production. Watters et al (2003) attributed an ENSO-scale climate change signature, induced or triggered by El\_Nino events ( 5-7 years, lasting 7 to 9 months) to pelagic ecosystems in the eastern tropical Pacific, although the cause for Pacific Decadal Oscillation (POD) is still not known. It is premature to conclude what causes interannual changes in sea-ice extent around Antarctica but we see a spatio-temporal trend in krill densities in Scotia Sea but statistically the krill biomass decline, if any, is significant. However, we believe that “A New Krill Mega-Data HUB” should be part of the ongoing NSF-SPOKE project (Senior author of this paper is one of the project senior scientists in this Super-Computer DATA\_BASE at Georgia Tech.) that promotes linking all ecological data-bases through IBM-WATSON program to Encyclopedia of Life (EOL).

US NOAA (National Oceanic and Atmospheric Administration) initiated the Antarctic Ecosystem Research Division (AERD) to provide advice on living marine resources in the Southern Ocean to CCAMLR. This NOAA program is called AMLR (Antarctic Marine Living Resources) that embraces krill, finfish and krill dependent predators such as penguins, seals and baleen whales. Recently Hinke et al (2017) reported on their findings from the grid off WAP (Fig. 11)

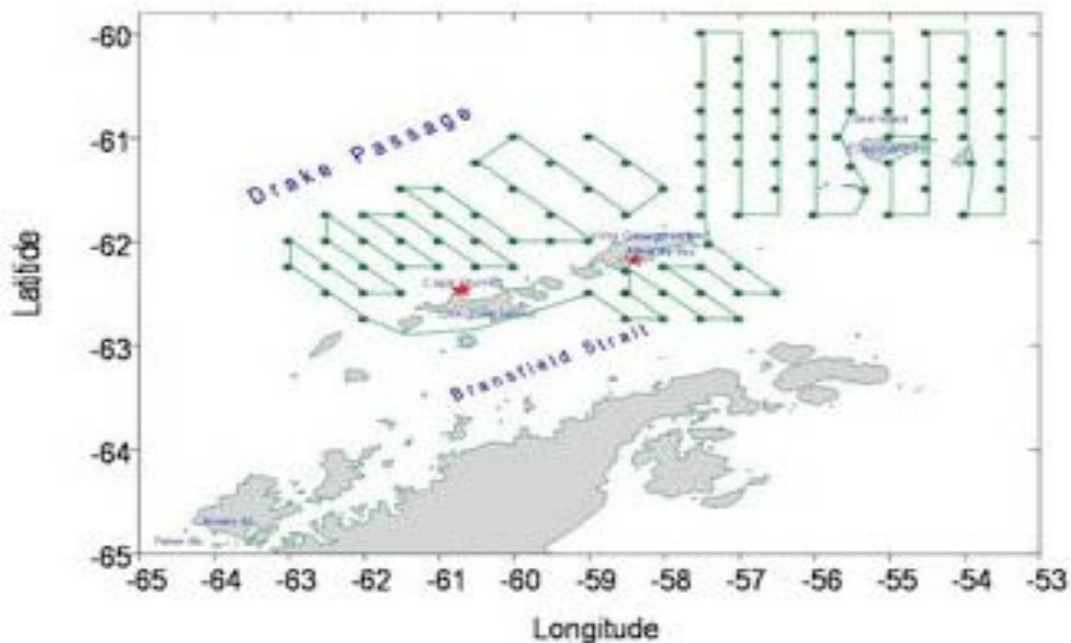


Fig. 11. US NOAA AMLR (Antarctic Marine Living Resources) – Area at the Tip of

## Antarctic Peninsula for Ecosystem Based Management

Hinke et al (2017) provided telemetry data to identify krill-foraging areas used by predators, with the goal of mitigating potential competition between predators and krill fisheries. Their work primarily focused on Pygoscelid penguins (Adelie and Chin-Strap penguins) female fur seals. All four species depend on krill as food. Their data demonstrated local movements near breeding colonies in the austral winter. Their results also demonstrated that over-lap of krill-dependent predators vs. krill fishery on small spatio-temporal scales is common throughout the Antarctic Peninsular Region. This study recommended a precautionary approach allocating krill catches in space to avoid large increases in catch.

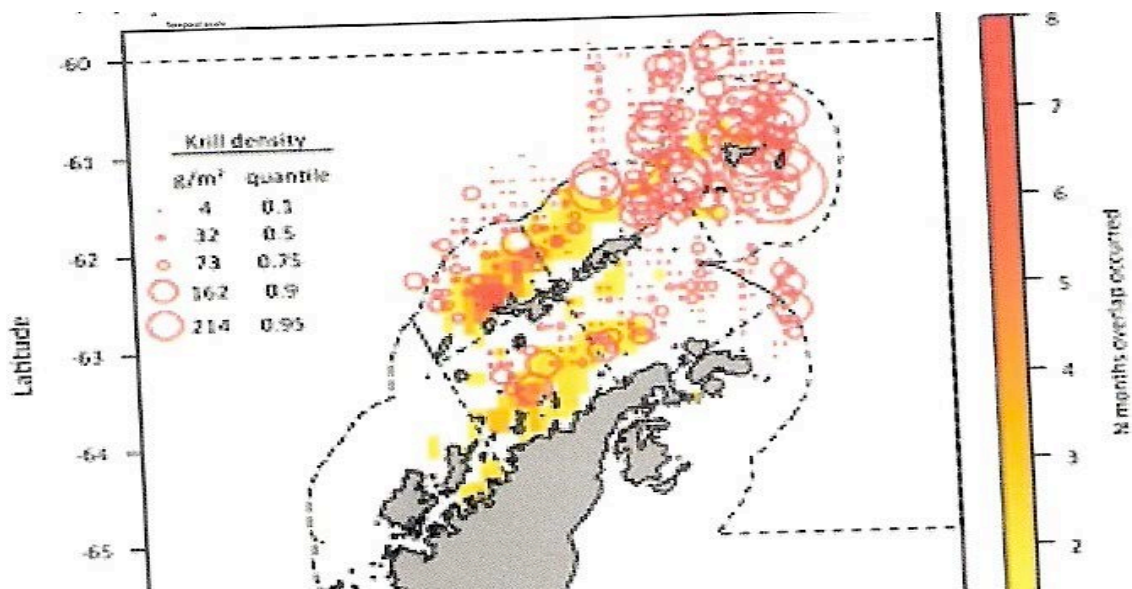


Fig. 12 Krill densities expressed in gm per sq. m in AMLR region (CCAMLR 48.1)

## RESILIENCE TO OCEAN ACIDIFICATION: PTEROPOD VS KRILL

Manno et al (2016) exposed female pteropods to present day pCO<sub>2</sub> conditions and also to future atmospheric CO<sub>2</sub> conditions of 750 ppm and 1200 ppm. They also exposed experimentally spawned eggs to ocean acidification stress. Eggs subjected to ocean acidification stress exhibited retardation in development. Combination of maternal and embryonic ocean acidification stress reduced percentage of eggs going through organogenesis by 80%. This study also proved that ocean acidification adversely impacted both somatic tissue and functioning of the gonads.





Fig 13 Pteropod *Limacina helicina antarctica* from Scotia Sea

It is important to point out that *Euphausia superba* does not have any external skeleton composed of aragonite as in pteropods and the exoskeleton in krill is made up of calcium carbonate. Since krill is a filter feeding planktonic animal, the mandibles are reduced and also the gastric mill is not well developed.

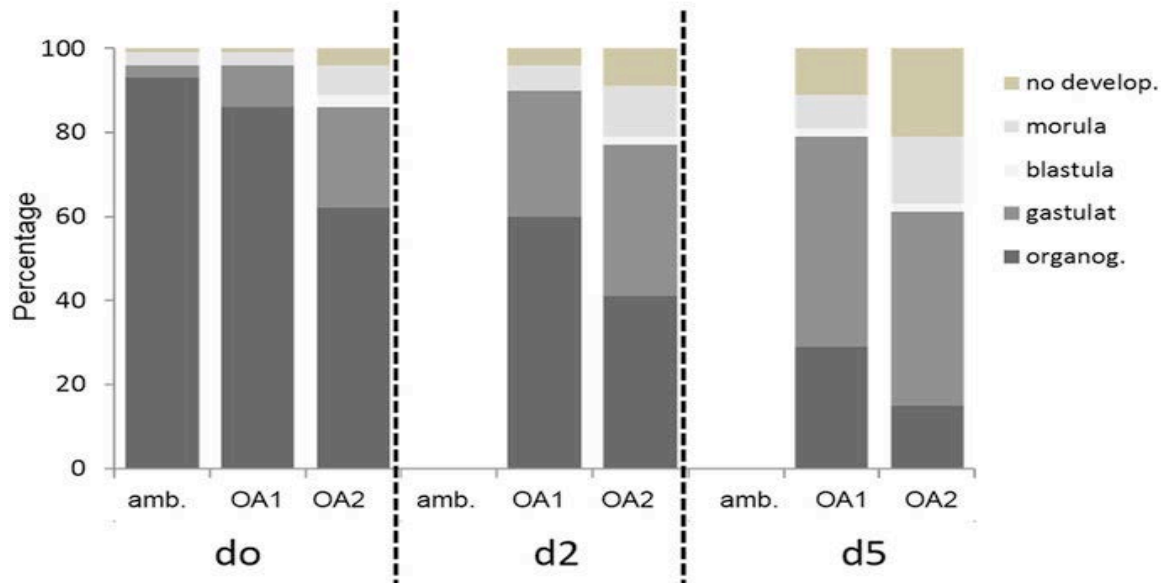
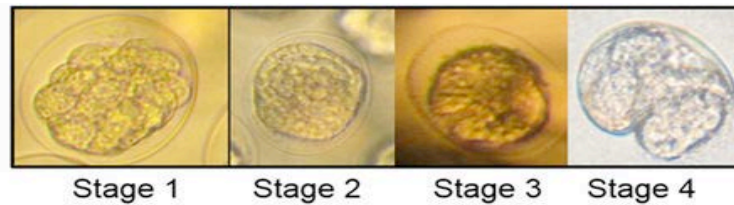


Fig 14. Pteropod embryonic stages 1. Morula 2. Blastula 3 Gastrulation and 4. Organogenesis. Note “d0” at 8.00 pH organogenesis was high and “d2” at 7.8 pH organogenesis was reduced and in “d5” organogenesis was further reduced. (from Manno et al., 2016).

The *in situ* study also found that post-larval pteropod stages concentrated at 600 m depth where pH was lower and this deeper exposure makes the pteropod larvae exposed to water unsaturated of aragonite because of ASH (Aragonite Saturation Horizon).

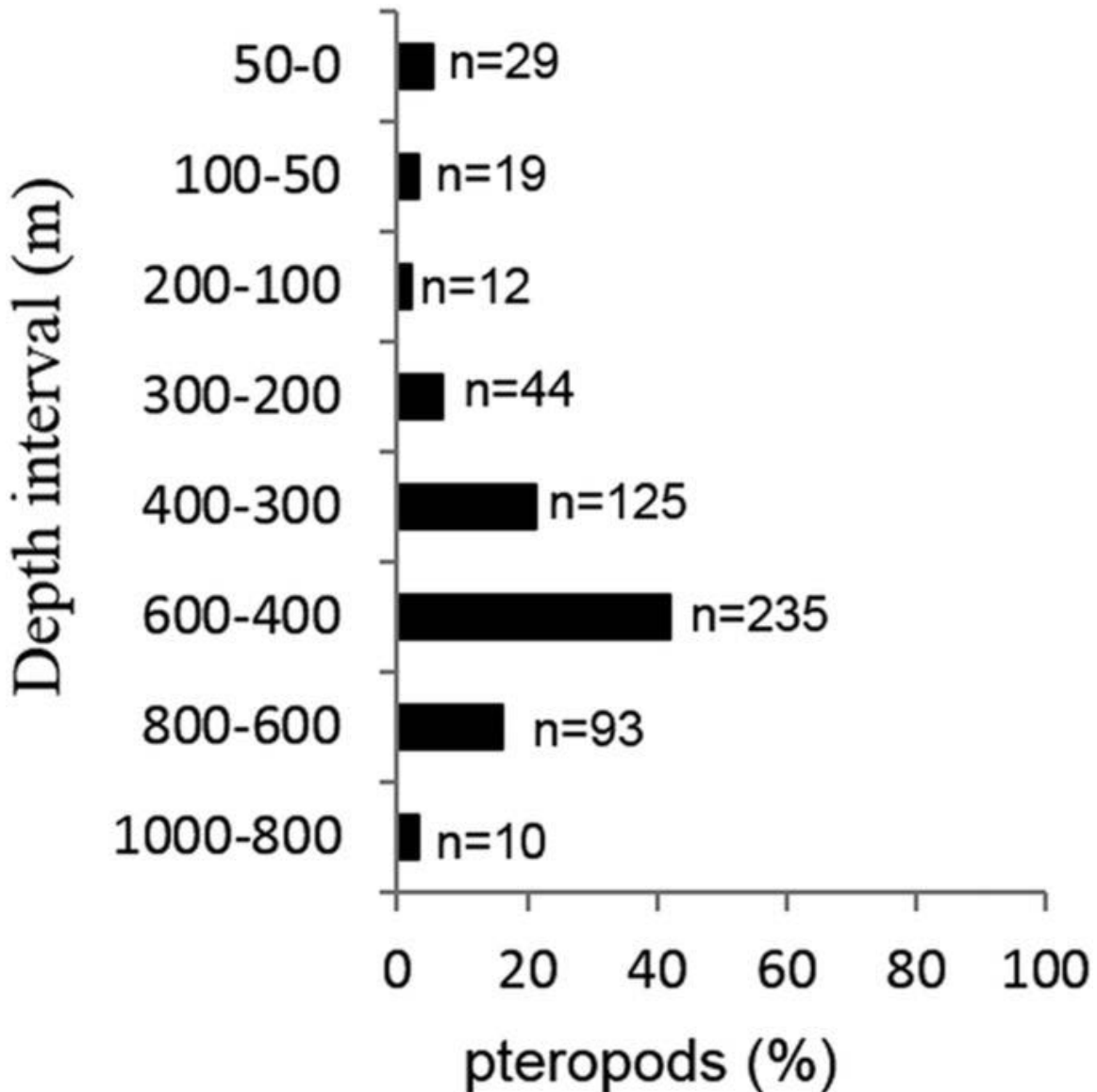


Fig. 15 Depth distribution of pteropod post-larvae in the water column in Scotia Sea. (From Manno et al., 2016).

## CONCLUSIONS

1 In recent decades, warming seems more pronounced in northern latitudes of WAP region than in the southern region. This ecosystem change has induced shift in structure and function of marine macro-zooplankton communities in Scotia Sea, and WAP region.

2. The reduction or loss of glaciers and ice-shelf such as what is described in this paper in Amundsen Sea opens up new bays that call for more field investigations to understand krill distribution and krill larval recruitment.

3 Our knowledge of krill distribution, krill spawning, larval dispersal in the Ross Sea is poor and calls for more research. We recommend Lagrangian particle transport investigations, as done by Pionon et al, 2013, in the Ross Sea MPA as well as Elizabeth City State University Bay in Amundsen Sea.

4. With new records of adult krill at depths as great as 3000 m. it is recommended that we develop pressure chambers to study the barotolerance and barophilism in adult *E. superba*.

5. In the light of new knowledge on lower pH in depths where krill hatch and climate change poses significant change in Carbonate chemistry of Southern Ocean, I suggest that we, in collaboration with CCAMLR's international network, pursue the recommendations that I made to US NSF for developing OOIS in WAP LTER region and or ROSS Sea new MPA area.

6. *E. superba* is less likely to be impacted by ocean acidification stress in the Southern Ocean in the near future but Pteropod *Limacina helicina antarctica* is far more vulnerable to pH decrease in the coming decades

#### ACKNOWLEDGEMENT

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#### REFERENCES

Atkinson, A. et al., 2017. KRILL DATABASE, A circumpolar data base of Antarctic krill and salp numerical densities, 1926 – 2016. Earth System Science Data 9: 193 – 210.

Emslie, S.D., L. Coats and K. Licht, 2007. A 45,000 yr record of Adelie Penguins and Climate Change in Ross Sea, Antarctica. Geology 35: 61 – 64.

Bernard, K. et al., 2012. Summer time grazing inputs of diurnal macrozooplankton off Western Antarctic Peninsula. Deep Sea Res. I. 622: 111 – 122.

Bernard, K. and D. Steinbeck, 2013. Krill biomass and aggregations structure in relation to tidal cycles in a penguin foraging region off Western Antarctic Peninsula. *ICES Journal of Marine Research* 70(4): 834 – 849.

Brierley, A.S., 2008. Antarctic Ecosystem: Are deep krill ecological outliers or portraits of Paradigm shift? *Current Biology* 18(6): 252 – 254.

Clarke, A. and P. Tyler, 2008. Antarctic krill feeding at abyssal depths. *Current. Biology* 18: 282 – 285..

Erickson, J., N. Hellesey, P.D. Nicholas, S. Nicol, S. Kawaguchi, N. Hoem and P. Virtue. 2017. Proceedings of the 3<sup>rd</sup> Krill symposium in St Andrews University, Canadian Journal of Fisheries and Aquatic Science (in this volume).

Ettershank, G. 1983. Age structure and cyclical annual change in the Antarctic krill *Euphausia superba* Dana. *Polar Biology* 2: 189 – 193.

Ettershank, G. 1984. A new approach to the assessment of longevity in the Antarctic krill *Euphausia superba* J. *Crustacean Bio.* 4 (Spec. Issue 1): 295 – 305.

Fevolden, S. and R. Y. George, 1984. Size frequency pattern of *Euphausia superba* in the waters west of the Antarctic Peninsula in the austral summer of 1983. *Journal of Crustacean Biology* 4 (Spec.No 1): 107 – 122.

Fuentes, V., G. Alundald, B. Meyer, G. E. Grunne, A. Canapa, A. Wolfi, H.C. Hass, G.N. Williams, and J. R. Schoss. 2016. Glacial Melting: An Overlooked threat to Antarctic Krill. *Scientific Repotsd.* Article No. 27234.

George, R. Y. 1971. Thermal sensitivity of hyposychral species of Antarctic and High Arctic Marine Crustacea. *Proc. Joint. Oceanogr. Assembly (Tokyo, 1970).* P 474.

George, R. Y. ,1981. Functional Adaptations of Deep-Sea Organisms. In: *Functional Adaptations of Marine Organisms.* Edited by F. J. Vernberg and W. B. Vernberg. Academic Press. Chapter 8: 279 –332.

George, R. Y., 1983. Metabolism of Antarctic krill *Euphausia superba* and its trophodynamic implications. In: *Antarctic Nutrient Cycles and Food Webs.* Edited by W. R. Sigfried, R.R. Condy and R.M Laws, Springer Verlag. Pp. 324 – 329.

George, R. Y. 1984. Ontogenetic adaptations in growth and respiration of *Euphausia superba* in relation to temperature and pressure. *Journal of Crustacean Biology* 4 (Spec. No. 1): 252 – 262.

George, R. Y. 1984a (Editor). *The Biology of the Antarctic krill Euphausia superba* (Proceedings of the First International Symposium on Krill held at Wilmington), North Carolina, 16 – 19, October, 1982). *J. Crustacean Biol.*

George, R. Y. 2017. Potential impact of carbonate chemistry change (pCO<sub>2</sub>) on Krill and krill-based food-chain in the Southern Ocean with emphasis on Embryogenesis of Antarctic krill. *Biogeosciences (in Press)*. 4 (Special No. 1). 337 pges.

George, R. Y. and J. Filelds., 1984. Ammonia excretion in the Antarctic krill *Euphausia superba* in relation to starvation and ontogenetic stages. *Journal of Crustacean Biology* 4(Special No.1): 263 – 272.

George, R. Y. and J. O. Stromberg, 1985. Development of eggs of Antarctic krill *Euphausia superba* in relation to pressure. *Polar Biology* 4: 125 – 133.

Hill, S. L. et al., 2016. Is current management of the Antarctic krill fishery in the Atlantic Sector of the Southern Ocean precautionary? *CCAMLR Science* 2016: 31 – 51.

Hinke, T. J. et al., 2017. Identifying Risk: Concurrent overlap of the Antarctic krill fishery and krill dependent Predators in the Scotia Sea. *Plos*:  
Doi.org.10.1371/journal.Pone.0170132.

Kawaguchi, S. et al., 2013. Acid Test for Krill: Risk Maps for Antarctic krill under projected Southern Ocean Acidification. *Nature Climate Change* 3: 847 – 858.

Le Compte, M., R. Bindshadler, L Hayden, M. Jeffersen, Ya Bridges, R. Lawrence, J. Bevens, J. Brownlow, R. Evans, K. Kawk and G. Koch, 2013. Reduction and Loss of an Ice Shelf in Elizabeth City State University Bay, Antarctica: 1972 – 2003. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. 6(3): 1509 – 1515.

Manno, C., V.L. Peck and G. A. Talling, 2016. Pteropod eggs released to high pCO<sub>2</sub> lack resilience to ocean acidification. *Scientific Reports* No 25752. doi:10.1038.Srep25752.

Mayor, D. J., N.R. Everett and K.B. Cook, 2012. End of century ocean warming and acidification on reproductive success in temperate marine copepods, *J. Plankton Res.* 34: 258 – 262.

Nicol. S., 2000. Understanding krill growth and aging: the contribution of experimental studies. *Can. J. Aqua.Sci.* Vol. 57 (Supp.3): 168 – 177.

Pinoes, A. et al., 2013. Modelling the remote and local connectivity of Antarctic krill populations along the Western Antarctic Peninsula. *Mar. Ecol. Prog. Ser.* 481: 69-92. Doi: 10.3354/meps10256.

Saba, G. K., O. Schofield, J.J. Torres, E. H. Ou and D. Steiberg, 2012. Excretion of adult Antarctic krill *Euphausia superba* exposed to enhanced Carbon dioxide (CO<sub>2</sub>). Doi.org/10.1371/0052224.

Scheuchl, B., J. Mougnot, E. Rignot, M. Morlighem, A. Khazendar. **Grounding line retreat of Pope, Smith, and Kohler Glaciers, West Antarctica, measured with Sentinel-1a radar interferometry data.** *Geophysical Research Letters*, 2016; 43 (16): 8572 DOI: [10.1002/2016GL069287](https://doi.org/10.1002/2016GL069287)

Steinberg, D. K., Ruck, K. E., Gleiber, M. R., Garzio, L. M., Cope, J. S., Bernard, K. S., Stammerjohn, S. E., Schofield, O. M. E., Quetin, L. B., and Ross, R. M.: Long-term (1993–2013) changes in macrozooplankton off the Western Antarctic Peninsula, *Deep-Sea Res. Pt. I*, 101, 54–70, doi:10.1016/j.dsr.2015.02.009, 2015

Thillart, Van den G., R. Y. George and J.O Stromberg, 1999. Hypoxia sensitivity and respiration of the euphausiid crustacean *Meganyctiphanes norvegica* from Gullmarn Fjord, Sweden, *Sarsia* 84: 105 – 109.

Watters, G.M., Olson, R.J., Francis, R.C., Fiedler, P.C., Polovina, J.J., Reilly, S.B., Aydin, K.Y., Boggs, C.H., Essington, T.E., Watters, C.J., and Kitchell, J.F. 2003. Physical forcing and the dynamics of the pelagic ecosystem in the eastern tropical Pacific: simulations with ENSO-scale and global-warming climate drivers. *Canadian Journal of Fisheries and Aquatic Sciences*. 60(9): 1161-1175.