ANTARCTIC SEA-ICE VARIABILITY: PRE-2000 AND POST-2000 COMPARISON

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KEY WORDS: Sea-ice, Antarctica, ozone concentration,

ABSTRACT

Sea ice plays an important role in the state and variability of regional and global climate through thermodynamic and dynamic processes, and feedback mechanisms operating over a hierarchy of space and time scales. In contrast to Arctic, Antarctic sea ice extent shows an increasing trend, with large inter-annual variability, since 1979. This study explores the trends and variability of Antarctic sea-ice in different sectors following literature: Weddell Sea (60°W–20°E), Indian Ocean (20°–90°E), Western Pacific Ocean (90°–160°E), Ross Sea (160°E–130°W) and the Bellingshausen-Amundsen Sea (130°-60°W). Using passive microwave sea ice concentrations derived from SMMR and SSM/I-SSMIS sensors for 1979-2015, we studied decadal and regional trends pre- and post-2000. The results indicated that Weddell Sea, Indian Ocean and Pacific Ocean sectors are exhibiting an increasing sea ice trend at a higher rate post-2000, whereas, Ross Sea sector experiences a slight decline. Sea ice in Bellingshausen-Amundsen sector has been decreasing since 1979; however post-2000 there is an increasing trend which contributes to an overall sea-ice increase. On a seasonal time scale opposite anomaly is being observed pre- and post-2000. Post-2000, Weddell Sea and Pacific sectors (Indian Ocean and Ross Sea sectors) experience a decreasing (increasing) trend. Monthly anomaly of Bellingshausen-Amundsen sector shows an increasing sea ice trend from a negative anomaly to a positive anomaly post-2000; January (November) months are contributing the most in decrease(increase) of total Antarctic sea-ice, respectively. Prior to 2000, the monthly sea ice anomalies were negative with slight positive slope, which switched to positive post-2000. Of the many contributing factors (remote forcing such as ENSO, Indian Ocean Dipole, Pacific Decadal Oscillation, Southern Annular Mode; regional forcing like winds, air/sea surface temperature warming, Antarctic Circumpolar wave, etc) for sea ice variability we discuss ozone hole-Amundsen Sea Low interaction for the changes post-2000.

1. INTRODUCTION

Polar sea ice is an important component as both a leading indicator of climate variability/change and as a key player in the global climate system (e.g., Thomas and Dieckmann, 2010]. Its spatio-temporal extent diminishes the ocean-atmosphere interaction and its bright surface reflects the solar radiation back to space thereby modulating the surface heat budget. The cold water formation and the convective circulation near Antarctica influence the ocean circulation through global conveyor belt (Broecker, 1991). When compared to a slight increase in Antarctic sea ice extent (1.5% per decade; $p<0.01$, for 1979–2013), Arctic sea ice has decreased drastically since the satellite-based monitoring began in 1979 (Simmonds, 2015). This is largely due to the result of different topographic factors and land-sea distribution (Turner and Overland, 2009). Sea ice variability is a result of both natural and anthropogenic radiative factors (Ding et al, 2017). Many factors affect sea ice variability, among them include teleconnections related to El Niño/ Nina - Southern Oscillation (ENSO) events, the Southern Annular Mode (SAM) (Thompson et al., 2011), Pacific Decadal Oscillations (PDO), Indian Ocean Dipole (IOD), while regional factors include wind-driven thermodynamic changes (Holland and Kwok, 2012), deepening of Amundsen Sea Low (ASL), increases or decreases in air /sea temperature, geometry of the coastline in different Antarctic sectors. When anthropogenic explanations are considered, the ozone depletion deepens the ASL (Turner et al, 2016; Coggins and McDonald, 2015), thereby strengthening the SAM resulting in changes in sea ice extent in different sectors differently (Turner et al. 2009). Atmospheric variability in Amundsen-Bellingshausen Sea is larger than anywhere else in the Southern Hemisphere, and exhibits significant correlations with both the SAM (Marshall, 2003) and ENSO (Yuan. It plays a significant role in the climate variability of West Antarctica and the adjacent oceans. The ozone hole also may induce a positive SAM trend, which in turn may lead to an increasing trend of the Antarctic sea ice extent (SIE). However, coupled atmosphere-ocean-sea ice models suggest that the ozone depletion may lead to a negative trend of the Antarctic SIE. Hitherto, the reasons why the SIE shows a positive trend are still debatable. But beyond the reasons for a positive trend, a more important question is, whether the trend is originated from anthropogenic forcings, or within the bounds of natural variability. Model simulations indicate that in response to a positive SAM, increased northward surface Ekman drift caused by enhanced downwelling near 45°S and upwelling near the Antarctic continent. In this study we address the sea-ice trends and anomalies pre- and post 2000 in different sectors. We studied the how the ozone and ASL components are affecting antarctic sea-ice seasonally by comparing pre- and post-2000 changes.

2. DATA AND METHODOLOGY

Based on the Dutch-Finnish Ozone Monitoring Instrument (OMI), total ozone column data are retrieved using both the TOMS (version 8) technique developed by NASA and a Differential Optical Absorption Spectroscopy technique developed by Royal Netherlands Meteorological Institute (KNMI). The OMI vertical ozone profiles provide maps of the global ozone layer in three dimensions on a daily basis with a horizontal resolution of at least 65 km x 48 km and capturing the vertical ozone structures from the surface up to 65 km in 18 pressure layers, with a vertical resolution of at least 6 km. These retrievals constitute a comprehensive data set to study the spatiotemporal distribution of ozone everywhere on the globe and the data is available at http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/index.shtml. This data set can potentially yield accurate estimates of tropospheric ozone columns either by sampling the retrieved profiles themselves or by subtracting a stratospheric column estimate obtained from the ozone profiles from a total ozone column estimate obtained at similar or longer wavelengths by means of the well-validated OMI-TOMS or OMI-DOAS ozone column techniques (Kroon et al., 2008). Fields of monthly mean SIC computed using the Bootstrap version 2 algorithm (Comiso 2000) were obtained on a 25 km resolution grid from the US National Snow and Ice Data Center (NSIDC) (www.nsidc.org). We used the NASA Bootstrap 2 data since it has been used in many previous studies and the sea ice trends in the recent IPCC Assessment Report 5 were determined using this algorithm. We examined sea ice trends for five sectors of the Southern Ocean that have been considered in a number of earlier studies (e.g., Zwall*y et al*., 2002): Ross Sea (160°E–130°W), ABS (130°W–60°W), Weddell Sea (WS, 60°W–20°E), Indian Ocean (IO, 20°E–90°E), and western Pacific Ocean sector (PO, 90°E–160°E). The ASL is the deepest climatological mean sea level pressure (MSLP) centre within the circumpolar trough that rings Antarctica between 60° and 70°S, and its presence has been linked to the interaction between the orography of the Antarctic continent and the strength of the westerly winds over the Southern Ocean (Baines and Fraedrich, 1989). Inter-annual variability of MSLP in the area of the ASL is larger than at any other location in the Southern Hemisphere (SH) (eg. Lachlan-Cope et al., 2001), with surface pressure here influenced by tropical climate variability in the Pacific and Atlantic Oceans. The ASL has deepened in recent decades (Turner et al., 2009), which is consistent with the dipole of ice loss/increase between the Antarctic Peninsula and the Ross Sea. ASL is defined as actual central pressure strongly modulated by the Southern-Hemisphere Annual Mode (SAM) across all seasons, with time series correlations significant at $p<0.01$. The ASL Relative Central Pressure is a regional pressure anomaly calculated by subtracting the ASL actual central pressure from the area-averaged pressure over the ASL domain (170°–298°E, 80°–60°S) using the ECMWF Interim reanalysis (ERA-Interim) fields on ~70 km grids. Among 6 reanalyses products assessed for Southern Ocean, ERA-Interim had the most accurate MSLP/surface winds between the Antarctic Peninsula and the Ross Sea (Bracegirdle, 2013). Southern Annular Mode (SAM-indices) used in the study were provided by British Antarctic Survey (https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based). The trends were computed using a standard least-squares method, with the methodology used to calculate the significance levels based upon Santer et al. (2000) We address how ozone hole concentration is influencing Antarctic sea-ice using correlation analysis (Press, 1992).

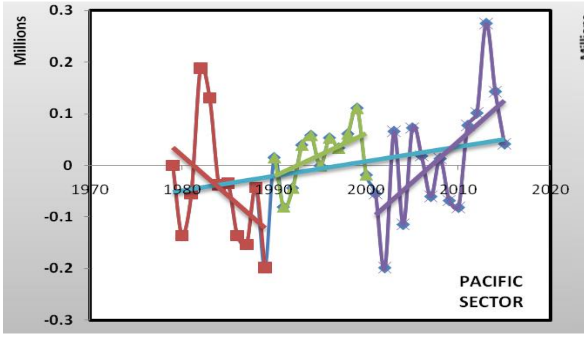
3. RESULTS

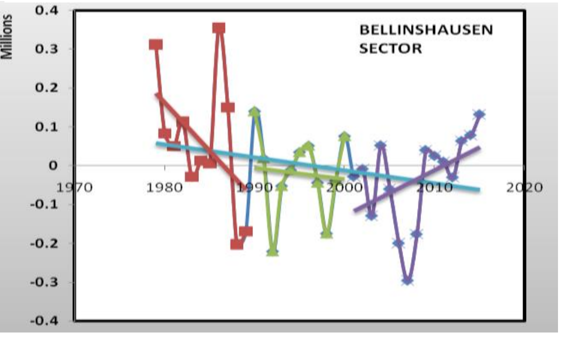
3.1 Sea ice trends

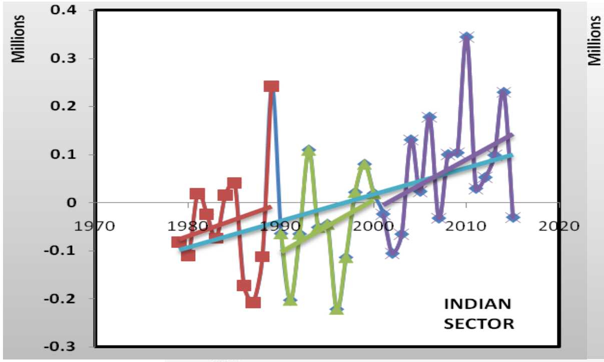
The sector-wise analysis of sea ice extent (1979-2015) showed that ABS exhibited a strong decreasing trend (-3300 km^2/decade), whereas WS, RS, IO and PO sector showed increasing trend, since 1979. It is noted that RS showed highest positive trend (11376 km^2/decade). In order to understand the long-term scenario of sea-ice, decadal trends for sectors were analysed. For 1979-1989, ABS, PO, WS (RS and IO) sectors exhibited decreasing (increasing) trends. For 1990-2000 period, PO sector sea ice trend shifted to positive, RS and IO (ABS and Weddell) trends remained positive (negative). Interestingly all the sectors showed positive trend post-2000. In order to understand the factors driving these decadal changes and forcing factors on different regions, we studied seasonal associations of each factor to each region of Antarctica.

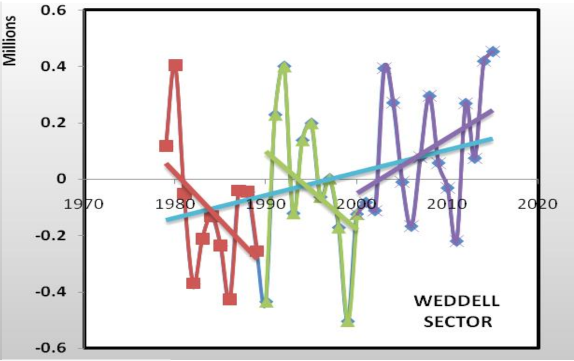
Table.1: Overall and decadal trends in Southern Hemisphere sea ice extent for 1979-2015 period.

Sectors	Overall (km^2/decade)	Decadal trend (km^2/decade)		
		1979-1989	1990-2000	Post-2000
Amundsen-Bellingshausen	-3300	-24848	-3039	11705
Western Pacific Ocean	2817	-15667	8156	15872
Ross Sea	11376	49454	48156	11283
Weddell Sea	8033	-34265	-27698	19748
Indian Ocean	5539	6803	10852	10584









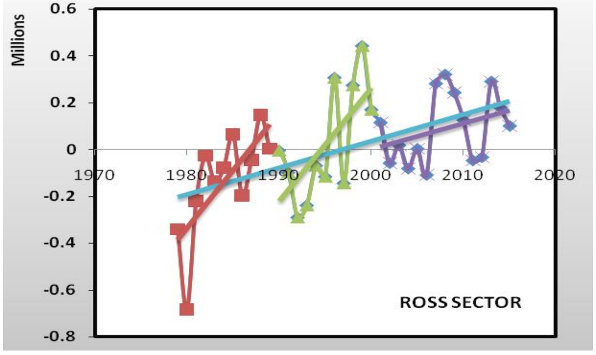


Fig. 1. Decadal (1979-1989, 1990-2000 and post-2000) sea-ice extent (million km^2) in the Southern hemisphere since 1979.

We examined month-wise trends and contribution of sea ice to the trend in pre- and post-2000 period (Figure 2). It is observed that WS and ABS exhibited a decreasing trend pre-2000, which increased post-2000. IO exhibited a positive slope pre-2000 and continued to stay positive post-2000. RS showed increasing trend pre-2000 (in fact it was positive for both decades: 1979-89: slope =49454 km^2/decade, 1990-2000, slope= 48156 km^2/decade), whereas post-2000, it showed a drastically fall below the overall trend line (post-2000: 11283 compared to overall slope of 11376). This is the only sector that exhibited a decreasing trend post-2000, which is associated with southern hemispheric teleconnections – ENSO. Since it is closely connected to Pacific Ocean, it has more associations with El-Niño/ La-Nina seasons – whose mechanisms are well studied and explained by Yuan (2004). PO sector showed a decline in 1979-89 (-15667 km^2/decade), and showed a positive trend in 1990-2000 (8156 km^2/decade), thereafter it is been increasing post-2000 (15872 km^2/decade).

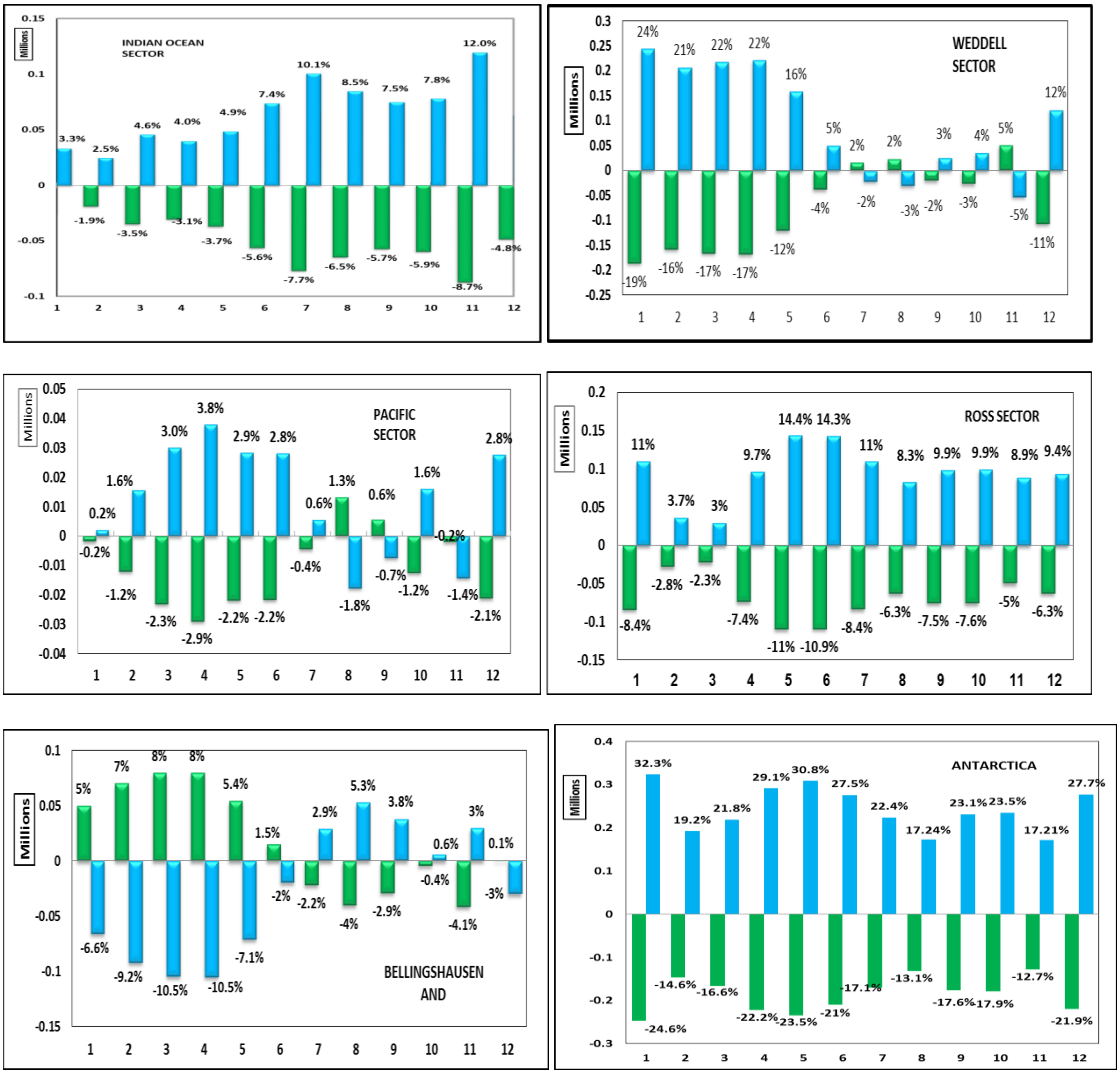


Fig. 2. Monthly anomalies (deviation of each month from the (1979-2015) average in km^2/decade) for Weddell Sea (60°W to 20°E), Indian Ocean (20°–90°E), Western Pacific Ocean (90°–160°E), Ross Sea (160°E–130°W) and the Bellingshausen/Amundsen Sea (130°–60°W). Percentage sea-ice contribution for each month in different periods is shown above.

Monthly anomlaies calculated for each sector pre and post 2000 are depicted on Fig. 2, in order to address intraannaul variation in sea ice. Results revealed that BAS (WS) were completely acting opposite by exhibiting an increasing (decreasing) trend post-2000. On the other hand, PO (IO sector) showed a decreasing (increasing) post-2000. As far as contributions of each sector towards the overall sea ice in different seasons are concerned, it is noted that WS sector and BAS contributed more during austral summer (DJF) and autumn (MAM), whereas, PO sector contributed most during February -June months. IO sector contributed most during austral winter JJA and spring season (SON), while RS sector contributed the least during February and March.

3.2. Ozone – Sea Ice variability: Pre and Post-2000 for SON season

The ozone hole is formed each year in the Southern Hemisphere spring (September-November). There was a sharp decline (currently recovered up 60%) in the total ozone over most of Antarctica before Protocols were brought in to cut emissions of chlorofluorocarbons. During the cold and dark Antarctic winter, stratospheric ice clouds (PSCs-polar stratospheric clouds) form when temperatures drop below -78C. These clouds are responsible for chemical changes that promote production of chemically active chlorine and bromine. When sunlight returns to the Antarctic in the Southern Hemisphere spring, this chlorine and bromine activation leads to rapid ozone loss, which then results in the Antarctic ozone hole. Stratospheric air in the Antarctica is relatively isolated from other regions for long periods in the winter (SON) months. Thus, austral spring season (SON)is considered for the study.

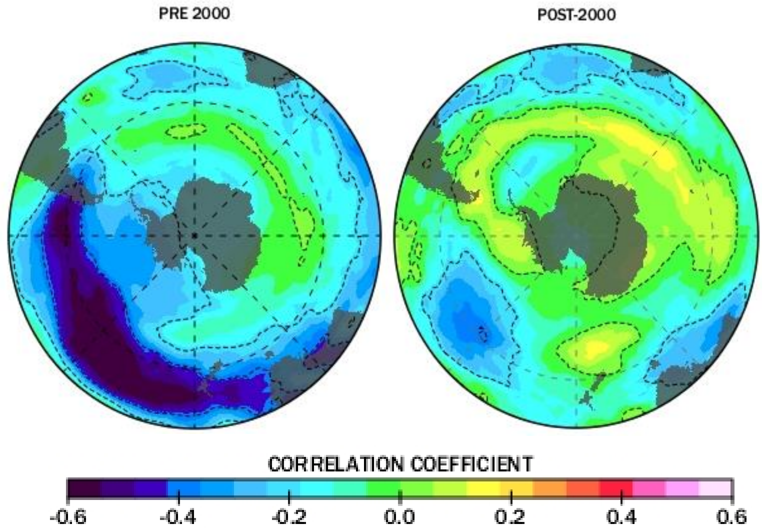


Fig.3 Mean Ozone from multi-sensor re-analysis data correlated to sea-ice concentration for austral spring season (left: pre-2000 and right:post-2000).Since the Ozone hole is recovering the negative association is weakened post-2000 and therefore, post-2000 sea-ice concentration is increasing.

We correlated the monthly mean ozone data derived from multi-sensor re-analysis data with sea-ice concentration for SON season highlighting on pre- and post-2000. A negative correlation is noted post-2000. We then studied SAM's behavior with ozone. SAM is said to be intense during SON, when the sea-ice reaches maximum extent. Because of the isolation of strong winds that encircle the poles, a polar vortex is formed over Antarctica which prevents substantial motion of air into or out of the polar stratosphere. This circulation strengthens in winter as stratospheric temperatures decrease, with the result that the isolation of air in the vortex is much more effective in the Antarctic. Thus the ozone hole is correlated for SON season pre- and post-2000. A strong significant correlation is noted in ASL region which is again connected to SAM. The results also showed the weakening in negative correlation (increase in ozone decreasing sea-ice extent) post-2000 since the ozone hole is recovering.

Annular SAM indices revealed that pre-2000, the lowest SAM index (-0.93) was observed in 1988 - post strong el-Niño period, whereas the highest (1.59) was found in 1998. Post-2000 analyses showed, the highest SAM (1.60) in 2015 and the lowest (-0.27) appeared in 2007 at the height of strong La-Nina. Thus, SAM and El-Niño events together act on Southern Hemisphere by changing the ocean surface temperature and wind patterns respectively.

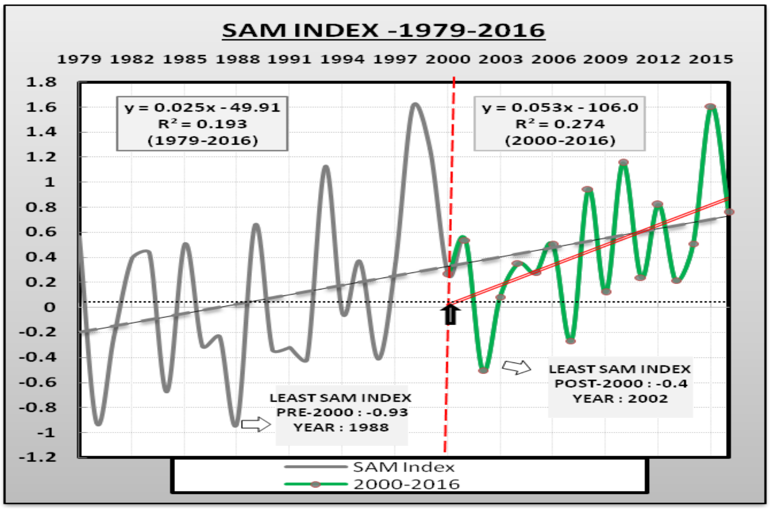


Fig. 4.Annual SAM index. SAM has been in positive phase since 1988, but it has intensified twice post-2000. (source: British Antarctic Survey)

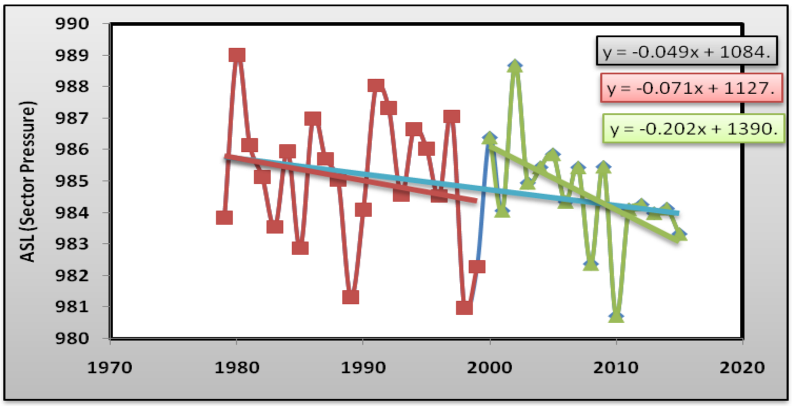


Fig.5. March of annual ASL index. Red represents pre-2000 and green post-2000. Post-2000 ASL is deepening at a higher pace (-0.2) compared to pre-2000 (-0.07).

Both global warming and ozone depletion could deepen the ASL, which strengthens the SAM index, weaken the westerlies near the Ross Sea and strengthen the southerly cold winds from the continent. This process makes the sea ice in the Ross Sea more isolated and increases its extent due to the southerly cold winds. Hadley circulation abruptly gives way to a mainly zonal circulation that circumnavigates the winter stratospheric polar vortex. This becomes stronger when the vortex is colder. Cold temperatures lead to ozone-destroying clouds. The seasons with the largest differences in zonal winds near the vicinity of the ASL are DJF and MAM. These are also the two seasons where we see the strongest poleward ASL shifts. Thus seasonality is consistent with projected increases in the westerly wind component over the Amundsen Sea which thereby affects the entire Antarctic sea-ice phenomenon.

4. DISCUSSION

We conclude that Ozone recovery – ASL deepening –SAM intensifying are all inter-connected which affects the local factors such as winds. Pre and post-2000 analysis confirm that ASL has deepened, SAM has intensified and ozone hole is slowly recovering, which is considered as one of the factors for the incerases in Antarctic sea-ice at a higher pace than pre-2000 era. Also, the sea ice in the western Antarctic regions -WS and BAS which are directly affected by ozone hole and ASL connection, have been increasing post-2000. Our study confirms that WS and BAS sectors contribute more deviations in DJF and MAM, thereby decreasing the sea ice extent. Decreases in PO sea-ice post-2000 is connected to El-Nino teleconnections, since post-2000, the number of El Nino episodes have decreased compared to pre-2000. Also, PO sector contributions are high in February to June the period after December –January when El-Nino starts taking shape. IO sector sea ice is affected by zonal winds influenced by the teleconnections, and this is the sector which is contributes the most to increasing Antarctic sea-ice because there are no gyres in the ocean, and ocean stratification (Jang, 2007) promoted more convenient conditions for sea-ice increase. Results show that the maximum contributing seasons are JJA and SON for IO sea ice extent. Ross sea sector on contrary contributes least in February and March months than the rest of the year.Thus , seasonal variations in antarctic sea-ice is highly associated with geographical attributes of each sector on which the local factors depend.

REFRENCES

Baines PG, Fraedrich K (1989) Topographic effects on the mean tropospheric flow patterns around Antarctica. Journal of Atmospheric Science, 46, pp.3401–3415.

Bracegirdle, T.J, 2013. Climatology and recent increase of westerly winds over the Amundsen Sea derived from six reanalyses. International Journal of Climatology, 33(4), pp.843–851.

Broecker, W.S., The great ocean conveyor. Oceanography, 1991. 4(2), pp. 79-89.

Coggins, J. H. J. and McDonald, A. J., 2015. The influence of the Amundsen Sea Low on the winds in the Ross Sea and surroundings: Insights from a synoptic climatology, Journal Geophysical Research - Atmospheres, 120 (6), pp. 2167–2189

Ding, Q., Schweiger, A, L'Heureux, M, Battisti, D. S., Po-Chedley, S., Johnson, N. C., Blanchard-Wrigglesworth, E., Harnos, K., Zhang, Eastman, R., Steig, E. J., 2017. Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice, Nature Climate Change, 7, pp. 289–295, doi:10.1038/nclimate3241.

Holland PR, Kwok R., 2012. Wind-driven trends in Antarctic sea-ice drift. Nature Geoscience, 5(12), pp.872–875

Hosking, J. S., A. Orr, T. J. Bracegirdle, and J. Turner, 2016. Future circulation changes off West Antarctica: Sensitivity of the Amundsen Sea Low to projected anthropogenic forcing: future change in the Amundsen Sea low, Geophysical Research Letters, vol. 43(1), pp. 367–376.

Kroon, M., J. P. Veefkind, M. Sneep, R. D. McPeters, P. K. Bhartia, *and* P. F. Levelt *(*2008*)*, Comparing OMI-TOMS and OMI-DOAS total ozone column data, Journal of Geophysical Research, 113, D16S28, doi:10.1029/2007JD008798.

Lachlan-Cope TA, Connolley WM, Turner J (2001) The role of the non-axisymmetric Antarctic orography in forcing the observed pattern of variability of the Antarctic climate. Geophysical Research Letters 28(21), pp.4111–4114.

Marshall, G. J., 2003. Trends in the Southern Annular Mode from observations and reanalyses, Journal of Climate, 16(24), pp. 4134–4143.

National Snow and Ice Data Center. [Online]. Available: http://nsidc.org/data/g02135. [Accessed: 24-Jul-2017].

Press, W. H., 1992.Editor, Numerical recipes in C: the art of scientific computing, 2nd edition, Cambridge, New York: Cambridge University Press.

Parkinson CL, Cavalieri DJ., 2012. Antarctic sea ice variability and trends, 1979–2010. Cryosphere, 6, pp.871–880

Polvani LM, Smith KL, 2013. Can natural variability explain observed Antarctic sea ice trends? New modelling evidence from CMIP5. Geophysical Research Letters, doi:10.1002/grl.50578.

Santer, B.D., Wigley T.M.L., Boyle, J.S., Gaffen D.J., Hnilo J.J., Nychka D., Parker D.E., Taylor K.E., 2000. Statistical significance of trends and trend differences in layer-average atmospheric temperature time series. Journal of Geophysical Research, 105(D6), pp.7337–7356

Simmonds I., 2015. Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35-year period 1979–2013. Annals of Glaciology, 56, pp.18–28. (doi:10.3189/2015AoG69A909)

Stammerjohn S, Massom R, Rind D, Martinson D, 2012. Regions of rapid sea ice change: an inter-hemispheric seasonal comparison. Geophysical Research Letters, doi:10.1029/2012gl050874

Thompson DWJ, Solomon S, Kushner PJ, England MH, Grise KM, Karoly DJ, 2011. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. Nature Geoscience, 4(11), pp.741–749.

Turner, J, J.C. Comiso, G. J. Marshall, T. A. Lachlan-Cope, T Bracegirdle, T Maksym, MP Meredith, Z Wang, and A Orr, 2009. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophysical Research Letters, DOI: 10.1029/2009GL037524

Turner, J., *and* J. Overland *(*2009*)*, Contrasting climate change in the two polar regions, Polar Res., 28, 146–164, *doi:*10.1111/j.1751-8369.2009.00128.x.

Turner, J., J. S. Hosking, T. J. Bracegirdle, T. Phillips, and G. J. Marshall, 2016. Variability and trends in the Southern Hemisphere high latitude, quasi-stationary planetary waves, International Journal of Climatology, *doi:*10.1002/joc.4848.

Thomas, D. N., and G. S. Dieckmann (2010), Sea Ice, 2nd edition, 621 pp., Wiley-Blackwell, Oxford, U. K.

Turner J, Comiso JC, Marshall GJ, Lachlan-Cope TA, Bracegirdle TJ, Maksym T, Meredith MP, Wang Z, Orr A., 2009. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophysical Research Letters, 36, L08502. doi:10.1029/2009GL037524

Yuan, X., 2004.ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms, Antarctic Science, 16(4), pp. 415–425.

Zhang, J., 2007. Increasing Antarctic sea ice under warming atmospheric and oceanic conditions, Journal of Climate, 20, 2515–2529.

Zwally, HJ, Comiso JC, Parkinson CL, Cavalieri DJ, Gloersen P, 2002. Variability of Antarctic sea ice 1979–1998. Journal of Geophysical Research, doi:10.1029/2000JC000733