CHANGING CLIMATE IN POLAR REGIONS FROM MICROWAVE AND INFRARED DATA

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ABSTRACT

This study reveals that the climate in the polar region may be experiencing a transition towards a different phase of change than what has been expected only a few decades ago. In the Arctic basin, the rapid decline in the perennial ice cover has been regarded as an important indicator of anthropogenic climate change with a high value of about 8 x 10^6 km^2 in 1980 and low value of only 3.4 x 10^6 km^2 in 2012. Since 2012, however, the sea ice cover remained relatively low but did not change much suggesting a more stable perennial ice cover. On the other hand, the sea ice cover in the Antarctic has been reported as having a positive trend with a record high of more than 20 x 10^6 km^2 in 2014 but has been declining abruptly starting in 2015 with 2023 having record lows continuously every month including the current month of June 2023. Such phenomenon for both the Northern and Southern Hemispheres is intriguing and appears not to be very well correlated with observed changes in surface temperature as also derived from satellite data. These developments suggest a need to better understand the role of changes in other variables such the amount of freshwater, wind patterns, water circulation and tropospheric temperature as well as effects of ENSO and PDO on the observed changes and trends.

1. INTRODUCTION

Many studies have shown that a doubling in anthropogenic greenhouse gases would cause a warming of the planet by as much as 3 to 4 °C. Initially, it was thought that such a doubling would take about three thousand years but actual measurements that started in the 1950s (Keeling et al., 1976) indicated that a doubling would likely happen within this century. Global average surface temperature data show an increase of about one degree since the industrial revolution (Hansen et al 2010) but during the last few decades, an acceleration of the increase has been observed, especially in the polar regions. Since satellite thermal-infrared data became available, the rate of increase in surface temperature in the Arctic region is observed to be more than 3 times that of the rate of increase globally (Comiso and Hall, 2014; Comiso et al., 2019) and this has occurred concurrently with significant changes in the cryosphere.

One of the most visible changes in the region is the drastic decline in the extent of the perennial sea ice cover that has been observed in situ in the last 1,450 years. The extent of the perennial ice, or ice that survives the summer, has been reduced to less than half of what it was in 1980 when continuous observation of data derived from satellite passive microwave sensors started (Comiso, 2002; Parkinson and Comiso, 2013). The trend in multiyear ice cover, or ice that survived the melt period for at least two summers and regarded as the mainstay of the Arctic sea ice cover, is even more negative (Comiso, 2009).

Although the perennial and multiyear ice cover has remained low, the extent has not dropped any lower than its lowest value in 2012 in the recent decade. Moreover, the ice extent in the Southern Hemisphere has been relatively stable with slight positive trend and record high value in 2014, the extent shows significant decline, extremely low values and large interannual variability in subsequent years. The goal of this paper is to provide an update of the status of the global sea ice cover data and gain insights into the unexpected changes in extent during the last decade.

2. PASSIVE MICROWAVE AND THERMAL INFRARED SYSTEMS

Multispectral passive microwave data have been used to monitor the sea ice cover since November 1978 shortly after the Nimbus 7/Scanning Multichannel Microwave Radiometer (SMMR) was launched (Gloersen et al., 1987). Several algorithms have been developed to derive sea ice parameters and they all took advantage of the high contrast in the emissivity of sea ice covered ocean and those from ice free ocean (Steffen et al., 1992). The basic parameter is sea ice concentration which is derived using a mixing algorithm that assumes that the brightness temperature of each satellite observed area is a linear combination of the brightness temperature of the fraction of ice covered area and that of ice free water. The brightness temperature of 100% ice varies from one area to another and is determined by taking advantage of the a unique pattern of data from consolidated ice when data from one channel is plotted versus another channel as described by Comiso and Nishio (2008). With the launch of the DMSP/Special Scanning Microwave Imager (SSMI) in 1987, EOS-Aqua/Advanced Multichannel Scanning Radiometer (AMSR-E) and JAXA GCOM-W/AMSR2, a relatively long term record of passive microwave data has been used to study the variability and trends of the sea ice cover (Parkinson and Comiso, 2013; IPCC 2014).

Satellite derived surface temperature in the Arctic and the Antarctic have been reported previously (Comiso, 1998; Comiso, 2003) using AVHRR data from 1980 to the present. The technique makes use of the thermal infrared window channels to account for atmospheric effects in conjunction with radiative transfer model. Several AVHRR sensors has to be launched for continued coverage because of the limited lifetime of about 5 years for each sensor. Also, for consistency in the time series, corrections have to be applied to take into account changes in the elevation of the satellite. Any residual biases in the data were corrected using in-situ data in a regression analysis. Data were compared and found consistent with Aqua/MODIS and Envisat/AATSR data which have more channels and improved capabilities but much shorter data record.

3. CHANGES AND TRENDS: SEA ICE COVER AND SURFACE TEMPERATURE

3.1 Northern Hemisphere

The color-coded plots of climatological decadal averages of daily ice extent and ice area, as presented in Figure 1, clearly show large decadal variations that also indicate an acceleration of the decline in the Arctic ice cover especially in summer. For comparison, similar plots for the individual years when the ice cover was unusually low, as in 2007, 2012 and 2023, are incorporated in the figure. Further insights into the yearly variability and trends, are provided in the monthly averages and monthly anomaly plots presented in Figure 2. The monthly average plot shows the large seasonality of the ice cover while the monthly anomaly plots depict the yearly changes better with the with more recent years having higher variability that the earlier period including the unusually low values in 2007, 2012 and also 2020. The data have also been used to quantify the trend in the ice cover which is estimated to be about -4% per decade. Quantitatively, using data from January 1979 to December 2022, the trend in the sea ice extent was -4.383± 0.111 %/decade in the Northern Hemisphere.

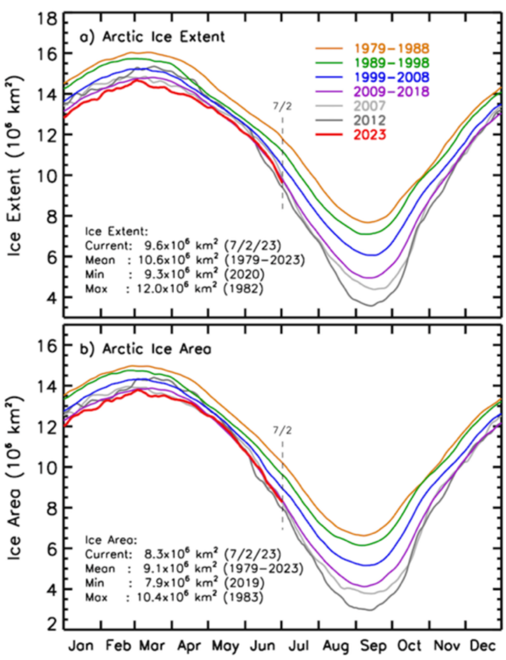

Figure 1. Decadal averages of (a) ice extent and (b) ice area in the Arctic. Also included are yearly data in 2007, 2012 and part of 2023 (in red).

The issue of strong interest is the interannual changes and trend of the perennial sea ice cover, which refers to the ice that survives the summer melt. The extent of the perennial ice provide information about the coverage of thick ice and also the open water area in the Arctic basin that contributes to farther warming through the ice-ocean feedback effect. Most ice in the Arctic basin has been observed to have average thickness of more than 3m in the winter and hence the large area of ice surviving the melt period. A decline in the perennial ice cover means a larger fraction of thinner ice that cannot survive the summer melt. The extent and area of the perennial ice can be inferred from the ice cover on the day the extent is at its minimum value during the year considering a small correction due to freezing conditions during this time period in some areas that lead to the presence of new ice. In addition, the thicker and desalinated component, called multiyear ice, or ice that survives at least two summers is

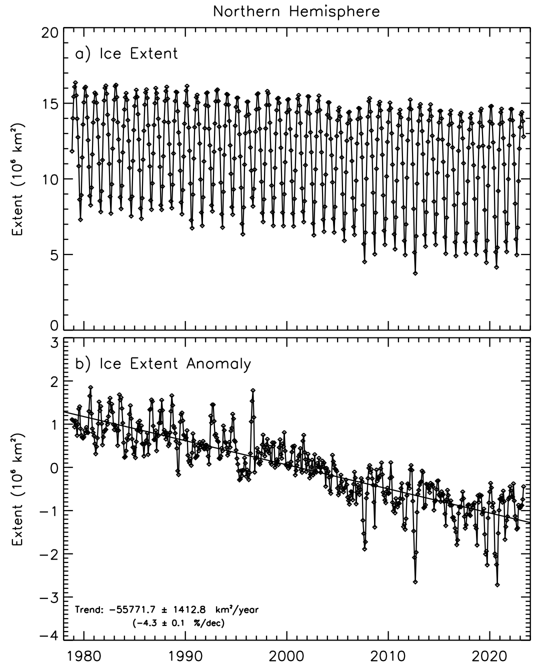

Figure 2. (a) Monthly average ice extent and (b) monthly anomalies of the ice extent from November 1978 to March 2023.

also quantified during the winter period by taking advantage of the large difference in the emissivity of seasonal ice and the desalinated multiyear ice cover (Comiso, 2012). The extent and area of the perennial and multiyear ice cover for every year from 1979 to 2022 is presented in Figure 3. The record high extent

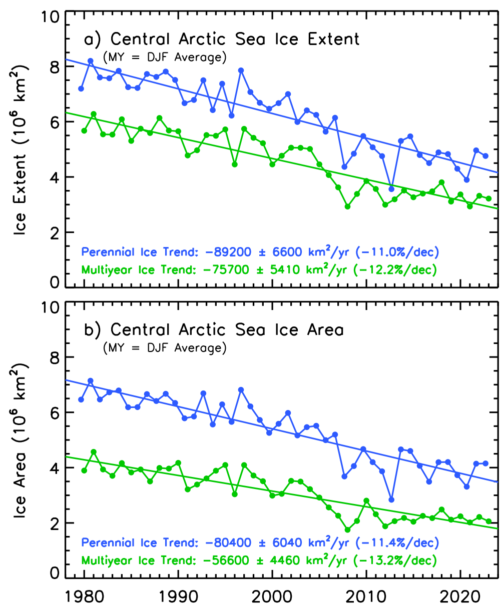

Figure 3 Yearly distribution of (a) perennial and multiyear ice ex tent and (b) perennial and multiyear ice area and trends using linear regression on the data.

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during the satellite era was around 8 x 10^6 km^2 in 1980 while the minimum value was around 3.5 x 10^6 km^2 in 2012. Regression analysis of the data reveals that the extent of the Arctic perennial ice cover has been declining at the rate of 11.2% per decade while that of the multiyear ice cover is at 12.4% per decade. It is remarkable that during the more recent period (i.e., 1999 to 2022), the trend accelerated to 16.3%/decade for perennial ice and 17.1%/decade for multiyear ice. If this rate continuous, the Arctic Basin will become a blue ocean within this century, a phenomenon that has not been observed for at least 1,450 (Kinnard et al., 2011). The change in the ice cover is more vividly represented visually in Figure 4 which depicts the ice concentration map in 2012 as derived from passive microwave data and compared with the average location of the ice edge as shown by the yellow contour.

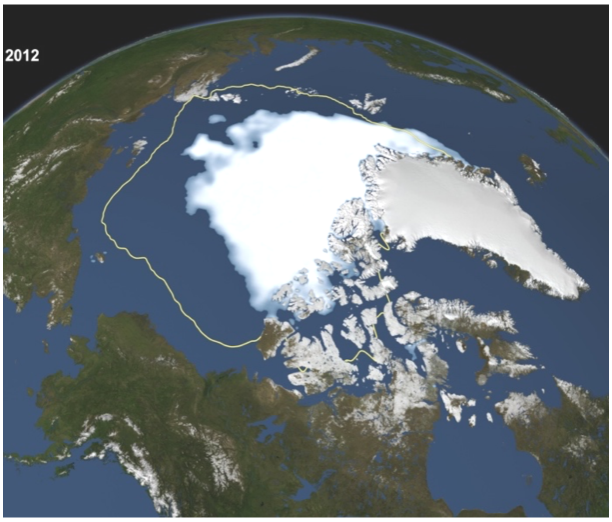

Figure 4. Ice concentration distribution of the sea ice cover in 2012 (with white corresponding to 100% ice) and contour line of the climatological average of the ice edge.

It should be pointed out, however, that since the record low value in 2007 that was followed by an even more drastic record low in 2012, a farther decline in the ice cover is not observed. This means that since 2012, the Arctic sea ice cover has been relatively stable. This can be inferred in Figure 2 but is even more apparent in the yearly values of the perennial and multiyear ice as shown in Figure 3. This suggests that the ice cover.in the Arctic region

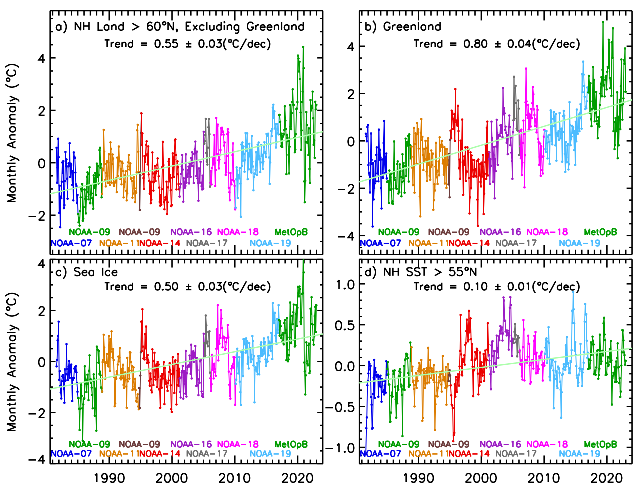

Figure 5. Satellite Observed Surface temperature in (a) land, (b) Greenland, (c) sea ice and (d) ice free water.

is not declining as fast as previously thought. During the same period, the concentration of CO2 in the atmosphere continued to rise and the surface temperature as observed from satellite data also were increasing over Greenland, land >60° except Greenland, and sea ice covered areas as shown in Figure 5. The exception is SST which appears to have been stable as well. This suggests that the temperature of the ice-free ocean surface may be the more significant factor affecting the variability of sea ice. As indicated in Figure 4, the open water areas in 2012 was much larger than the average over the satellite period and has become an important factor controlling the ice cover in the region.

3.2 Southern Hemisphere

The variability and trend of the sea ice cover in the Antarctic region is quite different from that in the Arctic region. In contrast to what is observed in the Arctic, the decadal averages of sea ice extent and ice area for the four decades from 1979 to 2018 have been relatively stable, as shown in Figure 5. The yearly averages, however, show significant variation from the decadal averages with 2014 having considerably higher values than the decadal averages and showing a peak value of more than 20 x 10^6.km^2 which is the record high extent during the satellite era. Also, the ice cover in 2012, when the perennial ice cover was a record low in the Arctic, exceeded those of the decadal averages. In the latter years, however, the opposite is true. For example, the ice cover in 2023 (in red) show unusually low values up to the most current data available. It is evident that the Antarctic sea ice cover that had been basically stable for 4 decades is undergoing a big transformation.

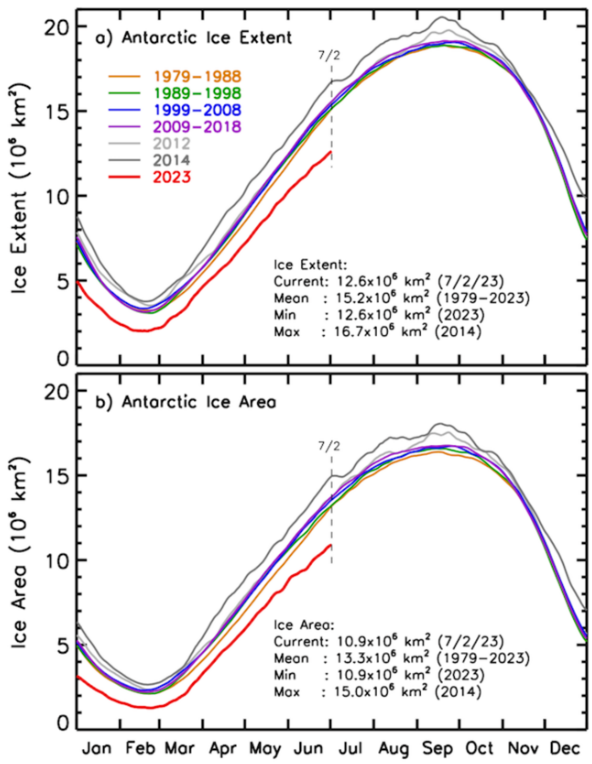

Figure 6. Decadal averages of (a) daily ice extent and (b) daily ice area since 1979. Yearly distributions for 2007, 2012 and part of 2023 (in red) are included for comparative assessment.

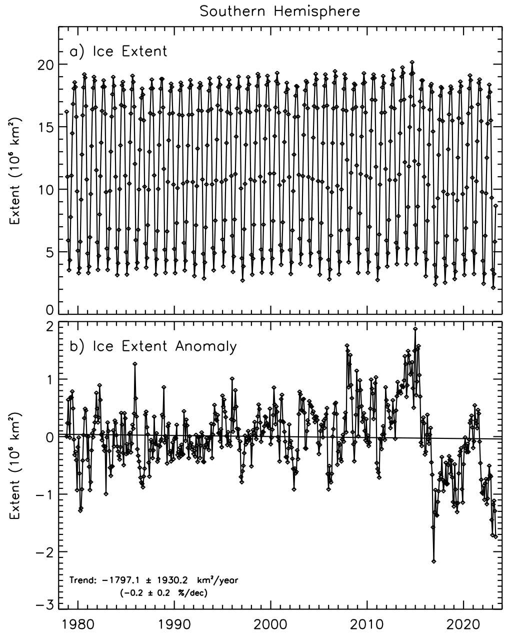

Figure 7. (a) Monthly averages of ice extent and (b) monthly ice Anomalies from November 1978 to December 2022.

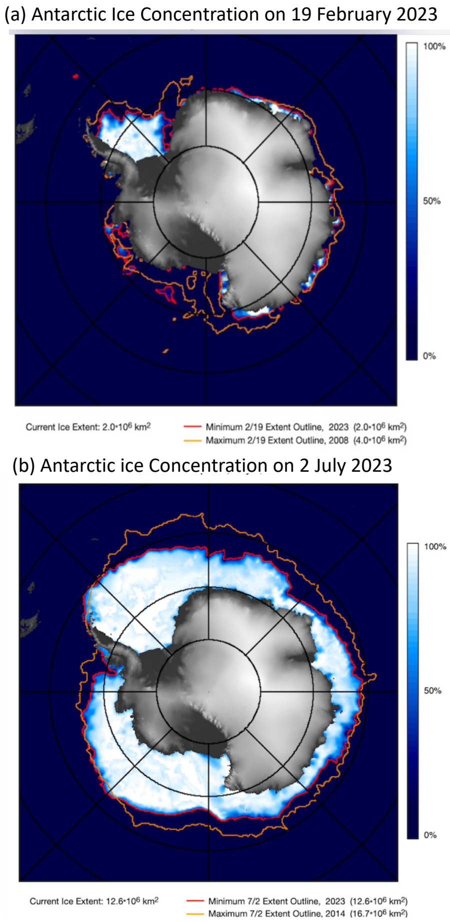

Figure 8. Color-coded ice concentration maps in the Antarctic on (a) 19 February 2023, representing summer; and (b) 2 July 2023, representing winter. Contour lines for 19 February 2008 and 2 February 2014 when ice cover was most extensive are also shown.

The plots of monthly averages and monthly anomalies from November 1978 to March 2023 of ice extent and ice area, as presented in Figure 7, provide more detailed information. The monthly averages (Figure 7a) show a seasonality that is even larger than that of the Arctic. Interannual variability is apparent only when looking at the peaks and dips for each year but the changes are overwhelmed by the large seasonal variability. The interannual changes and trends are more evident in the monthly anomaly plot (Figure 7b). The interannual variability is still substantial but indicate a positive trend up to 2014 when the record peak value was reached. After that, the trend was strongly negative and inconsistent with the previous historical trend. Quantitatively, the trend for the Antarctic sea ice cover, using monthly anomaly data from January 1979 to December 2022, is slightly negative at -0.007 ± 0.160%/decade and almost zero.

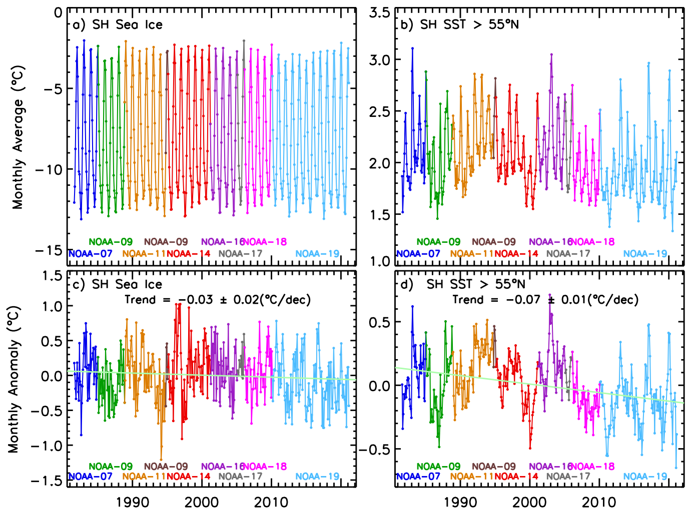

Figure 9. (a) Monthly averages temperature and (b) monthly anomalies in temperature in the Antarctic from 1980 to 2022.

The recent decline of the sea ice cover in the region is depicted by the color-coded maps of ice concentration in the summer and winter of 2023 shown in Figure 8a and 8b, respectively. The 19 February 2023 image, representing the summer ice cover, shows a very unusual pattern in the region west of the Antarctic peninsula called the Bellingshausen/Amundsen Seas. The region is basically baren with practically no sea ice all the way to the Ross Sea. Such phenomenon has not been observed from satellite data previously although a negative trend of ice in the region has been cited by Jacobs and Comiso (1997) and the climate in the Antarctic Peninsula region is significantly warmer than the rest of the Antarctic region (King and Comiso, 2003). For comparison, the location of the ice edge for the same period in 2008 is shown in red. In the 2 July 2023 image, representing winter, the ice cover is also unusually low as indicated previously in Figure 5. For comparison, the much more extensive ice cover in 2014 for the same day, is shown.

A plot of monthly averages of surface temperature in the Antarctic region from 1980 to 2022 is presented in Figure 9a. It is apparent that surface temperature also has a strong seasonality. It is surprising that during the last decade when the Antarctic sea ice cover was declining, there appears to be a negative trend in the surface temperature. It appears that the influence of surface temperature may not be very strong in the region and suggest that the role of other parameters like wind, water circulation and other factors have to be seriously considered

4. DISCUSSION AND CONCLUSIONS

The rapid decline of the perennial ice cover in the Arctic has been regarded as among the most significant indicators of anthropogenic climate change (IPCC 2014). In addition to extent, there were also reports about rapid thinning of the ice (Kwok and Untersteiner, 2011) and disappearing multiyear ice that are 3 or more years older (Maslanik et al., 2011). These reports would suggest an even more abrupt deterioration of the Arctic sea ice cover in subsequent years. However, such abrupt change has not materialized and in the recent decade, the perennial and multiyear ice cover have been observed to be relatively stable and resilient to change.

The sea ice cover in the polar regions has been reported to be anti-symmetric with the ice extent in the Arctic declining while that of the Antarctic ice increasing albeit only slightly for the latter (Cavalieri et al., 1997). The rate of increase of the Antarctic ice cover has been observed to be even more significant in a more recent report by Comiso et al (2017) which also cited the decline shortly after the record high extent in 2014. The positive trend has been reported to be in part due to the effects of the ozone hole which cause a decline in the sea level pressure in the West Antarctic region and subsequently an increase in wind driven sea ice production in the Ross Sea. The effect of the freshening of water in the region has also been cited by Jacobs et al. (2022). It should be noted that de la Mare (1997) has previously reported that over a longer-term period, there was a decline in the Antarctic sea ice cover. The ice cover during the whaling era in the Antarctic has been reported to be more extensive than during satellite era (de la Mare, 1997) although this has been reputed by Ackley et al (2003) who cited problems in the interpretation of the whaling data record. Many of the questions or puzzles associated with the Antarctic sea ice data have been described by Turner and Comiso et al (2017).

Meanwhile, satellite surface temperature data in the Arctic region indicate a lack of good consistency with changes in the Arctic sea ice cover. Generally, it has been shown that during the satellite era, the rate of increase in surface temperature is about 3 times higher for the Arctic region than that for the entire globe (Comiso and Hall, 2014). During the last decade, surface temperatures over sea ice, land and Greenland continued to increase while that for SST did not change much during the same time period making this variable consistent with the recently observed stability of the-Arctic sea ice cover. A cooling trend in large areas in the Antarctic region has been reported previously using satellite and in situ data. However, a longer time series than those provided by satellite data, that included data during the International Geophysical Year, shows a much higher rate of increase in surface temperature (Steig et al., 2009).

A question of significant interest is whether the pattern of change in the last decade will continue into the future. Would the perennial ice cover in the Arctic continue to be stable but remain low in the next decade despite expected impact of ice-albedo feedback? If this happens, serious considerations have to be made about the resilience of the Arctic perennial ice and the future state of the Arctic sea ice cover. On the other hand, is the recently observed abrupt decline in the Antarctic ice cover sustainable or are there some oscillatory effects like the Antarctic Circumpolar Wave that could alter the decline since 2014? There are of course other factors that need to be considered such as changes in wind patterns, salinity and the occurrences of atmospheric events like ENSO, PDO and similar phenomena.

REFERENCES:

Ackley, S.F., Wadhams, P., Comiso, J.C., Worby, A., 2003: Decadal decrease of Antarctic sea ice extent from whaling records revisited on the basis of historical and modern sea ice records, *Polar Research*, ***22***(1), 10-25.

Cavalieri, D.J., Gloersen, P., Zwally, H.J., Comiso, J.C., 1987: hemispheric asymmetry in global sea ice changes, *Science,* **278(**7), 1104-1106.

Comiso, J.C., 2000: Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements, *J. Climate*, *13*(10), 1674-1696.

Comiso, J.C., 2002: A rapidly declining Arctic perennial ice cover, *Geophys Res. Letts., 29(20),1956, doi:10.1029/2002GL015650*.

Comiso, J.C., 2003: Warming Trends in the Arctic, *J. Climate* , *16*(21), 3498-3510.

Comiso, J.C., 2009: Enhanced sea ice concentration and ice extent from AMSR-E Data, *J. Remote Sensing Soc. of Japan,* (1), 199-215.

Comiso, J.C., 2012: Large decadal decline in the Arctic multiyear ice cover, *J. Climate 25,* 1176-1193, doi: 10.1175/JCLI-D-11-00113.1.

Comiso, J. C., Hall, D., Rigor, I., 2019: Asymmetry in Surface Temperatures in the Polar Regions as Observed from Space, in "Taking the Temperature of the Earth," ed. by Glynn Hulley and Darren Ghent, Springer, https://doi.org/10.1016/B978-0-12-814458-9.00005-8.

Comiso, J. C. Hall, D.K., 2014: Climate Trends in the Arctic, *WIREs* (Wiley Interdisciplinary Reviews) *Climate Change*, Advanced Review: doi:10.1002/wcc.277.

Comiso, J. C. Nishio, F., 2008: Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.* ***113****,* C02S07, doi:10.1029/2007JC004257.

Comiso, J. C., Parkinson, C.L., Gersten, R., Stock, L., 2008: Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.,* 35, L01703, doi:10.1029/2007GL031972.

Comiso, J.C., Gersten, R., Stock, L., Turner, J., Perez G.J., Cho, K., 2017: Positive trends in the Antarctic sea ice cover and associated changes in surface temperature, *J. Climate,* 30, 2251-2267*, doi:10.1175/JCLI-D-0408.1.*

de la Mare, W. K. 1997: Abrupt mid-twentieth-century decline in Antarctic sea ice extent from whaling records, *Nature* **389,** 57–60.

Gloersen P., Campbell, W., Cavalieri, D., Comiso, J.C., Parkinson, C.L., Zwally, H.J., 1987: Arctic and Antarctic Sea Ice, 1978-1987: Satellite Passive Microwave Observations and Analysis, *NASA Spec. Publ. 511*.

Hansen J, Ruedy R, Sato M, Lo K., 2010: Global surface temperature change, *Rev Geophys*, **48**:RG4004.
doi: 10.1029/2010RG000345.

IPCC, 2014: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jacobs, S. S., Giulivi, C. F., Dutrieux, P., 2022: Persistent Ross Sea freshening from Imbalance from West Antarctic Ice Shelf melting. *J. Geophys. Res.* **127**(3).

Jacobs, S.S., Comiso, JC.,1997: Climate variability in the Amundsen and Bellingshausen Seas*, J. Climate, **10***(4), 697-709.

Keeling C., Bacaslow, R. B., Bainbridge, A. E., 1976: Atmospheric carbone dioxide variations at Mauna Loa Observatory, Hawaii, Tellus, 28(6), doi:10.3402telusa.v28i6.11322.

King, J. C., Comiso, J.C., 2003: The spatial coherence of inteannual temperature variations in the Antarctic Peninsula. *Geophys. Res. Lett. 30(2), 1040, doi:10.1029/2002GL015580.*

Kinnard C, Zdanowicz CM, Fisher DA, Isaksson E, De Vernal A, Thompson LG., 2011: Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature* **479**, 509–512.

Kwok, R., and N. Untersteiner, N., 2011: The thinning of Arctic sea ice, *Physics Today*, **64**(4), doi.org/10.1063/1.3580491.

Maslanik, J., Stroeve, J., Fowler, C., and Emery, W., 2011: Distribution and trends in Arctic sea ice age through spring 2011, *Geophy.Research Letters,* **38**(13), doi:10.1029/2011GL047735.

Parkinson, C. L. and Comiso, J. C.., 2013: On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm, *Geophy. Res. Lett*., **40,** 1-6, doi:10.1002/grl. 50349.

Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., J.C. Comiso, J.C.,. Shindell, D.T., 2009: Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year, *Nature,* **457**, 459-463.

Steffen, K., Cavalieri, D.J., Comiso, J.C., St. Germain, K., Gloersen, P., Key, J., Rubinstein, I. 1992. "The estimation of geophysical parameters using Passive Microwave Algorithms," Chapter 10, *Microwave Remote Sensing of Sea Ice,* (ed. Frank Carsey), American Geophysical Union, Washington, D.C., 201-231.

Turner, J., Comiso, J. C., Marshall, G.J.,. Lachlan-Cope, T.A., Bracegirdle, T., Maksym, T.,Meredith, M. and Wang, Z., 2009: Non-annular atmospheric circulation change induced by by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophy. Res. Lett.* **36**, L08502, doi:10.1029/2009GL037524.

Turner, J., Comiso, J. C., Et al., 2017 : Comment: Solve Antarctica's sea-ice puzzle, *Nature*, 547 (7663), 275-277, doi:10.1038/54727a.

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