A REVIEW OF SEA ICE TRENDS ON POLAR REGIONS

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ABSTRACT

This paper aims to establish a comprehensive trend database for sea ice extent (SIE), sea ice volume (SIV), and sea ice thickness (SIT) in polar regions, with the influence of global climate change. The analysis predominantly spans between 1979-2018, coinciding with the onset of satellite-based sea ice measurements. Arctic exhibits coherent negative trends in SIE, SIV, and SIT; conversely, in Antarctic, the trends in SIE and SIV are generally positive. Though, a comparison of the SIE trends and data for July 2023 in both polar regions reveals concerning results. The Arctic's SIE significantly deviates from the reference period average, surpassing the worst-case climate change projections, while Antarctic displays extreme levels of decline, deviating from previously observed positive trends. The underlying reasons for these deviations necessitate urgent investigation and further research, as they hold significant implications for Earth's polar regions and require heightened scientific attention.

Keywords: Arctic, Antarctic, Sea ice extent, Sea ice volume, Sea Ice thickness, Climate change
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1. Introduction

The Arctic Ocean is the smallest and shallowest of the five ocean basins of Earth, mainly covered by sea ice in winter but with more than half of the area ice-free during the permanently summer season (Ilicak et al. 2016). Its sea ice cover receives net heat input in summer, as shortwave radiation and sensible heat fluxes directly heat the sea ice, including its snow layer (Itoh et al. 2011). Being an expansive region, the Antarctic, covers the area below the starting latitude of Antarctic Circle (66°S) and includes the Southern Ocean together with the continent of Antarctica (Watt, 2023). With around 90% of the world's total surface fresh water and 60% of the world's total fresh water, Antarctic holds a significant portion of the planet's water resources. Antarctic is divided into five sectors: the Weddell Sea (WS), the Indian Ocean (IO), the western Pacific Ocean (WPO), the Ross Sea (RS), and the Bellingshausen and Amundsen Seas (BAS) as seen in Figure 1 (NASA, 2016).

The excessive increase of greenhouse gases in the atmosphere causes global warming and climate change. According to US National Aeronautics and Space Administration the air temperature around the world increase between 1980 and 2020 was approximately 1.0°C (NASA, 2020). In the third Special Report to be produced in the Intergovernmental Panel on Climate Change’s Sixth Assessment Report (AR6), projected change in global mean surface air temperature in our world would be increasing up to 4.8 °C until 2100 (IPCC, 2019). Global climate change exhibits a significant interconnection with the polar regions, stemming from the persistent poleward transfer of atmospheric thermal energy and moisture, the climate of the polar regions is highly influenced by the climate at lower latitudes (Ilicak et al. 2016). At seasonal to interannual time scales, sea ice may influence the climate of mid–high-latitude regions (Francis et al. 2009). The response to an increase in atmospheric greenhouse gases concentration simulated by general circulation models is generally stronger at high latitudes than at lower latitudes (e.g. Manabe et al. 1991; Houghton et al. 1996). Especially the warming in the Arctic has been much faster than in the rest of the world, a phenomenon known as Arctic amplification. According to Rantanen et al. (2021) that region has warmed four times faster than the globe since 1980. Climate change impacts the sea ice by reducing its coverage, which means that more solar radiation is absorbed by the ocean instead of being reflected back into space by the ice (Parkinson, 2014). This change in the physical properties of sea ice creates annual trend. Measurements of sea ice levels have increased since 1979 when the continuously satellites monitoring of the sea ice began. In this study, it is aimed to show the effects of the climate change to the sea ice by creating sea ice trends lists via using different studies and different measurement devices. The variation trends of sea ice extent (SIE), sea ice volume (SIV) and sea ice thickness (SIT) in the polar regions are analyzed in detail.

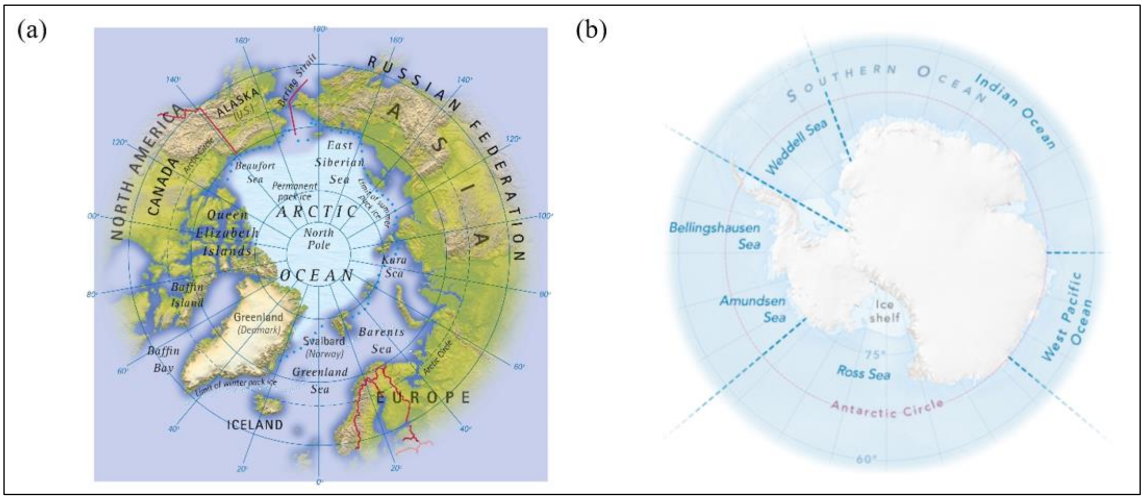

Figure 1. (a) Arctic (National Geographic, 2021) and (b) Antarctic (NASA, 2016) general view.

2. Sea Ice Data Systems

Various measurement techniques were employed in the generation of trend values described in the studies. These measurement systems possess distinct characteristics, which are briefly outlined: Submarine measurements were conducted using upward looking sonar instruments installed on Navy submarines, employing digital or analog recording methods. Satellite measurements are made by different satellites. Satellite measurements involved different satellites, such as the Ice, Cloud, and Land Elevation Satellite (ICESat), which serves as the reference Earth Observing System mission for measuring ice sheet mass balance ("ICESat", 2017). The CryoSat (CS) satellite measures sea ice by gauging 'freeboard,' the difference in height between sea ice and adjacent water, as well as ice sheet altitude, enabling the monitoring of changes in ice thickness ("CryoSat", 2021). Coupled models are computer-based models of the earth's climate, in which different parts (such as atmosphere, oceans, land, ice) are "coupled" together, and interact in simulations (Gerald et al., 1997). The Pan-Arctic Ice-Ocean and Assimilating System (PIOMAS) is a sea ice-ocean model with sea ice concentration and sea surface temperature assimilation using optimal interpolation by National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data which is globally gridded atmospheric data set (Lindsay and Zhang, 2006; Schweiger and others, 2011). The Coupled Model Intercomparison Project Phase (CMIP5 and CMIP6) is a collaborative framework designed to improve knowledge of climate change. The Nucleus for European Modelling of the Ocean (NEMO) is a framework of ocean related engines for ocean dynamics and thermodynamics ("NEMO", 2021). The MIT General Circulation Model (MIT GCM) uses the finite volume method to accurately represent the bottom boundary position (Adcroft et al., 1998). The National Snow and Ice Data Center (NSIDC) combines remote sensing, satellites and model data for determining SIE loss. Microwave radiometers (MR) are instruments that measure the power of the thermal noise emitted at a physical temperature larger than 0 Kelvin-absolute zero and can provide observations with all-time and all-weather coverage and has high sensitivity to sea ice permittivity (Emery and Camps, 2017; Wang et al., 2020).

3. Methods

The studies reviewed in this article used the linear trend method to determine the trends of values, despite the use of various sea ice data systems mentioned earlier.

$$y = a + bx$$

Linear trend refers to a pattern or tendency where the dependent variable (usually denoted as "y") changes in a linear manner over time (represented by the independent variable, denoted as "x"). In other words, the relationship between the two variables can be described by a straight line. To determine the linear trend, data is collected from past periods and analyzed using the equation as seen above. In this equation, "a" represents the constant coefficient or the intercept of the line, and "b" represents the slope or the trend of the line. The value of "x" represents time, which is used to estimate the value of "y" at different points in time. (Dokumcu, 2021). In this study, different time intervals of trend values are standardized annually. The fact that data has been obtained since 1979 considered in trend calculations meets the concept of a 30-year data set, which World Meteorological Organization (2017) claims is more accurate in normal and trend analysis. Trend list is listed on the basis of the date when the trend period started (if there is more than one trend in the same study, on the basis of reference). If a trend value is seasonal or for specific month it is specified after the period (i.e. 1979-2012 September, 2003-2013 Autumn).

4. Results and Discussion

Sea ice is the layer of ice formed on top of the sea when it freezes which is a sensitive indicator of climate change for the polar regions and beyond, so monitoring sea ice is important ("How we measure sea ice", 2021). The state of the sea ice is determined by its extent, thickness and volume ("SIE", 2020).

4.1 SIE Trends

SIE is a measurement of the area of the ocean where the integral sum of the areas of all grid cells with minimum ice concentration. Usually threshold of minimum concentration is defined to mark the ice edge; and “15 percent cutoff” provides the most consistent agreement between satellite and ground observations (Candanosa 2021; "Quick facts", 2021).

Table 1. Arctic SIE Trends.

Period	**Method**	**SIE Trend** $(10^3\ km^2 \cdot y^{-1})$	**Reference**
1979-2014 September	Satellites	-82 ± 18	Shu et al., 2020
	CMIP6	-70 ± 6	
2002-2017 July-October	CryoSat	-19	Wang et al., 2020
2002-2017 April-May		−2	
1972 – 2002	MR	-30 ± 3	Cavalieri et al., 2003
1979–2018 September	Satellites	-82.3 ± 7.3	Kumar et al. 2020
1979–2018 March	MR	-42.1 ± 3.53	
1979-2015	Satellites	-43.5 ± 4.1	Shu et al. 2015
	CMIP5	-37.1 ± 1.9	
1979-2012	Satellites	-51	Huang et al., 2017
1979-2012 March		-23	
1979-2012 June		-40	
1979-2012 September		-95	
1979-2012 December		-35	
2013-2100 RCP 4.5	CMIP5	-36	
2013-2100 March-RCP 4.5		-21	
2013-2100 June-RCP 4.5		-28	
2013-2100 September-RCP 4.5		-37	
2013-2100 December-RCP 4.5		-38	
2013-2100 RCP 8.5		-81	
2013-2060 March-RCP 8.5		-36	
2013-2060 June-RCP 8.5		-49	
2013-2060 September-RCP 8.5		-82	
2013-2060 December-RCP 8.5		-71	
1978-2013	NSIDC	-54.58 ± 3.70	Simmonds, 2015
1979-2007	MR	-65	Deser, 2013
1979-2010	MR	-14.6 ± 2.3	Cavalieri and Parkinson, 2012

Upon examination of the trend values for Arctic SIE in Table 1, a consistent and persistent negative trend is observed, notwithstanding variations in measurement techniques and time intervals. This decline in Arctic SIE can be attributed to various physical factors, including increased solar energy absorption by open water, strong southerly winds transporting warm temperatures, an intensified wind-driven transpolar drift leading to substantial ice outflow through

Fram Strait or ice accumulation at the edge of the Canadian Arctic Archipelago basin, and downward energy fluxes from the atmosphere and northward ocean heat transport (Kumar et al., 2020). Notably, the most significant decreasing trends in Arctic SIE occur during the autumn period. Furthermore, projections for future trend values are provided, considering two distinct scenarios: RCP 4.5 and RCP 8.5. Under RCP 4.5, a medium-mitigation emission scenario where radiative forcing levels stabilize at 4.5 W/m2 before 2100, Arctic SIE is anticipated to continue declining across all seasons from 2013 to 2100. Conversely, under RCP 8.5, a high-emission scenario where radiative forcing levels stabilize at 8.5 W/m2 before 2100, Arctic SIE is expected to decrease more rapidly in each month from 2013 to 2060, particularly in September and December. This projection suggests that the Arctic may experience ice-free conditions, where SIE decreases to less than 1 x 10^6 km^2, as early as September 2053 (Huang et al., 2017).

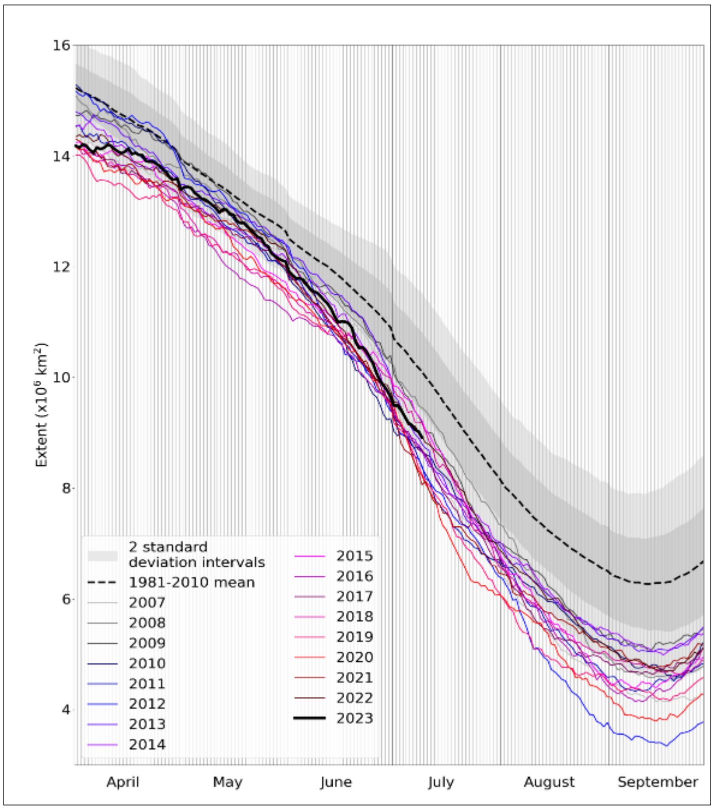

Figure 2. Arctic sea ice extent (Met Office, 2023).

Comparing the trends (Table 1) with July 2023 data (Figure 2) reveals worse results. In July 2023, SIE in the Arctic was recorded as 8.91 x 10^6 km^2 (Met Office, 2023), while the average extent for the reference period of 1981 to 2010 was 10.1 x 10^6 km^2. This significant difference of 1.19 x 10^6 km^2 (equivalent to an annual decline of 92 x 10^3 km^2y^{-1}) surpasses the projected annual decline of 81 x 10^3 km^2y^{-1} for the RCP 8.5 scenario until 2100, as documented in Table 1 (Huang, 2017). These observations imply that the current decrease in SIE exceeds the predictions for even the worst climate change scenario, raising substantial concerns for the future state of the Arctic region and its ecological implications.

Table 2. Antarctic SIE Trends.

Period	**Method**	**SIE Trend (10^3 km$^2 \cdot$y^{-1})**	**Reference**
1972 – 2002	MR	-15 ± 8	Cavalieri and Parkinson, 2003
1979-2005	GIOMAS	+12.9 ± 5.7	Shu et al., 2015
	CMIP5	-3.36 ± 1.5	
1979-2013	NSIDC	+18.6	Turner et al., 2015
1978-2013	NSIDC	+15.29 ± 3.85	Simmonds, 2015
1979-2018	Satellites	+4.0 ± 3.5 (WS)	Parkinson, 2019
		+2.6 ± 1.8 IO)	
		+2.6 ± 1.3 (WPO)	
		+5.8 ± 2.9 (RS)	
		-3.7 ± 1.8 (BAS)	
		+11.3 ± 5.3	
1979-2014	CMIP6	-70 ± 6	Shu et al., 2020
1979–2015	SB2	+20.2 ± 4.0	Comiso et al., 2017
1979-2013	NSIDC	+4.8 (WS)	Turner et al., 2016
		+5.6 (IO)	
		+2.3 (WPO)	
		+11.9 (RS)	
		-5.1 (BAS)	
		+19.5	
1992-2008	SICCI	+17.75 ± 11.50	He et al., 2016
1979-2012	NSIDC	+18	Turner et al., 2013a
1979-2005	CMIP5	+12.7	Turner et al., 2013b
1979-2005 September		-40	
1981-2000	NSIDC	+14.7 ± 8.6 (RS)	Laine, 2008
		-13 ± 6.4 (BAS)	

When analyzing the comprehensive records from 1979 presented in Table 2, a general positive trend in yearly average Antarctic SIE is observed. However, notable exceptions to this trend are found in the Bellingshausen/Amundsen Seas and CMIP5 measurements. The Bellingshausen/Amundsen Seas region displays a significant 40-year negative trend, characterized by decreasing yearly average ice extents during the initial three decades, reaching a minimum in 2007, followed by an overall upward trend since then. This behavior represents a reversal in the opposite direction compared to the other four sectors and the Antarctic sea ice cover as a whole (Parkinson, 2019). Additionally, it is evident that the CMIP5 models exhibit a remarkable deficiency in reproducing the observed increase in Antarctic sea ice extent. Despite attempts to implement the effects of ozone in these models, they still fail to capture the actual trend, highlighting the need for further refinement and improvement in modeling approaches (Maiming et al., 2017). These findings underscore the complex and region-specific dynamics governing Antarctic sea ice trends and emphasize the importance of advancing modeling capabilities to better comprehend and predict sea ice variations in the region.

Despite numerous proposed mechanisms, the underlying cause of the increasing trend in Antarctic sea ice extent (SIE) remains ambiguous, with ongoing debates about its anthropogenic or natural origins (Naiming et al., 2017). Polvani et al. (2013) argue that attributing the observed SIE trends to anthropogenic forcing is challenging. In contrast, Mahlstein et al. (2013) propose that the positive SIE trend observed via satellite data may be the result of natural variation combined with external forcing. Turner et al. (2014) identify a dominant positive trend in the RS sector, where SIE shows a significant correlation with the depth of the Amundsen Sea Low (ASL), which has intensified since 1979.

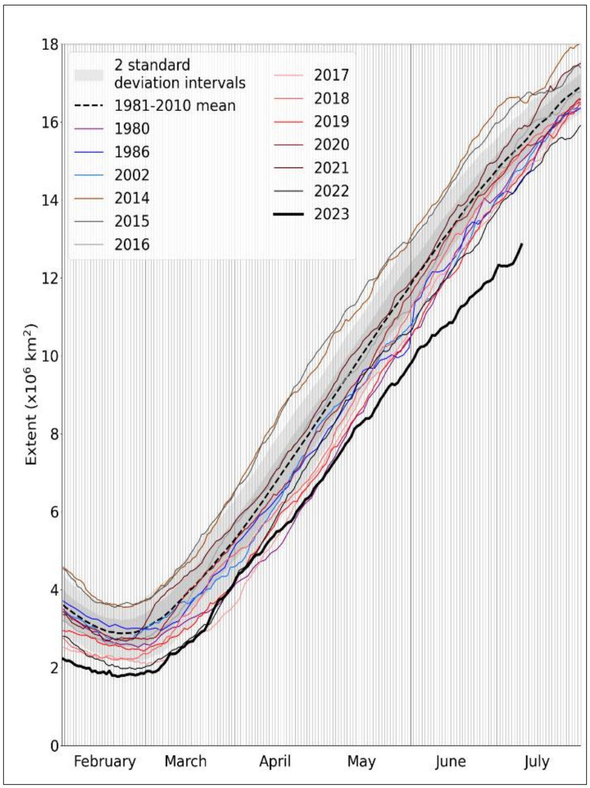

Figure 3. Antarctic sea ice extent (Met Office, 2023).

Analysis of July 2023 data in Antarctic (Figure 3) displays extreme levels of decline and creates opposition to positive trend bias. Although 1981 and 2010 average SIE was 15.41 x 106 km2, it decreased to 14.46 x 106 km2 in 2022, and further plummeted to 12.85 x 106 km2 in 2023. 2.56 x 106 km2 difference between 2023 and 1981-2010 period (197 x 103 km2y−1) is far from correlating with the previously observed positive trend values (Table 2). This discrepancy raises concerns as it deviates from the expected trend values and the specific reasons behind this deviation have not been clearly identified in the available information, warranting further investigation and research in this area (The Guardian, 2023). The urgency to investigate these unprecedented changes in SIE is evident, as it holds significant implications for the Earth's polar regions and beyond.

Table 3. Arctic and Antarctic Ensemble SIE Trends.

Period	**Method**	**SIE Trend (10^3 $km^2 \cdot y^{-1}$)**	**Reference**
1979–2013	Satellite	-35 ± 2.9	Parkinson, 2014
1979-1996		-21.5 ± 10.6	
1996-2013		-50.5 ± 20	
1979–2013 September		-68.2 ± 10.5	
1979–2013 May		-6.1 ± 10.6	
1978-2013	NSIDC	-35.29 ± 5.75	Simmonds, 2015

Parkinson (2014) and Simmonds et al. (2015) also calculated total loss of SIE of both Arctic and Antarctic regions ensemble. The values can be seen in Table 3. The trend values of Parkinson (2014) between 1979-2013 are remarkable. The reduction values after 1996 are more than twice the values up to 1996.

4.2 SIV Trends

SIV is a crucial parameter influencing the Earth's energy and water budget, but its direct observations are severely limited. Nevertheless, it can be estimated by integrating data from sea ice cover and SIT measurements spanning the entire Arctic region (Bunzel et al., 2018). Unlike SIE, SIV exhibits a more direct connection with climate forcing, making it an essential climate indicator in climate research (Shu et al., 2015).

Table 4. Arctic SIV Trends.

Period	**Method**	**SIV Trend (km^3/year)**	**Reference**
1979-2010	PIOMAS	-280	Schweiger et al., 2011
1979-2011 September	CMIP5	-226	Song, 2016
	Satellites	-321	
1979-2012 March	PIOMAS	no trend (Fram Strait)	Zhang et al., 2017
1979-2015	PIOMAS	-214 ± 14	Shu et al. 2015
	CMIP5	-145 ± 5	
1979-2016	PIOMAS	-310	Labe, 2017
1979-2018 September	Satellites	-300 ± 20	Kumar et al., 2020
1984-2008	Submarines (1984-2000) ICESat (2003-2008)	-411	Liu et al., 2020
1992-2014	Submarines Satellites	no trend (Fram Strait)	Spreen et al., 2020

2002-2010	Envisat PIOMAS	-177 (min)	Li et al., 2021
		-360 (max)	
2003-2008 Autumn	ICESat	-1450 ± 530	Zygmuntowska et al., 2014
2003-2008 Spring		-880 ± 260	
2003-2013 Autumn	ICESat (2003-2008) CSt-2 (2011-2013)	-210.8	Bi et al., 2018
2003-2013 Winter		-320.6	
2003-2014 Winter	ICESat-2, CS-2	-417	Kwok and Cunningham, 2015
2003-2014 Autumn		-776	
2003-2014 Winter	ICESat	-862	
2003-2014 Autumn		-1237	
2003-2015 Autumn	ICESat (2003-2008) CS-2 (2011-2015)	-390	Bi et al., 2018
2003-2015 Spring		-121.6	
2003-2018 Winter	Submarines ICESat CS-2	-287	Kwok, 2018
2003-2018 Fall		-513	
2004-2014 Winter	ICESat (2004-2008) CS-2 (2011-2014)	-402	Labe, 2017
2004-2014 Summer		-760	
2010-2018	CS-2 PIOMAS	no clear trend	Li et al., 2021

Upon scrutinizing the trend list for SIV in Table 4, a consistent and pervasive negative trend in the Arctic region becomes evident. Intriguingly, no discernible trend values were identified in the Fram Strait, a critical linkage zone between Greenland and Svalbard, connecting the Atlantic Ocean to the polar seas. The absence of a discernible trend there merits further investigation and may offer critical insights into the intricate dynamics governing sea ice volume transport and distribution in this significant region. Notably, the autumn season displays the most pronounced negative trend values, mirroring the pattern observed in SIE.

Table 5. Antarctic SIV Trends.

Period	**Method**	**SIV Trend (km^3/year)**	**Reference**
1979-2004	NCEP–NCAR	+20	Zhang, 2007
1980-2008	NEMO-LIM2	+35.5 ± 33.8	Massonet et al., 2013
		+15 ± 12.4 (RS)	
		+20.9 ± 36.2 (WS)	
		-4.5±5.4 (BAS)	
1990-2010	MITgcm	+30	Holland et al., 2014
2003-2008 Spring	ICESat	-266	Kurtz and Markus, 2012

2003-2008 Summer		-160	

When analyzing the trend list for Antarctic SIV in Table 5, a general increasing pattern in SIV values, SIE values, is observed. However, it is important to note that the article by Kurtz and Markus (2012) reports a contrasting negative trend, particularly more pronounced during spring than in summer. Remarkably, positive values in the trend list correspond to modeling results, while negative values are derived from satellite data. This pattern mirrors the findings observed in the SIE trend list, wherein satellite-derived data exhibit negative trends, while model-based data present positive trends.

4.3 SIT Trends

Table 6. Arctic SIT Trends.

Period	Method	SIT Trend (cm/year)	Reference
1980-2007	ICESat	-6.1	Kwok and Untersteiner, 2011
2000–2013	Satellites, Submarines	-5.8 ± 0.7	Lindsay and Schweiger, 2014
2002-2017 Autumn	Envisat, CS	-1.5	Wang et al., 2020
2002-2017 Winter		-1.8	
2002-2017		-5.1 (Hudson Bay)	
2003-2011	PIOMAS	-6 ± 0.4	Lindsay and Schweiger, 2014
2003-2011 Spring	ICESat	-7.5	Laxon et al., 2013
2011-2017 May-October	CS-2	-3, -4.5	Gao et al., 2021

SIT data is necessary for assessing sea ice mass balance, the surface energy budget, seasonal and annual sea ice prediction, and changes in the polar climate system (Labe, 2017). Observations of SIT are very sparse, compared to other observations which have a continuous satellite record from 1979 to the present. SIT is not measured directly by satellite due to the remote location of polar regions, and the difficulty of satellites signals to penetrate through the sea. Rather, it is freeboard that measured, or the height of the sea ice above the ocean surface, from which SIT may be calculated, given the depth of snow on top of the sea ice and hydrostatic equilibrium. One satellite mission (ICESat) evaluating SIT does not provide continuous measurements; rather, they only offer readings over two periods of the annual cycle, close to the minimum SIT in fall and close to the maximum SIT in spring. While the other satellite mission (CS-2) provides weekly and monthly data, its SIT estimates are only available during the cold season due to melt pond formation in the summertime. Only observations from submarines offer direct measurements of SIT, but those measurements are limited by small areal extent and sporadic temporal coverage (Massonet et al., 2013; Labe and Magnusdottir, 2018). Reconstructions using numerous observational sources show a 65% decline in annual mean SIT in the central Arctic since the 1970s (Lindsay and Schweiger, 2015). Looking at the trend list in Table 6, there are only satellite or submarine measurements and there is a consistent decrease in the Arctic region, as in SIE and

SIV; however in the Antarctic region, it can be seen that the value obtained with the satellite is negative, and the model and MR calculations are not negative as in Table 7.

Table 7. Antarctic SIT Trends.

Period	**Method**	**SIT Trend (cm/year)**	**Reference**
1990-2010	MITgcm	+0.15	Holland et al., 2014
1992-2011	MR	no negative trend	Aulicino et al., 2013
2003-2008 Spring, Summer	ICESat	-3	Kurtz and Markus 2012

5. Conclusions

The primary objective of this paper is to establish a fundamental trend database for SIE, SIV and SIT data of polar regions. The underlying driving force behind these trends is attributed to global climate change. Notably, trend analyses predominantly commence from the year 1979, coinciding with the initiation of satellite-based sea ice measurements. This time frame is deemed optimal for trend analysis, encompassing a 30-year period, which is considered more robust for assessing long-term variations. The research commonly employs satellite measurements, microwave radiometer remote sensing techniques, and numerical model calculations. Notably, the number of SIE and SIV data is greater compared to SIT. This discrepancy arises due to the challenges associated with accurately calculating SIT. SIE, SIV and SIT trend values are coherently negative in the Arctic region. For the seasonal and monthly trend, autumn, especially September, has the higher trend values than other seasons in negative direction. It is remarkable that in SIE; the negative trend values after 1996 are more than twice the values up to 1996. For future projections, it is predicted that the SIE value will decrease by more than 3 x 10^6 km^2 by 2100 in the Arctic under the RCP 4.5 scenario. If RCP 8.5 scenario happens, the Arctic will be almost free of ice in September before 2060, at approximately 2053. The similar thing is valid for SIV data. Under the RCP4.5 scenario after 2060, SIV in the Arctic becomes persistent around 1.2 x 10^3 km^3. If RCP 8.5 scenario happens, SIV value will be below 1 x 10^3 km^3 before 2060, just as in the SIE. In the Antarctic, as different from Arctic, SIE and SIV trends are generally positive. Some studies found the negative trend values, contrarily. The comparison of the trends and July 2023 SIE data in both the Arctic and Antarctic presents intriguing and concerning findings. In the Arctic, July 2023 SIE significantly deviates from the reference period average, surpassing even the worst climate change scenario projections. This unprecedented decrease raises substantial concerns for the future state of the Arctic region. Similarly, in Antarctic, the data for July 2023 reveals extreme levels of SIE decline, diverging from previously observed positive trend values. The reasons behind this deviation remain unclear, demanding urgent investigation and further research. Unprecedented changes in sea ice hold significant implications for the Earth's polar regions and beyond, necessitating heightened attention and scientific inquiry into this critical area of concern.

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