Global and Planetary Change 143 (2016) 228–250

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Invited review article

A review of recent changes in Southern Ocean sea ice, their drivers and forcings

William R. Hobbs [a,b,*], Rob Massom [a,c], Sharon Stammerjohn [d], Phillip Reid [a,e], Guy Williams [f], Walter Meier [g]

[a] Antarctic Climate and Ecosystems Cooperative Research Centre, Private Bag 80, University of Tasmania, Hobart, Tasmania 7001, Australia
[b] ARC Centre of Excellence for Climate System Science, IMAS, Private Bag 129, University of Tasmania, Hobart, Tasmania 7001, Australia
[c] Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia
[d] Institute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, CO, USA
[e] Australian Bureau of Meteorology, Centre for Australian Weather and Climate Research, Hobart, Tasmania, Australia
[f] Institute for Marine and Antarctic Studies, Private Bag 129, University of Tasmania, Hobart, Tasmania 7001, Australia
[g] NASA Goddard Space Flight Center, Greenbelt, MD, USA

ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form 3 June 2016
Accepted 16 June 2016
Available online 17 June 2016

ABSTRACT

Over the past 37 years, satellite records show an increase in Antarctic sea ice cover that is most pronounced in the period of sea ice growth. This trend is dominated by increased sea ice coverage in the western Ross Sea, and is mitigated by a strong decrease in the Bellingshausen and Amundsen seas. The trends in sea ice areal coverage are accompanied by related trends in yearly duration. These changes have implications for ecosystems, as well as global and regional climate. In this review, we summarise the research to date on observing these trends, identifying their drivers, and assessing the role of anthropogenic climate change. Whilst the atmosphere is thought to be the primary driver, the ocean is also essential in explaining the seasonality of the trend patterns. Detecting an anthropogenic signal in Antarctic sea ice is particularly challenging for a number of reasons: the expected response is small compared to the very high natural variability of the system; the observational record is relatively short; and the ability of global coupled climate models to faithfully represent the complex Antarctic climate system is in doubt.

Contents

---

* Corresponding author at: Antarctic Climate and Ecosystems Cooperative Research Centre, Private Bag 80, University of Tasmania, Hobart, Tasmania 7001, Australia.
E-mail address: whobbs@utas.edu.au (W.R. Hobbs).

http://dx.doi.org/10.1016/j.gloplacha.2016.06.008
0921-8181/

1. Introduction

Over the last 37 years, since the advent of regular satellite passive microwave observations of sea ice, there has been a small but statistically-significant increase in overall Southern Ocean (SO) sea ice coverage (Cavalieri et al., 1999; Zwally et al., 2002; Comiso and Nishio, 2008; Parkinson and Cavalieri, 2012), with several record maximum annual sea ice extents occurring in recent years (Turner et al., 2013a; Reid et al., 2015). This is in contrast to the Arctic, where there has been a strong decline in sea ice over the same period (Cavalieri et al., 2003; Comiso and Nishio, 2008; Cavalieri and Parkinson, 2012; Vaughan et al., 2013; Simmonds, 2015), and at a first pass is counter-intuitive in the context of a warming planet. Furthermore, coupled climate models run with realistic estimates of external climate forcings generally simulate a decrease in Antarctic sea ice coverage over the late 20th Century (Turner et al., 2013d; Shu et al., 2015).

Since sea ice occurs as a result of ocean-atmosphere exchanges of heat, freshwater and momentum, and therefore integrates elements of the ocean and atmosphere circulation, our understanding of the observed sea ice changes also reflects our level of understanding of the Antarctic climate system as a whole. This is demonstrated by the proven importance of sea ice biases in models. For example, sea ice biases contribute to large uncertainties in future predictions of precipitation changes over Antarctica (Agosta et al., 2015; Bracegirdle et al., 2015), an important component of ice sheet mass balance and therefore of sea level rise. Understanding these changes and their relationship to the broader issue of climate change is a significant and important scientific challenge (Kennicutt et al., 2015).

As well as being an indicator of ocean-atmosphere interactions, SO sea ice and its accumulated snow cover play a significant role in the global climate system. Changes in sea ice extent can shift the latitude of the mid-latitude storm track belt, with greater sea ice coverage driving a poleward migration of the jet (Kidston et al., 2011; Raphael et al., 2011). The SO is an important sink for anthropogenic carbon, and dominates the ocean uptake of excess heat trapped by carbon emissions, because it is a zone of upwelling deep water that is both cool and relatively low in carbon, and hence can readily absorb both at the surface (Orsi et al., 1999; Johnson, 2008; Marshall and Speer, 2012; Frolicher et al., 2015; Morrison et al., 2015). Most of this uptake is north of the sea ice zone, but further south sea ice regulates the rate at which this upwelled water reaches the surface or is returned to the deep ocean (Iudicone et al., 2008; Kirkman and Bitz, 2011; Ohshima et al., 2013; Delille et al., 2014).

In modulating the global ocean heat uptake, SO sea ice indirectly affects thermosteric sea level rise (i.e. sea level rise due to thermal expansion of the ocean). It may also have an indirect impact on barystatic sea level change (i.e. sea level increase due to freshwater input into the ocean). Ice sheet discharge is buttressed in many locations by floating ice shelves, and can accelerate rapidly in the event of an ice shelf collapse (Scambos et al., 2004; Dupont and Alley, 2005). In turn, in certain locations ice shelves and outlet glaciers are mechanically coupled to fast ice (i.e. sea ice that is fixed to features of the icescape, such as land or grounded icebergs), suggesting that fast ice loss could affect the stability of ice shelves and outlet glaciers, hence also the Antarctic Ice Sheet coastal margins and outlet glaciers (Massom et al., 2010). Thermodynamically, sea ice processes may have a role in modulating the exposure of Antarctic ice shelves to warm circumpolar deepwater (Holland et al., 2010; St-Laurent et al., 2015), and in changing the temperature and salinity properties of that water which may also affect basal melt (Dutrieux et al., 2014). Additionally, changes in sea ice extent (SIE) may affect the surface mass balance of the Antarctic ice sheets, by increasing or decreasing the distance of the ice sheet from marine-source moisture, with a consequent change in snow accumulation on the ice sheet (Weatherly, 2004; Krinner et al., 2007).

Sea ice also plays a crucially important role in the structure and function of high-latitude SO ecosystems (Thomas and Dieckmann, 2009) and biogeochemical processes (Delille et al., 2014). Changes in SIE and the timing of ice-edge advance/retreat are thought to affect krill biomass (Ross et al., 2008; Steinberg et al., 2015), with potential impacts for krill-dependent fauna at higher trophic levels (e.g., whales, seals and penguins) (Massom and Stammerjohn, 2010; Ducklow et al., 2012; Constable et al., 2014; Saba et al., 2014). Regional changes in the sea ice cover have impacted the distribution of penguin species, with sea ice-obligate Adélie penguins being replaced by ice-tolerant gentoo and chinstrap penguins in the western Antarctic Peninsula where sea ice is in strong decline (McClintock et al., 2008; Massom and Stammerjohn, 2010; Ducklow et al., 2013).

In this article, we provide a substantive review of research to date into the observed changes in SO sea ice, and their causes. In Section 2, we describe the magnitude, distribution and seasonality of the trends, and discuss uncertainties in the observations. In Section 3, we discuss the coupled atmosphere, ocean and cryosphere processes that may explain the observed trends. In Section 4, we review the evidence of anthropogenic forcing in the observed trends.

2. Measurements of sea ice change

A number of metrics are used to describe the local and large-scale time-varying sea ice cover. Here we describe changes in each observed metric separately.

2.1. Sea ice concentration

Sea ice concentration (SIC) is a pixel/grid-scale observation defined as the fraction of ocean area that is covered by sea ice. It is the core sea ice observation derived from satellite passive microwave data from which most other metrics are derived. The spatial and seasonal SIC trends are plotted in Fig. 1, based on the NASA Goddard-merged parameter in the NOAA/NSIDC Climate Data Record (CDR) product (Meier et al., 2013b), described in more detail below. During the austral summer and autumn (Fig. 1a and b), the largest trends are positive in the Weddell and western Ross Sea and negative in the Amundsen and Bellingshausen seas (ABS) (Liu et al., 2004; Holland, 2014), the latter especially along the western coast of the Antarctic Peninsula. In winter and spring (Fig. 1c and d), the statistically significant trends are much less widespread and occur largely near the ice edge of the Ross Sea, with a reduction in the Bellingshausen Sea along the western coast of the Antarctic Peninsula (Fig. 1c). East Antarctica has increased coastal sea ice in autumn and winter (Fig. 1b and d), and within the consolidated pack in spring (Fig. 1d). King Hakon VII Sea has increased coverage in autumn and winter (Fig. 1b and c).

2.2. Sea ice extent and area

Sea ice change and variability are often described in terms of sea ice extent (SIE), which is the total area of sea ice coverage with a SIC greater than some threshold value (typically 15%). SIE can be calculated over a range of domains: the total circumpolar region, specific sectors (such as those indicated in Fig. 1a), or as a continuous function of longitude (Fig. 2). Sea ice area (SIA) is a similar but less widely used metric, calculated as the total area of ice coverage for a given domain i.e., Σ $SIC(x,y) \times A(x,y)$, where A is the area of each grid cell (e.g., Comiso and Nishio, 2008). These metrics are subtly different, because SIA excludes regions of open water within the ice pack, whereas SIE just gives the area defined by the land and ice edge and includes grid cells within the pack with SIC < 15% (e.g. polynyas). In practice the two metrics are highly correlated, but SIE is more commonly cited because uncertainties in passive microwave retrievals have less effect on SIE.

The patterns of SIE trend and variability are shown in Fig. 2. The SIE trend pattern largely agrees with the SIC trends shown in Fig. 1, with large increased SIE in the Ross Sea in the warmer months (i.e. December–April) opposed by decreases in the ABS. Trends in the colder