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Southern Ocean sea ice and its wider linkages: insights revealed from models and observations

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Abstract: Early conceptual models and global climate model (GCM) simulations both indicated the likelihood of an enhanced sensitivity to climate change in the polar regions, derived from the positive feedbacks brought about by snow and ice. As GCMs developed, however, the expected enhanced sensitivity has been more robust in the North Polar Region than the South Polar Region. Some recent increased-CO_2 simulations, for instance, show little change in Southern Ocean sea ice extent and thickness and much less warming in the Southern Ocean region than in the sea ice regions of the Northern Hemisphere. Observations show a highly variable Southern Ocean ice cover that decreased significantly in the 1970s but, overall, has increased since the late 1970s. The increases are non-uniform, and in fact decreases occurred in the last three years of the 1979–2002 satellite record highlighted here. Regionally, the positive trends since the late 1970s are strongest in the Ross Sea, while the trends are negative in the Bellingshausen and Amundsen seas, a pattern that appears in greater spatial detail in maps of trends in the length of the sea ice season. These patterns correspond well with patterns of temperature trends, but there is a substantial way to go before they are understood (and can be modelled) in the full context of global change.

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Introduction

Sea ice covers vast regions of the Southern Ocean, spreading over 18 x 10^6 km^2 in winter, although reducing to only 3 x 10^6 km^2 at its summer minimum (Fig. 1). The wintertime coverage far exceeds the 10.5 x 10^6 km^2 area of Europe and substantially exceeds the 14.2 x 10^6 km^2 area of the Antarctic continent that the Southern Ocean surrounds. The vast sea ice coverage has numerous impacts on the regional climate and on the plants and animals living in its vicinity, and hence examining the ice cover and its changes has become an important element of Earth System Science research.

Among the key questions in Southern Ocean sea ice studies are:

What is the detailed seasonal cycle of the ice cover?

What is the interannual variability in the ice cover?

What are the decadal and longer time scale changes in the ice cover?

How is the ice cover likely to change in the future?

How closely is the ice cover tied to various oscillatory and non-oscillatory patterns in other components of the climate system?

What are the physiological adaptations allowing organisms to live within the ice?

How does the life within the ice affect the broader Southern Ocean ecosystem and climate?

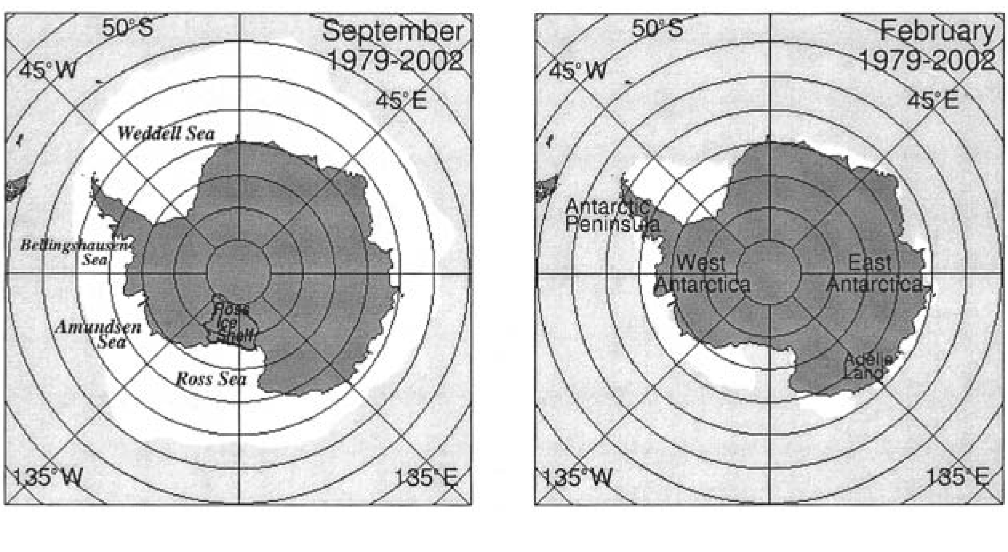

Fig. 1. Areal distribution (in white) of Southern Ocean sea ice in September and February, averaged over the 24-yr period 1979–2002 from satellite passive microwave data. September is frequently the month of maximum sea ice coverage, and February is almost always the month of minimum sea ice coverage. The maps also show the locations of places named in the text.

Obtaining solidly based answers to any of the above questions, except the one on physiological adaptations, prior to the last few decades would have been impractical in view of the huge area involved and the limited tools available. However, with the development of satellite and computer technology in the latter half of the twentieth century, at least preliminary answers have become possible. Satellites provide platforms for routinely monitoring the entire ice cover and thereby provide data for answering the questions regarding the current state of the ice cover and its changes over the course of the satellite record. The observations alone, however, cannot provide answers regarding the future. For such answers, some theory or model is essential, even if the model is a simple hypothesis of persistence of current conditions or persistence of current trends. Similarly, the observations alone cannot answer questions regarding linkages among system components. For answers regarding linkages or the future, the tools proving the most useful are computer models, as these allow strict control of individual variables in a range of sensitivity studies and calculations running indefinitely into the future. Neither the satellite-derived data products nor the computer models are perfect, but they are providing important advances toward improved understandings, and this paper attempts to highlight some of these.

The next section reviews the impacts of sea ice on climate and life, and the following section reviews modelling results regarding polar amplification, the propagation of sea ice impacts beyond the Polar Regions, and the response of Southern Ocean sea ice to other climate variables. These reviews are followed by results from observations on the Southern Ocean sea ice cover, derived largely from satellite passive microwave data, a section comparing the Arctic and Antarctic sea ice covers, and a concluding summary and discussion.

Summary and discussion

This paper reviews some of the impacts of Southern Ocean sea ice on other aspects of the climate system, examines some of the sea-ice-related issues addressed by climate modellers, and provides a summary of Southern Ocean sea ice coverage and changes as revealed through satellite passive microwave data. Major advances have been made both in numerical modelling and in satellite observations over the past several decades and, as a result, much new knowledge has been obtained about the Southern Ocean sea ice and other aspects of the climate system. However, as models have become more sophisticated, earlier results (such as the expectation of south polar as well as north polar amplification of climate change) have been called into question. Also, as observations have generated decades-long records of the full Southern Ocean ice cover, it has become apparent that interannual variability in the ice cover is quite significant (e.g. Fig. 7), complicating the identification of trends and linkages.

Still, the vastly improved database on sea ice and other elements of the global system, along with improved computer capabilities, are enabling a much improved picture of this system and the coupling within it. Among the named large-scale features of the global system with apparent sea ice connections are:

– The Southern Annular Mode (SAM), a large-scale, nearly zonally symmetric pattern of variability in the Southern Hemisphere extratropical atmospheric circulation. The SAM is characterized by fluctuations in the Southern Hemisphere circumpolar vortex. In model simulations, it generates sea ice variations on interannual to centennial time scales (Hall & Visbeck 2002, Thompson & Solomon 2002, Simmonds & King 2004).

– The Southern Oscillation, an irregular, interannual ‘seesaw’ in atmospheric sea level pressures over the tropical Pacific and Indian Oceans. Originally identified in 1924, the Southern Oscillation decades later was recognized as integrally tied with the oceanic El Niño phenomenon (Philander 1990, Glantz 1996). Simmonds & Jacka (1995) and Kwok & Comiso (2002) both explore possible connections between sea ice and the Southern Oscillation Index (SOI), finding that, temporally, correlations are strongest when the SOI leads the sea-ice-extent anomalies (Simmonds & Jacka 1995, using data from the 20 years 1973–92) and that, regionally, correlations are strongest for the Bellingshausen, Amundsen and Ross seas (Kwok & Comiso 2002, using data from the 17 years 1982–98).

– The El Niño/Southern Oscillation (ENSO), the coupled ocean/atmosphere phenomenon linking the Southern Oscillation with the Pacific Ocean fluctuations between the unusually warm conditions in the central and eastern equatorial Pacific known as an El Niño and the cool conditions labelled La Niña. The El Niño was first named in the late 1800s, as a local phenomenon off the west coast of South America, and was recognized as a widespread oceanographic phenomenon and as coupled to the Southern Oscillation in the mid-1900s. Since then, the ENSO has been linked to weather conditions around the globe (Philander 1990, Glantz 1996), including Southern Ocean sea ice (Yuan & Martinson 2000, Watkins & Simmonds 2000, Rind *et al.* 2001, Yuan 2004). Rind *et al.* (2001) examine the sea ice/ENSO connection theoretically, as part of a modeling study simulating climate responses to changes in latitudinal sea surface temperature gradients. Their results suggest that less sea ice could be expected in the Pacific portions of the Southern Ocean during El Niño events. Using approximately 18 years of observations, Yuan & Martinson (2000) calculate that up to 34% of the variance in Southern Ocean sea ice extent is linearly related to ENSO. Watkins & Simmonds (2000) more specifically suggest that observed increases in Southern Ocean sea ice in the mid-1990s could be a response to the 1990–95 El Niño.