Is Recent Sea Ice Expansion in the Southern Ocean Anthropogenic?

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Though Arctic sea ice extent has been declining, sea ice in the Southern Ocean has experienced modest expansion since the 1970s. This weak positive trend results from sea ice growth in the western Ross Sea (WRS) that slightly exceeds shrinkage near the western Antarctic Peninsula and in the southern Bellingshausen Sea. While the shrinkage near the western Antarctic Peninsula and in the southern Bellingshausen Sea is consistent with rapid warming in West Antarctica, the growth in the WRS appears contradictory in light of the warming, albeit small, over nearby Northern Victoria Land. Here we present results from an annually resolved ice core suggesting that the WRS sea ice advance may be largely natural in origin. We examine variations of the δD content of the Talos Dome ice core shown to be well correlated with WRS ice cover (the coefficient is -0.53, $p<0.008$). The δD content has varied irregularly about its long-term mean for the past eight centuries, and does not exhibit any significant trend over the past 150 years, the period of anthropogenic influence on global climate. The very red δD variability spectrum is a strong indication for an internal mode of decadal vari-

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ability in the WRS. In fact, this mode greatly complicates efforts to detect or predict future climate change in the Southern Hemisphere high-latitudes.

1. Recent Sea Ice Evolution

Sea ice records are most reliable after 1979, so we first examine the post-1979 Southern Ocean sea ice trends (Fig. 1). The sea ice advance in the WRS is particularly puzzling, given the modest warming over nearby Northern Victoria Land [Cavalieri et al., 1997; Cavalieri and Parkinson, 2008; Steig et al., 2009]. This counterintuitive sea ice advance has been attributed, at least in part, to an observed positive trend [Liu et al., 2004] in the Southern Annular Mode (SAM), the dominant pattern of Southern Hemisphere extratropical variability. The SAM trend is likely forced by both an anthropogenic increase in atmospheric greenhouse gas concentrations and depletion of the stratospheric ozone in the Southern Hemisphere high-latitudes [Arblaster and Meehl, 2006; Cai and Cowan, 2007]. Although it does induce positive sea ice anomalies in the WRS, these are of much smaller magnitudes than observed [Liu et al., 2004].

Alternatively, the observed sea ice advance may be interpreted as internal climate variability. There are at least two possible mechanisms by which climate variations on decadal or longer time scales can be generated in the WRS. First, they may arise from intrinsic variations in thermohaline circulations involving deep water formation in the Ross Sea [Saravanan and McWilliams, 1995; Santoso and England, 2008]. Second, they may arise from interaction between the Antarctic Circumpolar Current and oceanic mesoscale eddies [Wolff et al., 1991; Hogg and Blundell, 2006]. Both mechanisms induce variations in ocean circulation, which in turn produce sea ice anomalies.

Though the observed sea ice advance in the WRS could conceivably be internally-forced, it is impossible to determine whether such an internal mode of variability exists in the

WRS with existing sea ice records. To illustrate this, we show in Fig. 2 (blue line) the post-1979 sea ice record in the areas of the WRS with large positive sea ice trends, corresponding to the black box in Fig. 1. Sea ice in the WRS has exhibited a positive trend since 1986, and the largest trend occurs over the period 1986-1996. Conversely, prior to 1986 sea ice was declining. This decline hints that the WRS sea ice variation in the past 3-4 decades may be oscillatory and that the post-1979 trend could reflect the dominance of the increasing phase of an internal variation.

Observed sea ice records in the Southern Ocean prior to 1979 do exist, as the earliest satellite-measured sea ice records began in 1973 [Knight, 1984]. However, the early records are not often used in recent sea ice analysis, due to the quality concerns. Since they may contain critical information on past sea ice variations impossible to obtain otherwise, here we examine them, but with caution. As shown in Fig. 2, sea ice records over the period 1973-1978 appear consistent with the records after 1979, as the transition from 1978 to 1979 appears rather smooth. With the early years included, the sea ice variations appear more oscillatory, and the sea ice trend decreases almost by half, from 5.9% to 3.1% per decade.

2. Ice Core–Sea Ice Relationship

Because sea ice records in the early years may be helpful in the interpretation of recent sea ice trends, below we validate the early records by exploiting climate information preserved in an antarctic ice core—drilled at Talos Dome [Stenni et al., 2002]. As marked in Fig. 1, Talos Dome is located a few hundred km away from the WRS area with largest positive sea ice trends. In Fig. 2, we also show the δD content, a well-known climate proxy [Jouzel et al., 1997; Petit et al., 1999; Jouzel et al., 2003; Stenni et al., 2002], of the Talos Dome ice core for the same time period. There is a good correspondence between sea ice variations and δD variations during their periods of overlap. Almost all maximum (minimum) negative values of the δD content are associated with a sea ice maximum (minimum) in the WRS within a ±1 year offset, which is also the reported dating error of the Talos Dome ice core [Stenni et al., 2002]. Moreover, the positive sea ice trend during the 1986-1996 period corresponds very well to the decreasing trend of the δD content, and the negative sea ice trend during the 1973-1986 period corresponds very well to the increasing trend of the δD content. The correspondence is consistently seen in both the 1973-1978 and 1979-1996 periods, a further indication of the likely reliability of sea ice records in the early years.

Statistical analysis reveals a significant correlation between sea ice cover in the WRS and the δD content of the Talos Dome ice core, with the coefficient, -0.53 ($p<0.008$). This relationship likely arises from a strong link between the climates of the two locations. For example, as shown in Fig. 3, surface temperature in the WRS, based on ship and buoy measurements, is well-correlated with station-observed surface temperature at Talos Dome (the coefficient>0.8, $p<0.01$). Thus there is a high degree of regional coherence in a basic climate variable on interannual time scales and longer. This coherence probably arises from the fact that larger (smaller) WRS sea ice extent induces lower (higher) temperature over the WRS, and the cold (warm) near surface air is advected to Talos Dome [Trenberth, 1991; Simmonds and Keay, 2000]. This would lower (raise) the δD content of precipitation at Talos Dome, explaining the observed relationship between WRS sea ice and Talos

Dome δD. Of course, other factors may influence the isotope ratio. Most important in this region is the increased (decreased) distance from the moisture that results in a more (less) negative isotopic ratio. Other factors include isotopic composition of the moisture source and precipitation amount [Cole et al., 1999; Schmidt et al., 2007] which are also affected by sea ice extent in the WRS, given the coherence of climate in the region.

As shown in Fig. 4a, the δD content of the Talos Dome ice core extends back to 1217. In light of the ice core-sea ice relationship, we can use the δD content as a proxy for past sea ice cover in the WRS. Here we are concerned with past sea ice variations on decadal or longer time scales rather than those from year to year, as decadal-scale information is better preserved in the δD content (Fig. 2). The δD content has varies irregularly about its long-term mean for the past eight centuries, and does not exhibit any significant trend over the past 150 years. These suggest that recent δD variations are most likely the signature of natural variability rather than anthropogenic climate change. By extension then, recent sea ice variations in the WRS are likely natural in origin. Such large, low-frequency fluctuations in the δD content are a strong indication for an internal mode of decadal variability in the WRS. A simple way to measure the time scale for such a mode is to calculate the lag-one year autocorrelation [Manabe and Stouffer, 1996]. Lag-one year autocorrelations of the δD content and satellite-measured sea ice records are 0.68 and 0.66, both suggesting a strong decadal mode in the region.

3. Decadal Variability in Climate Simulations

The climate system's large and persistent decadal variability in this region is generally not seen in the output from current climate models. We demonstrate this by examining

13 control climate simulations with models used in the Fourth Assessment Report of the Intergovernmental Panel of Climate Change. In the simulations, radiative forcing agents are held constant so that all simulated climate variability is internally-generated. Lag-one year autocorrelations of simulated sea ice variations in the WRS are shown in Fig. 4b. Comparison with lag-one year autocorrelation of the δD content reveals that modes of decadal variability in most simulations are weaker than observed. Only one simulation (produced by CNRM CM3) exhibits a strong mode of variability. The inability of the current generation of climate models to produce modes of decadal variability comparable with those that are observed may have significant consequences for climate change prediction in the Southern Hemisphere high-latitudes. As modeling studies suggest [Manabe and Stouffer, 1996], strong decadal modes of variability are probably associated with variability in deep oceanic overturning circulations. Such regions ought to respond slowly to anthropogenic forcing [Stouffer et al., 2006]. Therefore, by underestimating decadal modes, the models may predict anthropogenic climate change at a faster pace.

4. Future Evolution of WRS Sea Ice

The signatures of both internal variability and anthropogenic forcing in recent WRS ice variations suggest that in the near-future sea ice cover in the region is likely determined by the evolution of both factors. Given past sea ice variations inferred by the δD content, we can speculate about the evolution of internal variability. As shown in Fig. 2, the WRS ice cover was very high over the period from 1995 to 2007. Judging from δD variations (Fig. 4a), this period was one of roughly 7 periods in the 8 centuries with very high sea ice cover. Thus, sea ice may retreat in the coming decade(s), due in large measure to natural factors. Nevertheless, given the high likelihood of continued greenhouse gas accumulation in the atmosphere, the SAM trend may persist into the future [Kushner et al., 2001], reinforcing sea ice extension in the WRS. Meanwhile, other anthropogenic influences such as the general warming and freshening of surface water may also modulate future sea ice in the region [Stouffer et al., 2006], further complicating efforts to project sea ice evolution. Disentangling these natural and anthropogenic influences is thus a crucial step toward a reliable sea ice projection in the WRS.

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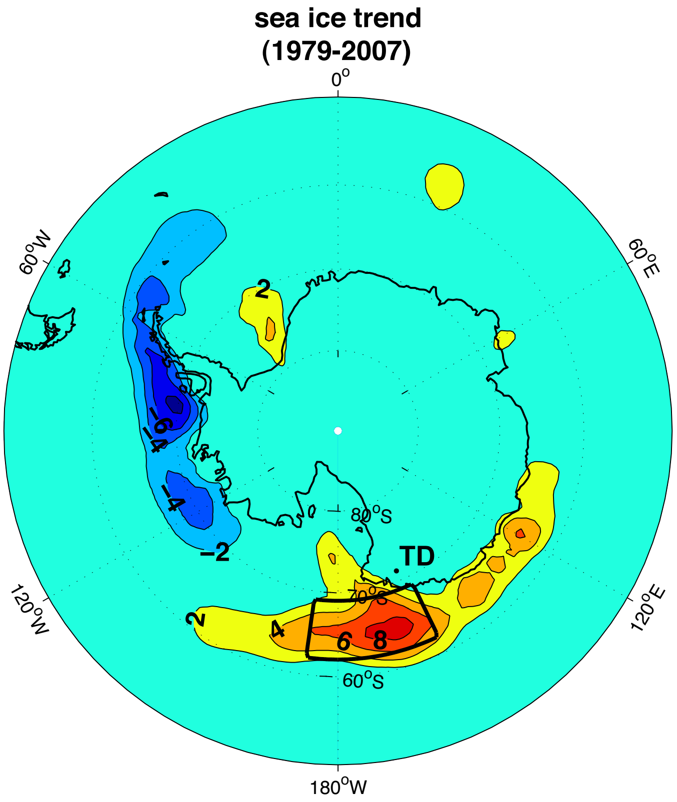
Fig. 1: Annual-mean sea ice trends (% per decade) over the period 1979-2007, based on HadISST data set [Rayner et al., 2003]. Contour interval is 2% per decade. Core region of the trends (black box), defined as longitude/latitude bands containing 6% per decade contours is used to construct regional-means in the WRS throughout this paper. Talos Dome is marked as "TD".

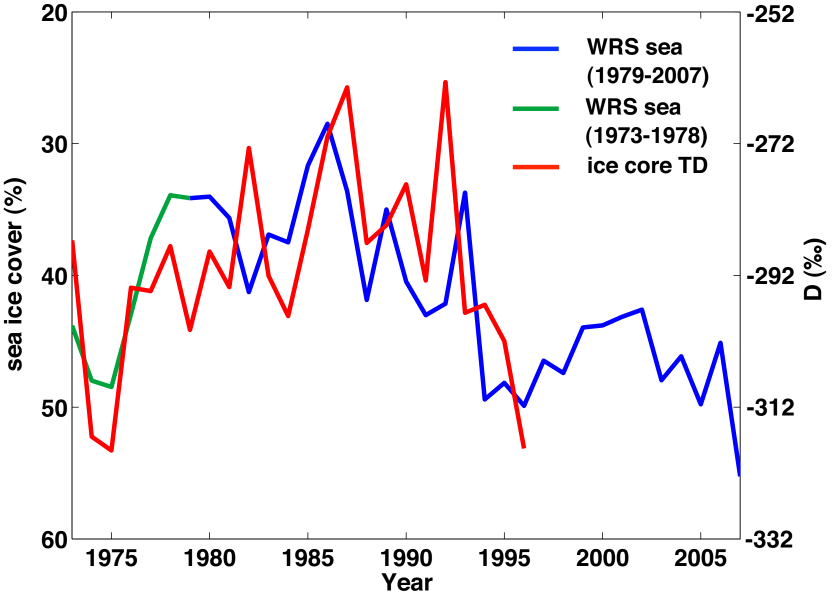
Fig. 2: Annual-mean sea ice records and annual-mean δD content of the Talos Dome ice core during their periods of overlap. The sea ice records are based on HadISST data set [Rayner et al., 2003].

Fig. 3: Geographic distribution of correlation coefficients of observed regional-mean surface temperature in the WRS to observed surface temperature in the Southern Hemisphere mid to high-latitudes during the 1958-2002 period [Chapman and Walsh, 2007]. The data were de-trended prior to the calculations. For clarity, only contours larger than 0.5 are shown. These coefficients are statistically significant at a 99% level or higher.

Fig. 4: (a) Annual-mean δD content with the 9-year unweighted running mean of the Talos Dome ice core. 7 periods with very low δD content are numbered. (b) Lag-one year autocorrelation of sea ice cover in the WRS in 13 control climate simulations. Models used to perform the simulations are CGCM3.1(T63), UKMO HadCM3, MIROC3.2(medres), CCSM3, GFDL CM2.0, CSIRO Mk3.5, CGCM3.1(T47), GFDL CM2.1, MRI CGCM2.3.2, PCM, GISS-ER, IPSL CM4 and CNRM CM3. They are ordered according to their values of lag-one year autocorrelation. The lengths of the simulations vary from 330 to 500 years. All data sets were de-trended prior to the calculations. Green line denotes lag-one year autocorrelation of the δD content.



sea ice trend
(1979-2007)


20
30
40
50
60
sea ice cover (%)
-252
-272
-292
-312
-332
D (‰)
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1985
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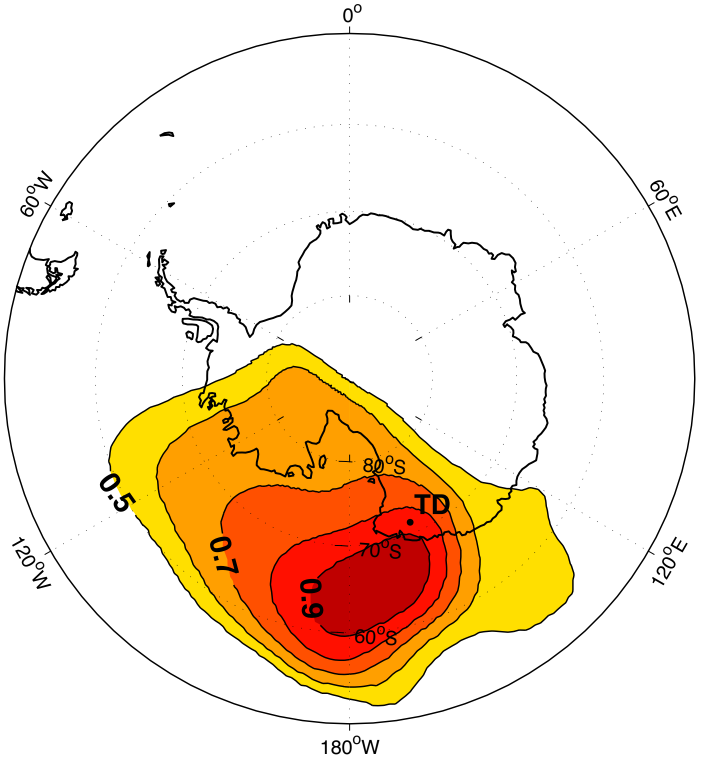
Year
WRS sea (1979-2007)
WRS sea (1973-1978)
ice core TD



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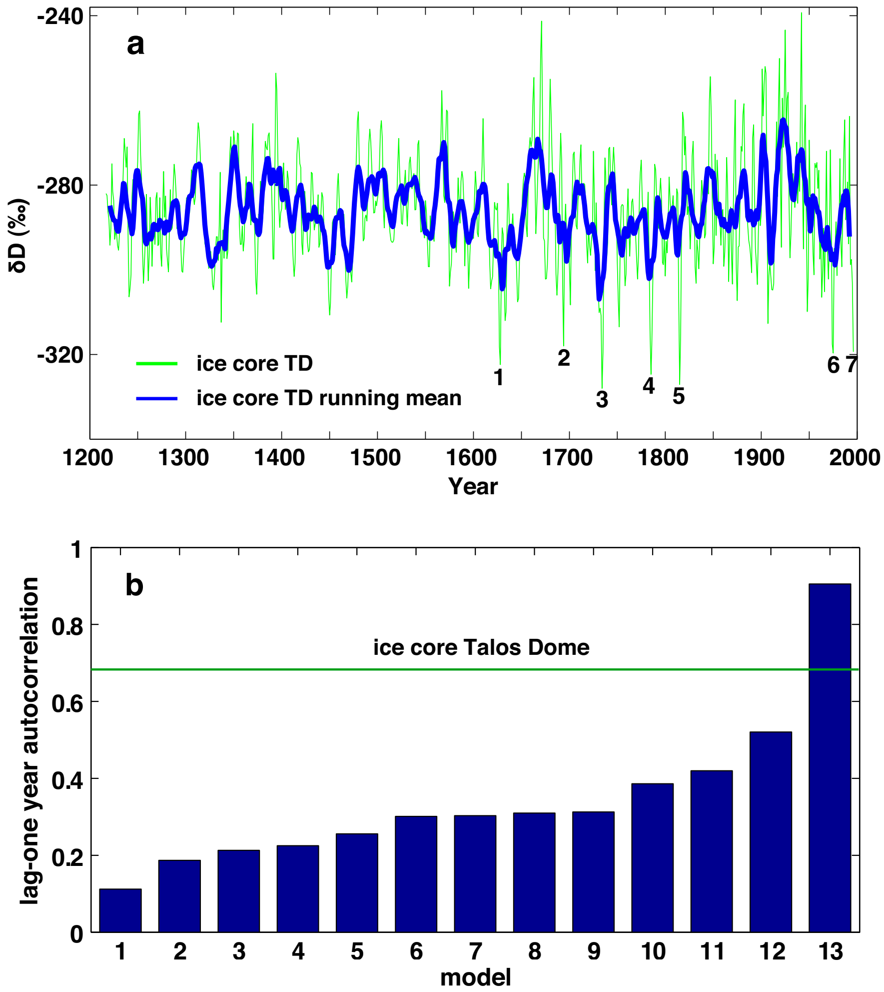
a
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δD (‰)
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ice core TD running mean
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Year
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model