# Rapid sea level rise along the Antarctic margins driven by increased glacial discharge

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**The Antarctic subpolar seas are of great climatic importance due to their vigorous interactions with the atmosphere and cryosphere, which influence continental deglaciation, global sea level, and the production of dense bottom waters. However, understanding these interactions and their impacts is confounded by sea ice, which blankets the region seasonally. In particular, the regional oceanic response to recent changes in Antarctic freshwater discharge is largely unknown. Here, we use satellite measurements of sea surface height (SSH) during ice-free months and an ocean circulation model to show that over the last two decades (1992-2011) Antarctic coastal sea level has risen at least 2 ± 0.8 mm $yr^{-1}$ above the regional mean south of 50°S, and that this signal is a steric adjustment to increased glacial melt from Antarctica. Our findings document the strength of the sea level response to accelerating Antarctic discharge, and demonstrate a significant climatic perturbation to the cryospheric forcing of the Southern Ocean.**

The Antarctic subpolar seas are a region of intense and complex interactions between the atmosphere, ocean and cryosphere, with an influence on Earth's climate that is greatly disproportionate to their area. Air-sea-ice interactions in these seas are central to the stability of the Antarctic Ice Sheet and global sea level[1,2], the volume and extent of Antarctic sea ice[3], the Earth's albedo[4], and the generation of the Antarctic Bottom Water (AABW) that cools and ventilates much of the global ocean abyss[5]. The subpolar seas are currently experiencing a significant increase in freshwater discharge from the grounded Antarctic Ice Sheet[1] and its fringing ice shelves[1,2,6]. The current state of knowledge concerning the impact on the adjacent ocean of this rapid change in freshwater forcing is, however, extremely limited, consisting of a few suggestive, yet highly localised and temporally sparse time series of *in situ* hydrographic observations[7-13]. Here, we use multiple lines of evidence (satellite measurements of SSH, *in situ* hydrographic measurements, and results from ocean model simulations) to reveal the local response to the recent Antarctic freshwater imbalance.

The grounded Antarctic Ice Sheet is currently losing mass overall through increased ice discharge, but gaining mass in places through enhanced snowfall[1,14]. With modest variability in evaporation and precipitation in subpolar waters[15], the increased discharge is expected to freshen the nearby ocean. Such freshening should be attributable to an 'excess' freshwater discharge above a baseline rate consistent with a steady ocean salinity. Discharge from the grounded ice sheet increased by 150 ± 50 Gt $yr^{-1}$ between 1992 and 2010 (ref. 14), implying an average of 75 ± 25 Gt $yr^{-1}$ excess discharge. An alternative estimate of the grounded ice contribution can be derived by assuming that the excess discharge is equal to net losses from West

Antarctica and the Antarctic Peninsula, which sum to 85 ± 30 Gt $yr^{-1}$ between 1992 and 2011 (ref. 1). Additional mass loss is occurring via the thinning of floating ice shelves. Whilst this mass loss is more uncertain than that of grounded ice, it may be estimated from satellite measurements and modelled surface accumulation, which indicate floating ice thinning of 280 ± 50 Gt $yr^{-1}$ between 2003 and 2008 (ref. 16-17) and 115 ± 43 Gt $yr^{-1}$ for 1994-2008 (ref. 6). Finally, a series of large ice-shelf retreats has occurred along the Antarctic Peninsula that is not included in the previous figures, and which averages 210 ± 27 Gt $yr^{-1}$ between 1988 and 2008 (ref. 6). However, it is unclear how much of the freshwater from these breakups was injected into the ocean over the Antarctic subpolar seas, and how much removed to distance by icebergs. All the above estimates represent changes since the early 1990s, but *in situ* measurements suggest that the ocean was already freshening then, so these values constitute a lower bound for the actual excess discharge above a 'steady salinity' rate.

The excess freshwater flux to the Antarctic subpolar seas in the last two decades is estimated hereafter as the sum of mass losses from the thinning of grounded and floating ice, ~350 ± 100 Gt $yr^{-1}$. The bulk of this discharge is focussed around the Antarctic Peninsula and the Amundsen Sea. This excess freshwater input is anticipated to freshen the Antarctic subpolar seas, and to raise regional sea level through both steric (density-induced) and barystatic (mass-induced) effects. Consistent with this, the few available time series of *in situ* hydrographic measurements, collated in Figure 1, suggest that Antarctic subpolar waters have undergone a marked freshening (by O(0.01) per decade) in recent decades[7-13]. An important limitation of these observations is their strong spatial bias to the Ross Sea, where tracer analyses suggest the implication of glacial meltwater in inducing the local freshening[7]. If the freshening is as widespread as suggested by the very sparse *in situ* measurements, and if the increase in Antarctic freshwater discharge is indeed the causal factor, we expect sea level rise to be especially pronounced across the Antarctic subpolar seas, and to occur at a rate commensurate with the increase in freshwater input modulated by ocean dynamics.

To test this, we examine the evolution of sea level around Antarctica over the last two decades using satellite measurements of SSH. The primary data analyzed are gridded Maps of Sea Level Anomaly (MSLA) generated by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic Data) for 1992-2011 (ref. 18; analysis methods and uncertainties are discussed in detail in Suppl. Mat.). Satellite-derived measurements of sea level cannot be readily obtained in the presence of sea ice, so our analysis focuses on the largely ice-free summer months (January-April). Using data from these months, the linear trend in SSH was derived and the global-mean rate of sea level rise for summer months (~3.2 mm $yr^{-1}$ between 1992 and 2012) subtracted to reveal the local anomaly (Fig. 1).

Over the mid-latitude Southern Ocean, the sea level rise anomaly varies zonally, with alternating sign (Fig. 1a). This pattern arises from the superposition of sea level impacts caused by various large-scale modes of atmospheric variability[19]. At high latitudes (south of ~62°S), however, our analysis reveals a circumpolar, topographically-influenced signal of anomalously rapid sea level rise that has not been observed previously (Fig. 1b), occurring at 1-5 mm $yr^{-1}$ above the global mean, with local peaks in the Ross Sea and Prydz Bay. The northern boundary of this rapid sea level rise is identified here as the line where the SSH trend anomaly first changes sign or reaches a minimum with increasing distance from Antarctica (Fig. 1a). The mean sea level rise south of this boundary is at least 2 ± 0.8 mm $yr^{-1}$ above the regional mean south of 50°S (1.2 ± 1.5 mm $yr^{-1}$ above the global-mean sea level rise). Whilst the signal covers the broad Antarctic subpolar seas, the signals are most significant over the continental shelves, which are our primary focus.

Although its statistical significance appears modest, the above quantification is a highly conservative estimate of the regional sea level rise anomaly induced by freshwater forcing. This is because the global-mean rate of sea level rise contains a large thermosteric contribution from the low- and mid-latitude oceans that is unrelated to polar processes[20-21]. A more appropriate approach to isolating the local effect of Antarctic freshwater discharge would entail the subtraction of the global-mean rate of barystatic sea level rise from the measured SSH trend (see Suppl. Mat.). This rate is unlikely to exceed 1.5 mm $yr^{-1}$ (ref. 16, 20-21), resulting in a mean sea level rise across the Antarctic subpolar seas of 2.8 ± 1.5 mm $yr^{-1}$ above the global barystatic mean. However, the global-mean rate of barystatic sea level rise has substantial uncertainty, so hereafter we consider only the more conservative estimate relative to the global-mean rate of sea level rise.

The temporal progression and regional distribution of SSH change across the Antarctic subpolar seas (Fig. 2) reveal several important features. For example, SSH displays a pronounced seasonal cycle that is most likely forced by seasonal fluctuations in upper-ocean temperature and salinity[22]. While this seasonal cycle is larger than the interdecadal sea level rise anomaly, it is distinct from the latter: the linear trend in SSH anomaly affects all stages of the seasonal cycle (see Suppl. Mat.).

To assess whether the enhanced rate of sea level rise measured across the Antarctic subpolar seas is consistent with forcing by the recent acceleration in glacial discharge from Antarctica, we consider three distinct lines of evidence. First, we use a global ocean circulation model forced with realistic rates of Antarctic freshwater discharge to simulate the regional response to increased discharge (see Suppl. Mat.). All model experiments produce a striking, circumpolar, steric sea level rise anomaly across the Antarctic subpolar seas that strongly resembles the altimetric observations, with a subpolar sea-average anomalous rise of 1-5 mm $yr^{-1}$ for a freshwater release of ~300 Gt $yr^{-1}$ (the approximate excess Antarctic freshwater discharge averaged over the last 20 years) centred in the Amundsen-Bellingshausen sector (Fig. 3). Remarkably, the modelled anomalous SSH signal is comprised of comparable halosteric and thermosteric contributions, with the former being focussed in the upper ocean and the latter at depth. Thus, the model suggests that the directly-forced halosteric sea level rise around Antarctica is amplified by a positive thermosteric feedback. The barystatic contribution of increased Antarctic freshwater discharge to the spatial distribution of the sea level rise signal is shown to be negligible by the simulations.

Second, we quantitatively compare the altimetric results with recent observational estimates of steric sea level rise around Antarctica. The altimetric rates of Antarctic coastal sea level rise anomaly are found to be in broad agreement with (slightly exceeding) the halosteric sea level rise contribution of ~0.5-3 mm $yr^{-1}$ implied by the available *in situ* measurements of interdecadal upper-ocean freshening around Antarctica[7-13] (Fig. 1 and Suppl. Mat.), in line with model predictions of an important upper-ocean halosteric contribution to the anomalous SSH signal. Similarly, Southern

Ocean deep and bottom waters have warmed significantly in the period of our study, inducing a thermosteric sea level rise of ~1 mm $yr^{-1}$ (ref. 23) that is comparable to the signal discussed here. While the spatial footprint of the deep thermosteric change extends well beyond the Antarctic subpolar seas[23], in poor agreement with our observed signal and model results, the lack of spatial correspondence between thermosteric effects and regional sea level trends may relate to other factors, such as changes in wind forcing or self-gravitation (see Suppl. Mat). Thus, the existence of a significant contribution of deep-ocean thermosteric adjustment to the observed Antarctic coastal sea level rise does not conflict with available observations.

Third, if it is assumed, based on the preceding modelling and observational evidence, that the Antarctic coastal sea level rise signal is partitioned approximately equally between a directly-forced halosteric component and a positive thermosteric feedback, the excess freshwater input required to explain the measured signal may be estimated. This involves multiplying half the linear trend in ocean volume inside the signal's boundary (11.6 $km^3$ $yr^{-1}$; 1.4 mm $yr^{-1}$) by a modified 'Munk multiplier' (36.7; ref. 24; see Suppl. Mat.), indicating a requirement of 430 ± 230 Gt $yr^{-1}$ of excess freshwater input above the nominal rate needed to maintain a steady ocean salinity. This agrees with the increase in Antarctic melt observed in the last two decades (~350 ± 100 Gt $yr^{-1}$), and lends support to our initial hypothesis that the recent imbalance in the Antarctic cryosphere is driving pronounced and widespread changes in the salinity of the high-latitude Southern Ocean.

Finally, we note that the observed anomalous SSH signal may also be influenced by several tertiary forcing mechanisms, which may account for at most ~10% of the signal and are discussed comprehensively in Suppl. Mat. The most significant of these is the ocean's barystatic response to wind forcing. The gravitational effect of Antarctic ice mass loss reduces relative sea level rise in the Amundsen and Bellingshausen seas by ~1 mm $yr^{-1}$ (ref. 25). Other mechanisms, such as upper-ocean warming, precipitation-induced freshening or the ocean's barystatic response to the acceleration in Antarctic freshwater discharge, were found to be insignificant.

In summary, austral summer satellite altimetry measurements show a pronounced circumpolar rise in sea level across the Antarctic subpolar seas that significantly exceeds the global mean. The trend contains a significant halosteric contribution that originates in the increasing discharge of freshwater from Antarctica. Thermosteric sea level rise from the observed warming of the deep Southern Ocean, which has itself been linked to the freshening of the shelf waters ventilating AABW (ref. 23,26; see also Suppl. Mat.), also contributes to the signal. Our findings therefore reveal that the accelerating discharge from the Antarctic ice sheet has had a pronounced and widespread impact on the adjacent subpolar seas over the last two decades, and indicate that a significant climatic perturbation to the cryospheric forcing of the Southern Ocean is underway. Given the key dependence of the Southern Ocean on freshwater forcing, this perturbation has major implications for the region's stratification, circulation and important biogeochemical and ecological processes[26-29].

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**Supplementary information** is linked to the online version of the paper at www.nature.com/nature

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**Author Contributions** C.D.R. conducted the data analysis, with regular input from A.C.N.G., A.J.G.N., C. W. H., M.P.M. and P.R.H. All these authors contributed to the writing of the manuscript. A.C.C. and D.J.W. assisted with the modelling component of the work.

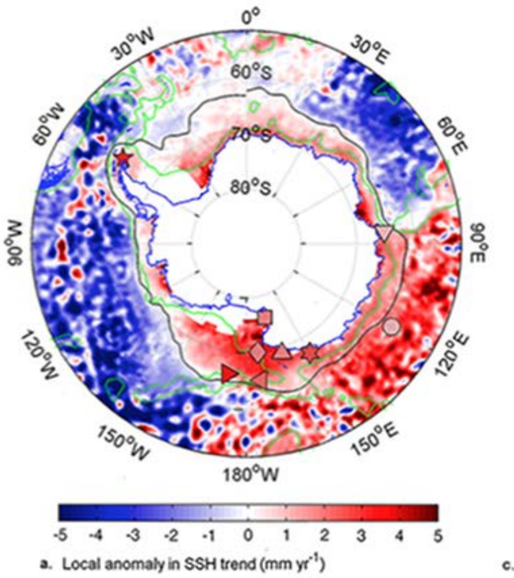
**Author Information** The altimetry data used in the study is available via the AVISO website (http://www.aviso.oceanobs.com/en/) as well as the MyOcean website (http://www.myocean.eu.org/). The reanalysis wind data is available via the ECMWF website (http://www.ecmwf.int/). Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to c.rye@noc.soton.ac.uk.

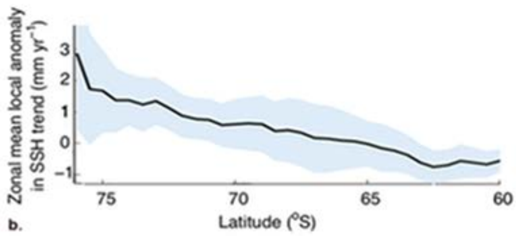
**Figure legends:**

**Figure 1 | Regional anomaly in summer (January to April) sea level trend, 1992-2011.** The anomaly is calculated relative to the full (barystatic and steric) global-mean rate of sea level rise for summer months. **a.** Circumpolar view, showing the northern boundary of the sea level anomaly in black. Markers indicate *in situ* estimates of interdecadal freshening, shaded by the magnitude of the corresponding halosteric sea level rise. The information for each marker is given in the table in c. The 3000-m isobath is shown in green. **b**. Zonal-mean regional sea level rise. Shading highlights the 2-$\sigma$ zonal variation.

**Figure 2 | Time series of sea level anomaly in the Antarctic subpolar seas, 1992-2011**. Dotted lines show the full time series, and solid lines the ice-free summer month record. Black: circumpolar average south of the signal's boundary (trend = 1.2 mm $yr^{-1}$); light blue: Bellingshausen and Amundsen seas (BA; 135-60°W; trend = 0.2 mm $yr^{-1}$); dark blue: Ross Sea (RS; 130°E-135°W; trend = 1.3 mm $yr^{-1}$); red: Australian-Antarctic basin (AA; 50-130°E; trend = 1.9 mm $yr^{-1}$); green: Amery Basin (AB; 10-50°E; trend = 1.0 mm $yr^{-1}$); pink: Weddell Sea (WS; 60°W-10°E; trend = 0.5 mm $yr^{-1}$).

**Figure 3 | Ocean model simulation of the regional anomaly in sea level trend, 1992-2007.** This is generated by subtracting a control run with a 'background' Antarctic freshwater forcing from an experimental run perturbed by an excess Antarctic freshwater runoff of 300 Gt $yr^{-1}$ (see Suppl. Mat.). The 3000-m isobath is indicated in green.




c.

| Author (et al.) | Time period | Depth range (m) | Trend in salinity (PSU/yr) | Halosteric SLR (mm/yr) | |
|---|---|---|---|---|---|
| Jacobs[8] | 1963-2000 | *200-900* | *-0.003* | 1.8 | ◆ |
| Jacobs[7] | 1979-2001 | *1900-3000* | *-0.002* | 1.4 | ▲ |
| Aoki[9] | 1994-2002 | *2500-3500* | *-0.004* | 2.8 | ✶ |
| Johnson[10] | 1995-2007 | 3000-3500 | *-0.0008* | 0.4 | ▽ |
| Johnson[10] | 1995-2007 | 3000-4500 | *-0.0004* | 0.5 | ● |
| Ozaki[11] | 1974-2004 | 2500-3300 | *-0.003* | 1.6 | ◀ |
| Ozaki[11] | 1969-2004 | 2600-3600 | *-0.004* | 3.3 | ▶ |
| Jacobs[8] | 1958-2005 | *200-800* | *-0.003* | 1.4 | ■ |
| Hellmer[12] | 1989-2006 | 0-500 | *-0.005* | 2.0 | ★ |

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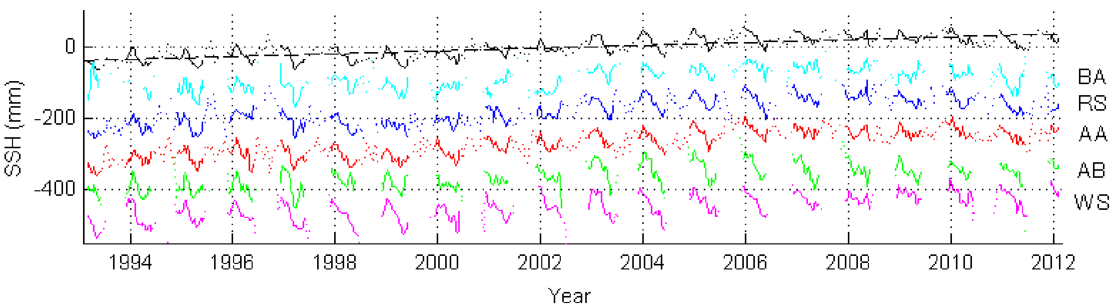

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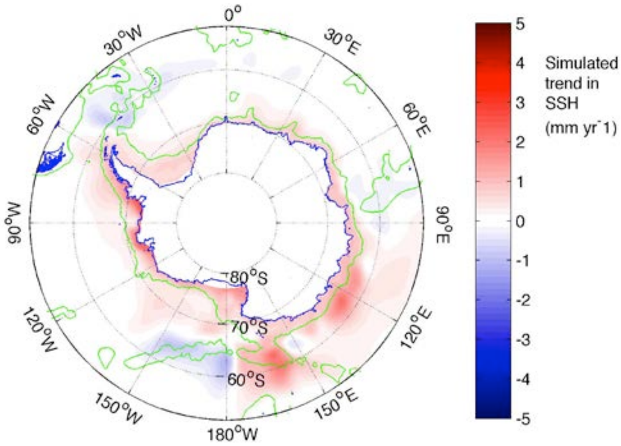


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