Weddell Sea anomalies: Excitation, propagation, and possible consequences

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Antarctic marginal seas are susceptible to significant decadal variability as revealed by the analysis of a 200-year integration of a regional ice-ocean model forced with the atmospheric output of the IPCC climate model ECHAM5-MPIOM. The strongest signal occurs on the southern and western Weddell Sea continental shelf where changes in bottom salinity are initiated by a variable sea ice cover and modification of surface waters near the Greenwich meridian. Related zonal shifts of the western rim current guide deep waters with different temperature out of the Weddell Sea. With a deep boundary current the temperature signal propagates westward through southern Drake Passage and along the upper continental rise in the southeast Pacific thereby influencing the hydrographic conditions on the continental shelf of Bellingshausen, Amundsen, and Ross Seas.

1. Introduction

The Southern Ocean represents an essential component of the global climate system. Inter alia, its interaction with the floating extensions of the Antarctic ice sheet creates water masses fueling the lower branch of the global meridional overturning circulation. A +40-year time series from the Ross Sea reveals long-term changes of shelf water characteristics [*Jacobs et al.*, 2002]. The continuous salinity decrease since the early 1960s might have changed the bottom water characteristics further to the west [*Rintoul*, 2007]. Reasons for the decrease are still debated: (1) an increased freshwater input due to ice shelf basal melting in Amundsen and Bellingshausen Seas [*Rignot and Jacobs*, 2002] or (2) a sampling-aliasing of a recurring salt anomaly initiated at the continental slope of the Amundsen Sea [*Assmann and Timmermann*, 2005]. The Ross Sea freshening coincides with a positive trend of the Southern Annular Mode (SAM) which can be linked to a strengthening and poleward shift of the westerly winds [*Thompson and Solomon*, 2002], enhanced upwelling of relatively warm Circumpolar Deep Water (CDW) onto the Antarctic continental shelf [*Walker et al.*, 2007], and thus increased ice shelf basal melting in the Pacific sector. Changes on shorter time scales were observed for the deep waters in the Weddell Sea [*Gordon*, 1982; *Fahrbach et al.*, 2004]. The earlier cooling can be related to the occurrence of the Weddell Polynya and might have spread to the north as far as the Argentine Basin [*Coles et al.*, 1996]. A link between the Weddell Sea and the seas west of the Antarctic Peninsula is still on dispute. A narrow boundary current in southern Drake Passage [*Naveira Garabato*, 2003; *Tarakanov et al.*, 2008] which, according to geological records [*Hillenbrand et al.*, 2008], sets southwest on the upper continental rise west of the

Antarctic Peninsula has been postulated only recently. Therefore, the southeast Pacific Ocean is still considered solely as intensifier and radiator of ocean variability generated in the southern hemisphere [e.g., *Beckmann and Timmermann*, 2001].

2. Method

We investigate the results of the coupled ice-ocean model BRIOS-2.2 [*Timmermann et al.*, 2002], which resolves the Southern Ocean on a grid of 1.5° zonally and $1.5^\circ \times \cos\phi$ meridionally (∼80 km in southern Drake Passage). The model is forced for 200 years (1900–2099) with the atmospheric output of the IPCC-20C3M scenario simulation of the coupled atmosphere–sea ice–ocean ECHAM5-MPIOM [*Roeckner*, 2004]. The latter scored best in an Antarctic assessment of IPCC AR4 coupled models [*Connolly and Bracegirdle*, 2007]. Because no spin-up was performed to reach a quasi- stationary state, the first 20 years (1900–1919) were discarded from the analysis. Seasonal and interannual variability was eliminated by considering annual means and applying a 5-year running mean filter, respectively. Trends were removed. The unfiltered time series contains one event, lasting for about 40 years, around the turn of the century which cannot be associated with the mechanisms proposed below. The analysis of the unfiltered data reveals essentially the same results; for a better presentation, however, we removed the longest time-scales by subtracting the 20-year running mean. In addition, in two sensitivity runs the atmospheric forcing in the Weddell Sea sector (60°W – 60°E) was altered by monthly mean composites of surface winds, 2 m-temperature, and dew point temperature from post-2000 years of extreme high and low bottom salinities in the south/western Weddell Sea, preceeding the bottom salinity by 5 years (lower panel in Fig. 1; for more information see auxiliary material).

3. Results

EOF-analyses of the model output for different variables and levels reveals a prominent mode for bottom salinity (S_{bot}) in the southern and western Weddell Sea (Fig. 1). The largest amplitude of this leading EOF-mode (48% described variance) amounts to about 0.03, corresponding to a peak-to-peak salinity range of 0.l. These changes in S_{bot} are significantly correlated (r = 0.56) with the ECHAM5-MPIOM's SAM index for S_{bot} lagging SAM by five years (Fig. 1). We defined the SAM index as the leading EOF of the annual mean sea level pressure (SLP) south of 20°S. Its distribution agrees well with published SAM patterns (e.g., Fig. 1 in *Lefebvre et al.* (2004)). The leading S_{bot}-EOF pattern covers the western Weddell Sea continental shelf and upper slope up to the tip of the Antarctic Peninsula (Fig. 1). A regression of the bottom velocities u and v on the leading S_{bot}-EOF time series (pc_1) shows that the highest correlation (r_{max} = 0.85) extends from the Weddell basin's western rim current into the southeast Pacific sector of the Southern Ocean. This strong correlation is also evident for the barotropic transport streamfunction (Ψ) regressed on pc_1 (Fig. 2), indicating the dominance of the bottom signal in the whole water column. A lagged-regression of the same quantities shows a maximum regression slope in the eastern Bellingshausen Sea for pc_1 leading the barotropic transport by four years. Within eight years the area of strong correlation (r > 0.5) between pc_1 and Ψ propagates westward along the continental slope until it fades approaching $\sim$ 75°E (Fig. 2). The overlap of positive correlation with an 8-year lag and negative correlation (r < -

0.5) with a 0-year lag in Amundsen and Ross Seas indicates a 16-year periodicity for the westward propagating anomaly generated in the Weddell Sea. The periodicity is triggered by the approximately 16-year cycle of the ECHAM5-MPIOM's SAM forcing (Fig. 1).

The lag-correlation between circumpolar bottom temperature (T_{bot}) and the first EOF of S_{bot} shows a very similar pattern in space and intensity as for the barotropic transport streamfunction, although of opposite sign (r_{max} = -0.85 for lag 0 years). T_{bot} exhibits maximum variability for lag +4 years at the southeast Pacific continental slope (Fig. 2) corresponding to temperature changes of up to 0.32 °C. A meridional section at 81°W (not shown) exhibits a vertical dipole at the continental slope with negative correlation (r = -0.7) in the 1000–3000 m depth range and positive correlation (r = 0.5) above. The dipole pattern suggests the deep signal being advected into the southeast Pacific Ocean rather than formed locally by atmosphere–ice–ocean interaction and deep convection. The deep temperature signal advances westward and onto the continental shelf without losing much of its intensity as it approaches the fringes of the West Antarctic Ice Sheet. For the 16-year period the squared coherency [*v.Storch and Zwiers*, 2003] between pc_1 and the modeled meltwater fluxes from these ice shelves is 0.5 at a significance level close to 90%. For lag +8 years (not shown) the anomaly enters the Ross Sea continental shelf at 180° with a correlation of r > 0.5 but fades as it reaches the western edge of the Ross Ice Shelf.

4. Discussion

Tracing the causes for the southern Weddell Sea salt variability, an additional analysis reveals that pc_1 is strongly correlated with the sea ice concentration and the sea surface salinity (SSS) near the coast at the Greenwich meridian. The SSS anomaly leads pc_1 by up to five years with a correlation r > 0.5. Long-term changes of sea ice conditions reflect the influence of the SAM through variable coastal winds. This agrees with a recent study which proposes a link between SAM and the occurrence of the Weddell Polynya [*Gordon et al.*, 2007]. From the eastern Weddell Sea the SSS-anomaly propagates westward into the central Weddell Sea and onto the southern continental shelf (see also Fig. A2 in the auxiliary material). Here, it influences the stability of the shelf water column such that local air-sea interaction together with sea ice formation and deep convection determine the signal at the sea floor with varying intensity. The shelf circulation carries the signal into the Filchner-Ronne Ice Shelf (FRIS) cavern. However, recirculation, mixing in relatively shallow waters, and ocean–ice shelf interaction damp the signal of the inflowing shelf water in the cavern interior. Therefore, a strong correlation between the S_{bot}-variability and the modeled freshwater flux due to melting at the FRIS base does not exist.

The mechanism which transfers the variability from the eastern to the western side of the Antarctic Peninsula is best explained by the results of the sensitivity study. The latter allows the comparison between the impacts of the bottom salinity extremes, solely caused by atmospheric variability in the Weddell Sea sector (see auxiliary material). A saltier (fresher) south/western Weddell Sea is related to a weaker (stronger) zonal density gradient across the western continental shelf break/slope which broadens (narrows and shifts eastward) the core of the western rim current (Fig. 3). As the temperature gradient across the continental slope is large, the shift is related to the transport of colder (warmer) deep waters across the South Scotia Ridge (Fig. 3). The outflow feeds the deep boundary current in southern Drake Passage which extends into the southeast Pacific Ocean thus cooling more (less) the deep layers at the continental slope of the Bellingshausen Sea and beyond.

The range of the S_{bot}-variability in the Weddell Sea of this study is comparable to the S-variability found in a 50-year hindcast with BRIOS-2.2 in the Amundsen Sea [*Assmann and Timmermann*, 2005]. The Amundsen Sea anomaly propagated primarily westward as part of the Antarctic circumpolar coastal wave [*Beckmann and Timmermann*, 2001]. Both publications do not consider a signal transfer from the Weddell Sea into the southeast Pacific Ocean but admit that a thorough analysis of both the atmospheric data and the ocean model results did not happen with regard to this feature. Recent oceanographic observations in southern Drake Passage support the modeled westward flow of Weddell Sea Deep Water [*Naveira Garabato et al.*, 2003], escaping through the gaps in the South Scotia Ridge [*Gordon et al.*, 2001]. Geological records confirm that the deep boundary current continues on the upper continental rise west of the Antarctic Peninsula at least as far as 94°W [*Hillenbrand et al.*, 2003].

5. Conclusions

The decadal variability of shelf water salinity in the south/western Weddell Sea inherent to our 200-year integration can be related to the periodicity of SAM as part of the model's atmospheric forcing (Fig. 1). The most obvious footprint of the atmospheric signal is the sea ice cover anomaly near the Greenwich meridian strongly influencing sea surface salinity. The Antarctic coastal current provides the link between eastern and southern Weddell Sea. The latter amplifies the surface disturbances and sends out westward propagating bottom anomalies which influence the shelf water properties on both sides of the

Antarctic Peninsula. Our statistical analysis is supported by the results of the sensitivity study which accentuates the role of the Weddell Sea as dominant source for variability in Antarctic marginal seas. Therefore, an influence from the east should be considered as a new aspect at the present search for mechanisms controlling the flow of warm deep waters towards the floating extensions of the West Antarctic Ice Sheet.

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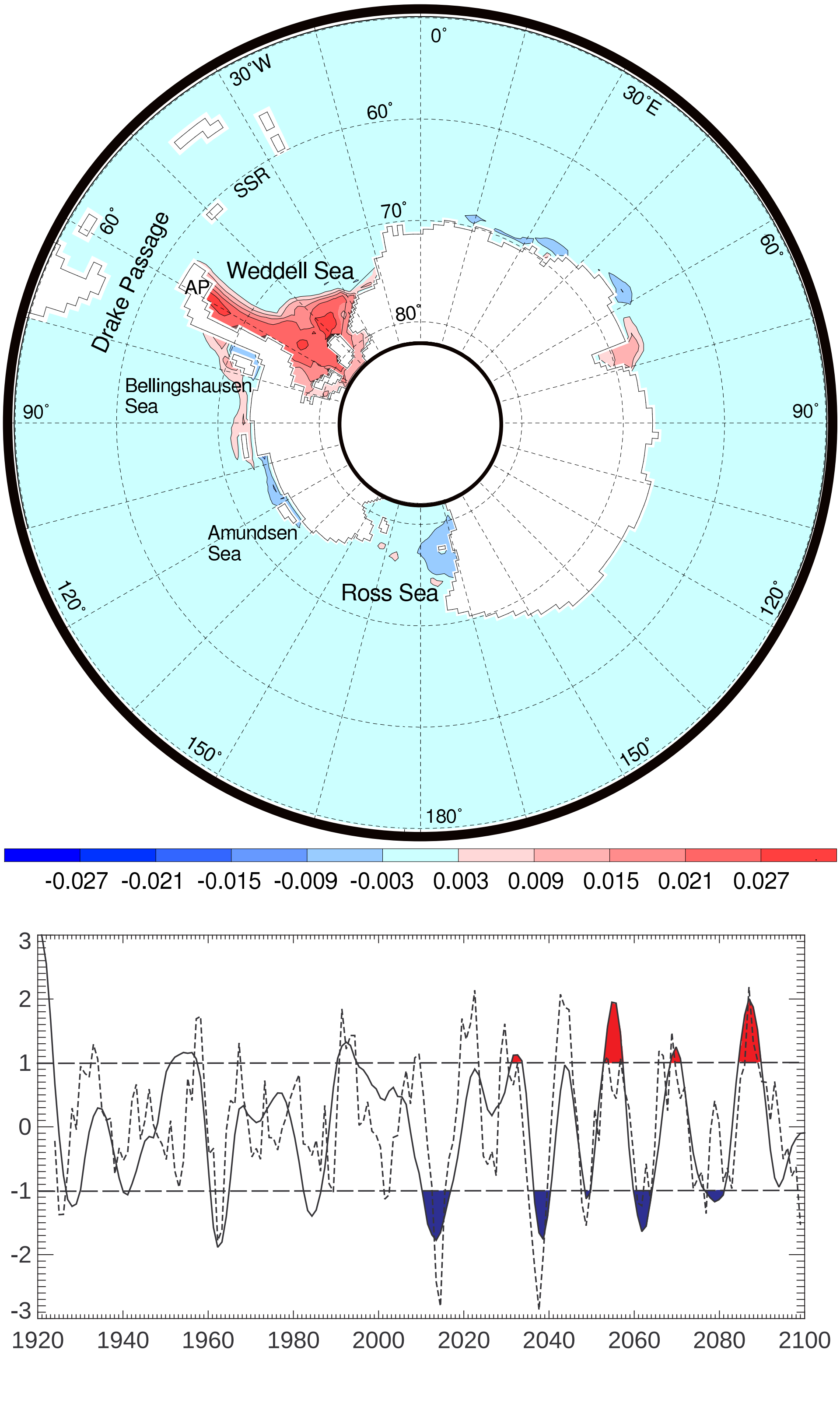
Figure Captions

Figure 1: Upper: Leading EOF pattern of Southern Ocean bottom salinity south of 50°S describing ∼48% of the variance. Black solid lines represent the model's continental border including the grounding lines in ice shelf caverns. AP: Antarctic Peninsula; SSR: South Scotia Ridge. Lower: Corresponding normalized time series (solid line) and 5-year leading Southern Annular Mode deduced from the ECHAM5-MPIOM forcing (dashed line) for the analyzed period 1920-2099. The correlation of the (5-year shifted) time series amounts to r = 0.56. The red and blue patterns mark years used for the construction of the composite forcing applied in the sensitivity study (see auxiliary material for a detailed description).

Figure 2: Upper: Positive (solid lines) and negative (dashed lines) lagged correlations between the salt anomaly in the southern Weddell Sea and the barotropic streamfunction (Ψ). Colored lines border areas with a correlation higher r = 0.5 (r_{max} = 0.85), and colors represent different lags in time (see insert; positive = salt anomaly leads Ψ). Lower: Regression slope of the circumpolar bottom temperature (T_{bot}) regressed on the leading S_{bot}-EOF time series (pc_1) for a positive 4-year time lag (pc_1 leads T_{bot}).

Figure 3: Bottom distribution of salinity (left), temperature (middle), and velocity (right) in the Weddell Sea sector for the sensitivity runs forced with the high (upper) and low (lower) atmospheric composites (see auxiliary material). Year 2007 and scale were chosen to best represent the two different phases controlling the flow of deep water out of the Weddell Sea.



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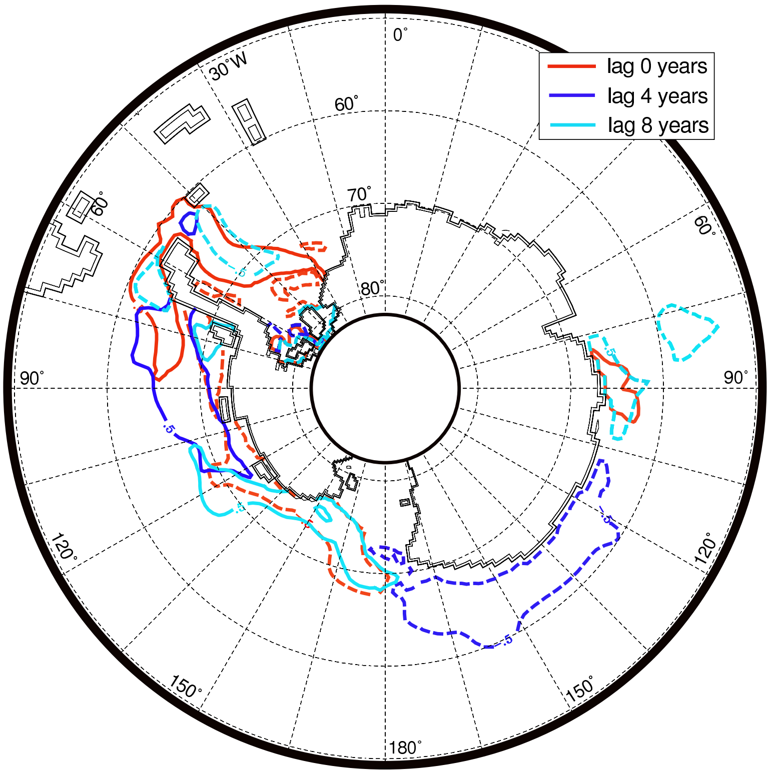

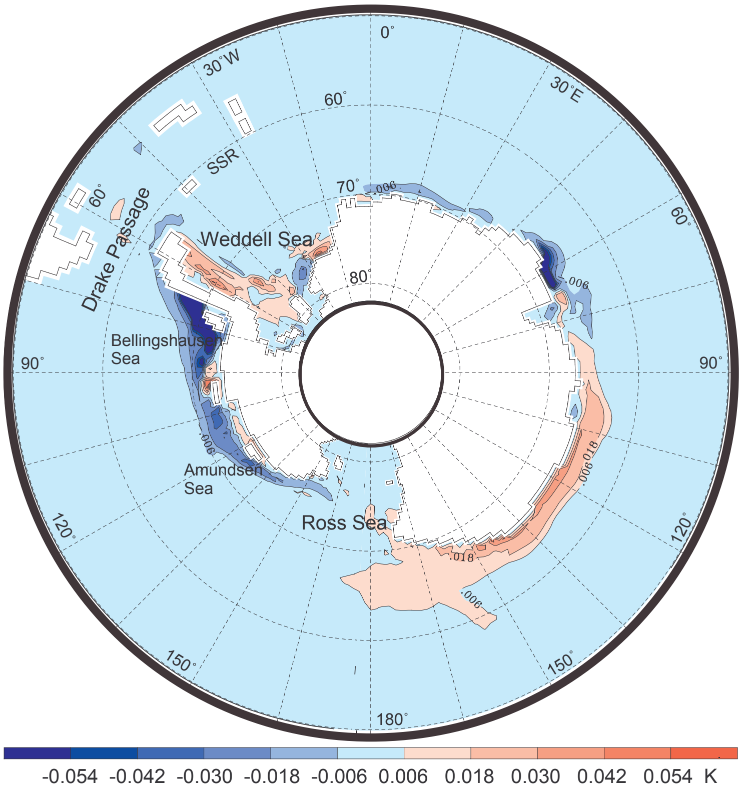

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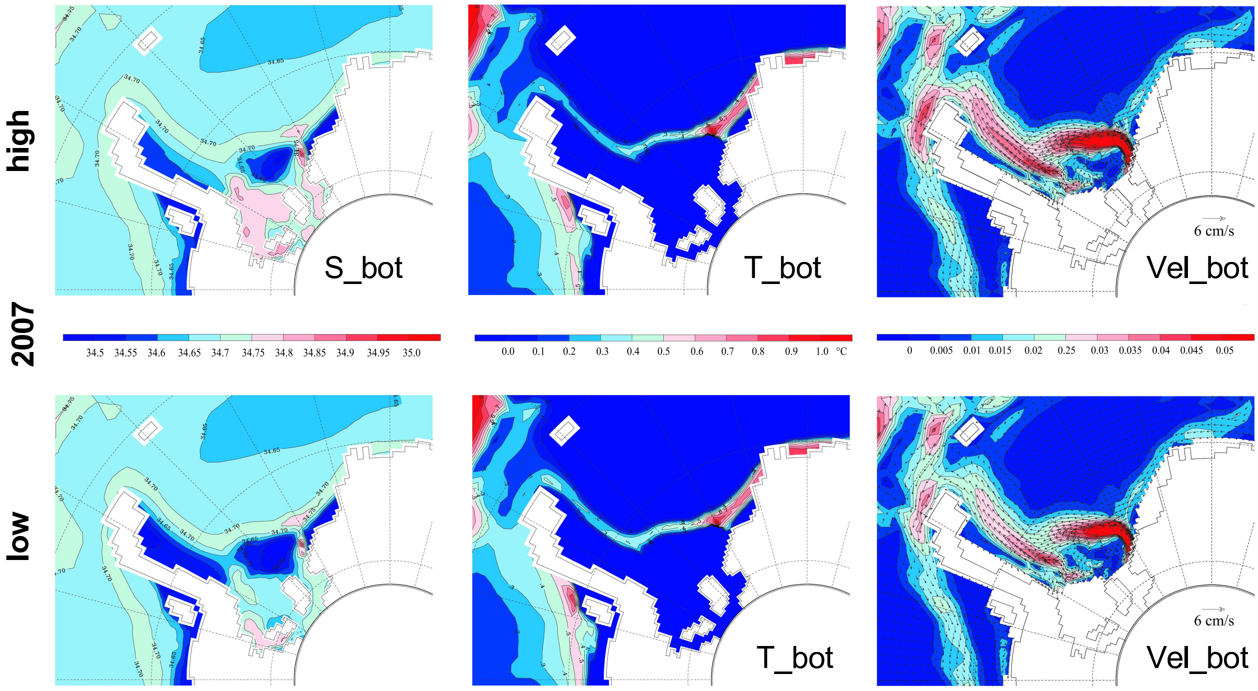

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