Decadal variability in the Antarctic Circumpolar Current of a stochastically forced Ocean General Circulation Model

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Abstract: Decadal fluctuations in the Antarctic Circumpolar Current (ACC) were considered. Recently, the concept of the Antarctic Circumpolar Wave was proposed to account for large-scale anomalies which tend to propagate along the ACC in both the atmosphere and the ocean. In the present study the Hamburg Large-Scale Geostrophic ocean general circulation model was forced stochastically to assess whether such anomalies can partially be explained by a simple ocean response to atmospheric forcing. The short-term atmospheric weather fluctuations were represented by a number of spatially coherent patterns of momentum, heat, and freshwater flux which were superimposed onto the climatological fluxes. These patterns were derived from an experiment with an atmospheric general circulation model forced with observed sea surface temperatures and were chosen randomly at each time step of the ocean model. We found that in this experiment anomalies which propagate along the ACC on a decadal time scale occur and that they can be explained by the combined effects of anomaly advection with the mean ocean circulation and integration of the short-term atmospheric weather fluctuations. In this case, the spatial scale of the anomalies as given by the atmosphere is converted into a time scale by the mean zonal velocity of the ACC.

1. INTRODUCTION

At high southern latitudes considerable interannual and decadal variability is observed. Observations of sea-ice extent suggest that these features tend to propagate along the Antarctic Circumpolar Current (ACC) [e.g. Lemke et al., 1980; Murphy et al., 1995]. Phase-locked anomalies of sea surface temperature (SST), sea-ice extent, sea level pressure (SLP) and meridional wind stress propagating eastward along the ACC were described by White and Peterson (hereafter WP) [1996]. They suggested that the anomalies circle around Antarctica in roughly 8-10 years at an average speed of 6-8 cms^{-1}. Since a wavenumber two like pattern was most dominant in their data a time scale of 4-5 years was deduced. WP called this phenomenon the Antarctic Circumpolar Wave (ACW). The ACW was also identified by Jacobs and Mitchell [1996] in variations of the sea surface height in the ACC using the most recent satellite data available.

Peterson and White (hereafter PW) [1996] suggested that the ACW basically reflects a propagation of Pacific ENSO signals and that the source for the interannual SST signals in the ACC is located in the western subtropical South Pacific ocean. They concluded that ENSO-related SST anomalies propagate southward into the Southern Ocean where they move eastward, phase-locked with SLP anomalies, around the entire southern hemisphere through some combination of geostrophic advection and ocean-atmosphere coupling.

Christoph et al. (hereafter CBR) [1997] tried to find and confirm WP's and PW's results in a 180-year integration of a coupled atmosphere-ocean general circulation model (CGCM). They found variability strongly reminiscent of the ACW but raised some noticeable differences. In the model the turn-around time of the ACC is closer to 12-16 years compared to the 8-10 years inferred from the observations and a wavenumber three pattern is more pronounced than a wavenumber two pattern. Additionally, CBR found noticeable regional differences in the amplitude of the ACW-like variability which is much smaller in the South Atlantic and Southern Indian Ocean than in the Pacific. Based on these findings they doubted that the ACW indeed circles around the globe, and concluded that an equally plausible description would have the ACW appear first south of Australia, subsequently moving eastward with intensification, and immediately attenuating after passing Drake Passage. Whereas PW speculated that the ACW has its source in the ENSO phenomenon CBR argued that the mode has its origins in the mid- to high latitudes themselves.

Both, WP and CBR concluded that the ACW is a mode of the coupled atmosphere ocean sea-ice system and that atmosphere-ocean interaction plays a dominant role in the mechanism of the variability. This is a typical approach often used to explain variability of the type described above. An alternative attempt at understanding climate variability was proposed by Hasselmann [1976] with the concept of stochastic climate models. For time scales of a few months and longer the atmosphere is assumed to be in a quasi-equilibrium. The integration of the short-term atmospheric fluctuations transforms the essentially white-noise atmospheric forcing into a red response signal. For a linear system the resulting response spectrum is proportional to ω^{-2} as long as the frequency ω is large compared to the inverse of the natural time scale of the slow system and constant at low frequencies. This concept was successfully applied to a number of problems such as mid-latitude SST variability [Frankignoul and Reynolds, 1983] or advection of sea-ice in the Arctic and Antarctic [Lemke et al., 1980]. Note, however, that ocean-atmosphere feedbacks are usually neglected in simple linear stochastic climate models.

The purpose of the present paper is to investigate to what extent the concept of stochastic climate models can be applied to explain decadal climate variability in the Southern Ocean. For that purpose we forced a stand-alone ocean general circulation model (OGCM) with stochastic wind stresses, heat and freshwater fluxes superimposed on the climatological fluxes and integrated the model for 7000 years. In this way a strong decadal signal was excited in the Southern Ocean which shows substantial similarities with the ACW. This signal can be understood as the oceanic response to the white-noise atmospheric forcing and can be explained mainly by an integration of the stochastic components of the atmospheric forcing plus ocean advection and some linear ocean feedback. Atmospheric feedbacks are neglected in our study.

2. MODEL AND EXPERIMENT

The Hamburg Large-Scale Geostrophic (LSG) OGCM as described by Maier-Reimer et al. [1993] was used. The model has a free upper surface. A mass flux boundary condition is used at the sea surface. A simple sea-ice model is included in which sea-ice is advected by the ocean mean surface velocity as well as by wind with an assumed equilibrium velocity proportional to the wind velocity. Furthermore, a simple run-off model is included. The LSG OGCM is formulated on an Arakawa E-Grid and was applied with a horizontal resolution of effectively 3.5°x3.5°. A realistic but smoothed topography was used and a time step of 15 days was applied.

A model spin-up was performed for 5000 years using monthly climatologies of COADS near-surface air temperature [Woodruff et al., 1987], wind stress [Hellerman and Rosenstein, 1983] and annual mean climatologies of sea surface salinities [Levitus, 1982] until a steady-state solution was obtained. Climatologies of net freshwater flux and heat flux were computed from the last 500 years of this spin-up. The model was integrated for another 4000 years using a fixed flux boundary condition for freshwater flux and a combination of a fixed flux forcing and restoring with a damping coefficient of 16 $Wm^{-2}K^{-1}$ as boundary condition for temperature [Mikolajewicz and Maier-Reimer, 1994].

To account for the short-term atmospheric fluctuations which influence the ocean at its upper boundary stochastic components were added to the climatological fluxes of momentum, freshwater and heat. These components were derived from a 10-year AMIP simulation with the ECHAM3-T42 AGCM [Arpe et al., 1993] by averaging the momentum, heat and freshwater fluxes and the near-surface air temperature over each month and subtracting the climatology. For each month, one set of these anomalies was chosen at random and added to the climatological fluxes in the OGCM simulation. To account for the differences in the variability of the summer and the winter season, only anomalies from the corresponding month of the atmospheric simulation were chosen. Thus, the stochastic components superimposed are spatially coherent, but have a white-noise spectrum with respect to time. In the absence of reliable and sufficiently resolved observational data this spatial coherence may be regarded as a reasonable approximation for representing the spatial coherence at the synoptic scale of the atmosphere. The model was integrated for 7000 years. Only the last 5000 years were examined in the present study to avoid analyzing of effects of the model's adaption to the new boundary conditions.

3. RESULTS

To describe the space-time dependent variability appearing in the OGCM we used the multivariate Principal Oscillation Pattern (POP) technique [e.g. von Storch et al., 1995]. POP's form an eigensystem of the analyzed data $y(x, t)$

$$y(x, t) = \sum_i z_i(t) \mathbf{p}_i(x) \quad , \qquad (1)$$

where $z_i = z_{i1} + iz_{i2}$ are the complex POP coefficient time series and $\mathbf{p}_i = \mathbf{p}_{i1} + i\mathbf{p}_{i2}$ are the spatial POP patterns. Vectors are typed in boldface. The system is expected to generate stochastic sequences

$$\ldots \rightarrow \mathbf{p}_2 \rightarrow \mathbf{p}_1 \rightarrow -\mathbf{p}_2 \rightarrow -\mathbf{p}_1 \rightarrow \mathbf{p}_2 \rightarrow \ldots \qquad . (2)$$

Note that the index i was dropped for convenience. Thus, if at time $t=0$ the system is in state $\mathbf{p}_2$, it will be with a high probability in state $\mathbf{p}_1$ one quarter of a period later, in state $-\mathbf{p}_2$ half a period later, and so on.

We performed a POP analysis for the sea surface salinity (SSS) of the Southern Hemisphere in the LSG experiment. The dominant mode of variability (Figure 1) is characterized by an oscillation period of roughly 6 years. According to (2) it describes the eastward propagation of salinity anomalies along the ACC. The amplitude of the mode is at maximum in the Pacific sector (roughly 0.15 psu southeast of New Zealand), and almost negligible in the Indian Ocean. There are clear indications of a zonal wavenumber three pattern, however, zonal modifications of the amplitude suggest that the mode must be a combination of more than only one wavenumber. The mode explains up to 35 % of the model's total SSS variability in the ACC (Figure 1c). Locally, the explained variance is highest in the Pacific sector. The cross-spectra of the POP coefficient time series are characterized by a pro-

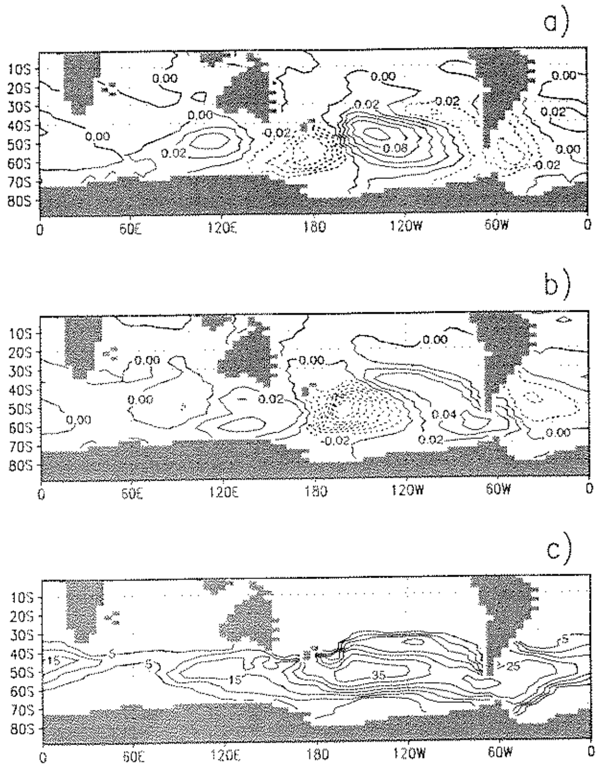

Figure1: Spatial patterns of SSS in practical salinity units [psu] of the dominant mode of decadal variability in the Southern Ocean, (a) imaginary part, (b) real part and (c) locally explained variance. Contour interval is 0.02 psu for imaginary and real part (a,b) and 5% for locally explained variance (c). The model topography is indicated in grey. Note that the model is formulated on an Arakawa E-grid and that data and topography were transferred to a regular grid for plotting

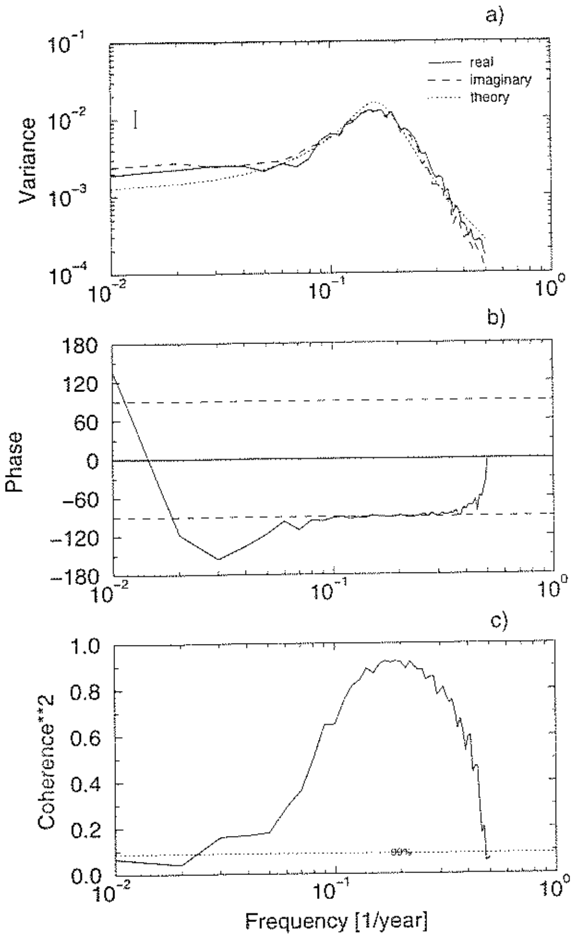

Figure2: Spectra of the POP coefficient time series of the dominant mode of decadal variability in the ACC, (a) power spectrum (solid line, real component; dashed line, imaginary component; dotted line, fitted theoretical model; The bar on the left hand side represents the 95% confidence interval.), (b) phase spectrum, and (c) coherence squared.

nounced peak near the POP period (6 years), strong coherence, and a constant phase shift of roughly 90^0 (Figure 2).

Associated patterns p_A of temperature and salinity at the uppermost 4 levels (25, 75, 150, 250 metres depth) were computed for this POP to test if the mode exists in other parameters than SSS. Associated patterns evolve in phase with the estimated POP pattern and are defined by

$$\|y(x,t) - z(t)p_A(x)\|^2 = Min \quad , \qquad (3)$$

where $y(x, t)$ represents the vector time series of temperature and salinity and $z(t)$ denotes the complex POP coefficient time series. The associated pattern for temperature at 75 m depth describes an eastward propagating wavenumber three signal which accounts for roughly 20% of the local variance in the Pacific sector of the ACC (not shown). Similar results were found for temperature at 150 and 250 m depth. The situation is slightly different for the salinities. Here the signal is more confined to the upper two layers. At 250 m depth anomalies of significant amplitude were only found southeast of New Zealand and account for roughly 25% of the local salinity variability. The confinement of the signal to a very limited region at deeper layers is probably due to the fact that anomalies here are induced by modified convection produced by the propagating surface anomalies.

The decadal variability described is to a large extent characterized by the eastward propagation of temperature and salinity anomalies. The path which the maxima of the anomalies follow coincides well with the trajectory of an imaginary passive tracer in the mean current. We therefore propose that the propagation of the anomalies is basically a result of ocean advection. On the other hand, the generation of the anomalies is probably mainly a result of the integration of the stochastic atmospheric forcing, and we propose that the decadal variability found in the LSG model can to a large extent be described as a combination of the integration of the white-noise atmospheric forcing, ocean advection, and some linear feedback. Frankignoul and Reynolds [1983] showed that the wavenumber-frequency spectrum of such a process is given by

$$F_{yy}(\omega) = \int \frac{F_{vv}(\omega, k)}{(\omega - k\bar{u})^2 + \lambda^2} dk \quad , \qquad (4)$$

where F_{ab} denotes the cross spectrum between a and b, ω the frequency, k the wavenumber, λ the linear oceanic feedback term, y any ocean variable, and v the stochastic atmospheric forcing.

It can be inferred from (4) that for a white-noise atmospheric forcing $(F_{vv}(\omega, k) = F_{vv}(0, k))$, the wavenumber-frequency spectrum of the ocean response F_{yy} has a maximum at $\omega_0 = k_0\bar{u}$ for each wavenumber k_0. In other words, in the wavenumber-frequency domain F_{yy} peaks along lines of constant ωk^{-1}. If, for instance, the spectrum of the forcing is almost constant with respect to frequency but has a distinct maximum at wavenumber k_0, the variance spectrum will have a peak at the frequency $k_0\bar{u}$. In this case, it is the spatial coherence of the forcing which is mapped onto the slow system and determines the time scale of the ocean response.

To check the consistency between the variability found in the LSG and the proposed mechanism we computed the wavenumber-frequency spectra of SSS and temperature at 75 m depth at 51° and 61° South from the LSG experiment data and compared them with the spectrum (4) of the physical model. A large fraction of the SSS variance at 51° South is accounted for by a standing wavenumber one pattern with a 40-50 year time scale (Figure 3). Near the POP period, most of the SSS variance is attributed to the propagating part of the spectrum at zonal wavenumbers 1-3. In accordance with the spectrum of the proposed simple model (4) the maximum of the propagating variance is centered along a line of almost constant $k\omega^{-1}$. For $k=1$, the maximum variance occurs at a period of roughly 18 years, for $k=2$ at roughly 9 years, and for $k=3$ at roughly 6 years, resulting in a propagation speed of 20° per year or 4.5 cms^{-1} at 51° South which coincides with the average speed of the ACC in the LSG model. The wavenumber-frequency spectrum of temperature at 75 m depth looks similar to that of SSS, however with a smaller signal-to-noise ratio (not shown). For both temperature and salinity, the wavenumber-frequency spectra were found to be similar to that of the simple model (4).

To test the hypothesis that the spatial patterns of the atmosphere are dominated by only a few wavenumbers and thereby might determine the time scale of the ocean response we computed the wavenumber-frequency spectra of all atmospheric forcing components (boundary temperature, net freshwater flux, and wind stress curl) in the LSG experiment (not shown). The terminology "atmospheric forcing" should be interpreted here in the formal sense, as representative of the true forcing, the assumption being that the true forcing is significantly correlated with the chosen atmospheric variable. Most of the variance in these spectra is attributed to the large scale (wavenumbers 1-3). Assuming that the proposed model (4) holds, a combination of more than one dominant wavenumber in the forcing fields is necessary to account for the zonal modifications of the amplitude of the ocean response as found for the POP mode. We found that with respect to frequency, the wavenumber-frequency spectra are almost constant which is typical for white-noise processes (not shown). The variance of the model forcing which is attributed to the standing part of the spectrum is usually one to two orders of magnitude larger than that associated with the propagating part. This results from the fact that the atmospheric forcing of the LSG experiment consists of a limited number of spatial patterns which were chosen randomly in time. Thus, there is no preferred propagation direction so that the variance is dominated by the standing part of the spectrum. Although we cannot draw any conclusions from the relative amount of atmospheric variance explained by the propagating and the standing part of the spectrum, there is some observational evidence that the chosen forcing nevertheless represents an adequate approximation of the real situation. For instance, Mo and White [1985] and Xu et al. [1990] report a preference of the atmosphere to attribute energy to the standing part of the spectrum in the mid-latitudes of the southern hemisphere.

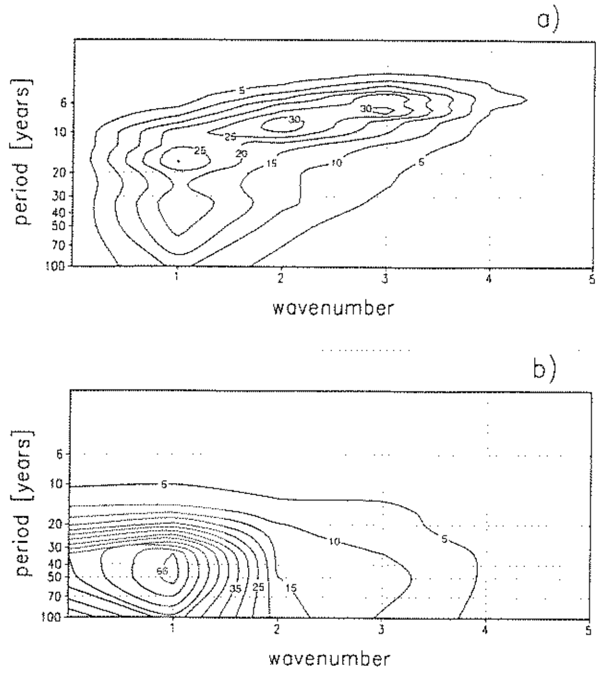

Figure 3: Two-sided wavenumber-frequency spectrum of the SSS at 51° South, (a) propagating variance and (b) standing variance in

10^{-5} $psu^2\Delta\omega^{-1}\Delta k^{-1}$

For simplicity, we assume that the white-noise atmospheric forcing $F_{vv}(\omega, k)$ is dominated by a wavenumber three pattern. Then (4) reduces to

$$F_{TT}(\omega) = \frac{A_{vv}}{(\omega - 3\bar{u})^2 + \lambda^2} \qquad (5)$$

where $A_{vv} = F_{vv}(\omega, k)$ is the constant amplitude of the stochastic forcing. We fitted the spectrum of the simple physical model to the spectrum of the POP coefficient time series and obtained a good agreement between the theoretical spectrum and that derived from the POP coefficient time series (Figure 2). The model parameters A_{vv}, $\bar{u}$, and λ were estimated by a least squares fit, minimizing the deviation between the power spectra of the POP coefficients and the advective model. In this way we obtained a mean velocity $\bar{u}$ of roughly 0.34 rad per year, which is equivalent to almost 19^{o} per year, or 4-5 cms^{-1} at 51^{o} South. This coincides with the average speed of the ACC in the LSG model and yields a turn-around time around Antarctica of roughly 19 years. Because of the assumed wavenumber three pattern in the atmospheric forcing, this corresponds to a characteristic time scale of roughly 6 years which coincides with the estimated POP period. The feedback term λ yields 0.28 yr^{-1} which corresponds to an e-folding time of almost 4 years. The white-noise forcing level was estimated to be $1.239 \times 10^{-3}\ yr^{-1}$. Note that POP coefficient time series are dimensionless in our case.

4. SUMMARY AND DISCUSSION

The Hamburg LSG OGCM was forced with stochastic components added to the climatological fluxes of momentum, heat, and freshwater. Thereby, pronounced decadal variability in the Southern Ocean was excited. It is characterized by salinity and temperature anomalies in the upper levels which tend to propagate eastward along the ACC at the mean current velocity. The amplitude of the anomalies is at maximum in the Pacific sector of the ACC and almost negligible in the Indian Ocean. The mode was identified by means of a POP analysis of sea surface salinities for which it explains up to 35% of the total variance. POP analysis and inspection of the lagged correlation matrix of the raw data (not shown) reveal that the anomalies are enforced or generated southwest of Australia. Accordingly, they are advected through the Pacific sector of the ACC and are decaying in the East Pacific and after having passed through Drake Passage. The time scale of the variability was found to be 6 years.

The wavenumber-frequency spectra of the raw salinity and temperature data of the LSG experiment correspond to those of a stochastic climate model with linear feedback and advection in which the ocean acts primarily as integrator of the short-term atmospheric fluctuations and transfers them into a red response signal. The wavenumber-frequency spectra of the random components which were superimposed on the climatological fluxes of heat, momentum, and freshwater were found to be dominated by wavenumbers one, two and three. Given that the linear feedback is small compared to the product of mean current velocity $\bar{u}$ and dominant wavenumber k_0 of the forcing, the time scale of the ocean variability in the stochastic model is given by $(k_0\bar{u})^{-1}$ which in our case yields roughly 6 years for $k_0 = 3$ and $\bar{u} = 4.5\ cms^{-1}$, the average speed of the ACC in the LSG model. For e.g. a given dominant wavenumber four in the atmospheric forcing the time scale would be decreased at given ACC speed or, the other way around, an average speed of the ACC of roughly 3.4 cms^{-1} would be required to maintain the time scale of the variability. Thus, the large-scale spatial coherence of the atmospheric forcing is transferred to the ocean which together with the mean velocity of the ACC determines the time scale of the variability.

There are strong similarities between the Antarctic Circumpolar Wave as described by WP for observations and by CBR for a CGCM and the decadal variability found in the LSG experiment. WP suggested that phase-locked anomalies of SST, SLP and mean meridional wind stress completely circle around the globe, whereas CBR emphasized that the ACW is basically confined to the Pacific sector of the ACC and is much weaker in the Atlantic and the Indian Ocean. In our ocean-only experiment in which atmosphere-ocean feedbacks are completely neglected the amplitude of the mode is at maximum in the Pacific sector of the ACC and almost negligible in the Indian Ocean which coincides with the findings of CBR. Note that, since the spatial characteristics of the atmospheric forcing were found to be important for the temporal and the spatial scale of the oceanic variability, our findings cannot be considered as completely independent of those of CBR: The atmospheric part of their CGCM is almost the same as the one used for the AMIP simulation from which the stochastic forcing of the LSG experiment in the present study was derived.

Both WP and CBR noted phase-locked anomalies of atmospheric and oceanic variables which propagate eastward along the ACC and concluded that the ACW reflects a mode of the coupled atmosphere-ocean system. In contrast, we found that even a stochastic atmospheric forcing is able to generate an organized oceanic response which shows noticeable similarities with the variability described by WP and CBR. Consequently, phase-locking between atmosphere and ocean and ocean-atmosphere feedbacks seem not to be prerequisites for such variability to occur. One might even speculate that the atmosphere responds with phase-locked signals to ocean anomalies whose time scale is eventually determined by the ocean itself. However, the resolution of the ocean model used in the present study is relatively coarse compared to the spatial scale of fronts, eddies, and jet-streams in the ACC which are considered to be crucial for its dynamics. As a result, the average speed of the ACC is only roughly 4-5 cms^{-1} in our model compared to the 6-8 cms^{-1} obtained by WP from observations. Consequently, the time scale of the variability is increased in the LSG model.

In order to investigate the physical mechanisms of the decadal variability in the ACC, CBR forced a simple one-dimensional ocean heat budget model for the ACC with a standing wave given by a spatially fixed wavenumber three and an oscillation period of 4 years. They were able to excite SST anomalies with a zonal wavenumber three distribution which propagate eastward along the ACC. However, no explanation was given where the 4-year period of the atmospheric fluctuations might come from. By using a similar simple model, Weisse et al. [1997] showed that irregular atmospheric fluctuations in time are sufficient to excite propagating signals in the SST or SSS.

Since basic features of the variability were reconstructed with our ocean-only experiment we suggest that the combined effects of anomaly advection by the mean ocean circulation, integration of random short-term atmospheric weather fluctuations and some linear ocean feedback might account for a considerable fraction of the observed variability.

(The manuscript is an excerpt of the full paper "Stochastically forced variability in the Antarctic Circumpolar Current" which was submitted by the authors to Journal of Geophysical Research at July 31, 1997.)

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