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Delayed baroclinic response of the Antarctic circumpolar current to surface wind stress

YANG XiaoYi[1], HUANG RuiXin[2], WANG Jia[3] & WANG DongXiao[1†]

[1] LED, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China;
[2] Woods Hole Oceanographic Institution, MA02543 USA;
[3] NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48105, USA

The Antarctic Circumpolar Current (ACC) responds to the surface windstress via two processes, i.e., the instant barotropic process and the delayed baroclinic process. This study focuses on the baroclinic instability mechanism in ACC, which was less reported in the literatures. Results show that the strengthening of surface zonal windstress causes the enhanced tilting of the isopycnal surface, leading to more intense baroclinic instability. Simultaneously, the mesoscale eddies resulting from the baroclinic instability facilitate the transformation of mean potential energy to eddy energy, which causes the remarkable decrease of the ACC volume transport with the 2-year lag time. This delayed negative correlation between the ACC transport and the zonal windstress may account for the steadiness of the ACC transport during last two decades.

Antarctic Circumpolar Current, zonal windstress, baroclinic instability, mesoscale eddy

The Antarctic Circumpolar Current (ACC) is the most powerful current in the world oceans, with a transport of approximately 130—140 Sv (1 Sv=10^6 m^3/s). ACC is the global artery which connects three major oceans in the world, and it transports heat, salt and other materials between them; thus it plays an important role in global climate system[1]. The momentum balance of ACC has its own distinct features, which remains an issue of hot debate and there is no consensus among experts studying ACC.

It is well known that the wind stress is one of the major factor regulating zonal transport of ACC. Wind stress affects ACC primarily through two mechanisms: the fast barotropic response process and the slow baroclinic process. The barotropic response involves the direct zonal momentum transport from the wind stress to ACC. On the other hand, the baroclinic response is through change in the density stratification which affects the transport of ACC with a long time lag. Webb and de Cuevas[2] simulated the rapid response of the Southern Ocean to the zonal windstress, and found that the transport of ACC responded to wind stress in about two days via a topography-controlled barotropic process. Another numerical study also demonstrated that the maxima of Drake Passage transport appeared in lagging the surface westerly maxima for 3 d[3]. On the other hand, the positive (negative) anomalies of the surface windstress causes not only the acceleration (deceleration) of ACC but also the weakening (strengthening) of the subsurface stress and bottom pressure[4,5]. The variability in transport appears primarily in the form of barotropy along potential vorticity isolines on the intraseasonal time scale[6]. Meridith et al.[7] suggested that the interannual variability of Drake Passage transport was related to the surface windstress, which presented the strong baroclinicity independent of sea surface height. Another support for this postulate is from Hughes and Stepanov[8], who showed that there was no significant correlation

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†Corresponding author (email: dxwang@scsio.ac.cn)
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between the interannual variability of the ACC transport and the surface windstress in a barotropic model. This indicates that in addition to the direct momentum input, the windstress can change the stratification in ACC via Ekman pumping. Combining with the buoyancy forcing (e.g., cooling in the south and heating in the north), Ekman pumping produces a baroclinic pressure gradient, enhancing the vertical shear of ACC zonal velocity and baroclinic transport[9]. Gnanadesikan and Hallberg[10] used a low-resolution ocean model to simulate the impact of the Southern Ocean surface wind to the circumpolar current. Their results indicate that the enhanced westerly leas to the increase of the northward Ekman transport, the deepening of pycnocline and the warming of the deep water in the north part of Southern Ocean. The resulting enhancement of the vertical shear leads to the strengthening of the baroclinic transport in ACC. However, these results were obtained from non-eddy resolving low-resolution ocean model, so the potentially important role of mesoscale eddies remains unclear.

It is well known that mesoscale eddies play an important role in the momentum balance of ACC. At the latitudinal band of Drake Passage there is no meridional boundary, thus the momentum input to ACC by surface wind stress cannot be balanced by the zonal pressure gradient. Lateral Reynolds stress appears too small to be an important factor in the zonal momentum balance of ACC. To balance the momentum input and restrain ACC from excessive acceleration, the momentum must be transported by mesoscale eddies from the upper ocean to deep ocean. The disturbances in isopycnal slope and zonal pressure gradient associated with mesoscale eddies give rise to interfacial form stress, which can transport the horizontal momentum across the isopycnals. Therefore, mesoscale eddies may be a key factor in shaping the Southern Ocean stratification and regulating the zonal transport[11,12].

According to results from recent studies, the zonal momentum balance of ACC can be qualitatively described as follows: The momentum input of the westerly is transported downward to the deeper level by the effect of stationary and transient eddies. The form stress, generated by the bottom pressure and the bottom friction force are the sinks of the zonal momentum which balance the surface wind stress. Hence, surface wind stress and mesoscale eddy activity are the two important dynamical factors regulating the variability of the ACC transport.

In this study, we investigate the connection between the zonal wind stress and transport have significant correlation on interannual to decadal time scale; however, they exhibit no consistent linear trends on the decadal time scales. In fact, wind stress had a strong upward trend during 1980—1999, whereas the ACC transport remained nearly unchanged. Our results suggest that this inconsistency may be attributed to the mesoscale eddy activity in the Southern Ocean. Wind stress directly drives the zonal mean flow, giving rise to the tilted isopycnals. Strong horizontal density gradient intensifies the baroclinic instability, which facilitates more energy transformation from the mean flow to eddies. The strengthening of mesoscale eddy activity transports more zonal momentum from surface downward to the deep ocean, where the momentum is dissipated through bottom form stress. Therefore the ACC transport could maintain its steadiness in the recent two decades.

1 Data and method

Simple Ocean Data Assimilation (hereafter SODA) reanalysis dataset was used in the statistical analysis reported in this study. SODA is a set of ocean assimilation data based on a global ocean circulation model (GFDL MOM2.2), which simultaneously assimilates satellite measurements and the *in-situ* observations, including temperature, salinity and velocity[13]. This is a monthly data spanned over the period of 1958—2001. The horizontal resolution is 0.25°×0.4° (projecting on a 0.5°×0.5° grid) and there are 40 levels in the vertical, ranging from surface 5 to 5347 m. The model is forced by the ECWMF 40-year (ERA40) reanalysis daily surface wind field. This SODA dataset is more reliable than other model output data for its assimilation of *in-situ* data; it also provides a dynamical picture with a more continuous coverage in spatial and temporal resolution, in comparison with the *in-situ* data.

Isopycnal slope is defined as $S=-\frac{|\nabla_h \sigma|}{\bar{\sigma}_z}$ (σ is the potential density), i.e., it is the ratio of the horizontal gradient with vertical gradient of potential density. The baroclinic conversion rate of the ACC comes from the baroclinic conversion term in the perturbation energy equation (see Appendix for the detail). The baroclinic conversion rate indicates the rate of the conversion of mean-flow potential energy to the eddy energy via baroclinic instability process. The baroclinic conversion rate is controlled by the two factors: the vertical component of EP flux (which indicates the strength of eddy activity) and the mean flow stratification (which regulates the baroclinic instability of the background field).

2 Response of the ACC to the surface windstress

Previous studies showed that the primary mode of variability of the Southern Hemisphere (SH) zonal wind stress has a zonally symmetric equivalent barotropic structure, i.e., a north-south vacillation dipole mode between 40° and 60°S. This mode can explain 33%[14] and 30%[15] of the total variance in the ten-day low-pass data and monthly mean data, respectively. However, recent studies indicated that the SH atmospheric circulation had not only the interannual variability but also remarkable interdecadal variability, which manifested in the form of the Southern Annular Mode (SAM) and changes in the westerly jet[16,17]. Furthermore, the zonal windstress showed a significant upward trend during 1980－1999[18−20]. The influence of this decadal variability of zonal wind stress on the ACC can be seen clearly from the spatial map of the surface windstress linear trends overlapped by the ACC stream function climatology (Figure 1). It was readily seen that the ACC lay between the 65°－45°S latitudinal bands with a quasi-zonal structure. Interestingly, the zonal windstress also exhibited a linear strengthening trend with zonally symmetric mode, and its positive maxima are coalition with the axis of the ACC.

In virtue of the zonal symmetric feature of the ACC and the surface windstress, we calculated the area average windstress between the 65º－45ºS bands, and then compared its time series (Figure 2(a)) with the time series of the Drake Passage transport (Figure 2(b)). Obviously, there are 4－5 a period oscillations in both time

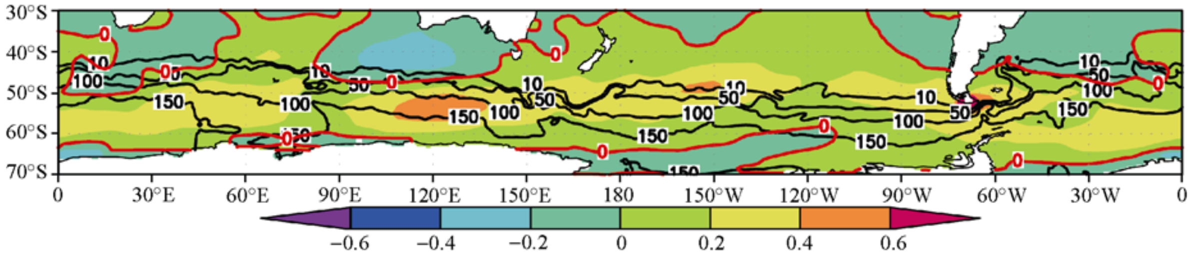

Figure 1 ACC steam function climatology (black contours, unit: Sv) and zonal windstress linear trend over period of 1980－1999 (shaded, units: dyn · cm^{-1} · 20a^{-1}). The red contours denote the zero lines of wind stress trend.

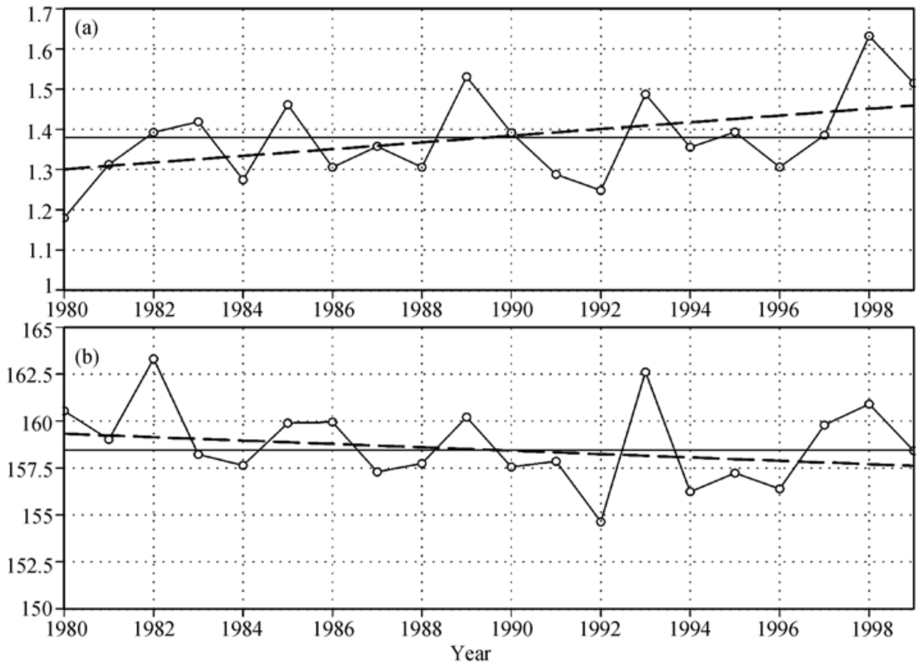

Figure 2 Time series of the 65°－45°S area averaged (a) windstress (unit: dyn · m^{-2}); (b) Drake Passage transport (unit: Sv) and their linear trends (dashed lines). The correlation coefficient for the two time series is 0.419; and their lag 2 a correlation is –0.589; both are significant for the 95% *t*-test.

series, and their interannual correlation can be 0.419, significant for 95% t-test. Thus on the interannual time scale, the strengthening of the windstress is related to the increase of the ACC transport.

We then analyzed the linear trend terms: for windstress, the linear trend is 0.167 ($\mathrm{dyn \cdot cm^{-2} \cdot 20\ a^{-1}}$), which is much larger than its standard deviation (±0.106 $\mathrm{dyn \cdot cm^{-2}}$). In another word, the windstress exhibited a remarkable strengthening tendency in the recent two decades. However, the significant correlation between the windstress and the ACC exists on the interannual time scale only, and it does not exist on the decadal time scale. In spite of the continuous strengthening of the surface windstress, the ACC transport remained relatively unchanged for the decadal time scale as its linear trend (−1.797 $\mathrm{Sv \cdot 20a^{-1}}$) was not significant compared with its standard deviation (±2.095 Sv). It is well-known that surface windstress is the main driving force of the ACC; in addition, on the interannual time scale, they both displayed a rather high positive correlation. However, why were they inconsistent on the decadal time scale? In the next section, we try to answer this question by analyzing momentum balance of the ACC and the baroclinic instability mechanism

3 Role of mesoscale eddy activity in the ACC momentum balance

Here we explore how momentum from wind stress is transported to the deep ocean, where it is balanced by the form stress and bottom frictional drag. Recent studies showed that the downward propagation of horizontal momentum could be realized by the mesoscale eddies (with the horizontal scale of approximate 150 km) and the topographic stationary waves. Hallberg and Gnanadesikan[21] proposed the "eddy saturation" effect, that is, the ACC transport manifests a linear correlation with the windstress forcing when wind is weak or buoyancy is dominating (the diabatic process); while in the case of strong wind, it is the eddy field that varies with the wind stress. In the latter case, the ACC transport remained steady. By analyzing the satellite data, Meredith and Hogg[22] found that the eddy kinetic energy (EKE) maxima always lagged the surface wind stress maxima by about 2—3 a. Using an eddy-resolving model, they came to a conclusion that this lagging effect may largely due to the baroclinic adjustment process. The wind energy input is first stored as the mean flow potential energy; then the mesoscale eddies, via the form stress, transfer the momentum from upper ocean to deep ocean, where the topographic effect further enhances the baroclinic instability of the mean flow, facilitating the conversion of mean potential energy to the eddy energy (including eddy potential/kinetic energy). Therefore, the mechanical energy input from the wind stress can be dissipated gradually through eddy activity.

Our results also indicate that the zonal wind stress and ACC transport displayed not only simultaneous correlation on the interannual time scale, but also for lagging period. The 2-year lag correlation is −0.589, which is far above the 95% significance level. Hereby we postulate that the strengthening of ACC transport in response to the wind stress intensification is followed by the 2 a lag weakening of ACC transport, which is probably connected with the ACC baroclinic instability and meso-scale eddies.

To testify this postulation, we calculated the Southern Ocean isopycnal slope as it can be used as a useful index for the stability of the ocean stratification against baroclinic perturbation. More tilting the isopycnal layer is, the stratification tends more baroclinic unstable. The 60°—45°S area-mean isopycnal slopes for the ACC upper ocean (25 and 268 m) were showed in Figure 3.

The isopycnal slopes showed an upward trend during 1980—1999, while before 1980, the trend was unobvious. This may be closely related to the acceleration of surface wind: due to the effect of geostrophy, the acceleration of zonal wind lead to the continuous strengthening of northward Ekman transport in the upper ocean, which, along with the anomalies of vertical velocity (ascending in the south and descending in the north), enhances the local meridional circulation. The further increase of isopycnal slope adds on more potential energy to the mean flow. As a result, the ACC is apt to generate eddies through baroclinic instability. The mesoscale eddies released by the unstable mean flow undoubtedly contribute to the momentum balance of ACC. In fact, baroclinic instability gives rise to the energy transfer from the large-scale to the meso-scale in ACC. This is a pathway for dissipating the wind energy input to ocean. Thus, eddy activity plays two major roles simultaneously, i.e., carrying the heat flux poleward (balancing the air-sea heat flux) and carrying the eastward momentum flux downward (balancing the surface

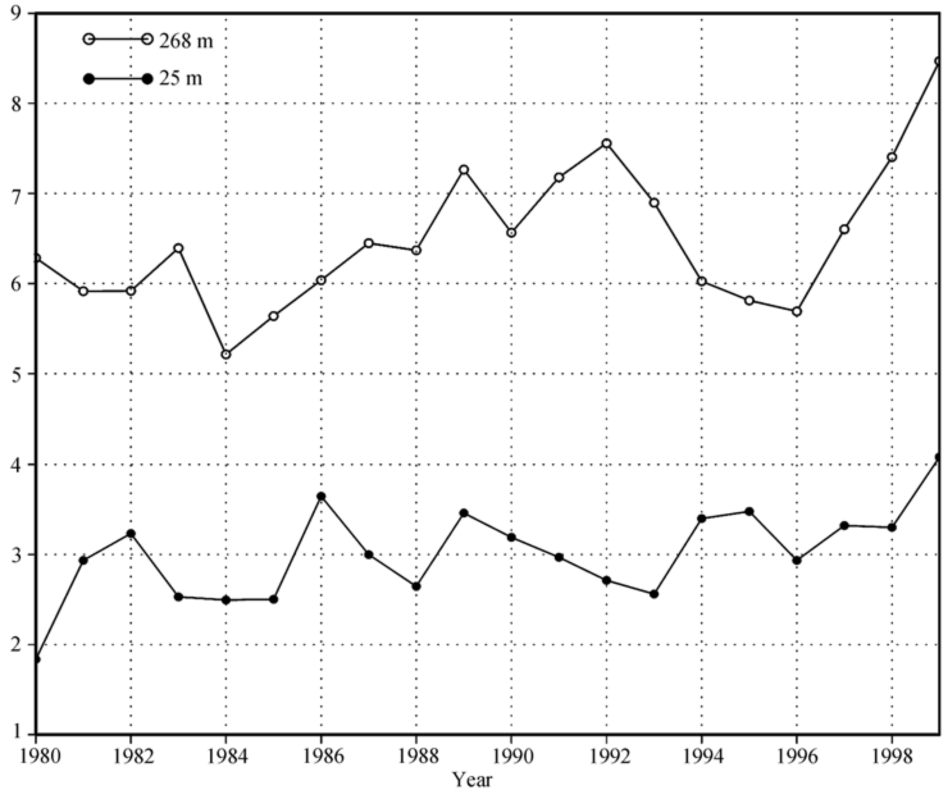

Figure 3 Time series of the 60°—45°S area-mean isopycnal slope. The line with open circle denotes the 268 m level slopes, while the solid circles for the 25 m level slopes. Both time series exhibited an upward trend, i.e., the isopycnal slopes increased.

wind momentum input). In this sense, the eddy-induced downward propagation of momentum may be regarded as the key factor to the momentum balance of ACC[23]. We further explored the effect of mesoscale eddies in the momentum balance of ACC, by analyzing the EP flux and baroclinic conversion rate.

As the EP flux (figure omitted) indicated that the perturbation energy associated with eddies is consistently downward, extending to the upper 2 km ocean (above the bottom topography). The vertical component of EP flux (i.e., the ratio of the eddy density flux to the stratification) may be used to denote the form stress effect in the ACC region, that is, the surface momentum is transferred by the eddies (through the form stress effect) downward to the deep ocean, where it can be balanced by the topographic form stress.

From the above analysis, the decadal strengthening of the zonal windstress corresponds to stronger tilting of isopycnal slope and the mean flow is baroclinically more unstable. To further explore the connection between baroclinic instability and zonal windstress, we calculated the baroclinic conversion rate (formula in the Appendix), and plotted the map of 60°—45°S averaged baroclinic conversion rate for the zonal windstress high index with time lag(above one standard deviation) (Figure 4).

Although the time-mean baroclinic conversion rate is positive, as predicted by the theory, the baroclinic conversion rate appeared as negative anomalies at zero time lag; thus the energy conversion from the mean flow to eddies decreased. As a result, potential energy of the mean flow increased, and the baroclinic transport of ACC enhanced, as regulated by the thermal wind relation. The negative anomaly propagated downward to deeper levels (about 1 km) at the half-year lag, which may partly account for the positive correlation between the ACC transport and zonal windstress. More importantly, along with the downward propagation of negative anomaly, the positive anomaly of conversion rate appeared at the ocean surface. This positive anomaly also propagated downward to 1 km depth with one-and-a half-year or two-year lag, and then weakened afterwards. Since the positive anomaly of conversion rate denoted the intensification of ACC mean potential energy to eddy energy, the windstress acceleration may induce the positive anomaly of baroclinic conversion, facilitating

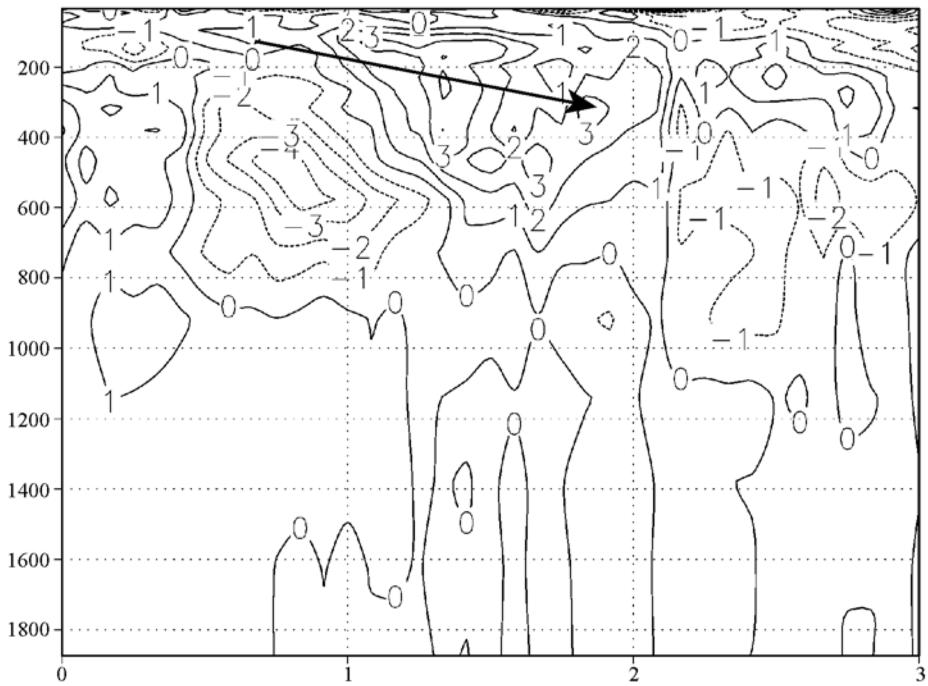

Figure 4 Composite map of the 60°—45°S averaged baroclinic conversion rate (unit: $m^2 \cdot s^{-3}$). The horizontal axis denotes the lagging year of conversion rate to wind stress; vertical axis is the depth (unit: m); black vector illustrates the positive anomaly centers of baroclinic conversion rate in different time lag stage. The positive anomaly (corresponding to the conversion of mean flow potential energy to eddy energy) appears firstly in the half-year lag period in the upper ocean (above 200 m). This anomaly propagated downward and arrived at the 1 km level with the 2-year lag; and it diminished hereafter.

the energy conversion from mean flow to eddy, hereby dissipating the mean flow energy and restraining the ACC transport.

4 Conclusions and discussion

Many previous model simulation studies suggested a consistent upward trend of surface windstress and the ACC transport in the decadal time scale. However, these models are of low resolution, so these models cannot account the response of mesoscale eddies to the wind stress accurately. As a result, the role of eddies in the momentum balance of ACC was underestimated. Recent *in-situ* data analysis (ISOS and WOCE data) did not support the significant decadal trend of the ACC transport, which inspires our study. According to our analysis, the significant interannual correlation exists between the ACC transport and surface wind. The ACC accelerates instantly in response to the increase of wind stress. However, the transport of ACC declines after 2 a. This lagging negative correlation is closely connected to the baroclinic instability of ACC. Strong zonal wind stress drives more northward Ekman transport, which leads to the acceleration of the local wind-driven meridional circulation and more sloping isopycnal surfaces. The resulting baroclinic instability activated the mesoscale eddies, and transformed the mean potential energy to eddy energy, leading to the 2-a lag deceleration of the ACC transport. It was this baroclinic dissipation effect of mesoscale eddies that kept the ACC transport from the impact of surface wind stress, and maintained its steadiness during the recent two decades.

It is worth noting that both wind stress and the ACC transport have 4—5 period oscillation in the interannual time scale, which is quite compatible with the interannual variability of tropical air-sea interaction phenomena like ENSO. Zhou and Yu[25] pointed out that the Southern Annular Mode (SAM) was influenced by the El Nino, and this effect had rather high predictability. In this sense, there may be certain connection between the high-latitude air-sea interaction and tropical air-sea interaction. Further study of the interannual variability of ACC needs to include the effect of both mid-latitude atmosphere and tropical oceans.

As the SODA data is a monthly data and its spatial resolution is only 0.5°×0.5°, the eddy flux and baroclinic conversion rate calculated in this study may be attributed mainly to the topographic-oriented stationary eddies. In contrast, the large portion contribution from the transient eddies was not included. Previous study showed that the small scale stationary eddies (the curve and distortion in the sharp topographic region of the ACC axis) could be regarded as the mesoscale eddies; eddies became dominate when the windstress enhanced, and the baroclinic instability always emerged in the rough topographic regions through the effect of stationary waves. Therefore, the connection of ACC transport and windstress relied on the response of the stationary eddies[21]. A model study of Wang and Ikeda[26] demonstrated the influence of the bottom topography on the growth rate of the baroclinic instability waves. Thus the mesoscale eddy activity and its effect on the mean flow should depend on topography. In addition, we used Estimating the Circulation and Climate of the Ocean (ECCO-JPL) dataset with resolutions of 10-day temporally and 1°×1° spatially to calculate the baroclinic conversion rate. The analysis results are basically consistent with this study. Due to the relatively high temporal resolution of ECCO data, the transient eddy activity obtained is more accurately. This justifies our results to some extent. On the other hand, both the stationary eddies and transient eddies should respond to the windstress variability in the case of strong wind, and both act as the brake to the zonal mean flow to balance the wind energy input. Therefore, in order to understand the momentum balance and the variability of the large-scale circulation in the Southern Ocean, higher (eddy-resolving) resolution data are needed.

Appendix

Since the ACC is zonally unbounded, its dynamics bears much similarity with that of the atmosphere. In this study, EP flux and oceanic wave-mean flow interaction methods were used to explore the momentum balance of ACC.

Eliassen-Palm theory was first put forward by Eliassen and Palm[28]. According to this theory, the effect of the wave perturbation to the zonal mean flow can be diagnosed from the vector F (EP flux) in the meridional section. The EP flux satisfies the quasi-geostrophic approximations in the β plane and its two components denote the poleward eddy heat flux and eddy momentum flux respectively. In the Southern Ocean, the fresh water flux due to the sea ice melting may also affect the ocean density stratification. Thus we generalized the EP flux in the form of $F = -\overline{u'v'}\hat{y} + \frac{f}{\rho_z}\overline{v'\rho'}\hat{z}$; the first term on the right hand side is eddy momentum flux, denoting the horizontal propagation of perturbations, while the second term is the ratio of eddy density flux and mean stratification, denoting the vertical propagation of perturbations.

EP flux has been used to diagnose the wave-mean flow interaction. According to the EP theory and energy conservation theory, perturbation energy equation can be written as $\partial_t \iiint (K' + A') = -\partial_t \iiint (K_m + A_m) = -\iiint U\nabla \cdot F$.

Obviously, the divergence of EP flux represents the energy conversion between eddies and the mean flow. Furthermore, as EP flux vanishes at the boundary, the energy conversion can be written as:

$$\begin{aligned}\partial_t \iiint (K' + A') &= -\iiint U(y,z,t)\nabla \cdot F = -\iint \mathrm{d}y\mathrm{d}z U\nabla \cdot F \\ &= -\iint \mathrm{d}y\mathrm{d}z U\partial_y F_y - \iint \mathrm{d}y\mathrm{d}z U\partial_z F_z \\ &= -\iint \mathrm{d}y\mathrm{d}z F_y\partial_y U - \iint \mathrm{d}y\mathrm{d}z F_z\partial_z U.\end{aligned}$$

The first term on the right-hand side of equation is the barotropic conversion term. This term involves the horizontal shear of the mean flow and horizontal component of EP flux, and it indicates the conversion between the mean kinetic energy and eddy kinetic energy. The second term is the baroclinic conversion term. This term depends on the vertical shear (horizontal density gradient) of the mean flow and the vertical component of the EP flux, and it indicates the conversion between the mean-flow potential energy and eddy potential energy.

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