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# A study on the Antarctic circumpolar wave mode-A coexistence system of standing and traveling wave

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**Abstract** The Antarctic circumpolar wave (ACW) has become a focus of the air-sea coupled Southern Ocean study since 1996, when it was discovered as an air-sea coupled interannual signal propagating eastward in the region of the Antarctic Circumpolar Current (ACC). In order to analyze the mechanism of discontinuity along the latitudinal propagation, a new idea that ACW is a system with a traveling wave in the Southern Pacific and Atlantic Ocean and with a concurrent standing wave in the southern Indian Ocean is proposed in this paper. Based on the ideal wave principle, the average wave parameters of ACW is achieved using a non-linear approximation method, by which we find that the standing part and the traveling part possess similar radius frequency, proving their belonging to an integral system. We also give the latitudinal distribution of wave speed with which we could tell the reason for steady propagation during the same period. The spatial distribution of the propagation reveals complex process with variant spatial and temporal scales—The ENSO scale oscillation greatly impacts on the traveling process, while the result at the south of Australia indicates little connection between the Indian Ocean and the Pacific, which may be blocked by the vibration at the west of the Pacific. The advective effect of ACC on the propagation process should be examined clearly through dynamical method.

**Key words** The Antarctic circumpolar wave, Sea level pressure, Wave propagation system, Traveling wave, Standing wave, Oscillation.

## 1 Introduction

The Southern Ocean is described as the oceanic domain south of the Subtropical Convergence Zone (SCZ) with an area of 25% of the global ocean (Fig. 1). The Antarctic Circumpolar Current (ACC) is the unifying link for exchanges of water masses at all depths between the world's major basins, and these exchanges play an important part in transmitting climate anomalies and heat fluxes around the globe. The interannual variability, reflected both in oceanic and atmospheric parameters, reveals the impact and feedbacks between global climate anomalies and the Southern Ocean meteorological system (Warren *et al.* 1996, 1999, 2000). During recent years, the most important interannual variability in the Southern Ocean is the Antarctic Circumpolar Wave (ACW).

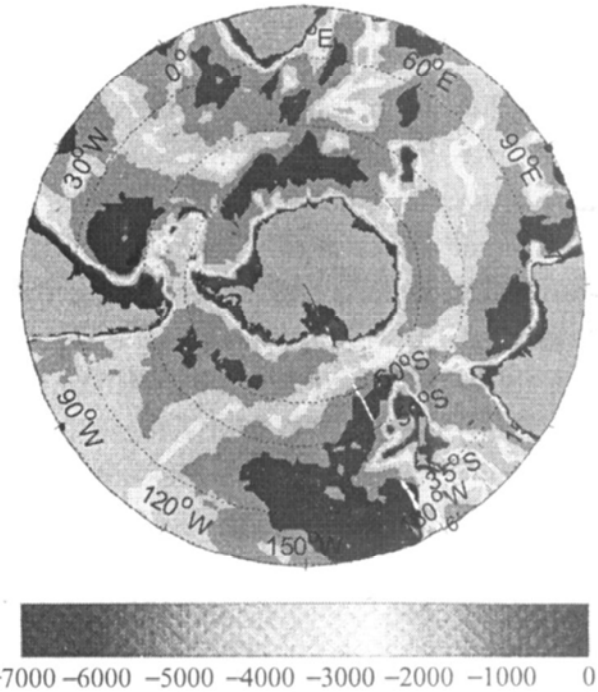

Fig 1 The Elevation Planform of the Antarctic and the Southern Ocean from the Polar Angle (Unit m).

The concept of the ACW was firstly proposed by Warren B. White (Warren *et al.* 1996), who analyzed the sea level pressure (SLP, 1985-1994), meridional wind stress (MWS, 1985-1994), sea surface temperature (SST) derived from spatial satellite altimetry (1982-1994) as well as the northward sea ice extent (SIE) from air-borne remote sensor (1979-1991). The result showed a wave of clear eastward propagation with a wave period of about 4-5 years, and spent 8-10 years to encircle the globe. Almost the same time, Jacobs found clear propagation of the interannual sea surface height anomaly (SSHA) through the analysis of Geosat-ERM and TOPEX/Poseidon altimetry data (Jacobs and Mitchell 1996). These resulted characteristics indicate the existence of an air-sea coupled wave in the Southern Ocean, which was defined as the Antarctic Circumpolar Wave (ACW) (Warren *et al.* 1996).

After its discovery in 1996, ACW has become a focus of the Southern Ocean research, for both oceanographers and meteorologists. They analyzed the satellite altimetry data (Park 2001), ECMWF data (Bonekamp *et al.* 1999), NCEP (National Centre for Environmental Prediction) data (Connolley 2003). They also used the air-sea coupled models to study the mechanism (Christoph *et al.* 1998; Cai *et al.* 1999). Much progress was made by the analysis. Venegas proved that ACW is closely related to ENSO signal (Venegas 2003; Peterson and White 1998), while the signal from modeling result showed similar phenomenon as ACW (Park 2001; Bonekamp *et al.* 1999; Weisse *et al.* 1999). Undoubtedly, the characteristic of air-sea interaction is the process in which people are interested.

In the past research, the standing and traveling parts are also a focus that people concerned. After its discovery, more research work has been done to analyze interannual variability in the Southern Ocean using longer-term datasets. The result showed that there was clear propagation during 1985-1994, when ACW appeared to be with a global wave number of 2, while no clear propagation existed beyond that period and with a global wave number of 3 (Park 2001; Christoph *et al.* 1998). From these results, ACW could be described as a phenomenon with the two alternate wave modes (Chritoph *et al* 1998; Vengas 2003; Cai and Baines 2001).

However, the explanation for the standing and traveling parts of ACW hasn't been clear yet. The ECMWF data was recognized to be trustworthy merely after 1979 (Cheinet *et al* 2005); NCEP data wasn't in good quality before 1980s. The sparsity of data restrained the breakthrough. Also, the former works mostly concerned on ACW's propagation characteristics, but its spatial distribution is less emphasized, and that the propagation signal is not clear in the Indian Ocean is not well reasoned. The Empirical Orthogonal Function (EOF) analysis is helpful to study the character like oscillations, but no advantage in studying the traveling waves (Cai and Baines 2001). Besides, former research mainly tried to get a general idea of the wave by 'looking at' the time-latitudinal figure, and didn't give accurate wave parameters for ACW. Result from different models turned out to be quite different conclusions, from which we could not know the sustenance factors for ACW (Bonekamp *et al* 1999; Christoph *et al* 1998; Cai *et al* 1999). Does it rely on driving force from atmosphere to the ocean (Bonekamp *et al* 1999; Weisse *et al* 1999); or is it an air-sea interaction indeed (Venegas *et al* 2003; White and Chen 2001; Baines and Cai 2000; Zhou and Zhao 2004)?

One definite thing is that ACW appeared to be occupied by standing wave somewhere and sometimes, but was occupied by traveling mode otherwise. We insist that the standing wave mode was controlled by its spatial sea-land distribution in the Southern Ocean which induced the interannual oscillation in pressure system. Even though they could be explained as 'Standing Wave', they are in fact not part of ACW. The exactly ACW should be a traveling wave so we mainly focus on the spatial character of it during 1985-1994. The aim of our paper is to study its spatial character during the propagation, to deeply understand the propagation identity in different areas of the Southern Ocean, to unravel why ACW wasn't a wave encircling the globe continuously. . On the bases, we propose and prove a new idea that ACW was a phenomenon with traveling and standing waves concurrently.

The data we used is the ECMWF SLP data from January 1st, 1958 to December 1st, 2001 with the resolution of 1.875° × 1.875°. The data we mainly used is the data during 1985-1992.

### *1.1 The general wave mode of ACW*

To represent the feature of ACW, we now use the 3-7 years Butterworth band-pass filter to exempt the high-frequency and long term variability in order that the result could clearly reflect the interannual variability. The Butterworth filter is a widely used filter, whose advantages are with relatively flat band-pass and band-block frequency responding function. For a higher order N, the character of the frequency are approaching square. We tried many times and finally used the 5 order filter.

We also analyze the 56°S latitudinal circle (Fig. 2) in order to make comparison with White's result. The result shows that the signal blocking the high-frequency disturbance matches well with White's conclusion but is smoother in details, well representing the character of low-frequency variation. To express conveniently, we use 0-360°E to represent both eastern and western longitude. The SLP anomalies varies up to 5-7pa, and the regular sloped line in this figure shows clear traveling wave propagation of ACW during that period. Relying on this character, White proposed the conclusion that ACW is a wave with wave period of 4-5 years, wave speed of 6~ 8 cm/s, and the global wave number of 2.

Fig 2 indicates that ACW is not a traveling wave encircling the globe, but mainly propagates prominently along 120°-300°E, which is the region of the South Pacific and Southwest Pacific Ocean; While in the Southern Indian Ocean, the traveling wave seems clearly blocked or as least weakened, showing similar characteristic like a standing wave. We could not find close connection between the Southern Indian Ocean and western Pacific near the longitude of 120°E, or in other words, a wave 'discontinuity'.

This wave with such a low frequency can be neither a free wave, nor an air-forced wave, and can only be an air-sea coupled wave. The formation and growing process of the coupled wave are determined by the air-sea interaction itself, and the wave parameters can be quite irregular, with no disciplinary restriction. However, the clear slope line across the longitude in Fig 2 indicates clear wave period and wave number, and is indeed quite particular. Former researchers are not determined why this wave was steady within so many years. Also, no convincing conclusion is drawn to explain the latitudinal discontinuity.

Based on the character of ACW in Fig 2, we now propose a new idea that ACW is never a traveling wave encircling the globe, but a coexistence system of standing and traveling wave with the same wave periods. When standing wave occurs in the southern Pacific and southwest Atlantic, traveling wave with the same wave period takes place in the southwest Pacific and the southern Indian Ocean. The differences between our idea and former researches lies on the following two points: the former researches emphasizing the traveling wave concludes that ACW is a traveling wave encircling the globe, but our idea insists that traveling wave only exists in part of the globe; researches focusing on the standing wave suggest that standing wave has a global wave number of 3 and is different from that of the traveling wave, but we proposed the idea that the standing wave during the prominent propagation possesses the same wave period as the traveling part, which is different from that of other period. The concurrent traveling and standing wave composes the basic characteristic of ACW, indicating special energy transportation process. In our paper, we retrieve the general parameter from wave mode to verify the existence of this system.

### *1.2 Using non-linear approximation to calculate wave number, wave speed and period of ACW*

In fact, the wave spatial distributions are only meaningful to those with relatively stable wave parameter. Fig 2 shows that the traveling wave is strong in the range of 120°-350°, while in the area of 30°-80°, the standing wave becomes dominant. In this part, we use the data of these two areas to determine the parameters of the traveling and standing waves, and to understand their stability.

Wave speed is one of the main parameters of the traveling part of ACW. However, due to the facts that the traveling part of ACW exists less than 10 years, and the observational data is scarce, the variation of wave speed has rarely been analyzed thoroughly. In the case of free wave, the variation of wave speed is related to the water depth and could vary from place to place, while in the case of air-sea coupled wave, the wave speed exhibits the whole moving speed as an integrity and is independent of water depth. Considering the traveling wave only, we draw data of 80° with each centered in 30° in the range of 120°-350°E to approximate its mean wave speed, and to show the speed distribution pattern which varies with longitude.

Although the mechanism of air-sea coupled wave is completely different with other waves, their conformations are the same and can be expressed as ordinary traveling and standing wave forms:

Traveling wave: $y_1 = A_1 \cos(k_1 x - \sigma_1 t + \Phi_1)$

Standing wave: $y_2 = A_2 \cos(k_2 x + \Phi_2) \cos(\sigma_2 t + \Phi_3)$ (1)

We hereby use the non-linear least square approximation, and the non-linear equation group supposing function y and independent variable x can be expressed as $\hat{y}_i = f(x_i, \alpha_1, \alpha_2, \cdots, \alpha_j, \cdots, \alpha_m)$, $i \in 1, 2, \cdots, n$

$\alpha_1, \alpha_2, \cdots, \alpha_j, \cdots, \alpha_m$ are the parameters needed to be approximated, $\hat{y}_i$ is the estimation of $y_i$. Non-linear least square approximation uses universal global optimization - UGO to do iteration until it becomes convergent and the error $\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$ reaches its minimum. Table1 shows the distribution of wave speed and wave number of the traveling part of ACW with longitude through the non-linear least square approximation.

Table 1 The Average Wave Number and Wave Speed Distribution of ACW (120°-350°E)

| Longitude range(°E) | 120-200 | 150-230 | 180-260 | 210-290 | 240-320 | 270-350 |
|---|---|---|---|---|---|---|
| Global wave number | 0.19 | 0.23 | 0.21 | 0.19 | 0.19 | 0.16 |
| Average speed(lon/a) | 52 | 40 | 43 | 51 | 49 | 53 |
| Average speed(cm/s) | 10.4 | 7.9 | 8.6 | 10.1 | 9.7 | 10.7 |

From table 1, the wave speed of ACW changes with longitude and within the range of 7.9 cm/s~ 10.7 cm/s, a little larger than White's estimation (6~ 8 cm/s). The corresponding wave number also varies with longitude. These changes demonstrate that the variation ranges for wave speed and wave number are small and can be recognized as stable. We obtain the average wave number 0.03 rad/longitude, average wave speed 51 longitude/year and average radian frequency 1.55 rad/year. The approximation of these parameters leads to the solution for traveling wave:

$$y = 196\sin(0.03x - 1.55t + 2.10462) \quad (2)$$

Through the same way, we do non-linear approximation for the standing wave in the area of 30°– 80°E, and find the solution:

$$y = 168.65\cos(0.03879x + 0.5928)\cos(1.4684t - 1.0488 + \pi) \quad (3)$$

The wave number is 0.038 radian/longitude, showing almost 2 waves around the globe.

From the above approximation, the radian frequency for traveling wave is 1.55 rad/year and 1.4684 rad/year for the standing wave. They are quite close. Considering the error involved in approximation, we believe that the traveling and standing wave have completely the same radian frequency, substantiating their coexistence system presented in this paper.

## 2 The propagation features of ACW at 56°S

According to previous researches and comparisons of propagation features at all other latitudes, ACW has the strongest propagation signal at 56°S, showing the main characteristics of ACW. First, we use parameters at 56oS to define the main feature of ACW.

The same radian frequency of the coexistence system for the traveling and standing waves implies that both the traveling and standing waves occur concurrently and harmoniously. According to Fig2, the movement of the system is as follows.

The signal firstly happens in the western part of the South Pacific, and then gradually propagates to the east. The signal covers the whole Pacific and enters South Atlantic, retaining traveling wave features in the western part of South Atlantic with reduced strength compared to that in the South Pacific. In the western part of Southern Indian Ocean, traveling wave signal is no longer apparent, instead, standing wave signal is clear and strong within 10 years and its period is the same with that of the traveling wave in the South Pacific.

Traveling wave signal is clear and apparent in the South Pacific and it needs about 4 years to travel across Pacific with its almost constant propagation speed.

Standing wave signal in Indian Ocean implies that there exists a stable oscillation center and the strength of this center increases and decreases periodically. Oscillation center shows that the atmospheric system in South Indian does not propagate westward or eastward but only change its strength.

Previous researches (Warren *et al.* 1996; Jacobs and Mitchell 1996) believe that the disappearance of traveling wave in the East Atlantic and Indian is caused by wave divergence induced by topography. However, ACW is not a free wave but an air-sea coupled wave and topography can not cause wave divergence. Therefore, this belief may be inappropriate in interpreting mechanisms. Some geostrophic modeling results suggested that ACW may be caused by the one-way driving system from atmosphere to ocean and ACC' s response to the atmospheric anomalies play a critical role in the formation process of ACW (Christoph *et al.* 1998; Weisse *et al.* 1999). However, the meridional form of the traveling and standing wave coexistence system is still not clear and needs further research.

## 3 Analyzing spatial propagation process of ACW

Fig 2 shows the propagation features of ACW along 56°S latitude. Although this latitude is representative, it can not present the spatial distribution of ACW. To study the propagation features of ACW, we use continuous SLP spatial fields to analyze the propagation process of ACW in detail.

The SLP field obtained from raw data is seriously affected by high frequency processes, therefore, SLP at every latitude in the range of 0– 75°S is filtered for 3-7 years, and then gain the spatial distribution at every time. Limited to the space of the paper, the SLP spatial distributions within a period of every six month from Jan, 1985 are presented (Fig 3) and followed by the analysis of ACW' s propagation features.

Fig 3 shows most representatively the complex movements in the South Pacific. In the South Pacific, there exists SLP variation at half global scale in the time scale of 3-7 years. By detailed analysis of these figures, we can see that SLP variations are not processes with single time scale, but are combined with complicated time and spatial scale movements.

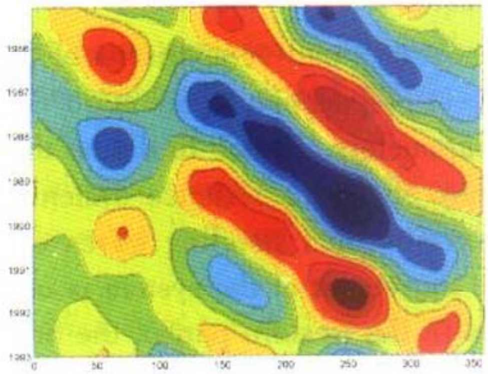


Fig 2 The General Wave Mode of ACW reflected in SLP at 56°S latitudinal Circle (1985– 1992).

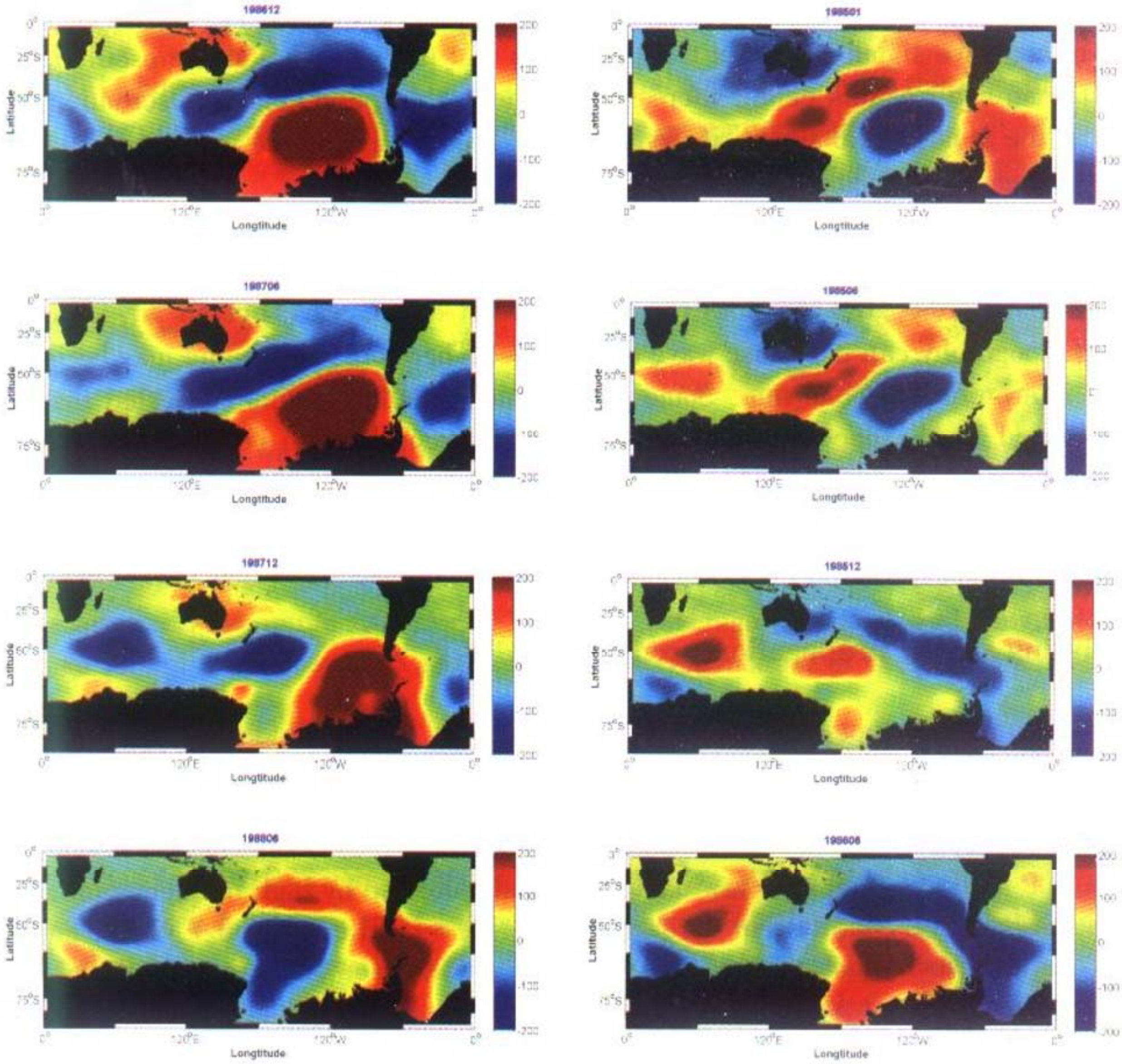


Fig 3 The Spatial Distribution of ACW Reflected in SLP within a Wave Period (Unit pa) (1985– 1992).

For instance in the equator area there exists oscillation in ENSO scale during most of the times the Pacific meridional oscillation is apparent these movements in varied scales interact with each other The processes in mid and low latitudes affect the processes in the southern ocean to a great extent and SLP variations in the Pacific are far more complex than those of the Atlantic and Indian However no matter how complicated the processes in Pacific are one feature is clear that disturbing signal from the Pacific firstly reaches the western part of the South Pacific (Western Pacific for short) and then propagate eastward Therefore the SLP disturbing source in the Western Pacific is a clear spatial and temporal variation feature

In the Pacific and Atlantic ACW covers large space area stretching from 56°S to Antarctic continents and even the inland Ross Sea is involved in ACW is SLP's large scale movement and its coverage is equivalent to the east-west scale of the Pacific When the center of the system lies in the central area of the Pacific a reversed response is presented between the mid latitudes of the Pacific and the Southern Ocean when the center of the system lies at the two sides of the Pacific the mid and high latitudes of the Pacific present a main reverse action in the latitudinal orientation The system continues to propagate after its entry into the Atlantic by crossing the Drake Passage but its strength and coverage are both reduced greatly

Another most distinct feature in Fig 3 is the demonstration of Indian Oscillation Although the oscillation at 56°S latitude is definite we can not rule out the possibility of meridional movement of SLP system. Series figures in Fig 3 show that in Indian Ocean SLP system does not exhibit apparent meridional or latitudinal movement but present the periodical variation of strength fully substantiating the fact that ACW features a standing wave in Indian Ocean

Since the current axis of ACW has large meridional variations people have all long paid special attention to ACW pathway or main propagation axis From Fig 3 ACW seems to have no pathway or main propagation axis but spread all over the whole Southern Ocean That is why the features presented by 56°S latitude almost represent the basic characteristics of ACW.

## 4 Discussing the movement form of ACW as a coexistent system

Fig3 shows the movements of ACW as integrity including the Western Pacific disturbing traveling waves in the Pacific and Atlantic and the standing wave in the Indian Ocean Therefore it is appropriate to use the coexistence system of traveling and standing wave to present ACW. The main character of the coexistence system is the same period for the traveling and standing waves and this propagation process should conform to this feature Besides the interpretation of the system movements needs to satisfy atmospheric dynamics since the system is one of sea surface air pressure

We can interpret the propagation of ACW as a string with one end fixed to a vibration source and the other open and free When a wave is propagating along the string and reaching the open end the features at the open end would be regarded as oscillation with no propagation The oscillation on the string is similar to the ACW, the oscillation end is the

Western Pacific; propagation section is the Pacific and Atlantic; and the open end is the Indian Ocean.

The Western Pacific is the driving end of ACW and it is formed by the processes in the Pacific; and it plays a significant role in the propagation of ACW. From SLP data, south of Australia does not exhibit apparent propagation, showing little influence exerted on the Western Pacific by the Indian Ocean and its impossibility of disturbing the driving process of the Western Pacific. Therefore, the Indian Ocean becomes the terminal of ACW and also be the open end controlled by traveling waves. Although the vibration and open ends present a circle formation, in fact, they are in the very similar condition as they are separated.

This kind of figuration enables the traveling and standing wave to have the same period, just like the same period of the vibration end, the propagating wave and the open end on the string. There exists phase discrepancy between the vibration and open end. The phase discrepancy between the Indian Ocean and the Western Pacific is about a quarter of the period with the Western Pacific preceding.

The only problem in interpreting the series of figures is why the disturbance in Western Pacific does not propagate westward and enter the Indian Ocean, but only propagate eastward. This is an initial problem in exploring the ACW. In my mind, it may be related to ACC. SLP is an air-sea coupled system. When a signal is formed through air-sea interaction, ACC carries this signal eastward, which surely drives the whole air-sea coupled system transport eastward, forming the propagation formation.

However, why does the signal in Indian Ocean can not advect to the Pacific? The signal formed in Indian Ocean does also advect to the Pacific, but the Western Pacific is the SLP's disturbing end which inhibits the SLP signal in Indian Ocean to propagate further to the Pacific, making the formation of eastward propagation depending on ACC impossible and keeping this air-sea coupled signal in Indian Ocean. It shows the air pressure variation at 56°S latitude south of Australia. In the figure, the air pressure exhibits no propagation feature near the west of Indian Ocean (about 105°E). This result demonstrates that the processes in the Indian Ocean exert little influence on the Western Pacific through south of Australia.

## 5 Results and Discussions

In this paper, In order to explain the latitudinal discontinuity of the Antarctic Circumpolar Wave (ACW), we proposed a new idea that ACW is a wave with concurrent standing wave in the southern Pacific and Atlantic Ocean, and with concurrent standing part in the Indian Ocean. These two parts both belong to the propagation system of ACW. Also, based on the analysis of ECMWF SLP anomaly data from the year 1985-1992, we retrieve the main wave parameters of the standing and traveling wave, which verifies the existence and the spatial characteristic of this system. We also discussed the mechanism of the propagation process. These results are:

(1) The prominent propagation of ACW occurs during the year 1985-1992, and the wave mode is almost invariant. However, current research could not explain why the wave parameter is steady. To answer this question, we now use the non-linear approximation

method (with least error quantity) to gain the average wave number and wave speed during this period. The results show that the average wave number is 0.03 radians/latitude; the average wave speed is 51 latitude/year; and the frequency is 1.55 radians/year. Using the non-linear approximation method, we found that the wave speed of ACW varies from latitude to latitude. Also, we calculated the average speed, wave number and frequency and wave number of standing wave.

(2) The coexistence system is composed of three part. The SLP oscillation occurring in the western Pacific which is correlated with mid-low latitude process; Traveling wave propagate clearly in the Pacific; weakens in the Atlantic; In the Indian Ocean, the traveling wave turns out to be a standing wave. The three parts are with the same wave period, indicating the coexistence of the dynamical system and verifying that this system could be used to describe the spatial and temporal feature well. We describe ACW as a wave in a string with an open end, whose propelling vibration, propagation, standing part and the mechanism are all similar with ACW and could represent ACW appropriately.

(3) By analyzing the interannual variability at south of Australia, we verify that there is no clear propagation in this region, thus no signal from Indian standing wave to the Pacific; and the Indian Ocean and Pacific are blocked to some extent. The paper conclude that ACW be correlated with ACC. SLP is an air-sea coupled system. When there occurs a signal in the ocean surface through air-sea interaction process, ACC advects the signal, leading the entire coupled system eastwards, forming the propagation condition. In the Indian Ocean, because the SLP signal is blocked by the disturbance of vibration originality in the west Pacific, the air-sea coupled system signal stays in the Indian Ocean, even though there is advective effect from ACC.

The result from this paper indicates that the coexistence system well represents the feature of ACW, which is a new explanation of the ACW structure. However, this paper couldn't unravel what impulses the vibration in the western Pacific Ocean as well as why ACW merely propagate clearly between 1985~1994. All these questions are required to be answered through deep dynamical study.

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