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Excitation of Annual Polar Motion by the Pacific, Atlantic and Indian Oceans *

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Abstract The global oceans play important roles in exciting the annual polar motion besides the atmosphere. However, it is still unclear about how large the regional oceans contribute to the annual polar motion. We investigate systemically the contributions of the Pacific, Atlantic and Indian Oceans to the excitation of the annual polar motion, based on the output data of ocean current velocity field and ocean bottom pressure field from "Estimating the Circulation and Climate of the Ocean (ECCO)" ocean circulation model over the period 1993–2005. The result shows that due to its particular location and shape, the Atlantic Ocean makes a less significant contribution to the x-component of the annual polar motion excitation than the Pacific and Indian Oceans, while all these three oceans contribute to the y-component of the annual polar motion excitation to some extent.

Key words: annual polar motion — excitation — oceanic angular momentum function (OAMF) — atmospheric angular momentum function (AAMF)

1 INTRODUCTION

Recent simulation results of oceanic general circulation models suggested that the global oceans play important roles in exciting the annual polar motion in addition to the atmosphere (Ponte et al. 1998, 2001; Zhou et al. 2001, 2005; Gross et al. 2003; Chen et al. 2004; Zhong et al. 2006). However, it is still unclear about how much the regional oceans contribute to the annual polar motion. In parallel many studies of the oceanic effect focused on the global scale. Furuya et al. (1998) detected a significant effect of the Pacific Ocean on the Earth's seasonal wobble on the basis of the National Center for Environmental Prediction (NCEP) ocean analysis data. Zhou et al. (2004) singled out a large-scale ocean anomaly, determined from satellite observations of the Western Pacific Warm Pool (WPWP). Through analyzing the non-atmospheric Earth rotation excitation contributed by the WPWP during the period 1970–2000, they found non-negligible effects of the WPWP on the annual polar motion. The aim of the presented paper is to investigate systemically the contributions of the Pacific, Atlantic and Indian Oceans to the annual polar motion excitation. In Section 2, we compute the contributions of the Pacific, Atlantic and Indian Oceans to the polar motion excitation, based on the output data of ocean current velocity field and ocean bottom pressure field from "Estimating the Circulation and Climate of the Ocean (ECCO)" ocean circulation model during 1993–2005 (Marshall et al. 1997a,b; Chen et al. 2004). The ECCO ocean circulation model data have a higher precision, better temporal and spacial resolutions than the NCEP ocean analysis data employed by Furuya et al. (1998). The "observed" polar motion excitation function is calculated based on the Jet Propulsion Laboratory (JPL)

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Space2005 time series (Gross et al. 2004). In Section 3, we investigate the excitation of annual polar motion by the Pacific, Atlantic and Indian Oceans. The main results are summarized in Section 4.

2 OCEANIC AND ATMOSPHERIC, AND "OBSERVED" POLAR MOTION EXCITATION

2.1 "Observed" Polar Motion Excitation

In the terrestrial coordinate system, the polar motion is usually expressed as a complex function $\boldsymbol{p} = p_1 - ip_2$, where p_1 (along the Greenwich Meridian) and p_2 (along longitude 90° W) are the x and y coordinates of the Celestial Ephemeris Pole (CEP). Under the conservation of the Earth's total angular momentum, the polar motion excitation is depicted as (Lambeck 1980; Barnes et al. 1983; Gross 1992, 2000):

$$\boldsymbol{p} + (i/\sigma_c)\dot{\boldsymbol{p}} = \boldsymbol{\chi}\,, \tag{1}$$

where $\boldsymbol{\chi}$ ($\boldsymbol{\chi} = \chi_1 + i\chi_2$) is the "observed" polar motion excitation function, $\sigma_{\mathrm{c}} = 2\pi F_{\mathrm{c}}(1 + i/2Q)$ is the complex Chandler frequency, F_{c} is about 0.843 cycles year^{-1}, and Q is the damping factor of the Chandler oscillation, with $Q = 179$ (Wilson et al. 1990). We compute the "observed" polar motion excitation function (OBS) during the period of 1993–2005, based on Equation (1) using the daily EOP time series of the JPL Space2005 data.

2.2 Oceanic and Atmospheric Polar Motion Excitation

The Oceanic angular momentum function (OAMF) consists of an axial component (χ_3) which contributes to the variation of Earth's axial rotational rate, and two equatorial components (χ_1, χ_2) which contribute to the Earth's polar motion. Each equatorial component is further composed of a matter term (χ_1^p, χ_2^p) due to the ocean bottom pressure variation, and a motion term (χ_1^{uv}, χ_2^{uv}) due to ocean currents. The equatorial OAMF can be expressed as (Eubanks 1993):

$$\begin{aligned}\chi_1 = \chi_1^p + \chi_1^{uv} = &\frac{-1.098\overline{R}^4}{(C-A)g}\iint p_{\mathrm{b}}\sin\theta\cos^2\theta\cos\lambda d\lambda d\theta \\ &- \frac{1.5913\overline{R}^3}{\Omega(C-A)g}\iiint(u\sin\theta\cos\theta\cos\lambda - v\cos\theta\sin\lambda)dp\,d\lambda\,d\theta,\end{aligned} \tag{2}$$

$$\begin{aligned}\chi_2 = \chi_2^p + \chi_2^{uv} = &\frac{-1.098\overline{R}^4}{(C-A)g}\iint p_{\mathrm{b}}\sin\theta\cos^2\theta\sin\lambda d\lambda d\theta \\ &- \frac{1.5913\overline{R}^3}{\Omega(C-A)g}\iiint(u\sin\theta\cos\theta\sin\lambda + v\cos\theta\cos\lambda)dp\,d\lambda\,d\theta,\end{aligned} \tag{3}$$

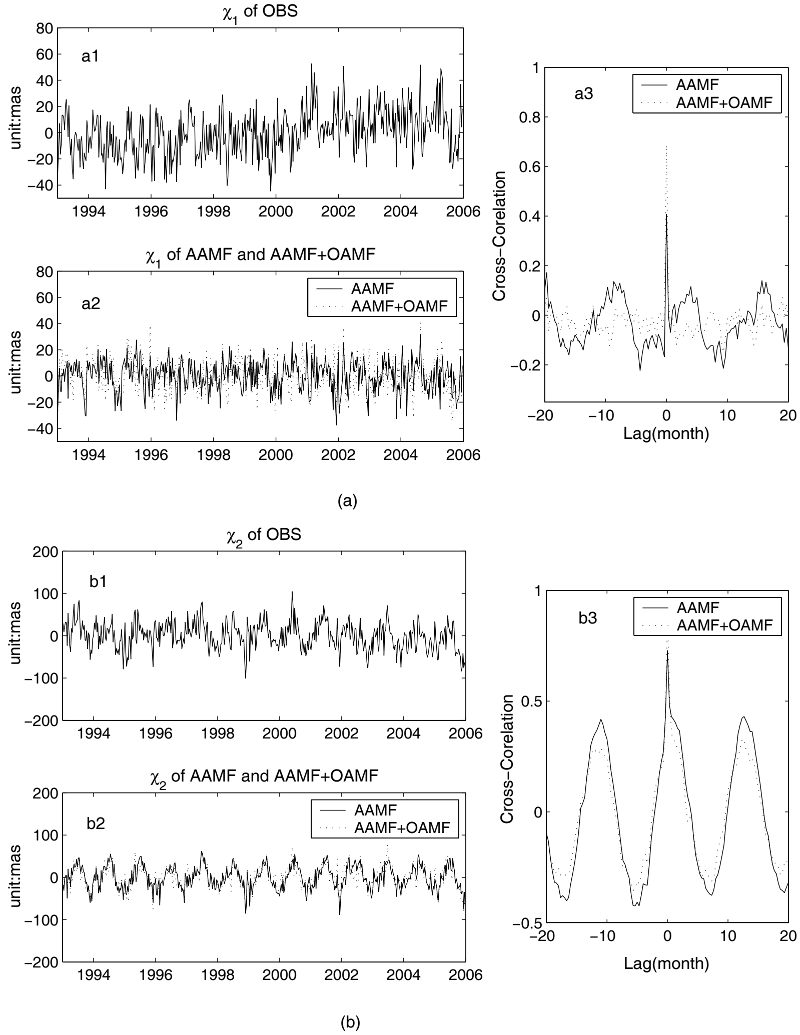
where $\overline{R}$ and Ω are the Earth's mean radius and angular velocity, A and C are the Earth's principal moments of inertia, g the gravitational acceleration, λ and θ the longitude and latitude at the given grid point, p_{b} the ocean bottom pressure, u and v are the zonal and meridional ocean current velocities, respectively (Ponte et al. 2001).

We calculate the OAMF using the ECCO data from 1993 to 2005. The ECCO ocean circulation model has 46 levels of varying thickness ranging from the surface to 5000 m down. We can obtain variables such as the ocean bottom pressure, temperature, salinity, zonal and meridional velocities of ocean current and so on for each level. The coverage is nearly global from 79.5 °S to 78.5°N with a telescoping meridional grid with a 0.3° resolution in the tropics (10°S to 10°N) that gradually broadens to a 1° resolution away from the equator. The resolution in longitude is 1°. The different variables have different temporal resolutions. The ocean bottom pressure is sampled at 12-hour intervals, while the temperature and ocean current velocity are sampled at 10-day intervals.

Similar to the OAMF, each component of the equatorial atmospheric angular momentum function (AAMF) contains the pressure terms (χ_1^p, χ_2^p) and the wind terms (χ_1^w, χ_2^w), u and v are the zonal and meridional wind velocities. For the calculation of the AAMF, we merely change p_{b} in Equations (2) and (3) to p_{s} (the surface pressure). The AAMF data during 1993–2005 are obtained from the Special Bureau for Atmosphere (SBA) of the Global Geophysical Fluids Center of the International Earth Rotation and

Reference Systems Service (IERS). They are calculated based on the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis 6-hourly wind and pressure fields (Kalnay et al. 1996). The pressure term is computed based on the inverted barometer (IB) assumption. The wind term is obtained by integration using the winds from the Earth's surface to 10 hPa, the top level of the atmospheric model (Salstein et al. 1993; Kalnay et al. 1996; Zhou et al. 2006).

We compare the AAMF and OAMF+AAMF with the "observed" polar motion excitation time series during 1993–2005. Figure 1 shows the χ_1 (a) and χ_2 (b) components of the polar motion excitation time series. The curves in a1 and b1 represent the time series of OBS, the curves in a2 and b2, those of AAMF (solid curves) and AAMF+OAMF (dotted curves), a3 and b3 display the cross-correlation functions of OBS with AAMF (solid curves) and OBS with AAMF+OAMF (dotted curves), respectively. It can be seen that the correlation between OBS and AAMF+OAMF is higher than that between OBS and AAMF. The result indicates that the oceans make important contributions to the polar motion excitation during the period of 1993–2005.



(a)

(b)

Fig. 1 OBS, AAMF and AAMF+OAMF polar motion excitation time series and the cross-correlation functions of OBS with AAMF and OBS with AAMF+OAMF, respectively. (a) and (b) refer to χ_1 and χ_2, respectively.

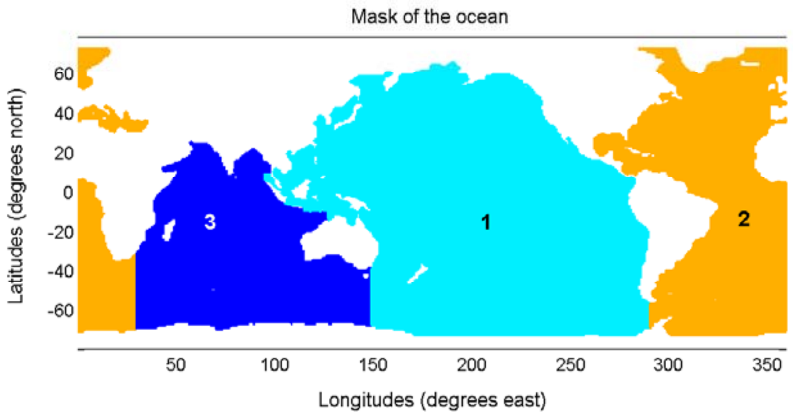


Fig. 2 Geographical Distributions of the Pacific, Atlantic and Indian Oceans.

3 EXCITATION OF ANNUAL POLAR MOTION BY THE PACIFIC, ATLANTIC AND INDIAN OCEANS

To investigate in detail the contributions of different ocean areas to the polar motion excitation, we divide the global oceans into three portions – the Pacific, Atlantic and Indian Oceans – and calculate their effects on the polar motion excitation quantitatively (the ECCO data do not contain information on the Arctic Ocean).

3.1 Geographical Partition of the Pacific, Atlantic and Indian Oceans

Figure 2 shows our delineation of the Pacific, Atlantic and Indian Oceans. The white area represents the land, and the areas 1, 2 and 3 mark the Pacific, Atlantic and Indian Oceans, respectively (Huang et al. 2001).

3.2 Excitation of Annual Polar Motion by the Pacific, Atlantic and Indian Oceans

We use the ECCO data to compute the OAMF of the Pacific, Atlantic and Indian Oceans on the basis of Equations (2) and (3) in Section 2.2, and then make a least squares fit to the OAMF and OBS with a linear combination of a trend, annual, semiannual and terannual components. Table 1 lists the amplitudes and phases of OBS, the annual OAMF of the Pacific, Atlantic and Indian Oceans and the sum of these three oceans. In this paper, the reference date for zero phase is 1 January 1990, 0000 UT.

Table 1 Comparison of amplitudes and phases of the “observed” annual polar motion excitation functions and the annual OAMF ($\chi_{1,2}$) of the Pacific, Atlantic and Indian Oceans and their sum for 1993–2005.

Var.	OBS		Pacific Ocean		Atlantic Ocean		Indian Ocean		the Oceans	
	Amp. mas	Pha. deg	Amp. mas	Pha. deg	Amp. mas	Pha. deg	Amp. mas	Pha. deg	Amp. mas	Pha. deg
χ_1	7.88	16.6	3.32	119.1	0.66	–72.2	4.45	93.8	6.94	104.3
χ_1^p	–	–	2.74	142.4	0.90	–29.5	0.48	129.3	2.33	136.6
χ_1^{uv}	–	–	1.35	65.6	0.61	–162.9	4.07	89.9	5.12	90.2
χ_2	24.22	-54.8	4.42	40.5	2.43	131.1	2.21	74.7	7.23	71.1
χ_2^p	–	–	3.29	57.4	1.33	172.9	2.76	59.4	5.63	70.8
χ_2^{uv}	–	–	1.59	3.6	1.69	99.4	0.86	–163.5	1.60	72.1

Figure 3 shows the phasor diagrams of the matter terms of annual polar motion excitation of the Pacific, Atlantic and Indian Oceans ($\chi_{1,2}^p$). It is seen that both χ_1^p and χ_2^p of annual polar motion excitation of the Atlantic are relatively small, which could be related to the special location and shape of the Atlantic.

To show the reasons more clearly, the matter terms of OAMF for the Atlantic ocean were calculated separately from Equations (2) and (3), and the results are listed in Table 2. Because the Atlantic Ocean can be characterized as a long belt around 0° longitude, the coefficient of $\sin\lambda$ (when calculating χ_2^p) remains

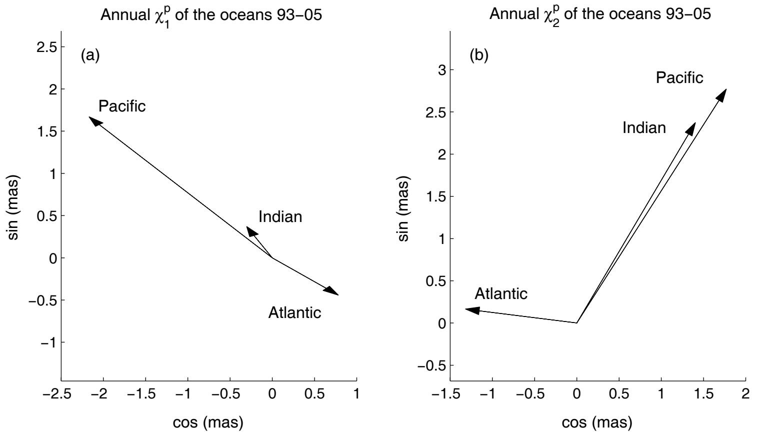


Fig. 3 Annual $\chi_{1,2}^p$ of the Pacific, Atlantic and Indian Oceans for 1993–2005, (a) and (b) refer to χ_1^p and χ_2^p, respectively.

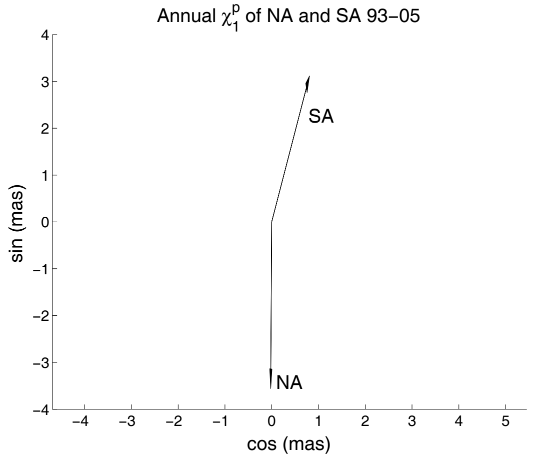


Fig. 4 Annual χ_1^p of the North and South Atlantic Ocean for 1993–2005.

small, leading to a small amplitude of χ_2^p for the Atlantic. From the χ_2^p data listed in Table 2 we can conclude that each component of χ_2^p of North and South Atlantic is a small value, which results in χ_2^p of the whole Atlantic being indeed smaller than those of the Pacific and Indian Oceans. See Figure 3(b). Figure 3(a) shows that χ_1^p of the Atlantic is also relatively small. As the coefficient of $\cos\lambda$ (when we calculate χ_1^p) is not a small value, we suspect that a majority part of χ_1^p of the North and South Atlantic may have cancelled each other out, resulting a small χ_1^p vector for the whole Atlantic.

Figure 4 displays the χ_1^p data of North and South Atlantic, listed in Table 2, with NA for the North Atlantic and SA, the South Atlantic. It is seen that χ_1^p of NA and SA are both of large values, but their phases are nearly opposite. Therefore, mutual cancelling leads to a small value of χ_1^p for the whole Atlantic.

Figure 5 shows the motion terms of annual polar motion excitation of the Pacific, Atlantic and Indian Oceans ($\chi_{1,2}^{uv}$). It is seen in Figure 5(a) that χ_1^{uv} of the Pacific and Atlantic Oceans are noticeably smaller than that of the Indian Ocean, while χ_2^{uv} of the Pacific and Atlantic Ocean are a little larger than that of the Indian Ocean in Figure 5(b). We calculated $\chi_{1,2}^{uv}$ of the North and South Pacific and Atlantic Oceans, and the results are listed in Table 3.

Using the data in Table 3, Figure 6 displays the phasor diagrams of the North and South Pacific and Atlantic $\chi_{1,2}^{uv}$, where NP denotes the North Pacific and SP denotes the South Pacific (Fig. 6(a) and (c)). We can see that χ_1^{uv} of NP and SP partially counteract in Figure 6(a). Figure 6(b) shows that the phases of NA

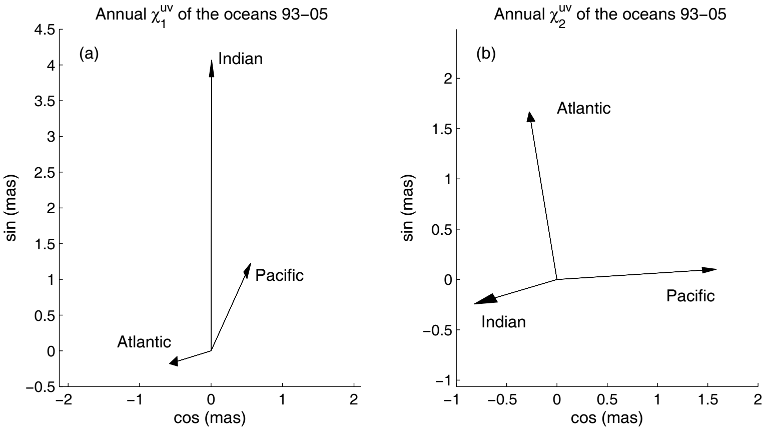


Fig. 5 Annual $\chi_{1,2}^{uv}$ of the Pacific, Atlantic and Indian Oceans for 1993–2005, (a) and (b) refer to χ_1^{uv} and χ_2^{uv}, respectively.

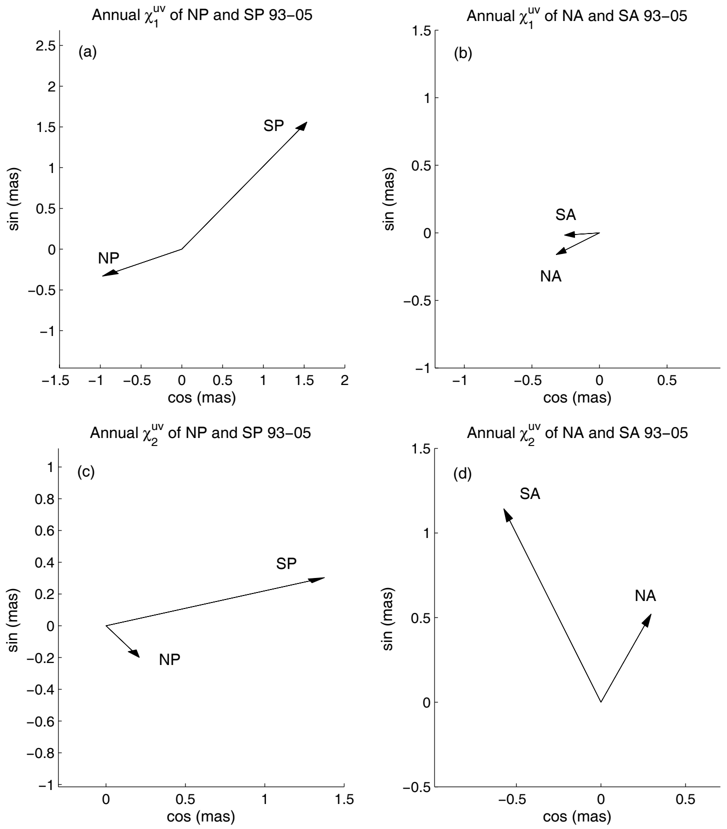


Fig. 6 $\chi_{1,2}^{uv}$ of the North and South Pacific and Atlantic Oceans for 1993–2005, (a) and (b) refer to the χ_1^{uv} of the Pacific and Atlantic Oceans, respectively, (c) and (d) refer to the χ_2^{uv} of the Pacific and Atlantic Oceans, respectively.

Table 2 Annual $\chi_{1,2}^p$ of the North and South Atlantic Ocean for 1993–2005

Variable	North Atlantic Ocean		South Atlantic Ocean	
	Amp. mas	Pha. deg	Amp. mas	Pha. deg
χ_1^p	3.56	–90.3	3.22	75.5
χ_2^p	0.85	149.5	0.65	–155.9

Table 3 Annual $\chi_{1,2}^{uv}$ of the North and South Pacific and Atlantic Oceans for 1993–2005

Var.	North Pacific Ocean		South Pacific Ocean		North Atlantic Ocean		South Atlantic Ocean	
	Amp. mas	Pha. deg	Amp. mas	Pha. deg	Amp. mas	Pha. deg	Amp. mas	Pha. deg
χ_1^{uv}	1.03	–161.2	2.19	45.5	0.36	–153.3	0.26	–176.1
χ_2^{uv}	0.29	–43.6	1.41	12.4	0.60	60.4	1.28	116.7

and SA χ_1^{uv} are not opposite, but their values are rather small. This makes the vector sum of χ_1^{uv} of NA and SA a small value too. Figure 6(c) and (d) display the χ_2^{uv} of NP, SP, NA and SA. We can see no distinct opposite phases between χ_2^{uv} of the NA and SA or between that of NP and SP. The Pacific, Atlantic and Indian Oceans all contribute the χ_2 of polar motion excitation.

Figure 7 shows the "total" annual polar motion excitation vectors ($\chi^p + \chi^{uv}$) of the Pacific, Atlantic and Indian Oceans. Here χ_1 of the Atlantic is the smallest among three oceans, which is due to the small values of χ_1^p and χ_1^{uv}. The Pacific, Atlantic and Indian Oceans all contribute to χ_2 of the annual polar motion excitation to a certain extent.

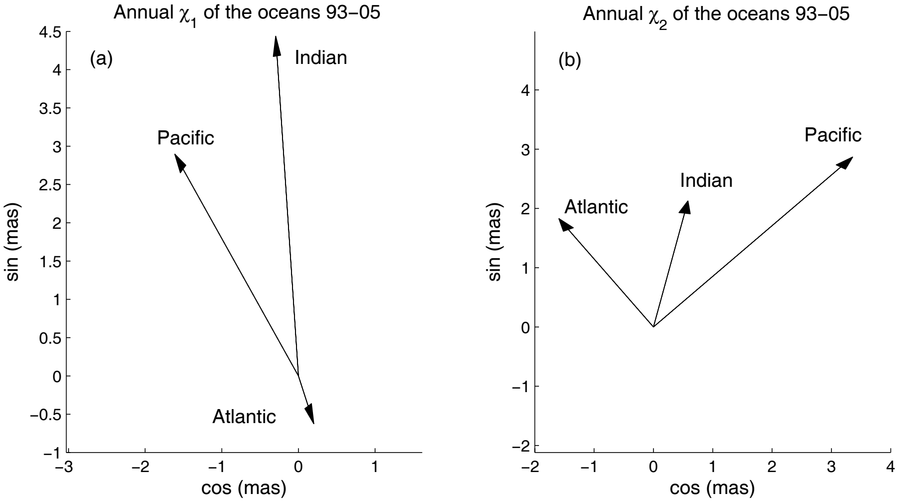


Fig. 7 Annual $\chi_{1,2}$ of the Pacific, Atlantic and Indian Oceans for 1993–2005, (a) and (b) refer to χ_1 and χ_2, respectively.

4 SUMMARY

The oceans play important roles in exciting the annual polar motion in addition to the atmosphere. In this study, we investigated systemically the contributions of the Pacific, Atlantic and Indian Oceans to the excitation of annual polar motion on the basis of the output data of ocean current velocity field and ocean bottom pressure field from the ECCO ocean circulation model for the period 1993–2005. The result shows that the Atlantic Ocean makes less significant contribution to the x-component of the annual polar motion excitation than the Pacific and Indian Oceans because of its particular location and shape, while all these three oceans contribute to the y-component of the annual polar motion excitation to some extent. It would be interesting to explore how the Pacific, Atlantic and Indian Oceans contribute to the polar motion excitation on inter-annual (including Chandler wobble) and intra-seasonal time scales. These topics await further investigations.

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