Movement of earth rotation and activities of atmosphere and ocean

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Abstract **The rotation of the earth, including the variation of the rotational rate and polar motion, represents the statement of the earth's overall movement and interactions among the solid earth, atmosphere and ocean on a variety of space-time scales. They make the earth's complex dynamical system under the conservation of angular momentum. The application and development of recent space geodetic techniques greatly promote the researches on the interactions between the earth rotation and the activities of atmosphere and ocean. This review will mainly report the progress in researches on the earth rotation and the activities of atmosphere and ocean as well as the air-sea interaction in the tropics, and prospect the direction for future theoretical investigations.**

Keywords: earth rotation, atmospheric activity, oceanic activity ENSO.

The earth rotation represents not only the statement of the earth's overall movement but also the couplings among the solid earth, atmosphere, ocean, mantle and core on a variety of space-time scales[1, 2]. The earth rotation can be mainly divided into two parts: the variation of the earth's rotational rate which is directly expressed by the observed length-of-day (LOD) change, and the motion of the earth's instantaneous rotational pole with respect to the earth's crust or the mean pole of the epoch, which is briefly referred to as the polar motion.

For the last 30 years, the rapid development of space geodetic techniques, such as very long baseline interferometry (VLBI), satellite laser ranging (SLR) and global positioning system (GPS), has led to advances in earth rotation measurements with the spatial resolution up to the magnitude of sub milli-arc-second and the temporal resolution up to a few days or even a few hours[3]. At the same time, the improvements in atmosphere and oceanic circulation models and the applications of the satellite altimeter and GPS atmospheric parameter measurement have also greatly promoted the researches on the atmospheric and oceanic activities.

With the developments of observational techniques and theories of astronomy, meteorology and oceanography, researches on the earth rotation, atmosphere and ocean have become the new disciplinary topic in the world. In 1995, IUGG/IAG set up a special research group devoting to the interaction among atmosphere, ocean and earth rotation (SSG-5.173). In 1998, the International Earth Rotation Service (IERS) established the Global Geophysical Fluids Center (GGFC) on its 10th anniversary day. The GGFC contains seven sub-centers of atmosphere, ocean, land water, tide, core, mantle and geocenter. Each sub-center regularly distributes the latest observation data and model results, in an effort to support the international research community in areas related to the interactions among the various layers of the solid earth rotation, atmosphere and ocean.

The researches combining the earth rotation with atmosphere and ocean not only promote the exploration of physical mechanisms of earth rotation, but also provide new outer constraints for atmosphere and ocean dynamics, so as to enhance the crossover researches on astronomy, atmosphere and oceanography. The above work has been listed as one of the major research objectives of the ongoing Solid Earth and Natural Hazard (SENH) Program of USA and the Asia-Pacific Space Geodynamics (APSG) project organized by China. This paper will mainly review the progress in researches on the earth rotation and the activities of atmosphere and ocean as well as the air-sea interaction in the tropics, and prospect the direction for future theoretical investigations.

1 Earth rotation and atmospheric activity

(i) The LOD variation and atmospheric activity. The LOD variations on seasonal, intraseasonal and interannual time scales are closely related to global atmospheric activity[4]. The seasonal LOD change consists of an annual term of ~0.4 ms amplitude and a semiannual term of ~0.3 ms amplitude, which add together to give double peaks with the amplitude minima in January and July[5].

The optical astrometric data are subject to seasonal system errors, while those of space geodetic data are much smaller[6]. After removing a fairly large semiannual tidal term, the seasonal variation in LOD is primarily driven by the friction and mountain torques on the surface of the solid earth, which causes the exchange of angular momentum between the atmosphere and the solid earth[7]. Over 90% in the seasonal LOD variation are from the change of wind velocity and the left from the change of atmospheric pressure and the oceanic excitation[8].

The fluctuation of LOD on the time scale of couple of days or tens of days is called the subseasonal oscillation of LOD. It contains a broadband continuum and a significant quasi-periodic variation of ~50 d which is briefly called the 50 d oscillation. They are mainly excited by the atmosphere[9]. Dickey et al.[10] found the significant coherence between the LOD change and the axial component of atmospheric angular momentum (AAM) at periods higher than 8 d. However, the coherence declines at periods lower than 8 d. This might be due to the random error in the data or the absent excitation sources. For the subseasonal oscillation of LOD, the 50 d oscillation was most discussed. On the basis of the observational data of Chinese time determination system, Zheng[11] first found 50 d oscillation in the high frequency variation of UT1 using the AR spectral technique. This finding was later confirmed by Fessel et al.[12] who used four kinds of independent space geodetic UT1 data and Langley et al.[13] who used four years of meteorological data and LOD data observed by LLR technique. Li et al.[14] treated the 50 d oscillation as a damped oscillator by the random excitation, and estimated the resonance periods ranging from 45 to 52 d.

The 50 d oscillation also exists in the zonal wind of the tropical Pacific, which is called the Madden-Julian oscillation[15]. The similar subseasonal oscillation was additionally found in the tropical atmospheric convection, the earth's geopotential, the monsoon precipitation, the Indian circulation and the sea level height in the Pacific. For the cause of this oscillation, Madden[16] supposed it to be a global manifestation of the tropical oscillation. Gill et al.[17], however， believed it to be excited by the inherent instabilities of the subtropical zonal flow of the atmosphere, owing to the interaction between the atmospheric jet streams and large mountains. The physical cause for the 50 d oscillation remains unknown until now.

The interannual LOD variation refers to the fluctuation of LOD on the time scale of a couple of years whose amplitude is equivalent to that of the seasonal LOD change, reaching up to 0.5 ms. The current researches show that most of the interannual LOD variation is excited by the atmosphere with the left part excited by the ocean. Therefore, the interannual LOD change is closely related to the atmospheric and oceanic activities (see section 3).

In 1991, the American National Center of Environment Prediction and National Center of Atmospheric Research (NCEP/NCAR) cooperatively put forward a reanalysis program[18]. It adopted more data and improved the Global Data Assimilation System (GDAS) of the American National Meteorological Center (NMC, the formal of NCEP). Therefore, the reanalyzed AAM series have higher precision than formal NMC series. Yu et al.[19] further studied the relation between the atmosphere and earth rotation using these new AAM series. The results show that the new AAM series have the characteristics of low noise and high resolution and better explain the LOD variations on intraseasonal to interannual time scales. The AAM and LOD variations agree well especially on the quasi-biennial time scale.

Highly accurate LOD variation series might be applied as a reference to the verification of global atmospheric and oceanic models. Zhou et al.[20] compared the LOD variation series and the axial AAM simulated by the global circulation model of Japan Meteorological Agency (JMA). They found that the annual component of the axial AAM was very well simulated, while the semiannual component was unsuccessfully estimated with the model due to an incompleteness in the simulated subtropical zonal winds.

(ii) The polar motion and atmospheric activity. The polar motion mainly includes the periodic terms of 12 and 14 months, i.e. the annual and Chandler polar motion. A lot of scholars calculated the atmospheric excitation of annual polar motion using a variety of meteorological data. But there are some differences among their results owing to the accuracy of the data[21—23]. Zhou et al.[24] analyzed the atmospheric excitation of the annual component of the prograde and retrograde polar motion on the basis of the AAM reanalyzed by American NCEP/NCAR and the polar motion series obtained by recent space geodetic techniques. The results show that considerable differences exist in the amplitudes and phases of the atmospheric excitation and in those of the observed excitation, although the atmosphere plays an important part in the excitation of annual polar motion. The left excitation might come from the ocean and the variation of land water distribution (see section 2).

In 1891, Chandler found the oscillation at the period around 14 months, i.e. the Chandler wobble, when he searched for the free Euler period term of 305 d in the data of latitude observations. The difference between the theory and observation had been explained by the elastic earth model [1]. As a free motion, the Chandler wobble is presumed to be an attenuation process because of the existence of the energy dissipation source of mantle viscoelasticity[25]. However, the observations of over 100 a have shown that the Chandler wobble has no signature of secular attenuation although its amplitude varies somehow. This illustrates that there must exist some excitation factors which maintain the wobble.

There are four possible mechanisms to maintain the Chandler wobble, i.e. the periodic force, the parametric resonance, the nonlinear effect and random perturbation. Among them, the random perturbation theory most possibly explain the maintenance of the Chandler wobble[26]. If the Chandler wobble is driven by the periodic force, then there must exist a force whose period happens to be the Chandler period. Because the Chandler period is determined by the intrinsic property of the whole earth, the local motions within the earth unlikely exert the force with the Chandler period from the view of probability. In fact, the periodic force with the Chandler period has not been found so far. The cause of parametric resonance is substantially that the moment of inertia varies at the period approximate to the Chandler period or its integral times. From the preliminary estimation of orders of magnitude, the prerequisites for the parametric resonance can hardly be satisfied. If considering the nonlinear effect of the Liouville equation which governs the excitation of the earth rotation, the secular deceleration of the earth's rotation rate might increase the amplitude of the Chandler wobble. But the order of magnitude is too small to maintain the Chandler wobble.

A usual assumption is to view the signal of Chandler wobble excitation as the Gauss white noise, and the atmosphere as the broadband excitation source of the Chandler wobble[27]. Munk et al.[28] calculated the atmospheric excitation of the Chandler wobble and concluded that the redistribution of mass of atmosphere had very little effect on the Chandler wobble. The result of Wilson et al.[29], however, reflected another opinion that the atmospheric excitation amounted to 1/4 of the observed excitation energy. Vondrak[30] analyzed 11.5 a of the space geodetic data and believed that the atmospheric excitation drove 10%—20% of the Chandler wobble. Chao[31] extracted the Chandler wobble excitation from the observed data during 1986—1990 and demonstrated an important contribution of the AAM to the Chandler wobble. Furuya et al.[32] used about 11 a of the JMA and NMC AAM data after 1983, and further revealed that the AAM wind term contributed more to the Chandler wobble excitation than the AAM pressure term.

The variation of polar motion on the time scale of a couple of years is briefly called the interannual polar motion. Abarca et al.[33] analyzed the interannual variation in polar motion series using periodograms and the technique of wavelet analysis, and found two prominent components, a quasi-biennial component and a component of ~ 4—6 year period. They compared the polar motion excitation series and AAM data for the period of 1980—1991. At the biennial period, the polar motion and the AAM are well correlated. At longer periods of 4—6 years, the east components of polar motion and AAM vary coherently while the north components of them exhibit some differences. In fact, one important excitation source of interannual polar motion is the North Atlantic Oscillation (NAO). The NAO is characterized dominantly by N-S interannual pressure variations in both the subtropical anticyclone belt and the subploar low near Iceland[34]. Its intensity is customarily measured in terms of certain indices constructed from the sea surface temperature, the sea level pressure or height field. Zhou et al.[35] found the significant correlation between the NAO index and interannual polar motion excitation function, and concluded from the preliminary dynamical analysis that the NAO is an important source in exciting the interannual polar motion.

The accuracy of modern space geodesy has been improved by about two orders of magnitude in comparison with that of the traditional optical observation. The polar motion data at the interval of one day or even a few hours might be obtained, which leads to the finding of subseasonal polar motion. Eubanks et al.[36] studied the atmospheric excitation of subseaonal polar motion with the JMA and NMC AAM data and the SLR and VLBI polar motion series during 1983—1986. The results demonstrated that the pressure term of the AAM could account for 60% of the subseasonal polar motion. Xie et al.[37] considered the influences of both pressure and wind terms of the atmosphere. During the period of 1983—1992, the contribution of atmosphere to the excitation of subseasonal polar motion reaches up to 70%, with the left part possibly relating to the ocean.

2 Earth rotation and oceanic activity

(i) The LOD variation and oceanic activity. The angular momentum theory of the atmospheric circulation is now well established. However, the angular momentum method has not been widely applied in the study of ocean dynamics, because the movement of the oceanic current is much more complicated than the circulation of atmosphere. The investigation of the average angular momentum of global oceans did not play its role, until people analyzed the earth's variable rotation and the balance of global angular momentum. The accurate oceanic angular momentum (OAM) could not be obtained due to the lack of the observational or simulated data of the global oceanic velocity and mass field. With the development of the ocean simulation technique and the use of advanced parallel computers, the oceanic circulation model has been established and now can be used for numerical simulations under various boundary conditions. This contributes a lot to the studies of the earth rotation and oceanic activities[38].

Brosche et al.[39] applied a numerical oceanic model to studying the oceanic excitation of seasonal LOD change, and concluded that the oceanic contribution amounts to the amplitude of 20 μs. Dickey et al.[40] estimated that the contribution of the axial angular momentum of the Antarctic Circum-Polar Current to annual LOD excitation is about 2—4 μs. Marcus et al.[41] simulated three years of oceanic angular momentum using two independent oceanic general circulation models, forced by the sea surface temperature, the salinity and wind stress during 1992—1994. The results indicated that the ocean currents and changes of mass distribution influence the LOD variations. The oceanic circulation model might simulate or detect the oceanic contribution to the LOD changes on seasonal and shorter time scales. Johnson et al.[42] calculated the oceanic angular momentum during 1988—1998 from the parallel ocean climate model. They suggested that the oceanic activity could explain a significant port of LOD variations on interannual to subseasonal time scales after subtracting the atmospheric effects.

Studies of sea level changes have depended on the data of tide gauge stations for a long time. Zheng et al.[43] analyzed the relationship between the LOD variation and interannual change of sea level on the equator and high latitude region, using the sea level data of nearly 300 tide gauge stations in the Pacific. The results indicated that the sea level of the equatorial Pacific rises up and the sea level of the high latitude region drops down when the earth rotation accelerates, and *vice versa* when the earth rotation decelerates.

The TOPEX/POSEIDON altimeter launched in August 1992 made the high accurate observation of global sea level possible[44]. Zheng et al.[45] analyzed the TOPEX sea level data from December 1992 to December 1994, and found the correlation between the LOD variation and sea level change on the seasonal time scale.

(ii) The polar motion and oceanic activity. Ponte et al.[46] and Johnson et al.[42] used different oceanic circulation models to study the oceanic excitation of polar motion on interannual to subseasonal time scales. Both their researches revealed the significant correlation or coherence between the oceanic angular momentum function and the polar motion excitation function after subtracting the atmospheric effects. The oceanic activity might account for a significant part of polar motion excitation on interannual to subseasonal time scales after subtracting the oceanic contributions. The ocean also plays an important role in exciting the Chandler wobble.

Zhou et al.[24] analyzed the oceanic excitation of annual polar motion using the OAM series during 1985—1995 simulated by the oceanic circulation model of American Massachusetts Institute of Technology (MIT). The result reveals that the oceanic excitation approximates to half of the atmospheric excitation. The sum of oceanic and atmospheric excitations approximates more to the observed annual polar motion excitation, as compared with the atmospheric excitation only. Of course, there are still some differences between the observed annual polar motion excitation and the sum of atmospheric and oceanic excitations. This shows that additional excitation factors need be taken into account, for example, the annual variation of the land water distribution. The current results about the excitation of annual polar motion by the land water differ a lot because of the different data used[47,48]. The technique of satellite gravity measurement is expected to greatly boost the observational accuracy of the global land water, and thus finally solve this problem[49].

3 Earth rotation and tropical air-sea interaction

(i) Tropical air-sea interaction-ENSO event.
The tropical zone, about half of the earth's surface, mainly occupied by ocean, receives most radiation energy of the sun. It is not only the major source of vapor energy in the atmosphere, but also the area of the most active air-sea interaction on the earth.

The El Niño event represents the process of atmosphere-ocean interaction in the tropics. It is characterized by the anomalous rise in sea surface temperature in equatorial eastern Pacific[50]. In normal years, the sea surface temperature in equatorial eastern Pacific is lower than that in the western Pacific area. This is because the Peru cold current goes northward along the western side of the Southern America Continent, some of which changes into southern equatorial ocean current and flows westward; The westward trade wind along the low-latitude sea areas makes the equatorial warm water accumulate toward the western Pacific; The cold sea water uprises in the eastern Pacific accompanying the trade wind. In some years, the trade wind in the Pacific suddenly collapses. The warm water in the western Pacific flows eastward and accumulates in the eastern Pacific. Then, the sea surface temperature gets higher than that in normal years from Southern America coasts to equatorial areas in the eastern Pacific. The El Niño event comes out.

After the 1970s, eight El Niño events happened consecutively in 1972—73, 1976—77, 1982—83, 1986—87, 1991—92, 1993, 1994—95 and 1997—98. The 1982—83 and 1997—98 El Niño events are the strongest among them[51]. The interval of time between two El Niño events is usually about 2—7 years. This kind of non-periodic change in Pacific sea surface temperature on interannual time scale reflects one of the important characters of El Niño events.

The Southern Oscillation in the tropical atmosphere is closely related to the El Niño event. It reflects a long-term large-scale irregular variation of the atmospheric pressure in the Pacific[52]. There are usually two big air masses in the equatorial Pacific: one near the Easter Island in the southern Pacific and another near the Indonesia. In normal years, the high air pressure is located in the Easter Island. The strong trade wind makes the air over the equatorial sea surface flow from the eastern Pacific to the western Pacific and rise in the low air pressure areas of Indonesia and the warm sea water areas of northern Australia. The air rising to the high altitude flows back to the eastern Pacific and sinks in the areas of low temperature sea water. In this way, the air current over the equatorial Pacific forms wholly a west-east circulation, i.e. the famous Walker circulation. This kind of condition is not always the same. In some years, the air pressures over the Easter Island and Indonesia reverses. Then, the trade wind and Walker circulation are weakened. The seesawing phenomenon of the air pressure over the eastern and western Pacific is called the Southern Oscillation.

Because the El Niño event and the process of the Southern Oscillation are closely connected. They are jointly called the El Niño-Southern Oscillation (ENSO) phenomenon. A series of researches in recent years reveal that the signal of ENSO not only exists in the variations of the sea surface temperature, the atmospheric pressure, the wind, the cloud cover and ocean current intensity in the tropical areas, but also reflects in interannual changes of the atmospheric circulation and climate in many areas in the world[53—55].

(ii) Earth rotation and ENSO event. With improvements in oceanic and atmospheric observations and enlargements of observational scales, the widespread researches on El Niño events in recent years further promote the investigations of connections between the earth rotation and the air-sea interaction.

Stefanick[56] first reported the correlation between the interannual AAM and ENSO. Rosen et al.[57] found the strong 1982—83 El Niño signal in the AAM and LOD series. Chao[58—60] showed that the interannual LOD variation is mainly due to the ENSO and the Quasi-Biennial Oscillation of the AAM. Zheng et al.[61] established the good agreement among the interannual LOD change, the variation of sea surface temperature in eastern equatorial Pacific, and the interannual variation of AAM calculated from global zonal wind data, in which the interannual variation of atmosphere leads the others for 1—3 months. By the preliminary quantitative dynamical analysis, they thought that the interannual variation of the earth rotation and the El Niño event are respectively the responses of the solid earth and ocean to the anomaly of the atmospheric circulation[62].

Zheng et al.[63] investigated the relation between the equatorial oceanic activity and the LOD variation, based on the observational sea level series of the data center of the international TOGA project during 1962—1990. The results showed that there are large-scale west-east motions of water in the upper equatorial Pacific, which accounts for about 30% of the change in interannual earth's rotation rate. They further calculated the change of water volume in the upper tropical Pacific (20°N—20°S), with the maximum change reaching up to 10^{15} m^3. The interannual LOD variation is in opposite phase with the change of the water volume in the upper tropical Pacific while the LOD variation leads to the water volume change. This suggested that the interannual variation of the earth rotation might exert the counteraction on the ocean and influence the distribution of water in the tropical Pacific.

Liu et al.[64] applied the horizontal equations of motion to dynamically analyzing the influences of the variation of the earth's rotation rate on the atmospheric and oceanic oscillations. It is shown that the variation of earth's rotation rate affects not only the amplitudes of the atmospheric and oceanic oscillations, but also the change of zonal wind and oceanic current, which in turn causes the variation of sea level.

Zheng et al.[63] proposed a mode of interaction between the earth rotation and the equatorial oceanic activity, which consists of two stages as shown in fig. 1. In stage 1, the strong westward trade wind causes the westward Pacific oceanic flow and results in a rise of sea level in the western equatorial Pacific and a drop in the eastern part. Because the westward trade wind and equatorial oceanic flow causes the change of angular momentum in the opposite direction of the earth rotation, the interannual earth's rotation rate increases. The warm sea water on the surface of south and north Pacific converges due to the counteraction of the acceleration of interannual earth rotation rate on the ocean, enhancing the rise of sea level in the western Pacific. In stage 2, the trade wind intensity decreases or the anomaly of trade wind appears, relative to stage 1, causing the ocean to flow eastward and result in a rise of sea level in the eastern equatorial Pacific and a drop in the western part. The anomalous wind and equatorial oceanic flow lead to the angular momentum change in the direction of the earth rotation and the reduction of the earth rotation rate. The warm sea water on the surface of the south and north Pacific diverges owing to the counteraction of the deceleration of interannual earth rotation rate on the ocean, weakening the rise of sea level in the eastern Pacific. In the above process of the interaction between the earth rotation and the equatorial oceanic activity, the change of interannual earth rotation rate affects the variation of the Pacific sea level during El Niño epochs. The signal of this effect was confirmed in monitoring 1997—98 El Niño event with the technique of TOPEX satellite altimetry[65].

In the interaction among the tropical ocean, atmosphere and the earth rotation, the variation of earth's interannual rotation rate also counteracts on the tropical ocean and affects the forming of El Niño event, although the anomal change of the atmosphere dominates the process. Eubanks et al.[66] found the negative correlation between the interannual LOD variation and the Southern Oscillation Index (SOI) that represents the intensity of the ENSO event, with the LOD leading the SOI by roughly 26 months. This makes it possible to predict El Niño events using the LOD data[67]. Zheng et al.[68] successfully predicted the 1991—92 El Niño event through the method of monitoring the minimum of the interannual LOD change.

Apart from the above interannual variation, the subseasonal LOD variation is also possibly linked with the ENSO events. The 50 d oscillation was anomalonsly active during the 1982—83 El Niño epoch. At the same time, the axial AAM reaches the maximum because of the influence of the anomalously strong 5°N—30°N zonal wind[57]. Eubanks et al.[66] suggested that the El Niño event increases the atmospheric temperature gradients from pole to equator through the release of warm water in the tropical Pacific which further strengthens the unstable oscillations. Gambis[69] pointed out that the high frequency component of LOD usually has high variance during the northern hemisphere winter, when the atmospheric temperature gradients from pole to equator are very large. In particular, the 1982—83 El Niño event happened at the depth of the northern hemisphere winter. The already large temperature gradients were enhanced, causing the burst of the high frequency component of LOD.

Gambis[69] used the method of wavelet transform to analyze the short periodic variation of LOD ranging from 1962 to 1991, and suggested that there is no tendency for the 50 day oscillation to be more active during the El Niño epochs except during the period of the 1982—83 eventHowever, Zhong et al.[70] applied the Hilbert transform to extract the signal of the amplitude modulation of the subseasonal LOD oscillation during 1962—1996. The results demonstrated that the amplitude modulation of the sub. seasonal LOD variation has not only a positive linear trend but also an interannual variation which leads to the ENSO evolution. Therefore, it is necessary to investigate the relation between the LOD change and ENSO from the composite contribution of atmospheric oscillations on multiple time scales.

The El Niño events correlate with the polar motion except

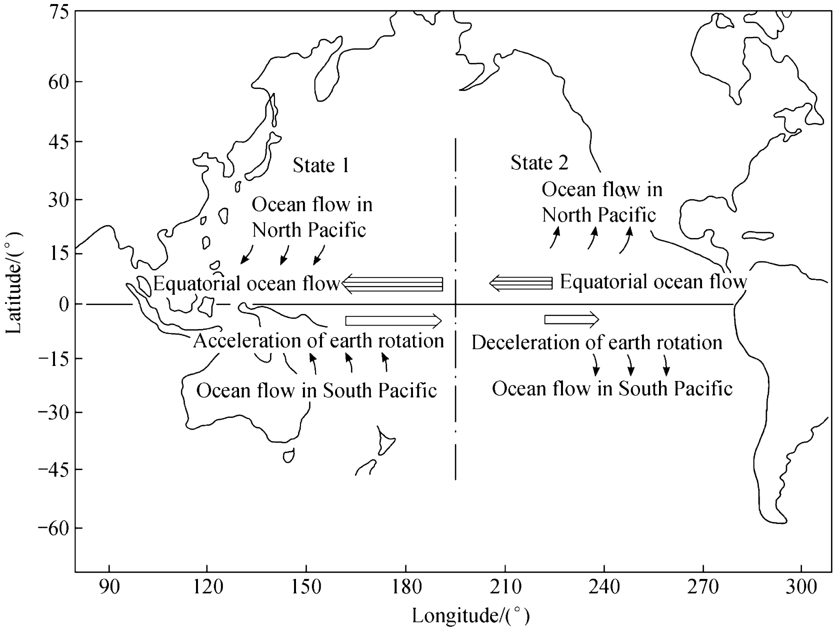

Fig. 1. The interaction between the equatorial oceanic activity and earth rotation.

for the LOD variation. Kolaczek et al.[71] found the time-varying correlation between the short periodic changes in the period range of 20—150 d of the atmospheric and observed excitation functions of polar motion during 1980—1998. It has similar periods of 2, 3, and 5 a with the series of the Southern Oscillation Index. The correlation coefficients between the atmospheric and observed excitation functions of polar motion during El Niño epochs are significant at the confident level of 0.05. Impacts of El Niño on polar motion have an obvious impulsive character which causes irregular variations of polar motion during the epoch. It is worth pointing out that further studies ought to take into account the effect of oceanic excitation during El Niño epochs because of the oceanic contribution to the short periodic changes of polar motion.

4 Perspective

Because of the improvement of space geodetic techniques and corresponding researches, people have achieved a lot in the interdisciplinary area between the earth rotation and activities of atmosphere and ocean. Meanwhile, there are still a number of basic problems unresolved, for instances, (i) What is the mechanism of the 50 d oscillation? (ii) How does the Chandler wobble be maintained? (iii) How about the non-periodic high frequency fluctuations of the earth rotation and the activities of atmosphere and ocean as well as their interactive processes? (iv) How to build the comprehensive model of the coupling among global atmosphere, ocean and the earth rotation, so as to reveal the process of the exchanges of angular momentum in the geodynamical system by considering the functions of mountain torque and friction torque?

The above complex and challenging topics will attract people to explore and make further research, which might become a hot point of researches in this early century.

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