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The Impact of the Processes in the Southern Ocean on ENSO Development

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Abstract: The paper presents the review of the model study of the role of the Southern Ocean in the processes of interaction of the ocean-atmosphere system at short time scales impacting the El Niño–Southern Oscillation (ENSO). It is shown that the variability of wind and atmospheric pressure over the Antarctic Circumpolar Current (ACC), together with the effects of the topography and coastline, significantly impact the development of ENSO events. A new paradigm for ENSO is proposed that allows explaining the current weakening of the interrelation between the variability in wind and water volume in the tropical warm pool in the western equatorial Pacific and the onset of ENSO. The weakness of the interrelationship between ENSO and variability in the equatorial warm water volume of the equatorial Pacific, together with wind variability in the western equatorial Pacific, can be explained by the fact that the process occurred in the Southern Ocean recently became a major contributor amplifying ENSO events. The reproduction in numerical models of ocean dynamics for the mechanism found can improve the accuracy of the forecast of El Niño events.

Keywords: ENSO, The Southern Ocean, Numerical Modelling

1. Introduction

It is known that fluctuations of the Earth's dynamic oblateness *J2* are a measure of global redistributions of mass between equatorial and polar regions, sensitive to the component which is symmetric about the equator. Cox and Chao [7] have demonstrated that a time series of monthly values of *J2* based on satellite orbit determination showed rapid fluctuations from month to month, as well as a large change in *J2* in 1997/1998 associated with ENSO. Hughes and Stepanov [13] have investigated the ocean dynamics associated with these rapid fluctuations using a barotropic ocean model [32] forced by atmospheric wind stress and pressure. They showed that much of the model variability is related to coherent circumpolar fluctuations in Arctic and Antarctic bottom pressure. The Antarctic mode is forced by circumpolar winds, whereas the Arctic mode is forced by northward winds over the entrances to the polar sea. While there is no correlation between Arctic and Antarctic bottom pressure, but there is an anticorrelation between the Antarctic or Arctic pressure and tropical Pacific bottom pressure. This suggests that when water is removed from the Arctic or Antarctic as the polar modes are excited, that water converges preferentially in the Pacific rather than other ocean basins.

The paper demonstrates a relationship between the polar modes and ENSO. For this the link between the short-period variability of meridional water fluxes in the Pacific sector of the Southern Ocean and El Niño due to the processes of ocean-atmosphere interaction in the Southern ocean at short time scales is considered. It is shown that the wind processes over the ACC, and particularly the atmospheric conditions upstream of the Drake Passage, can strongly influence the ENSO events. Also the reasons why the mass loss from both polar regions appears to converge in the tropical Pacific rather than being spread uniformly around the tropics are suggested.

2. Climatic Variability and ENSO

An ENSO is an irregular periodical variation in winds and sea surface temperatures in the tropical central and eastern Pacific Ocean, affecting much the tropics and subtropics. Forecasting of ENSO events is an important task in climate researches since ENSO events have a global influence the weather at different regions of the Earth: both in the tropical Pacific (where the ENSO events occur) and at moderate/high latitudes (e.g., [21, 27, 28, 29, 37] etc. demonstrated the influence of warm ENSO on the weather in the Northern Hemisphere).

Many publications provide evidence that the interactions between high latitudes and the tropics can impact the ENSO variability (e.g., [1, 5, 8, 30, 39, 40-42]). For example, Wang et al. [42] have shown that the winter sea surface temperature (SST) anomalies in the western North Pacific influence the development of wind anomalies over the equatorial western Pacific triggering oceanic Kelvin waves, which propagate eastward and initiate the developments of ENSO. However, not only teleconnections between different regions of the Pacific can impact the ENSO. So, Dong et al. [8] demonstrated from global coupled ocean atmosphere modelling that a kind of teleconnection exists between the Atlantic and ENSO: the warm phase of the Atlantic Multidecadal Oscillation leads to a weaker phase of the El Niño development. These authors supposed that this occurs due to the fast processes in the atmosphere, which transfer the influence of the Atlantic to the tropics of the Pacific Ocean through an “atmospheric bridge.” Numerical models and data of observations in the Southern Ocean demonstrate a statistically significant correlation between the processes near the Antarctic continent and in the tropical regions both with positive and negative lags approximately a few months long. The analysis of the data of observations [19, 31, 44] demonstrate that the location of the Antarctic sea ice spreading boundary is strongly correlated with the ENSO events on time scales of a few months: a correlation is observed between the ENSO events and the location of the boundary of the Antarctic sea ice spreading when the ENSO event either leads or lags with respect to the variability of the sea ice. Yuan and Martinson [44] explained the latter correlation by the existence of a sort of atmospheric teleconnection between Antarctica and the equatorial Pacific. Terray [39] also suggested that there is link between extra-tropical atmospheric forcings in the Southern Hemisphere and ENSO. However, the model results [3, 14, 15, 34, 35] make us suppose that the role of the ocean in the transfer process of seasonal signals from high latitudes to the tropics can be even more important than was considered earlier.

As was noted by Stepanov [34, 35], the above mentioned correlations between ENSO and weather at distant regions from the tropical Pacific can be explained by the fact that ENSO events could be considered as a consequence of the change of the global meridional atmospheric circulation rather to be a local phenomenon. The link between the tropics and the high latitudes can exist due to the result of the interaction between the tropics and the mid-latitudes that then influence the high latitudes and vice versa. For example, warming (cooling) of the upper ocean layer in the tropics (which can be related, for example, to the seasonal cycle, or consequence of the frequent occurrence of the weak warm-pool El Niño) leads to an increase (decrease) in the warming of the troposphere in the zone of atmospheric mass upwelling in the tropics (the Pacific Ocean is the largest ocean and its contribution to these changes is maximal). This means that the warmer (colder) air rising from the tropical zone is transported by the Hadley circulation cell to the descending subtropical zone. Here the warmer (colder) air decelerates (accelerates) air movement in the descending branch of the Hadley cell due to buoyancy forces and leads to the weakening (strengthening) of wind in the mid-latitudes that, in turn, leads to similar changes in the high latitudes. For this reason, many teleconnections are observed between ENSO and weather variability in the areas distant from the tropical Pacific.

It is a generally accepted opinion that ENSO events are caused by the interaction processes between the ocean and atmosphere in the tropics. Previous studies have shown that there are some ENSO precursors. In accordance with recharge/discharge paradigm for ENSO [16] McPhaden on the basis of the analysis of observation data has shown that the variability of wind and water volume in the tropical warm pool in the western equatorial Pacific precedes ENSO by two–three seasons [24] and, hence, may be a good ENSO predictor [25]. A similar approach was proposed by Clarke and Van Gorder [6] who alternatively used zonal wind stress over the Indo-Pacific tropics.

However, Horii et al. [12] demonstrated that the reliability of ENSO predictability using these predictors changed in the 2000s. The canonical ENSO prevailed in the equatorial Pacific till 2000 (characterized by the anomaly of SST in the eastern equatorial Pacific). After 2000 it changed into the increase of the frequency of El Niño Modoki events characterized by the development of SST anomalies in the central equatorial Pacific [2, 17, 18, 20, 22]. It resulted in the breakdown of the typical physical relationships which were revealed for canonical ENSO and were used for its prediction. For example, during two decades till 2000 the increase/decrease in the water volume in the tropical warm pool in the western equatorial Pacific (recharge/discharge phase of the “recharge oscillator”) accompanied by the strong/weak wind in this region was observed 2–3 seasons before the onset of ENSO. However, in the 2000s the interrelation between the variability in these predictors and the following ENSO became weak, especially for the ENSO events after 2005.

According to [12] these changes may be caused by the more frequent occurrence of El Niño Modoki as compared with the previous ENSO (in the 1980s–2000s), likely, due to the change in the zonal slope of the equatorial thermocline owing to the global warming [2, 43]. During warm periods, when the meridional gradients of dynamic parameters of the atmosphere are not high, the inter-latitudinal exchange decreases; therefore, the variability in the field of sea level pressure in the tropics decreases that leads to the development of frequent but weak events of ENSO (with

SST anomalies concentrated in the central equatorial Pacific). It is interesting that the frequent events of El Niño Modoki observed in the 2000s agree with coupled model simulations under global warming [43]. It should be noted that Gushchina [11] based on the modeling data made the conclusion that the increase in the frequency of El Niño Modoki is favored by the decrease in the zonal gradient of temperature of the surface ocean layer in the tropics, when the climatic parameters became more homogeneous.

As follows from the analysis of variability in ENSO indices presented by Stepanov [36], the atmospheric impact of the western equatorial Pacific on ENSO decreased after 2000: the standard deviation of difference between NINO3.4 and NINO4 for 1989–1999 (that characterizes the intensity of the Walker circulation cell) is indeed by twice larger than that for the period from 2000 to 2013. Besides, the difference between NINO3.4 and NINO4 demonstrates statistically significant correlation with SOI (this index also characterizes the intensity of the Walker cell and is defined as the normalized difference in sea level pressure between Tahiti (17°52′S) and Darwin city (Australia, 12°25′S)) for 1989–1999 (–0.51) whereas the value of this coefficient for 2000–2013 is close to zero.

Proceeding from the values of coefficients of correlation between ENSO and SOI (≤0.7), one may conclude that only about 50% of ENSO variability can be explained by variations in the atmospheric impact in the equatorial Pacific. So, the development of ENSO can also be associated with another mechanism, for example, with the variation in the global meridional atmospheric circulation affecting the high and low latitudes. Thus, it may be supposed that the changes in the global meridional atmospheric circulation which start in April (i.e., at the beginning of ENSO development) may lead to almost synchronous variations in the tropics and in the Southern Ocean; and some links between atmospheric processes in the Southern Ocean and ENSO can exist. For example, the results presented by Stepanov [34, 35] lead to the conclusion that the wind processes over the ACC, and particularly the atmospheric conditions upstream of the Drake Passage [36], can strongly influence the ENSO events.

There is a significant amount of scientific publications devoted to ENSO phenomena, but the nature of their occurrences is still unclear. Particularly, many authors distinguish the phenomena that are developed either in the central (El Niño Modoki events) or eastern parts of the Pacific tropics (canonical ENSO), but they do not provide a sensible explanation why it happens. The results [36] help to understand why such phenomena occur and this paper develops these ideas further.

3. The Transport Processes in the Southern Ocean and Its Relation to ENSO

Numerical experiments [34, 35] have demonstrated that the variability of the wind forcing over the ACC, together with the effect of the bottom topography, lead to the appearance of anomalies in the fields of the pressure and density in the Southern Ocean. This variability of the oceanic mass in the Pacific Ocean is negatively correlated with the wind forcing over the ACC, significant at the 99% level. As a measure of wind strength the SAM index (Southern Hemisphere Annular Mode) has been used that is determined as the normalized difference between the zonal-mean SLP between 40°S and 70°S (obtained from the National Oceanic and Atmospheric Administration). The signals from the Southern Ocean are transported to the equatorial latitudes of the Pacific Ocean by means of the wave mechanism described by Ivchenko et al. [14]. Here, they change stratification and lead to an elevation of (deepening) the thermocline in the western (eastern) part of the equatorial Pacific (in the case of low values of the SAM index), which intensifies the warm El Niño event (Figure 1). On the contrary, the negative value of fluctuations of the meridional fluxes in the Southern Ocean (the case of high values of the SAM index) causes deepening (shallowing) the thermocline in the western (eastern) part of the equatorial Pacific; hence, the cold La Niña event can develop more intensely.

The appearance of these anomalies in the tropics is caused by the short-period variability of the meridional mass fluxes in the Pacific sector of the Southern Ocean north of 47°S whose average value at 40°S ($M(t)|_{\varphi=40S}$) from July to September is estimated to be greater than 2000 Gt (gigatons, 1 Gt $=10^9$t), which allows us to estimate the typical signal reaching the tropics of the Pacific. Such mass variation corresponds to more than a 50 cm displacement of the thermocline boundary over the tropical region with a size of 5 degrees by 50 degrees, which is comparable with the effect of onshore/offshore phenomena in the tropical Pacific.

The above mentioned variability of the meridional mass fluxes in the Pacific sector of the Southern Ocean, as it has been studied by Stepanov and Hughes [33], is due to mass exchange occurring between the Southern Ocean, Atlantic, and Pacific regions at periods of 30–100 days. Such mass exchange is accompanied by global adjustment processes in the ocean, which are approximately one month long. The main mass exchange occurs between the Southern and Pacific oceans, which is determined by the balance of wind stress by form stress (a pressure difference across topographic obstacles) in the Drake Passage. According to [33], three main regions exist in the Southern Ocean (regions near the Drake Passage, the Kerguelen Plateau, and the Pacific Antarctic Rise) that are responsible for approximately 65% of total form stress on the ACC. The Drake Passage is the most significant topographic feature among the three regions mentioned above, accounting for about 30% of the total form stress. The eastward directed wind stress leads to a decrease in the bottom pressure near the coasts of Antarctica. At the same time, the balance of the wind stress over a topographic obstacle requires that the bottom pressure on the western side of the obstacle exceeds that on the eastern side. Thus, the wind variability over the ACC together with the above described topographic effects can lead to a variation in the meridional mass fluxes near bottom ridges that was demonstrated early by Stepanov [34, 35] can impact the development of ENSO effects (Figure 1).

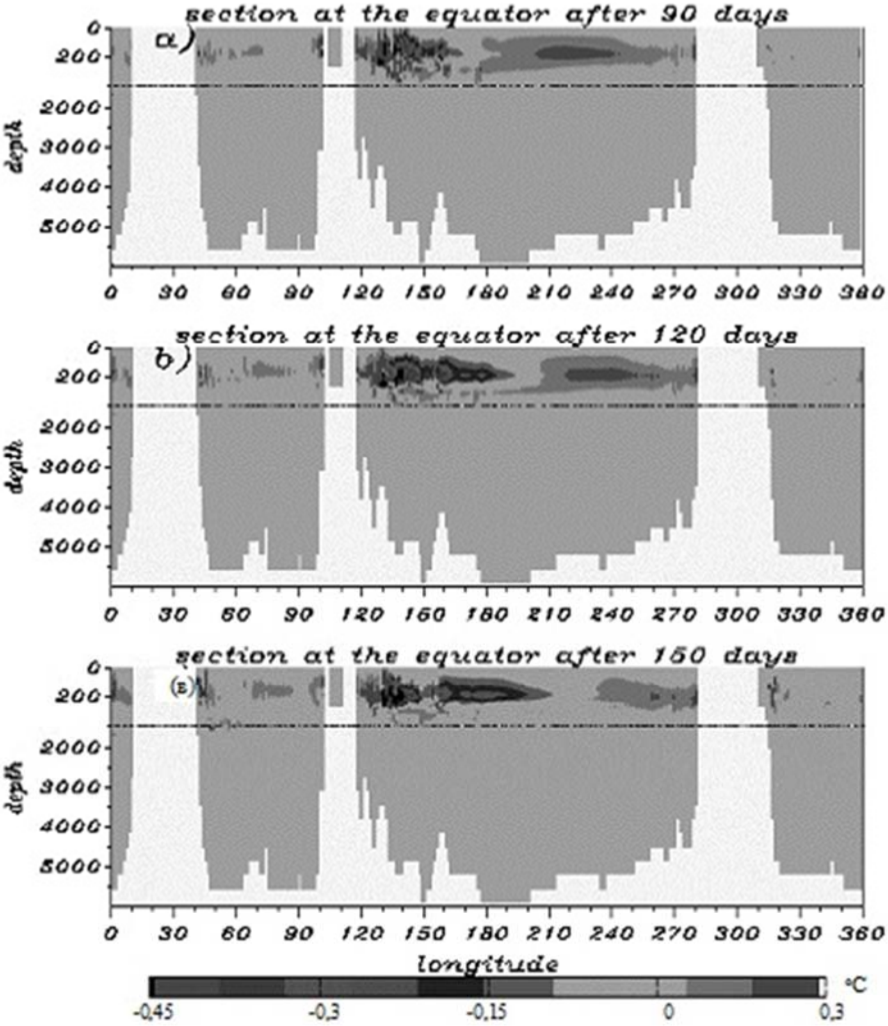


Figure 1. Field of the modelled temperature anomalies (°C) over a section along the equator from [34] for three time moments: t=90, 120, and 150 days (a, b, and c, respectively) as a result of the propagation of a signal from the Southern Ocean. In the experiment a perturbation in the Pacific Ocean in the latitudinal zone between 47° and 37°S was defined as a uniform by depth and latitude perturbation of the meridional velocity corresponding to the total equatorward meridional flux. The model perturbation of the meridional component of the velocity field was corrected so that the total meridional mass flux was zero in the entire perturbation zone of the Pacific sector. The dotted line indicates a depth of 300 m.

Therefore the change of atmospheric conditions over the ACC, and particularly over the region upstream of the Drake Passage, can substantially influence the bottom pressure on the western side of the Drake Passage and a balance between the wind stress and form stress in the Drake Passage that can impact the variability of the meridional mass fluxes in the Pacific sector of the Southern Ocean. The model effect of this variability on ENSO is seen in Figure 1. The next section describes the plausible atmospheric conditions over the ACC favourable to amplify ENSO events. Since, as it was shown by Stepanov [34, 35], there is the time lag of 4–6 months between the variation of $M(t)|_{\varphi=40S}$ in the winter–spring season of the Southern Hemisphere and the maximum phase of ENSO development (which is determined by the time needed to transport the density anomalies appearing in the Southern Ocean to low latitudes by means of a wave mechanism described by Ivchenko et al. [14, 15]), therefore we have to pay attention to the atmospheric variability occurred about 4 months before the maximum phase of ENSO development.

4. The Southern Ocean as a Main Trigger of the Development of the Maximum Phase of ENSO During Warm Epochs

Stepanov [36] has shown which sea level pressure (SLP) pattern settled over the region upstream of the Drake Passage are correlated with ENSO events. In spite of almost zonal structure of the field of SLP over the ACC there is a high variability of the SLP upstream of the Drake Passage. It means that sometimes in this region instead of a usual low atmospheric pressure an anticyclonic/cyclonic atmospheric circulation pattern can be settled over this area. Correlation between the monthly average SAM index and SLP shows that the wind strength over the ACC is maximal when a low SLP is settled over the southern part of the Southern Ocean, particularly near 250-260°E, and vice versa [36].

Since the region upstream of the Drake Passage is an important from point of view a balance between the wind stress and form stress in the Drake Passage therefore there is a link between SLP pattern settled over the region upstream of the Drake Passage and the variability of the meridional mass fluxes in the Pacific sector of the Southern Ocean. Stepanov [36] has demonstrated that a high atmospheric pressure settled over the upstream of the Drake Passage region can "lock" the Drake Passage resulting in equatorward meridional flux anomaly in the Pacific sector of the Southern Ocean that, as was shown by Stepanov [34, 35], leads to conditions favourable to trigger warm ENSO. While a low pressure developed over this region "accelerates" the wind over the ACC leading to poleward meridional flux anomaly in the Pacific sector of the Southern Ocean that results in the development of cold ENSO. There is a lag between the changes of atmospheric conditions over the ACC (4-6 months) that is in accordance with previous finding [34]. Such SLP anomalies over the upstream of the Drake Passage region have been observed 3-5 months before the development of maximal phase of the ENSO in 1988, 1992, 1994, 1995, 1997, 1998, 2000, 2002, 2006, 2007 and 2010 [36]).

Stepanov [34] has shown that there is negative significant correlation between SAM index and $M(t)|_{\varphi=40S}$ variability (or NINO index), however the correlation coefficient between SAM index and NINO index is low (~-0.2). Therefore Stepanov [36] suggested other index. There is a zone of divergence (convergence) of the meridional mass fluxes in the latitude zone of 47°–48°S. The direction of the water mass motion cyclically changes with a period determined by the external forcing [34]: for the case of weak (strong) wind, water masses move to the equator (to the pole), to the north of these zones, while, south of these zones, they move to the pole (equator). This latitude zone of 47°–48°S is the boundary between the regions, in which atmospheric cyclones south of 48°S and anticyclones north of 47°S propagate in the eastern direction over the ACC generating fluctuations in the fields of the atmospheric pressure and wind velocity. Near the western coast of the Southern America at 30°S there is a region of high atmospheric pressure and an analysis of ERAInterim SLP shows that sometimes the area of high pressure crosses the latitude circle of 47°S between 260-290°E and penetrates to the south, in the region upstream of the Drake Passage. Therefore Stepanov [36] suggested to use the averaged sea level pressure anomaly along 280°E between 35°S and 45°S, Δp, as a good indicator predicting changes in atmospheric pressure field over the ACC. The correlation coefficient between NINO3.4 index (SST averaged in area of 5°-5°S; 170-120°W) and Δp time series for 1989-2011 period is about 0.6 (Δp leads 4 months), however the contribution of the 1989-1999 period to this correlation is slightly bigger: for 1989-1999 period the correlation between the above mentioned time series is about 0.65, while for 2000-2011 or 2000-2008 periods this correlation is lower ~0.5 (the test that determines the significance of the difference between these correlation coefficients, demonstrates that this difference is not statistically significant).

Similar correlation analysis with NINO3.4 and 5-month running average SOI index shows similar features: the negative correlation coefficient between these time series with lag of 4 months (SOI index leads the NINO3.4) is decreased from 0.5 (for 1989-1999 period) to 0.3 (for 2000-2011 period, note that for 2000-2008 period the correlation is lower: -0.2) yielding the value of the correlation coefficient of about -0.4 for whole 1989-2011 period. It is worth noting that SOI and NINO3.4 indexes vary in phase rather than SOI index leads the NINO3.4: the maximal correlation between SOI and NINO3.4 indexes is obtained for zero lag: it is equaled to about -0.7 and -0.6 for 1989-1999 and 2000-2011 periods respectively, while the correlation coefficients between these time series when either SOI leads or lags NINO are less (~-0.4). Similar dependences are obtained for the values of correlation coefficients between SOI and NINO4 time series, but they are not so dramatically expressed.

Thus, higher correlation between NINO3.4 index and Δp (~0.5) and lowest ones between SOI and NINO indexes after 2000 (~0.3) says that the variability over the Southern Ocean recently contributes more in the processes of ENSO developments than it was before the 2000s.

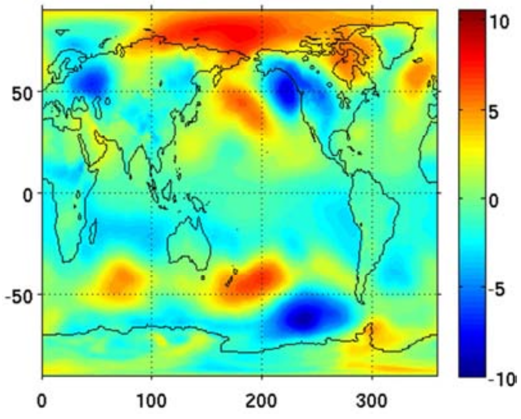
Stepanov [36] has shown that atmospheric variability near Antarctica has not been substantially changed: only over the upstream of the Drake Passage region a high variability of the SLP became more localized near the Drake Passage, while in the Pacific tropics, the SLP variability decreased in the 2000s: in the 2000s the atmospheric pressure patterns show weaker variability (~70% from 1989-2011 mean variability), while during 1989-1999 period the area of higher atmospheric pressure variability (>100% of 1989-2011 mean one) occupied almost the whole tropical Pacific. Since the atmospheric variability in moderate and high latitudes of the Southern Hemisphere almost did not change that assumes the effect of processes near Antarctica so far impact the tropical region of the Pacific Ocean with the same efficacy. Lower correlation between NINO and SOI index in comparison with the value of the correlation between NINO index and Δp time series after 2000 can be explained by the fact that the contribution of the interaction of atmosphere with the ocean in the tropical Pacific has been decreased during that period while the processes occurred in the Southern Ocean continue influencing the tropics (see details in [36]).

The analysis of the air pressure field in the southeastern part of the Pacific Ocean by the EOF decomposition method revealed the additional mechanism explaining the variations in ENSO parameters in the 2000s. According to [36] the instability of the air jet stream over the Southern Ocean region leads to the formation of the above described air pressure field anomalies favourable to ENSO development. It was shown that this instability becomes an essential process for the development of the ENSO maximum phase after 2002 and is 8 months ahead of the maximum phase of this event development, i.e., the time of this event coincides with the time of ENSO onset [20].

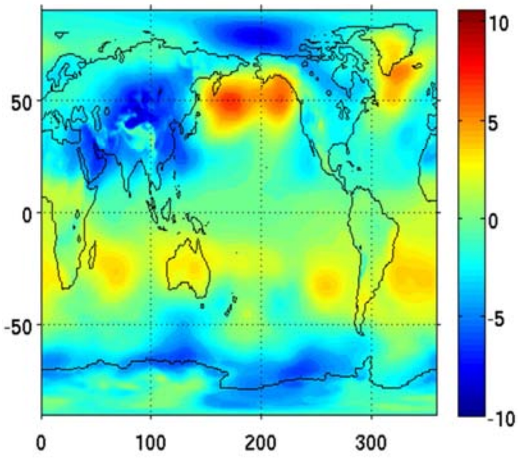
Due to the jet stream instability in the cold periods (when the value of the meridional shear of zonal wind is greater), over the area close to the Drake Passage high air pressure may set in more often; therefore, the number of ENSO warm events is greater than that of cold events. For example, as follows from the analysis of the NINO index, 15 warm and 11 cold ENSO events were observed in 1950–2002, and the number of warm and cold events was equal after 2002. The NINO index data agree with the analysis of the time series of the principal components from EOF analysis (PC2 and PC5 characterizing the zonal dipole pattern located close to the Drake Passage and the value of zonal wind speed over the Southern ocean, respectively, see [36]). These time series are asymmetric relative to the zero value. Skewness coefficients for the unsmoothed time series of PC2 and PC5 for the period of 1989–1997 are by about twice greater than for the period 1989–2013. Positive values of skewness coefficients mean that high air pressure sets in over the area upstream/near the Drake Passage more often.

5. Reasons for Amplified and Decayed ENSO Development

The above described mechanism of ENSO development allows explaining such, at a first glance, inexplicable phenomena, that the start of ENSO active development with abrupt stop in the middle of summer (or in early autumn). Such examples show the events in 2012 and 2014. From January to the summer of 2012 and 2014 everything looked like the ENSO event is developing, and the ENSO development in 2014 was very similar to the onset of very intense ENSO in 1997–1998 [26]. However, in 2014 ENSO turned out to be very weak whereas in 2012 it did not occur at all [38]. Stepanov [34] demonstrated that the variability in meridional mass flux in the Pacific sector of the Southern Ocean northward of 47°S significantly correlates with NINO not only from June to September (the correlation coefficient is >0.8) but also in March (the correlation coefficient is ~0.7) (in both cases this variability leads NINO index by ~3–4 months). Since the wave mechanism of the signal transfer from the Southern Ocean to the tropical Pacific described by Ivchenko et al. [14, 15] does not depend on the season, like in the above cases, the sea level pressure anomalies set in March affect the wind speed over the Antarctic Circumpolar Current. This leads to the variability in the meridional mass flux in the Pacific sector of the Southern Ocean which then affects the tropics (with the time lag of ~4 months). The analysis of sea level pressure from the ERA-Interim data reveals that low air pressure set in over the Antarctic Circumpolar Current near the Drake Passage in March in 2012 and 2014 (Figure 2a, c) and favoured the development (in 3–4 months) of negative temperature anomalies in the tropical Pacific. Therefore, in 2012 and 2014 the development of ENSO warm events in the central part of the tropics decelerated by July (according to the time lag needed for the signal from the Southern Ocean to reach the central tropics, see above). In July–October 2012 the distribution of air pressure in this region of the Southern Ocean corresponded again to the development of negative temperature anomalies in the tropical Pacific (Figure 2b). As a result, ENSO did not occur in 2012. However, in August–September 2014 high air pressure set in close to the Drake Passage (Figure 2d) and favoured the development of the ENSO warm event in 2014. This event was weaker than ENSO in 1997 because both in March and in the late summer–early autumn of 1997 (not shown) over the Antarctic Circumpolar Current near the Drake Passage high air pressure set in and favored the development of positive temperature anomalies in the tropical Pacific and, hence, the development of the warm ENSO event. Thus, the superposition of contributions of the processes that occur in the Southern Ocean in spring and late summer–early autumn and exert considerable influence on the ENSO development, can explain why both weak and intense ENSO may develop under the same initial conditions.



a)



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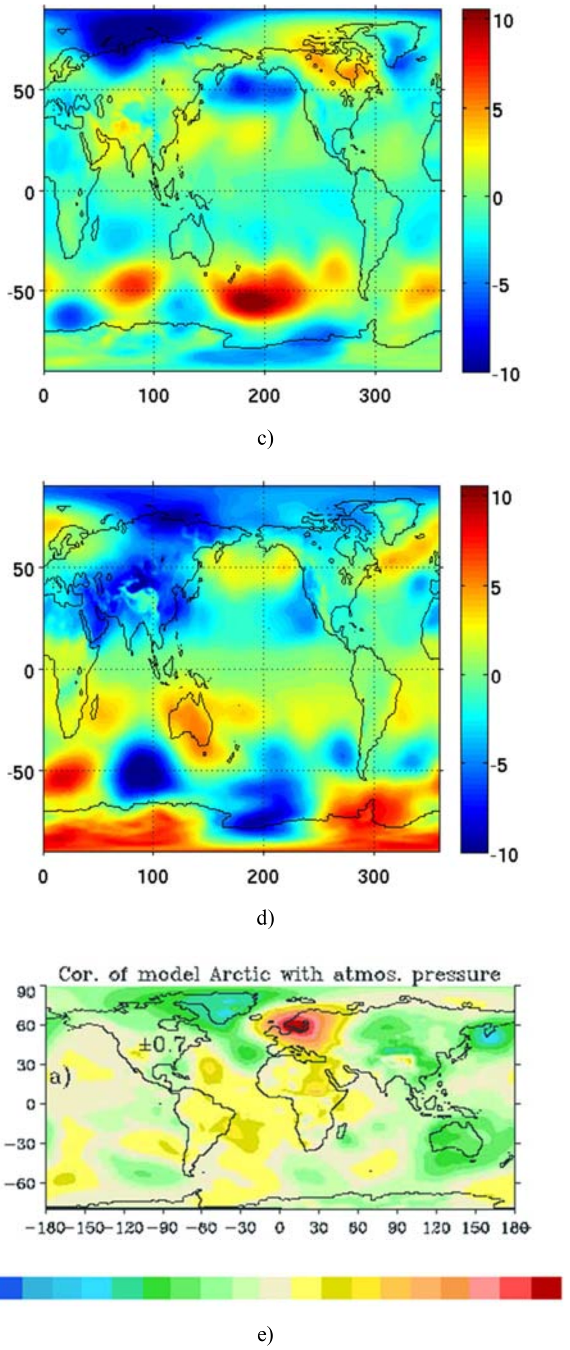

Figure 2. *Anomalies of sea level pressure (hPa) averaged for March–April in (a) 2012 and (c) 2014, and (b) July–October of 2012 and (d) August-September of 2014, and (e) correlations of atmospheric sea level pressure with modelled Arctic mean ocean bottom pressure (the scale bar represents the range marked over North America).*

As was mentioned in introduction, the mass lost from both polar regions converge in the tropical Pacific. The above presented results explain this link between the Southern Ocean and the tropical Pacific. The Arctic cannot impact directly the tropical Pacific since the variability of the transport through the Bering Strait (less than 1 Sv, 1Sv=10^6 m^3/s) unlikely can be significant for such link shown by Hughes and Stepanov [13]. Therefore the link between the Arctic and the Pacific Ocean can be carried out only due to a change of a global atmospheric circulation. Figure 2 (e) shows global correlations between the mass variability in the Arctic and the sea level pressure in different regions of the Earth. Particularly, the mass lost from the Arctic is correlated with the high sea level pressure over the area upstream the Drake Passage. That is, as was shown above, these atmospheric conditions are favourable for the increased water mass in the tropical Pacific due to the variability in the meridional water flux in the Pacific sector of the Southern Ocean.

6. Discussion and Summary

The paper presented the results of the model study of the role of the Southern Ocean in the processes of interaction of the ocean-atmosphere system on short time scales impacting El Niño events. It asserts that the atmospheric variability over the Antarctic Circumpolar Current can considerably intensify the ENSO events. Using the analysis of sea level pressure fields, this hypothesis enables explaining why after 2000 it has become impossible to predict the ENSO events using the predictors proposed by McPhaden [24]. It is demonstrated that the maximum phase of the development of the majority of ENSO is associated with variations in atmospheric conditions in July–October near the Drake Passage when the atmospheric variability over the Southern Ocean is especially high.

In the 2000s due to higher sea surface temperature in the tropics more homogeneous dynamic conditions are formed; hence, after the beginning of ENSO development in the central equatorial part of the Pacific Ocean the subsequent atmosphere-ocean interaction in the tropics is weakened and the intense ENSO event cannot develop in the east of the tropical Pacific. As a result, the frequent occurrence of El Niño Modoki events is observed which are characterized by the development of sea surface temperature anomalies in the central equatorial Pacific.

The significant correlation between the coefficient PC5 characterizing the value of zonal wind speed over the Southern ocean and the NINO index started in 2002. It indicates that the instability of the air jet stream over this region in the warm periods can considerably affect the formation of ENSO. Due to this instability of the air jet stream formed over the area near the Drake Passage, either high or low air pressure can set in that favours the development of warm or cold events of ENSO, respectively.

Based on the difference in the values of skewness coefficients for the PC2 and PC5 for warm and cold periods, the hypothesis is made which explains why the number of ENSO warm events is greater in the cold periods (compared with cold ENSO).

The EOF analysis has revealed the best possible ENSO predictor for warm periods: this is PC5 which highly correlates with NINO3.4 (with coefficient ~0.8) with a lead time of 8 months. This means that the processes in the Southern Ocean during warm periods caused by the instability of the air jet stream significantly contribute to the development of the ENSO maximum phase.

The ENSO events should be considered as the effects of variations in the global meridional atmospheric circulation when the tropics and high latitudes interact with each other, but not as a local phenomenon in the tropics. The interaction between the tropics and high latitudes depends on random processes which are always present in the case of atmosphere-ocean interaction (e.g., see [9, 10]). Therefore, the time lag between atmospheric variations over the Southern Ocean and the time of the development of the ENSO maximum phase varies in a wide range (3–5 months).

It is noteworthy that results from Stepanov and Hughes [33] demonstrated that the large-scale mass exchange is observed not only between the Southern and Pacific oceans. There are also mass exchanges at shorter time scales (with the periods from several days to 3 months) in the Atlantic and Pacific basins, and there are slightly weaker ones in the Indo-Pacific region. So, it is quite likely that this exchange may also result in the formation of certain signals in the tropics and mid-latitudes both in the Indian and Atlantic oceans. The hint of such signal in the Indian Ocean can be seen in Figure 1 presenting temperature anomalies on the zonal cross-section along the equator in the Indian and Pacific oceans. The formation of the anomalies is caused by wind variability over the Antarctic Circumpolar Current jointly with the effect of topography although in this experiment the forcing was specified only in the Pacific sector of the Southern Ocean. It is quite probable that the interseasonal variability in the tropical atmosphere (the Madden–Julian oscillation [23]) and, for example, the variability in the subtropical dipole in south of the Indian and Atlantic oceans which affects ENSO and, according to Terray [39], is caused by the atmospheric variability in the Southern Hemisphere mid-latitudes, are a result of such global inter-basin mass exchange. Further studies are needed to test this hypothesis.

The mechanism of ENSO development described in the paper allows explaining such phenomena, that the start of ENSO active development with an abrupt stop in the middle of summer or in early autumn.

The results presented here are in good agreement with [4]. Byshev et al. [4] demonstrated that ENSO warm events are accompanied by the global atmospheric oscillation, when high air pressure is formed in the equatorial-tropical latitudinal zone (~45°N–45°S; 60°W–180°) and low air pressure develops along the outer boundaries of this region (in the zone with the width of $(2–3)\times10^3$ km). Thus, the value of the meridional gradient of zonal wind speed over the Southern Ocean increases, and favourable conditions are formed for the instability of the air jet stream over the Antarctic Circumpolar Current and for the formation of the blocking anticyclone over the southeastern part of the Pacific sector of the Southern Ocean.

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