Global Atmospheric Oscillation in Geopotential Fields of the Free Atmosphere

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Abstract. The three-dimensional structure of geopotential anomalies arising in the troposphere and the lower stratosphere during a Global Atmospheric Oscillation (GAO) is studied. It was previously detected in temperature and pressure fields. It has been established that these anomalies have a high statistical significance. This serves as another formal evidence of the GAO authenticity. In the troposphere (850–100 hPa) and in the lower stratosphere (100–10 hPa) the structure of GAO substantially changes in comparison with the near-surface fields, gradually acquiring a zonal character. Apparently, this is due to the fact that the atmospheric polar tide, caused by the Chandler wobble of the Earth's poles and lunar-solar nutation, bends around the Earth almost unhindered, experiencing only a small topographical impact from the continents.

1. Introduction
In studies of the dynamics of the atmosphere and the ocean, the notion that the El Niño – Southern Oscillation (ENSO) phenomena that develop in the equatorial strip of the Pacific Ocean influence the climate almost everywhere on Earth is widely used. This, as a possible circumstance, was also mentioned by the pioneers of the ENSO research J. Walker, G. Berlage, A. Trope, and K. Wyrtki. Then works appeared in which it was established that at different phases ENSO develop their specific anomalies in areas of the Earth often very remote from the tropics of the Pacific Ocean. The first publications were probably [1, 2]. Now there are so many such works that it is impossible to list all of them in any journal article.

Although no direct evidence was presented that just ENSO was the cause, and these specific anomalies were the result, but the relationships found were interpreted precisely in the spirit of such causality. For example, K. Trenberth - one of the most well-known modern ENSO researchers - begins his article [3] with the phrase: "One of the most prominent sources of interannual variations in weather and climate around the world is the ENSO phenomenon".
This interpretation may be understood in a manner that says “tail” (ENSO) “sees the dog” (weather and climate everywhere on the Earth). Byshev et al. [4-6] have questioned this opinion. They carried out a thorough analysis of the differences in the global spatial structure of the near surface temperature (NST) and sea level pressure (SLP) fields at the extreme phases of ENSO processes, i.e. the occurrence of El Niño and La Niña, as well as in the period preceding these events. For this purpose, the most complete of the arrays of meteorological observations available at that time were used. As a result, the spatial structure of NST and SLP anomalies was found, called Global Atmospheric Oscillation (GAO). This structure is symmetric about the equator, despite the differences in the configuration of the continents within the Northern and Southern Hemispheres. It covers almost the entire Earth, including the anomalies attributed to the manifestation of long-range links with the ENSO. These anomalies are detected at the time of appearance far before either El Niño or La Niña event occurs. Therefore, the direct dependence of these anomalies on ENSO events may hardly be considered correct. From all this it was concluded that the GAO was primary and the ENSO was secondary, i.e. "The dog wags its tail, and not the tail wags the dog".

In a later work of Byshev et al. [7], the Student’s t-test was applied to the differences in the spatial structures between the El Niño and La Niña events. The test showed that the differences in the values of SLP and NST, characteristic of the events of El Niño and La Niña, are statistically highly significant almost everywhere on the globe, and not only in the tropics of the Pacific Ocean (an area of the ENSO). Thus, an additional formal proof of the real existence of the GAO was obtained. Although the problem of the GAO and ENSO causality was not specifically considered in [7], based on the above its authors formulated and substantiated a working hypothesis that the ENSO should be considered as a structural element of the GAO in the Pacific region.

Careful computations of the ENSO and GAO power spectra were made in [8-10]. These computations reveal that a part of these spectra, corresponding to the periods from two years to one decade, is prominent by the existence of several narrow bands of increased spectral density centered at the subharmonics 2:1, 3:1, and 4:1 of the Chandler wobble in the Earth’s pole motion (~ 1.2 years), the superharmonics 1:2, 1:3, and 1:4 of the luni-solar nutation of the Earth’s rotation axis (~ 18.6 years), as well as the superharmonics 1:2, 1:3, and 1:4 of the 11-year cycle of the Sun spots. The existence of similar bands in the ENSO power spectra was recognized many years ago [11, 12]. However, it turns out that the above spectral bands have been also seen in spectra of the GAO characteristics outside of the tropics. Moreover, the respective climatic variations are globally synchronized. The synchronization takes place because the above-mentioned external periodicities must influence short-term climatic variations globally. It is very probable that the periods of the external periodicities indicated are incommensurable with each other. Therefore, if these periodicities actually influence short-term climatic variations, they would have to do it discordantly. As a result, no resonances can exist which could make the affected climatic variations chaotic. A linear dependence of the logarithms of serial numbers of the spectral bands on the logarithms of the band magnitudes, as well as a linear decrease in the accumulated sum of the squared autocorrelations of the respective atmospheric characteristics confirm that the dynamics of the interannual to decadal climatic variations are not chaotic.

In [13] it was established that an integrity named GAO coevs both the ENSO and all its so-called extratropical teleconnections revealed as the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the Northern Hemisphere annular (NHA) mode, as well as the Pacific – North American (PNA) pattern, and their analogs in the Southern Hemispher in the interannual timescale. Investigations of the GAO indices revealed that the GAO extratropical components may be real irrespective of the ENSO, while the latter accompanies the GAO in all cases. Moreover, in view of a general eastward propagation of the GAO as a spatial structure, some of its extratropical components show their features before an El Niño (La Niña) begins to form.

The purpose of this work is as follows: without discussing the problem of causality, which requires special consideration due to its extreme complexity for such a nonlinear dynamic system as the
variability of the global climate (see paper on this subject [14]), to trace the manifestation of the GAO spatial structure throughout the entire troposphere and lower stratosphere.

2. Materials and methods of the study
The baseline data for this work were reanalyses of 20thC_ReanV2c, ERA-20C, and NCEP/NCAR global monthly fields of geopotential height and air temperature on standard isobaric levels of the atmosphere, as well as SLP. The NOAA CIERES 20th Century Global Reanalysis Version 2c (20thC_ReanV2c) data are specified at 2°x2° regular grid nodes on 24 main isobaric levels from 1000 to 10 hPa for the period 1851-2014 [15]. The ECMWF ERA-20C data are specified in the regular grid of 1°x1° on 37 main isobaric levels from 1000 to 1 hPa for 1900-2010 [16]. The NCEP/NCAR Reanalysis data are specified at regular grid points of 2.5°x2.5° on 17 basic isobaric levels from 1000 to 10 hPa for 1948-2018 [17].

For each time series of the listed data sets at each grid point, the average seasonal signal of the considered climatic characteristics was calculated, which was then subtracted from the initial data. According to the fields obtained in this way, the geopotential height and air temperature anomalies were calculated using the Extratropical GAO index (EGAO) [10]. It is calculated as the combination of the normalized (by standard deviations of their time series) anomalies of the average SLP in six geographical areas coinciding with the extratropical extremes (maxima and minima) in the GAO field: (55°-65°N, 95°-85°W) + (65°-55°S, 95°-85°W) − (45°-55°N, 175°-165°W) − (45°-55°N, 15°-5°W) − (55°-45°S, 15°-5°W) − (55°-45°S, 175°-165°W). To remove high frequency dynamics, the EGAO time series were smoothed by the three months running mean. Linear trends were removed from the obtained EGAO time series by the least squares method in order to suppress the interdecadal climate changes. The positive and negative GAO phases, corresponding just timely to the events of El Niño and La Niña, were determined by the centered and normalized EGAO index so that the value of this index either exceeded the sub-series +0.5 for 5 months or more, or it was less than -0.5, respectively.

The sequences of the fields of the anomalies of the geopotential height and air temperature for the standard isobaric levels, corresponding in time to the positive and negative GAO phases, were selected, and their mean differences were calculated as described in [13]. In addition, the standard deviations of the global fields of the indicated characteristics for the time of each such specific event from the corresponding average field at the time of the positive and negative GAO phases were calculated. Then, for each node of the regular grid, the Student’s t-test was calculated, estimating the statistical significance of the difference from zero of the average difference of the specified global fields at this node of the computational grid.

3. Results
A comparison of the global fields of geopotential height differences and air temperature anomalies between the opposite phases of the GAO, calculated in relation to the time evolution of the above EGAO index, constructed according to the indicated reanalyses, showed their close similarity. Based on this, these fields are illustrated in the paper only by the example of NCEP/NCAR Reanalysis, which contains the sample: 20 positive and 18 negative GAO phases for 1948-2018.

Figure 1 shows the average field of differences in anomalies of the air temperature at the level of 1000 hPa (a) and the corresponding field of values of probabilities according to the Student’s t-test (b) between the two opposite phases of the GAO, which coincide with El Niño and La Niña. The region of the largest temperature differences in modulus (more than 1°C) is visible in the east and in the center of the equatorial zone of the Pacific Ocean, i.e. in the canonical area of the ENSO. The probability that these differences are non-zero, in the center of this area exceeds 99%. This is to be expected according to the definitions of the events of El Niño and La Niña as components of the GAO adopted in this work.
Figure 1. Fields of differences in air temperature (a) and geopotential (c) anomalies at the level of 1000 hPa between the opposite phases of the GAO and the corresponding probability fields according to the Student's t-test (b, d).

The probabilities of non-zero differences are quite large (95% and higher) not only in the canonical El Niño area. Thus, in the south of the Pacific Ocean, where the temperature difference between the events of El Niño and La Niña (the opposite phases of the GAO) is, on average, +0.5 °C, these probabilities exceed 99%. As one can see in Figure 1, the same significant positive temperature differences (+0.5 °C) between the opposite phases of the GAO occur in the near-coastal region of Alaska and western Canada symmetrically located relative to the equator. More than 95% of the probabilities of the positive temperature differences are more seen in the other three areas: 1) in the Indian Ocean, 2) in the tropics of the Atlantic Ocean and on the Atlantic coast of Brazil, 3) in the northern and southern Africa.

Statistically significant negative temperature differences (with probabilities greater than 95%) are observed in several geographic areas. Two of them are the middle latitudes of the western part of the Pacific Ocean. These two areas are located symmetrically with respect to the equator in relation to each other.

Turning to the manifestations of the GAO in the geopotential height fields (Figure 1 c,d), we note that at the level of 1000 hPa the GAO field is very similar to that characteristic of the field of mean SLP anomalies difference shown in figures in [4, 7, 13]. Negative values (up to 30 m by module) in the field of Figure 1c, whose probabilities reach 99% (Figure 1d), cover almost the entire water area of the Pacific Ocean to the east of the date line and the middle latitudes of the Atlantic Ocean, making up an X-shaped structure.

Positive differences (up to 10 m) almost completely cover the tropics of the Indian and Atlantic Oceans, as well as Africa, the archipelago of Indonesia, most of Australia, and the adjacent area of the Pacific Ocean within ±30° latitude. The probability values of the geopotential differences in these areas reach 99% due to the relatively small variability of the geopotential of the 1000 hPa level in the tropics. Outside the tropics, statistically significant (with probabilities of more than 95%) regions of the positive difference are in Canada and in the southeast Pacific. Although the average geopotential difference in the southeast Pacific region is very large (up to 30 m), it loses its significance from the point of view of statistical significance due to the enormous variability of the geopotential in this region, both real and caused by the errors of observations. Also statistically significant are the
branches of the X-shaped structure, going from its center to the side to: Europe, South Atlantic, New Zealand, and the Chukotka Peninsula.

For the level of 850 hPa (Figure 2a), the spatial structure of the field of the average difference in the geopotential height anomalies remains, in general, similar to that of the 1000 hPa level. However, the center of the X-shaped structure of the negative difference at the level of 850 hPa is already beginning to collapse. The average geopotential difference directly in the canonical region of El Niño (the center and east of the near-equatorial area of the Pacific Ocean) is less than 5 m in absolute value, i.e. less than for the level of 1000 hPa, and it is already statistically insignificant (probability values less than 80%) (Figure 2b). On the other hand, the values of the positive geopotential difference and the corresponding probability values in the Indian Ocean, the tropics of the Atlantic Ocean, and in the region of Indonesia slightly increase. The regions of positive geopotential differences in the north of Canada and in the southeast of the Pacific Ocean are also somewhat intensified.

**Figure 2.** Fields of differences in geopotential anomalies at the levels of 850 hPa (a) and 700 hPa (c) between the opposite phases of the GAO, and the corresponding probability fields according to Student’s t-test (b, d).

For the level of 700 hPa (Figure 2c), the spatial structure of the field of the average difference of the geopotential height anomalies changed to a more zonal one. The geopotential anomalies in the center and east of the equatorial Pacific Ocean are already positive. Therefore, the tropical belt at the level of 700 hPa has positive anomalies of the geopotential height differences between the opposite GAO phases.

For the level of 500 hPa, the global structure of the mean field of the geopotential difference is shown in Figure 3a. It is almost zonal, which corresponds to the results obtained in [18]. In the entire tropical belt, the average difference of the geopotential height exceeds 10 m, and the values of its probabilities exceed 95% (Figure 3b). Outside the tropical belt in the north and south of the Pacific Ocean, there are areas of very large negative differences of the geopotential (up to 30 m in absolute value) with a high level of the statistical significance (over 99%), as if preserved from the ends of the X-shaped structure described above for the geopotential field of the 1000 hPa level. The branches of the X-shaped structure stretching to the north and south of the Atlantic are also visible, and they are statistically significant. Two areas of positive mean geopotential differences corresponding to the anticyclones mentioned above in the south of the Pacific Ocean and Canada became even more
powerful and statistically significant (the probabilities are over 99%). Thus, the reduction of the influence of the location of oceans and continents on the spatial structure of the GAO has an effect. Apparently, this is due to the fact that the atmospheric polar tide caused by the Chandler wobble of the Earth’s poles and lunisolar nutation bends around the Earth, experiencing only a small topographic impact from the continents.

Figure 3. Fields of differences in geopotential anomalies at the levels of 500 hPa (a) and 100 hPa (c) between the opposite phases of the GAO, and the corresponding probability fields according to the Student’s t-test (b, d).

Figure 3c shows the average difference field for the level of 100 hPa. The zonal structure of this field is even more pronounced than for the level of 500 hPa. In the tropical belt, positive geopotential differences exceed 30 m. All other areas of the significant differences also increased. However, due to much greater variability of the geopotential height field itself for the level of 100 hPa compared to the field for the level of 500 hPa, the values of the corresponding probabilities have somewhat decreased (Figure 3d), although the fairly high statistical significance of some areas of the largest values of the geopotential difference in the middle and high latitudes is preserved.

The field of average difference for the level of 50 hPa (Figure 4a) does not qualitatively differ from the field for the level of 100 hPa (Figure 3c). However, the statistical significance of regions in the 50 hPa level field is decreasing (Figure 4b). For the level of 10 hPa (Figure 4c), the formal statistical significance is lost almost everywhere (Figure 4d), but some elements of the GAO zonal structure are retained at this stratospheric level.

Thus, the GAO spatial structure gradually becomes zonal with height up to the level of 10 hPa, where it is destroying. The absence of such zonal structure in the GAO induced anomalies of surface fields is easily explained by the significant influence of the oceans and continents on it. In papers [10, 19] it is shown that a polar tide in the Pacific Ocean caused by the Chandler wobble of the Earth’s poles and the lunisolar nutation of the Earth’s axis of rotation transformed after its reflection from the western coasts of North and South America and turned into a wave running west along the equator. This wave gives rise to the El Niño’s positive anomalies of surface ocean waters.
Figure 4. Fields of differences in geopotential anomalies at the levels of 50 hPa (a) and 10 hPa (c) between the opposite phases of the GAO, and the corresponding probability fields according to the Student’s t-test (b, d).

Since the Chandler wobble in the Earth’s pole motion is one of the external drivers of the climate system, it excites tides propagating eastward not only in the extratropical oceans, but also in the atmosphere. The phases of these tides are opposite in the Northern and Southern Hemispheres. Therefore, a general eastward zonal propagation must be a property inherent to the GAO-field. And the spatial structure of the GAO as a whole propagates eastward [13]. Continents affect the west-east distribution of the atmospheric tidal wave as topographic obstacles. However, this influence is much less significant than the reflection of the oceanic pole tide from the coasts of America.

4. Conclusions
It was found that the Global Atmospheric Oscillation, which was previously detected in sea level pressure and near surface temperature fields, extends to the entire troposphere and the lower stratosphere (up to 10 hPa), maintaining the symmetry of its spatial structure with respect to the equator.

The statistically significant differences between the opposite phases of the GAO in the air temperature field at the level of 1000 hPa are quite similar to those that were revealed earlier in the field of near surface temperature. The differences in the field of geopotential height at the level of 1000 hPa form an X-shaped structure similar to that previously found in the field of sea level atmospheric pressure. The branches of this X-shaped structure extend to the middle and high latitudes of the Pacific and Atlantic Oceans and lock themselves over Eurasia and the south of the Indian Ocean. However, the last statement has not been confirmed by Student’s t-tests due to the large variability of the geopotential in this area.

The spatial structure of the GAO gradually becomes zonal with height. The absence of such zonal structure in the GAO induced anomalies of surface fields may be explained by the fact that the oceans and continents have a significant influence on it.

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