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# Simulation of the influence of the ocean and the El-Niño – Southern Oscillation phenomenon on the structure and composition of the atmosphere

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Abstract. The influence of El-Niño and La-Niña on the Arctic stratosphere is studied. Sea surface temperature (SST), potential vorticity, air temperature, ozone mixing ratio, and column ozone ERA Interim data are analyzed for 1997, 1999, and 2016. It is shown that El-Niño leads to a series of sudden stratospheric warmings and, consequently, to instability of the polar vortex and to an increase in column ozone, whereas La-Niña leads to a stable polar vortex and low temperatures in the stratosphere and, therefore, to a decrease in column ozone. The influence of SST and CO<sub>2</sub> levels on the air temperature in the troposphere and stratosphere, and ozone content from 1980 to 2015 is also studied. It is shown that there is warming of the ocean and the troposphere, as well as cooling of the stratosphere. It is also shown that the changes in air temperature in the troposphere are mainly due to changes in SST, whereas for the stratosphere the impact of CO<sub>2</sub> variability prevails. It is also shown that ozone content varies little.

## 1. Introduction

In the Earth's atmosphere there are a lot of processes caused by the interaction of the atmosphere and ocean. Among them, one of the most known events is the phenomenon of El-Niño, representing the current in the eastern part of the tropical region of the Pacific Ocean. The El-Niño is a regional phenomenon, and it leads to a rise in the temperature of the ocean top layer, but the influence of this phenomenon is revealed on a global scale [4]. The El-Niño atmospheric component is the Southern Oscillation [1,4] at which there are fluctuations of atmospheric pressure between the eastern and western parts of the Pacific Ocean. Because of low pressure in the eastern part of the Pacific Ocean, there begins deep convection and easing of trade winds.

La-Niña represents a cold phase of this phenomenon, at which there is a temperature downturn in the ocean top layer [4]. Thus, the atmospheric pressure increases, and the convective processes stop.

An important dynamic process occurring in a polar stratosphere is the circumpolar vortex, which has an essential influence on the temperature and gas structure of the stratosphere of polar areas. The stability of a circumpolar vortex is defined by the stability of the carry zone of air weights, whereas the meridional carry leads to instability of this vortex [5]. The stability of a vortex also influences the maintenance of ozone and temperature: under the theory a circumpolar vortex exists longer, there will be an ozone hole, and below there will be temperature in a polar stratosphere [7].

The temperature of a polar bottom stratosphere is an important factor of reduction in the maintenance of ozone. The cold winter season with 1996 for 1997, which was a consequence of



lowered distribution of the wave activity, led to strengthening of the ozone destruction due to heterogeneous activation of the chloric and bromic gases and to easing movement of the planetary waves, whereas the warm winter season with 1998 for 1999 was characterized by a strengthened distribution of the wave activity [6]. The temperature in a stratospheric polar vortex defines the volume of stratospheric polar clouds, on which the force of destruction of ozone also depends. Easing of planetary waves can lead to the downturn of polar temperatures and easing of ozone carry, which can lead to tropical tropopause heating [6, 8].

Changes in the sea surface temperature (SST) leading to the meridional gradient of SST can have an essential influence on the stratosphere [7.] The SST meridional gradient has a stronger influence on the zone circulation than the SST global variability. This means that the SST gradient has a strong influence on the circumpolar vortex and the maintenance of ozone in the northern hemisphere. Also, it has been revealed with the assumption that reduction in the maintenance of ozone can cause the phenomenon of El-Niño - southern fluctuation, which causes redistribution of the heat streams in the ocean and atmosphere, whereas increase in the maintenance of ozone can provoke La-Niña [9]. It can lead to the transition of energy of ultra-violet radiation in the ocean, increasing its heat maintenance. Simulation has shown that the influence of the El-Niño on the parameters of the Europe ground climate is carried out through the stratosphere [10].

Increase in the CO<sub>2</sub> level leads to the fact that infrared radiation of the Earth is late an atmosphere, which leads to increase of average by the ground temperatures of the air [2,3]. As a result of the ocean surface heating, there are gradients of temperature and density which lead to various ocean currents. These currents have an essential influence on the weather and a climate of separate regions, and of the Earth as a whole [1].

In this article, results of two studies connected with the influence of oceanic processes on the atmosphere are presented. In the first study, data of reanalysis ERA Interim for 1997, 1999, 2010, 2011, 2015, and 2016 are analyzed. In the second one, results of numerical experiments by means of a chemistry-climate model (CCM) and data of reanalysis for the period with 1980 for 2015 are analyzed. The purpose of this work is revealing the interrelation of oceanic processes (the El-Niño and La-Niña) and structures of the bottom and average atmosphere.

## 2 Materials and Methods

The CCM model represents a combination of two parts: a dynamic part developed at the Institute of Numerical Mathematics of the Russian Academy of Sciences (INM RAS) and a chemical part developed at the Russian State Hydrometeorological University (RSHU) [11,12].

The resolution of this model is  $-5^{\circ}$  longitude and  $4^{\circ}$  latitude. The scope on longitude is from  $185^{\circ}$  W to  $180^{\circ}$  E, and on latitude, from  $88^{\circ}$  S to  $88^{\circ}$  N. On the vertical the number of levels of the model is equal to 39 (from 0 to 88 km or from the surface to a level of 0.003 hPa). Thus, the results of the simulation are interpolated in an isobaric system of coordinates on 31 standard isobaric surface. The quantity of units in the model is 72 on longitude and 45 on latitude. The time step is 6 minutes. In order to account for the temporal variability of the influencing factors, the external parameters are updated every six hours [11,12].

The chemical part of the model describes changes in the concentration of 74 basic gases which influence the maintenance of ozone in the atmosphere. The model solves the system of equations of carry of gas impurity in view of the photochemical interaction for a long-living gas impurity. For short-lived gases, the equations are solved not taking into account the atmospheric carry [11,12].

The model considers the interaction between the chemical and physical processes at each time step. The solar radiation streams first pay off. Thus, the current maintenance of ozone and the molecular dispersion of light are considered. These streams are used for the calculation of the photodissociation speeds of gases on which count the speeds of photochemical formation of gases. Thus, for the calculation the temperature values calculated in the dynamic part of the model are used. These speeds of chemical reactions allow one to model the evolution of ozone and other gases in the atmosphere [11,12].

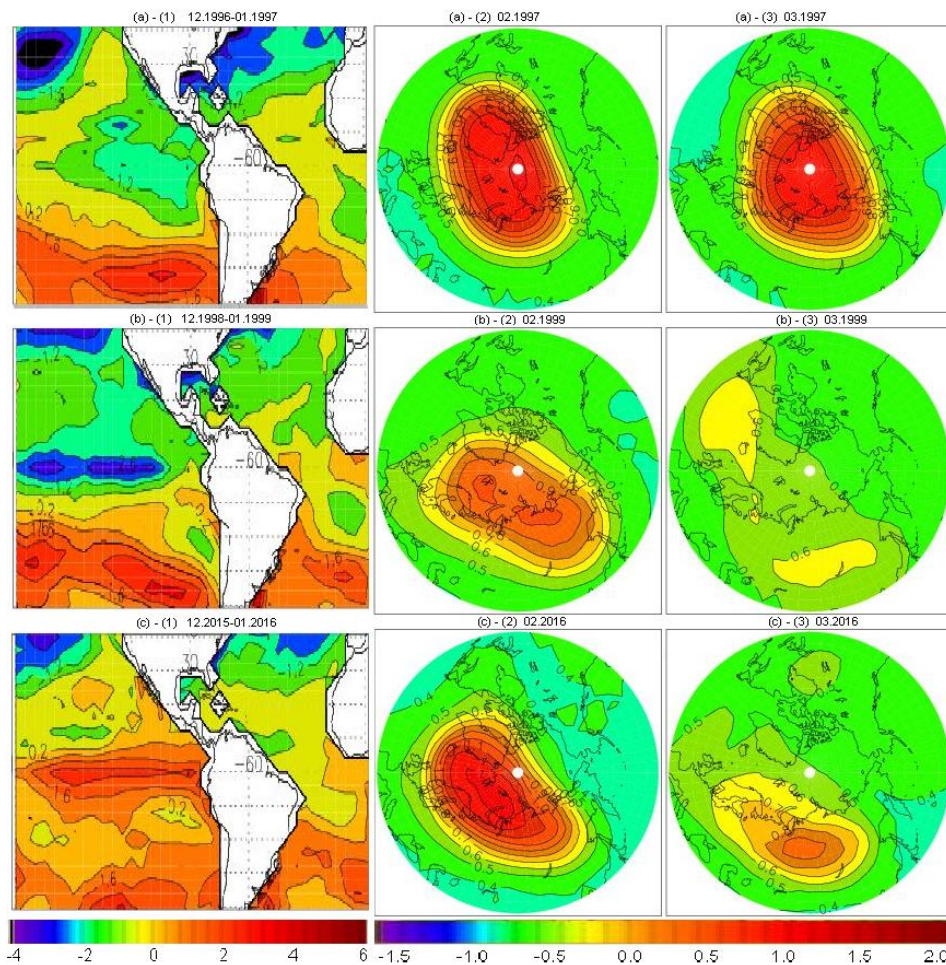
The basic method of the research is numerical simulation of atmospheric processes. As mentioned earlier, changes in the basic meteorological parameters (temperature and humidity of the air, atmospheric pressure, density of the air and speed of the wind) are described by the equations of thermodynamics, preservation water pair, the conditions of air, the indissolubility and movement of the atmosphere. These equations are solved only by numerical methods [11.] The non-adiabatic processes connected with the solar radiation, turbulence, convection and the influence of a spreading surface on the atmosphere, are considered by means of parameterization. The evolution of gas impurities is defined by means of the equations of their carry, which are also, certainly, solved by different methods. Thus, to solve the given problem the speeds of chemical reactions [11,12] are defined. Between the dynamic and chemical parts of the model there is an exchange of settlement data, which allows considering the influence of all these processes on each other [11,12].

The initial data for the meteorological parameters were taken from CIRA-86 and NCEP [14,15]. The ozone distribution data were taken from TOMS satellite data [16]. To study the influence of the ocean on the atmosphere, various experiments were performed. In each of these experiments, different data on the ocean surface temperature and the ice cover area, namely, data Met Office [17], data ERA Interim [13], and ERA20C and ERA5 [13] were used.

These results of the simulation, which could be compared with processes observed during simulation in the atmosphere, were used given reanalysis data about the temperature, wind speeds, the concentration and total column of ozone: MERRA, MERRA2 [18], ERA Interim, ERA20Century, ERA5 [19], JRA [20], with which the simulation results were compared. Thus, in MERRA, ERA, and JRA there are 25, 21, and 21 vertical levels, respectively. Also, data on the total column of ozone were used. Reanalysis data led to a simulation grid (72 units on longitude, 45 units on breadth, and 31 level on the vertical) for a comparison with the simulation results. The simulation was carried out for the period with 1979 on 2015. For reanalysis data MERRA the period with 1979 for 2015, for MERRA2 with 1980 on 2016, for ERA Interim and JRA with 1979 on 2015, for ERA20Century with 1979 on 2010, and for ERA5 with 2010 on 2016 were chosen.

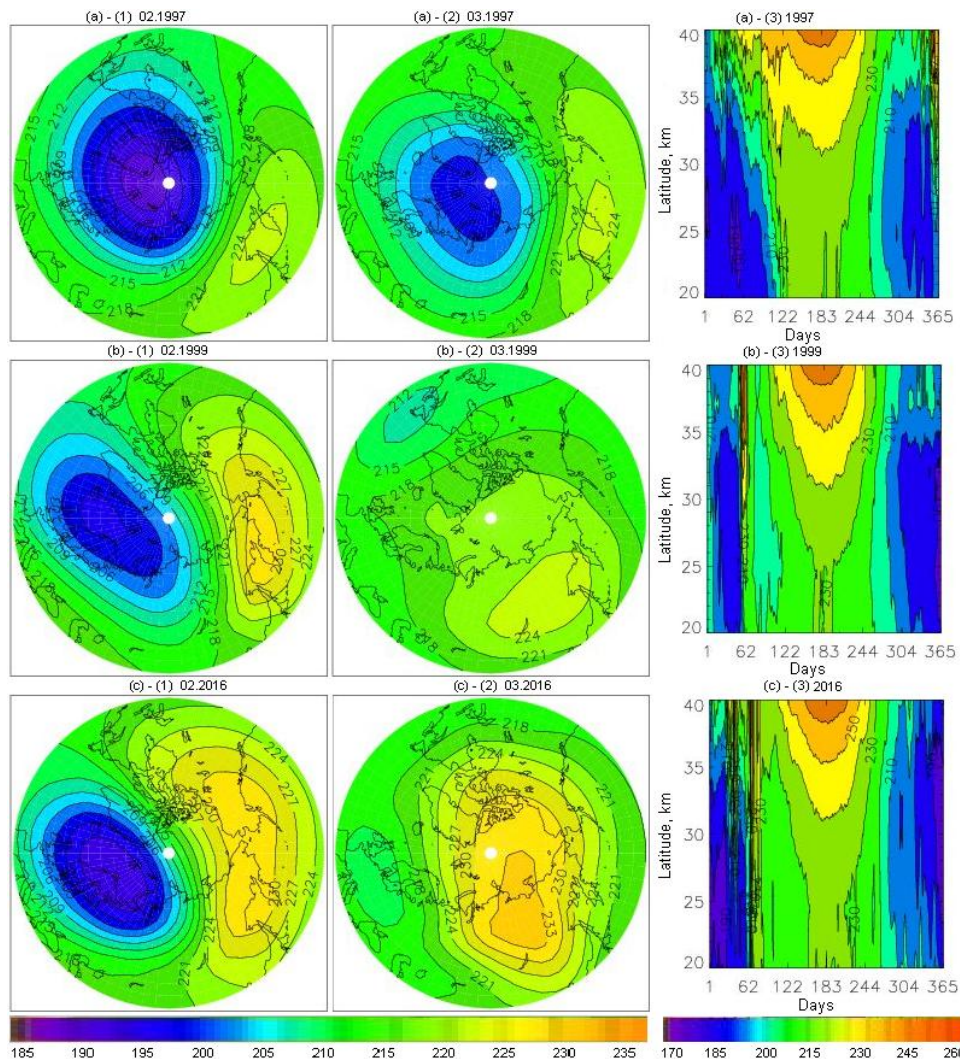
### 3. Results and Discussion

Figure 1 demonstrates the SST anomalies for December-March of 1996-1997, 1998-1999, and 2015-2016 when different phases of the Southern Oscillation [21,22] took place. Polar projections of potential vorticity (PV) at a potential temperature level of 500 K were also presented for these years according to ERA Interim reanalysis data [19]. In 1997 and 1999 there is an area of negative SST anomalies (up to -2 K) in the equatorial part of the Pacific Ocean, whereas in 2016 there is an area of positive SST anomalies (up to 2 K). For all three years, the polar vortex is stable in the first half of the winter of the Northern Hemisphere, but in the second half of the winter the polar vortex continues to be stable for the years with negative SST anomalies, which corresponds to the La Niña phenomenon, and is getting unstable for the years with positive temperature anomalies, which corresponds to the El Niño phenomenon. In general, it can be noted that the years with El Niño correspond to the unstable polar vortex in the second half of the winter of the Northern Hemisphere and the years with La Niña facilitate the formation of a stable polar vortex.



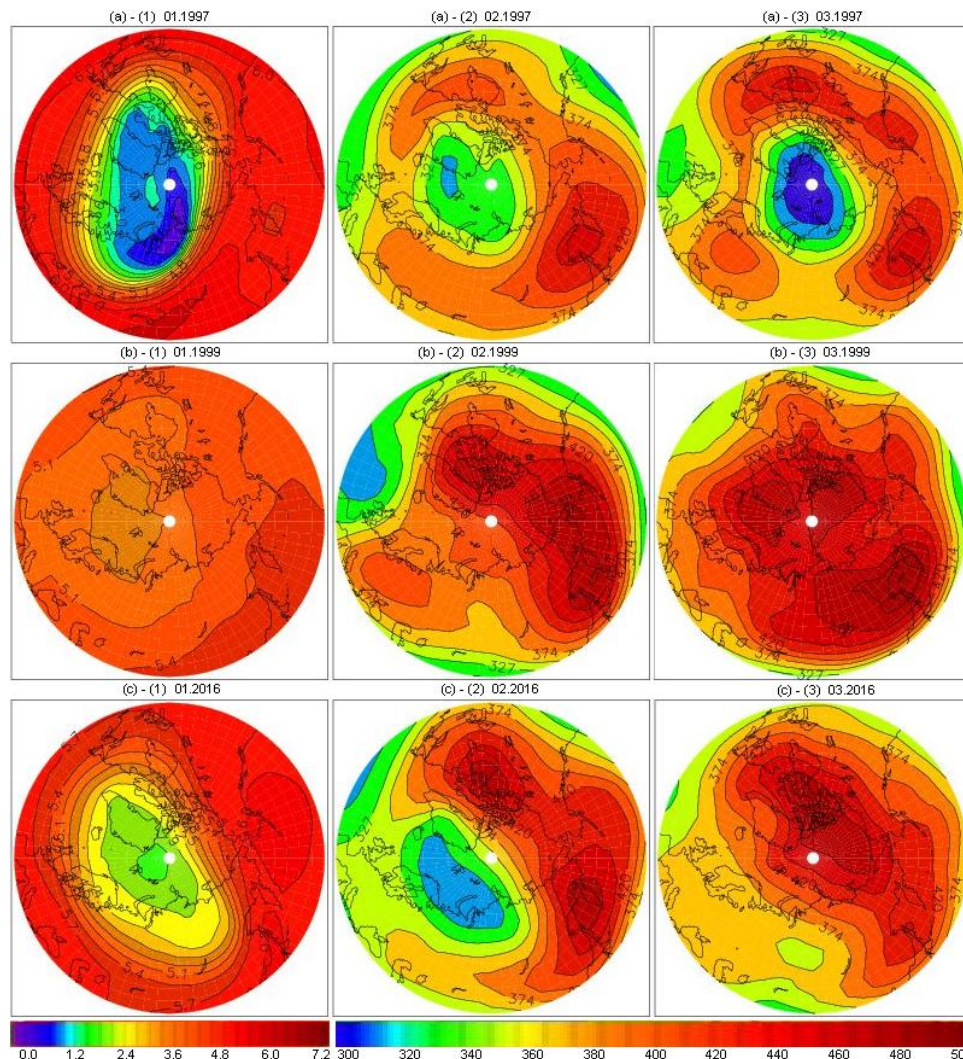
**Figure 1.** ERA Interim reanalysis data of SST anomalies (K) at  $40^{\circ}\text{S} - 40^{\circ}\text{N}$  and  $180^{\circ}\text{W} - 0^{\circ}$  for December-January of 1996-1997 (a - 1), 1998-1999 (b - 1), 2015-2016 (c - 1), and monthly average potential vorticity ( $10^4 \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$ ) for northern polar region ( $40^{\circ}\text{N} - 90^{\circ}\text{N}$ ) at 24.5 km (30 hPa) for February and March of 1997 (a - 2 and 3), 1999 (b - 2 and 3), and 2016 (c - 2 and 3).

In Figure 2, polar projections of the air temperature at the level of 30 hPa and vertical zonal average annual profiles of temperature for 1997, 1999, and 2016 according to ERA Interim reanalysis [19] are shown. In 1997, when there was the La Niña phenomenon, the low temperature region in the Arctic stratosphere was larger and lasted longer than in the years with the neutral phase (1999) and the El Niño phenomenon (2016). Thus, in these years low temperatures interrupt a series of sudden stratospheric warming (SSW), which leads to instability of this area, apparently on vertical profiles [22].



**Figure 2.** ERA Interim reanalysis data of monthly average air temperature (K) for northern polar region ( $40^{\circ}$  N -  $90^{\circ}$  N) at 24.5 km (30 hPa) for February and March, 1997 (a - 1 and 2), 1999 (b - 1 and 2), 2016 (c - 1 and 2), and annual vertical profiles of daily average air temperature (K) at latitude  $84^{\circ}$  N for 1997 (a - 3), 1999 (b - 3), 2016 (c - 3).

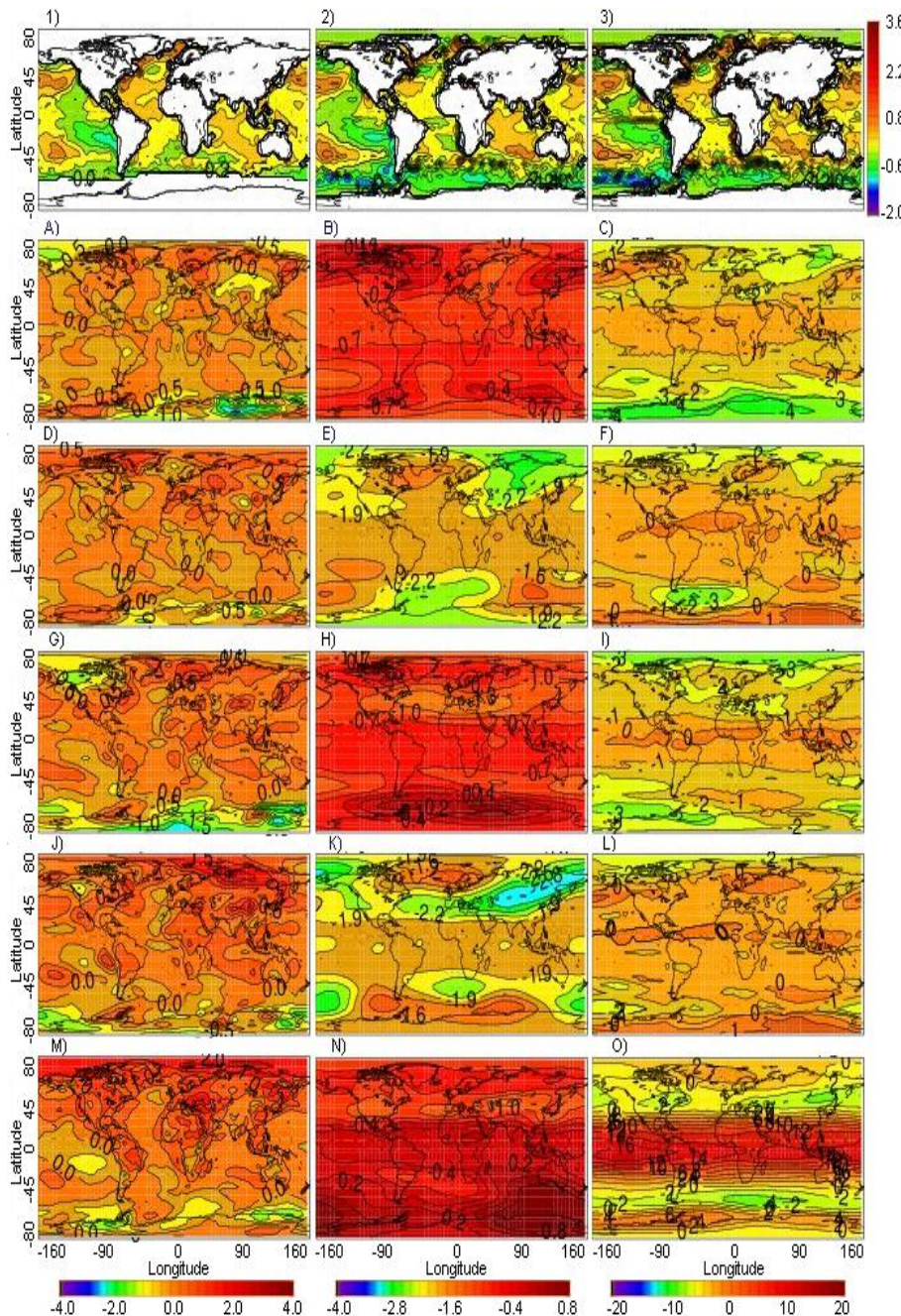
In Figure 3 polar projections of the ozone mixed ratio in ppm (the ozone density divided by the air density and multiplied by  $10^6$ ) at a height of 30 hPa and the total column of ozone in Dobson units (DU) are shown. In 1997, following the La Niña phenomenon, the ozone content in the lower stratosphere in February and March was significantly lower than in 1999 and 2016. At the same time, in 2016, when the El Niño phenomenon was observed, in February the ozone content was even lower than in 1997, but a sudden stratospheric warming in March 2016 led to the destruction of the polar vortex and an increase in the ozone content.



**Figure 3.** Monthly average distribution of the ozone mixed ratio in Northern Hemisphere in ppm in an area of  $40^{\circ}$  N -  $90^{\circ}$  N and at a height of 24.5 km (30 hPa) according to ERA Interim for February 1997 (a - 1), January 1999 (b - 2), March 2016 (c - 3), monthly average distribution of the total column of ozone in Northern Hemisphere in Dobson units (DU) in an area of  $40^{\circ}$  N -  $90^{\circ}$  N according to ERA Interim for February and March 1997 (a - 2 and 3), 1999 (b - 2 and 3) and 2016 (c - 2 and 3).

The results of the model experiments with the CCM under different scenarios of the influence of SST variability and  $\text{CO}_2$  content during the climatic period from 1980 to 2015 are shown in Figure 4. A comparison of the ozone and temperature at the beginning of the given climate period (1980-1985) and at the end of the period (2010-2015) compares the effects of SST variability and  $\text{CO}_2$  increase. Differences of the SST values, air temperatures at levels of 925 and 20 hPa, and the ozone mixed ratio at a level of 20 hPa for the period with 1980 for 2015 are presented. During this period, warming of the ocean on average on the planet (Figure 4, 1, 2 and 3) at 0.7-0.8 K is observed though about Antarctica and South America downturn of temperature at 0.6-0.8 K. By the results of the experiments in view of the SST changes (Figure 4, G and J) and ERA Interim data (Figure 4, M), warming troposphere on average on the planet at 0.5-0.7 K is observed. Thus, the character of distribution of the temperature differences corresponds to the distribution of the SST differences (the correlation factor is equal to 0.7-0.9). In the experiments not taking into account the SST changes (Figure 4, A and D) warming on the planet at 0.2-0.4 K is observed. In the stratosphere, in the experiments in view of  $\text{CO}_2$  changes (Figure 4, E and K) a cold snap at 2.2-3.0 K is observed. In the experiments with a fixed  $\text{CO}_2$

level (Figure 4, B and H) and according to ERA Interim data (Figure 4, N) the air temperature in the stratosphere varies little. The ozone mixed ratio in all experiments (Figure 4 C, F, I, L) varies little, although in the experiment with fixed SST values and CO<sub>2</sub> (Figure 4, C) a downturn of the mixed ratio at 4 ppm above Antarctica is observed. According to Era Interim (Figure 4, O) there is an increase in the mixed ratio at 15 ppm in the tropical belt and a reduction by 4 ppm in latitudes 40°-60°.



**Figure 4.** Difference of averaged sizes for 2010-2015 and 1980-1985: sea surface temperatures (K) according to Met Office (1), ERA Interim (2), ERA20Century and ERA5 (3), differences of simulation results averaged for the periods with 2010 on 2015 and with 1980 on 1985: in experiments with fixed SST, SIC, and CO<sub>2</sub> values at a level of 1979 (2 line), with fixed SST and SIC at a level of 1979 (3 line), with fixed CO<sub>2</sub> at a level of 1979 (4 line), base experiment (5 line) and ERA Interim reanalysis data (6 line); (from 2 line) left column: air temperature (K) at a level 925 hPa, average column: air temperature (K) at a level of 20 hPa, right column: ozone mixed ratio (ppm) at a level of 20 hPa.

It is well-known [21,22] that in 1997-1998 there was a powerful El-Niño. Thus, in 1997 and 1999 (before and after the El-Niño) there were La-Niña phenomena, which are shown in Figure 1. In 2016 there was also an El-Niño phenomenon. Besides, 2010, 2011, and 2015 were also analyzed. Thus, in 2011 there were La-Niña, and in 2010 and 2015, El-Niño.



As a result of study [22] it is found that the instability of CPV can be a consequence of El-Niño, whereas its stability can be a consequence of La-Niña. Within La-Niña (1997 and 2011) the CPV was steady and it kept till March. Also, steady CPV is characteristic for years of weak El-Niño (2010, 2015 and 2016) but, thus, it breaks up in February. In 1999, after a powerful El-Niño the CPV was unstable. Thus, the El-Niño phenomenon reduces the stability of CPV.

The CPV and El-Niño also influence the temperature in the stratosphere. Within a steady CPV (1997 and 2011) when a La-Niña phenomenon took place there was a steady area of low temperatures (150-180 K) till April. Within the El-Niño (2010, 2015, and 2016) and also after the El-Niño 1997-1998 (in 1999) the period of low temperatures interrupted the SSW series, which led to the fact that the area of low temperatures broke up already in the middle of March. It means that the SSWs can be a consequence of El-Niño and are the reason of instability of the CPV.

As for the concentration and maintenance of ozone in the atmosphere, its steady reduction was observed in 1997 and 2011 till April when a La-Niña phenomenon took place, there were a steady CPV and an area of low temperatures, although the given reduction is also caused by the chemical processes in the atmosphere. In 2010, 2015, and 2016 from February to March there was an increase in the maintenance of ozone that can be caused by a SSW series and, hence, by the El-Niño phenomenon. In 1999 the maintenance of ozone varied a little and remained high, which caused unstable CPV and SSW series, and, probably, means a phenomenon of El-Niño in 1997-1998. It means that the El-Niño can lead to increase in the maintenance of ozone by means of SSW.

Besides the El-Niño, the ocean also has a general global influence on the atmosphere by means of SST. It is shown that the distribution of temperature changes in the troposphere corresponds to the distribution of SST changes, which is apparent from Figure 4, with a correlation at 0.7-0.9. Also, it is shown that there is a warming of the ocean at 0.8 K and, thus, there is also a warming at 0.7 K in the troposphere according to the reanalysis and experiments in view of the SST changes. It means that the SST is a significant factor in the troposphere. Changes in the CO<sub>2</sub> level are poorly significant for the troposphere. However, they indirectly influence the SST (increase in CO<sub>2</sub> leads to heating of the atmosphere and thawing of ices, which leads to increase in the open ocean area and the area of absorption of solar beams, and, hence, to increase in the SST).

In the stratosphere, according to the results of the experiments considering changes in CO<sub>2</sub>, there is a downturn of temperature on average on the planet at 2.5-3 K. This corresponds to the theory of global warming, whereas not taking into account changes in CO<sub>2</sub> the temperature varies but little. It specifies that changes in CO<sub>2</sub> are of great value for the stratospheric temperature, whereas the SST is poorly significant.

As for the concentration of ozone, CO<sub>2</sub> level also matters for it. However, the processes connected with ozone are of great value. In Figure 4, the results of the experiments in view of the return influence of ozone on the atmosphere are presented. In this case changes in CO<sub>2</sub> influence the maintenance of ozone a little, and it varies little during time. In the experiments not taking into account the return influence of ozone, the CO<sub>2</sub> level becomes a significant factor: at a fixed CO<sub>2</sub> there is a reduction of the concentration of ozone on average on the planet, whereas at a varying one there is an increase.

Thus, it is assumed that the El-Niño leads to the SSW, CPV instability, and increase in the maintenance of ozone, and La-Niña - on the contrary. Also, it is supposed that the increase in the CO<sub>2</sub> level leads to cooling of the stratosphere and increase in the concentration of ozone on the planet, whereas heating of the troposphere occurs, mainly, due to increase in the SST on the planet.

#### 4. Conclusions

Research on the influence of the El-Niño-La-Niña phenomenon on the stratosphere of the Arctic regions and the ozone layer was carried out. It was shown that El-Niño events are connected with SSW series, instability of the CPV, and increase in the maintenance of ozone. La-Niña events are connected with a steady CPV, low temperatures, and also a reduction in the maintenance of ozone. Also, a research was carried out on the influence of the changes in the SST and CO<sub>2</sub> level on the

troposphere and stratosphere. It was shown that there is warming of the ocean and the troposphere on average on the planet, and also cooling of the stratosphere. The results of this research may be of great value in studying the influence of the ocean, the El-Niño phenomenon, and the CO<sub>2</sub> level on the atmosphere.

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