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VARIABILITY OF CLIMATICALLY ACTIVE ATMOSPHERIC IMPURITIES BASED ON THE RESULTS OF 40 YEARS OF OBSERVATIONS ON THE BASIS OF THE ISSYK-KUL RESEARCH STATION (42.62N; 76.98E; 1640M) AND ON SATELLITES (SBUV)

ИЗМЕНЧИВОСТЬ КЛИМАТИЧЕСКИ АКТИВНЫХ ПРИМЕСЕЙ АТМОСФЕРЫ ПО РЕЗУЛЬТАТАМ 40 ЛЕТНИХ НАБЛЮДЕНИЙ НА БАЗЕ НАУЧНОЙ СТАНЦИИ «ИССЫК-КУЛЬ» (42.62N; 76.98E; 1640M) И НА СПУТНИКАХ (SBUV)

«Ысык-Көл» илимий базасында атмосферанын климаттык активдүү аралашмаларына кырк жылдан бери мониторинг жүргүзүүнүн жыйынтыгында эксперименттик маалыматтардын жыйнапгы түзүлгөн. Ошол маалымат жыйнагынын негизинде Борбордук Азиянын тоолуу аймактарындагы атмосферанын курамын түзгөн аэрозолдуу, буу газдарынын жана озон катмарынын өзгөрүлмөлүү касиеттеринин бир катар өзгөчөлүктөрүн аныкталды. Изилдөөлөрдүн натыйжалары тропо-стратосферанын термодинамикалык процессине олуттуу салым киргизип жаткан ички контитенталдык натыйжаларды эсепке алуу менен озон катмарынын абалын жана климаттын өзгөрүшүн болжолдоого өбөлгө боло турган атмосферанын жаны моделин иштеп чыгууга жана азыркы абалына өзгөртүү киргизүүгө пайдаланылат.

Өзөк сөздөр: *озон, климат, атмосфера.*

По результатам сорокалетнего мониторинга климатически активных малых примесей атмосферы на базе научной станции «Иссык-Куль» создан банк экспериментальных данных, который позволил выявить некоторые особенности в изменчивости озонового слоя, парниковых газов и аэрозольных составляющих атмосферы над горным регионом Центральной Азии. Результаты исследований используются для корректировки существующих и разработки новых моделей атмосферы, позволяющих прогнозировать состояние озонового слоя и изменения климата с учетом внутриконтинентальных горных эффектов, вносящих существенный вклад на термодинамические процессы тропо-стратосферы.

Ключевые слова: *озон, климат, атмосфера*

Based on the results of forty years of monitoring of climatically active constituents of the atmosphere at the Issyk-Kul scientific station, a bank of experimental data was obtained, which made it possible to identify specific features in the variability of the ozone layer, greenhouse gases and aerosol components of the atmosphere over the mountainous region of Central Asia. The research results are used to correct existing and develop new models of the atmosphere, which make it possible to predict the state of the ozone layer and climate change, taking into account inland mountain effects that make a significant contribution to the thermodynamic processes of the troposphere-stratosphere.

Key words: *ozone, climate, atmosphere*

INTRODUCTION. Nowadays, the anthropogenic impact on the ozone layer and the climate seems to be real and dangerous.

However, correct identification of the anthropogenic effect against the background of high variability of natural factors that significantly affect the fluctuations in ozone and greenhouse gases is an important and complex scientific problem. Such changing natural factors include solar, volcanic, seismic activity, as well as the activity of thermodynamic processes in the atmosphere and hydrosphere (El Niño, quasi-biennial oscillation of zonal winds, jet streams, etc.). In this regard, experimental studies of spatial and temporal variations in the content of climatically active impurities in the atmosphere under conditions of changing exogenous and endogenous factors are highly relevant.

Monitoring of the atmospheric ozone, greenhouse gases and optical features of aerosols in the atmosphere of mountainous region of Central Asia has been conducted at Issyk-Kul Station (42.62 N; 76.98 E; 1640 m.) since 1980. There were received a unique experimental database (more than 40 years) on TO and other climate active impurities of the atmosphere, which complimented the measurement results of the monitoring network managed by the World Meteorological Organization (WMO). These data are used to develop new and adjust existing atmospheric models to predict changes in ozone layer and climate.

Unlike the vast majority of stations of the global network located in the oceanic and coastal regions of the planet, the Issyk-Kul station is located in the inland, poorly studied mountainous part of Central Asia (Fig. 1). The exclusivity of the station's location is determined by the fact that this inland mountain ecosystems of Central Asia (Himalayas, Tien Shan, Pamir-Alai, Tibet Plateau), generating powerful orographic waves, have a significant effect on the turbulence of the troposphere and stratosphere and high-altitude jet streams, that play a special role in the spatiotemporal variability of ozone content and other climatically active minor impurities in the atmosphere.

Figure 1. The location of Issyk-Kul OMD Station relative to other GAW monitoring stations

1. OBSERVATION

1.1 Monitoring of total ozone

Measurements of total ozone (TO) were carried out by a spectrophotometric scanning set (SPS), developed by Kyrgyz State University, which was updated in 1999 (SPS-99) and in 2011 (SPS-11). The total ozone content in the atmospheric column was determined by the multi-wave method, according to the results of measurements of the absorption of solar radiation by the atmosphere at six wavelengths: 303.3; 305.2; 308.6; 311.0; 313.8 and 315.0 nm. A detailed description of the measurement procedure is given in [1-18].

In order to increase the efficiency and reduce the complexity of obtaining information on TO using SPS, in 1999, a transition to the automated control system of the ozonometric complex was made, which consists of a digital measurement module, a spectrum scanning module, a solar tracking system, a controller, and a central computer.

In 2011, the synchronous engine of the scanning system was replaced by a step-by-step one. This reduced the measurement time of one spectrum by 3-4 times and amount of processed and stored information and, thereby, significantly reduced the systematic errors associated with the scanning time of one spectrum. The systematic measurement errors that appeared in 1999 and their reduction in 2011 are well demonstrated in Fig. 2, where the results of comparing the data of the Issyk-Kul station and satellite data (www.acd-ext.gsfc.nasa.gov) above the observation point are presented.

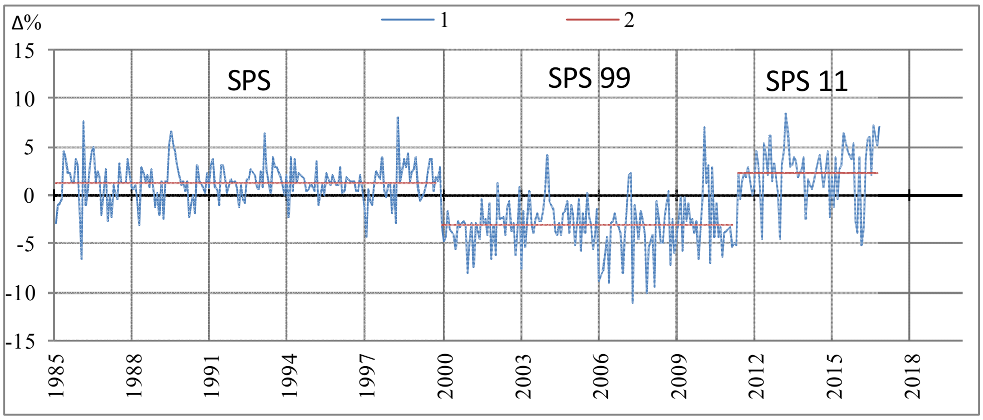

Figure 2. Deviations Δ% of TO measured by SPS (1) compared to satellite data (sbuv). (2) – average values of deviations TO by SPS from satellite data (sbuv) for periods of: (SPS) 1985-1999,
Δav. = 1.29 %; (SPS 99) 2000-2010, Δav. = -3.1 % and (SPS 11) 2011-2016, Δav. = 2.19 %

The corrected results of TO monitoring for the period from 1980 to 2019 are presented in Figures 3, 4, 5, 6. The figures show that TO variability has a complex oscillatory character with pronounced seasonal (Fig. 3, 4), quasi-biennial cycles (Fig. 5, 6). Analysis of the distribution of seasonal components (Fig. 4) in TO fluctuations shows that the maximum values of standard deviations occur in February and April, and the minimum - in August and September. The amplitude of fluctuations in the rate of TO change (Fig. 6) varies widely, with an increase in the amplitude range at the beginning, and then its decrease at the end of the observation period, similar to a beating of amplitudes.

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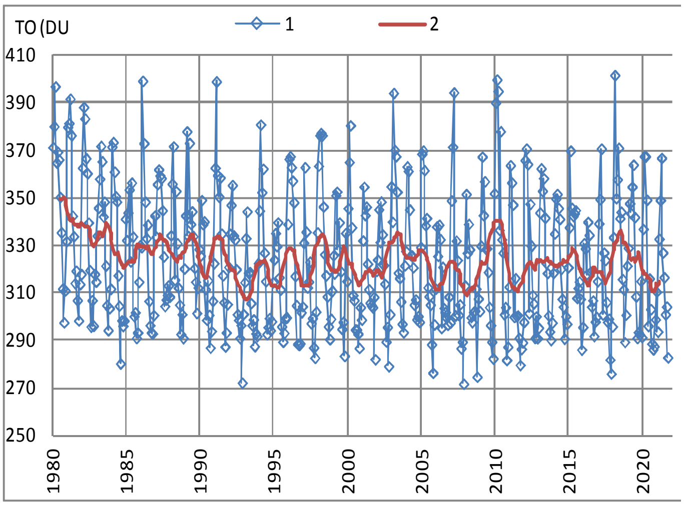


Figure 3. Temporal variations of monthly average (1) and inter annual values of TO (2) according to data measured at Issyk-Kul station

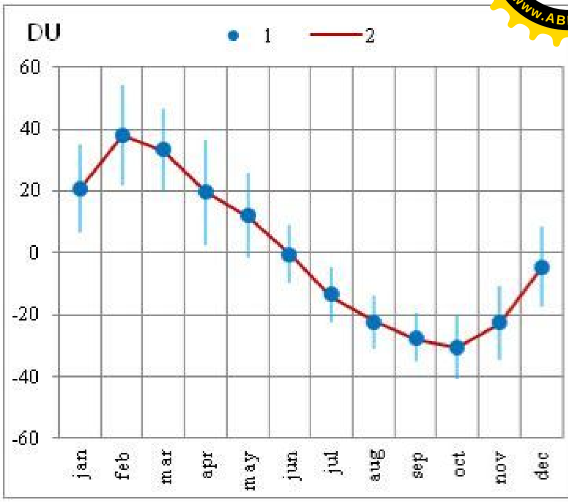


Figure 4. Mean (1981-2013) seasonal change of TO (2) in comparison to model (curve 1), the correlation coefficient between (1) and (2) r= 0.99

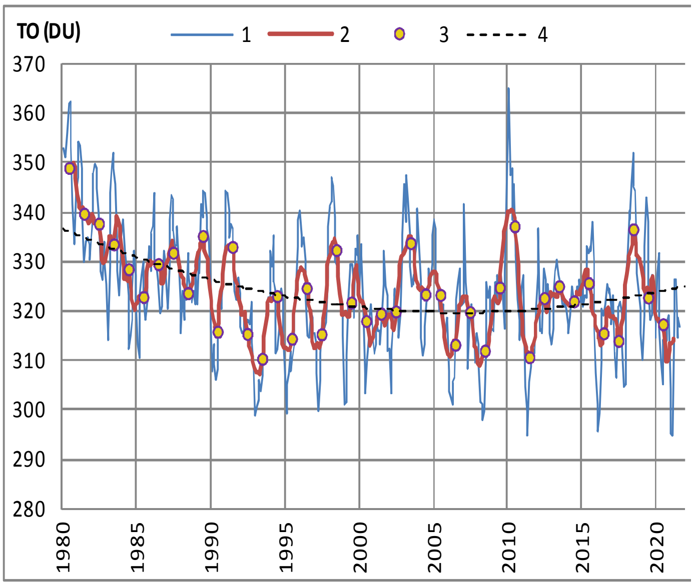


Figure 5. Variations of inter-annual (2) and average annual (3) TO (DU) values with parabolic trend (4)

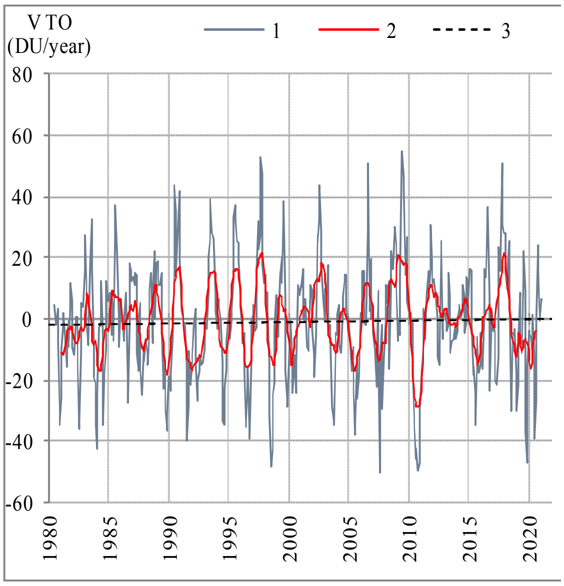
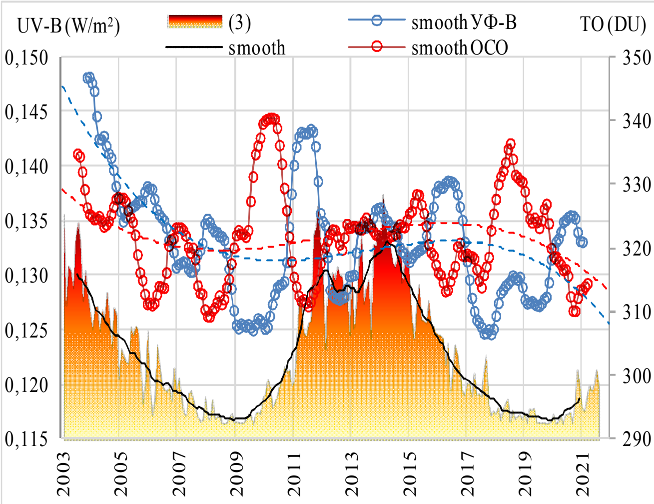


Figure 6. Fluctuation of TO change rate (1), smooth (2) for 12 months and trend (3)

1.2 Monitoring of surface ultraviolet radiation (UV-B)

The monitoring of the total erythema ultraviolet radiation at the Issyk-Kul station has been carried out using an automatic 501 model UV Biometer since 2003.

Fig. 7 depicts interannual variations in surface UV-B radiation (curve 2) and TO polynomial trends of 3rd orders (red and blue dashed lines) and monthly average values of fluctuations in sunspot number SSN (curve 3). An analysis of interannual variations in TO and UV-B and their rate of change shows that the intensity of ultraviolet radiation reaching the earth's surface depends on both TO and solar index fluctuations (Fig. 8).



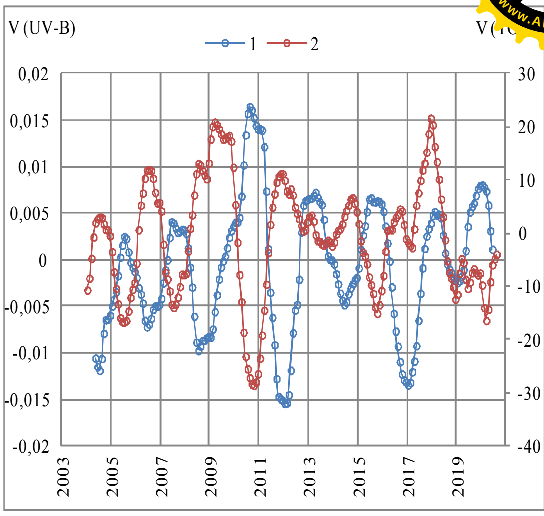


Figure 7. Inter annual variation of TO (1), surface UV-B radiation (2) with polynomial trends of 3rd order and variation of monthly average fluctuations in sunspot number (SSN) value (3) and its smooth (smooth)

Figure 8. The rate of inter annual variations in TO (1) and UV-B (2)

1.3 Monitoring of total nitrogen dioxide (NO_2)

The need for constant monitoring of NO_2 content in the atmosphere is dictated by the fact that NO_2 plays a crucial role in radiation and chemical processes in the atmosphere, including the greenhouse effect and ozone photochemistry. The variability of NO_2 content in the atmosphere directly and indirectly affects both climate fluctuations and the state of the ozone layer.

Monitoring of the total nitrogen dioxide (NO_2) at the Issyk-Kul station has been carried out since 1983. Based on the duration of measurements the Issyk-Kul station is a leader in the former USSR and the second in the world. In terms of NO_2 measurement, the station is included in the NDACC network (www.ndsc.ncep.noaa.gov/sites/stat_reps/issykkul/). The need for constant monitoring of the atmospheric NO_2 content is dictated by the fact that NO_2 plays a crucial role in radiation and chemical processes in the atmosphere, including in the photochemistry of ozone.

Fig. 9 shows the temporal variations of the monthly and interannual values of total NO_2 for the period from 1983 to 2019. The methodology for calculating the monthly average values of NO_2 using the data of morning and evening measurements, the values of which differ significantly, is given in [5, 6, 14]. Rapid and significant changes during sunrise and sunset are associated with rapid transformations between NO and NO_2.

During the observation period the growth rate of total NO□, according to a linear trend, in the atmospheric column was $v = 11.7 * 10^{12}$ mol. /cm^2 or 0.37 % per year. Total NO_2 content over this period increased by 12.7 %.

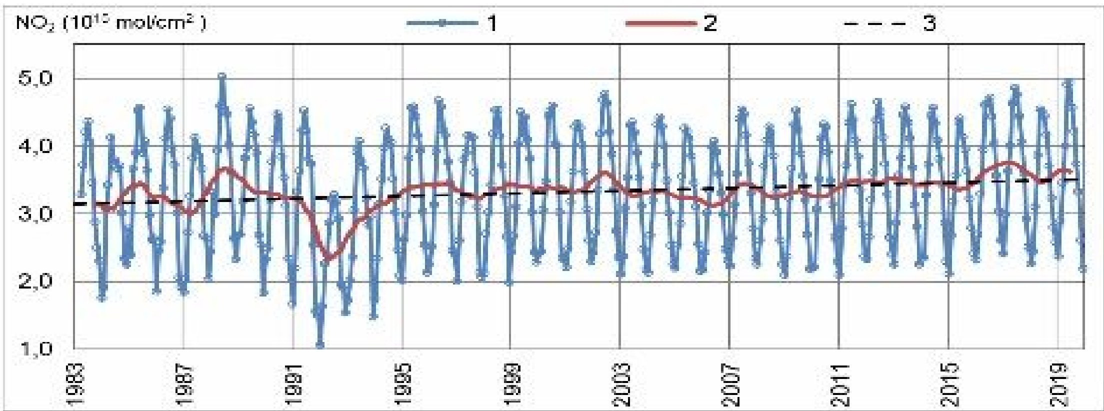


Figure 9. Time series of monthly average values of total NO_2 (1), obtained from average daily data, smooth (2) and linear trend (3)

1.4 Monitoring of aerosol optical depth

From 1984 to 2009, the AOD value was calculated using the value of the atmospheric transparency measured at the Issyk-Kul station [12,13]. Since August 2007, the monitoring of the optical characteristics of aerosols has been carried out by the modern automatic radiometer CIMEL, CE 318N-V8S5-M9 model. The results of these measurements are published on the AERONET NASA website [http://aeronet.gsfs.nasa.gov].

Fig. 10 and 11 show, as an example, AOD values measured in 2019, as well as in 2020, respectively.

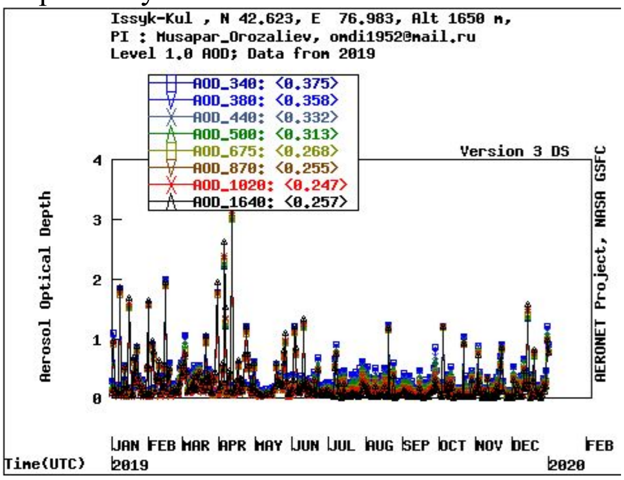


Figure 10. AOD in 2019

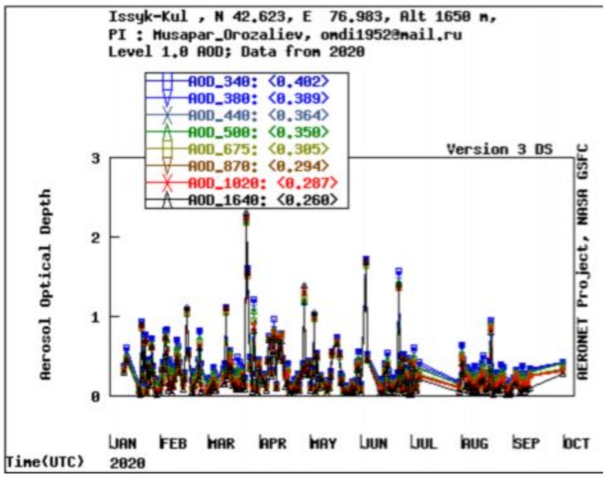
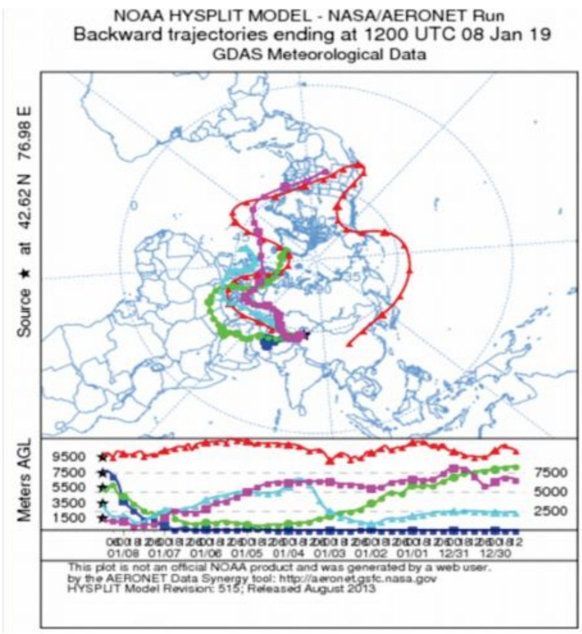


Figure 11. AOD in 2020

To study the localization of aerosol sources that affect the atmospheric AOD over the aquatic area of Issyk-Kul Lake, we analyzed the trajectories using the HYSPLIT model (https://www.arl.noaa.gov/HYSPLIT_pubs.php), which describes atmospheric transport, dispersion and sedimentation of pollutants (aerosols) from various stationary and mobile sources of various kinds of aerosols. As an example, fig. 12 depicts the trajectories of aerosol transport by air masses for 10 days from a reference source to the region of the Issyk-Kul station at altitudes of 1500, 3500, 5500, 7500 and 9500 m, which had a significant impact on AOD recorded on 08/01/2019. It can be seen that for an altitude of 9500 meters, the aerosol trajectory begins from the territory of China and, almost rounding the globe, reaches the waters of Issyk-Kul Lake.



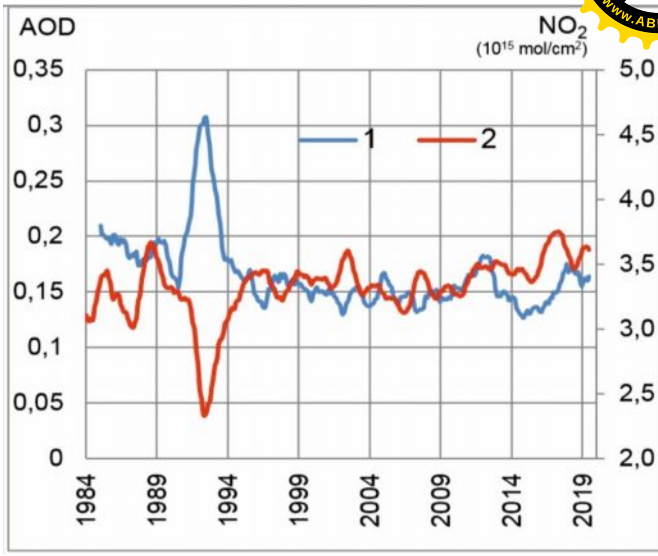


Figure 12. Altitude transport paths of aerosol particles from a reference source to the region of Issyk-Kul station from 12/30/2018 to 01/08/2019 according to the HYSPLIT model

Figure 13. Comparison of inter annual values of AOT (1) and NO_2 (2) (r = - 0.56) based on data of Issyk-Kul station

Comparison of inter annual AOD and NO_2 variations based on data of synchronous measurements at the Issyk-Kul station (Fig. 13) shows a good inverse correlation (r=-0.56) in their dynamics.

Basically, an increase in AOD is accompanied by a decrease in NO_2 in the atmosphere. The value of the correlation coefficient r = - 0.56 is high enough, because the correlation procedure was carried out for the entire time series of AOD and NO_2 without sampling. This dependence is most pronounced in the period from 1991 to 1996, when the Pinatubo volcano erupted in 1991, and about 10 km^3 of gas and dust clouds emitted to altitudes of 19-34 km. Synchronous measurements of small impurities (O_3, NO_2, CO_2, H_2O, AOD, UV-B, etc.) in the atmosphere at the Issyk-Kul station showed abnormal changes in their content during the eruption of the Pinatubo volcano.

2. RESULTS OF OBSERVATIONS AND ANALIYSIS

Fig. 14 shows the deviations of the average monthly TO values (1), expressed in % relative to the average annual TO cycle for 1980. The second-order polynomial trend (3) shows the depletion of the ozone layer until 2008 and its recovery in subsequent years. It is seen that the depletion of the ozone layer for the period 1980 - 2008 was an average of 8.5%. According to a parabolic trend estimate, the recovery of the ozone layer over the northern Tien Shan to the level of 1980 is expected approximately in 2032. However, at various periods during observation, the depletion and recovery of the ozone layer occurred at different rates (Fig. 5, 14, 15). So, in 1980-1984 the rate of depletion was approximately -4.65 DU/year, in 1984-1989 the recovery rate was 0.84 DU/year, in 1989-1994 the depletion rate was -2.13 DU/year, in 1994-1998 the recovery rate was 1.72 DU/year, in 1998-2007 the depletion rate was -0.64 DU/year, in 2007-2015 the recovery rate was 0.47 DU/year, in 2015-2020 the depletion rate was -0.25 DU/year.

It should be noted that world community has made undeniable contribution to the recovery of the ozone layer on a regional and global scale, due to successfully implementation of programs on reduction of ozone-depleting substances emissions listed in the Montreal Protocol (1987) of parties to the Vienna Convention, UNEP. However, in recent years, despite the reduction of ozone depleting substances in the atmosphere, significant depletion of the ozone layer has been observed, such as in July 2011, April and December 2012, February and March 2016, December 2019 and May 2020 (Fig. 14). As a result of such failures in TO, the rate of TO recovery slowed down (Fig. 14, 15). Finding out the causes of such failures in the atmospheric ozone content requires further thorough studies of the influence of various solar geophysical processes, as well as the mutual influence of climate variability and the ozone layer. Amongst other things, the studies of the dynamics of the troposphere and stratospheric exchange over a mountain regions of Central Asia and the Himalayas, where powerful orographic waves are generated, affecting the features of turbulence and high-altitude stream flows, which play a significant role in the spatial and temporal distribution of ozone and other climate and ozone forcing constituents of the atmosphere.

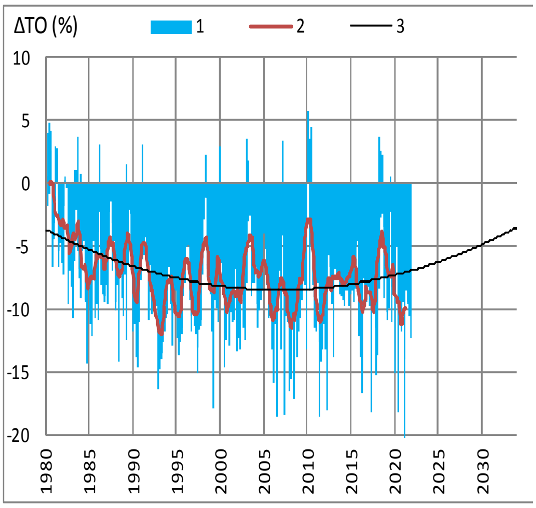


Figure 14. TO value deviation in % (1) relatively to TO values in 1980 and smooth (2) and parabolic trend (3)

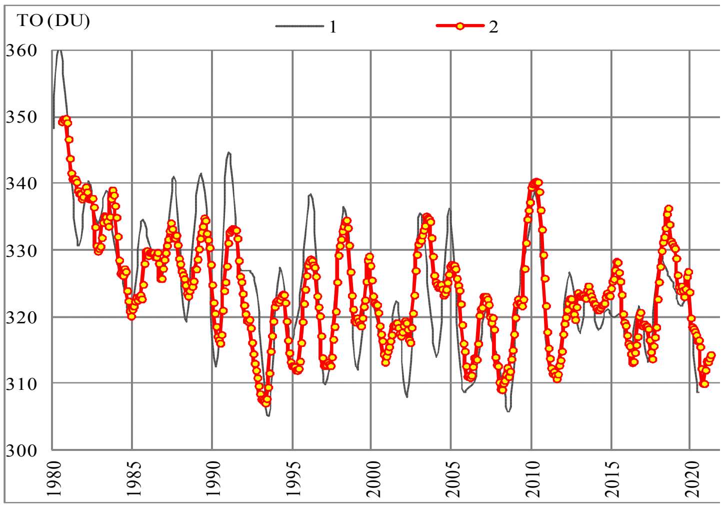


Figure 15. TO evolution: model (1) based calculations with quasi-biennial content in inter annual fluctuations of TO; experimental data for 1980-2019 (2)

Fig. 16 presents the comparison of relative norms of TO, that was determined for the monitoring stations: ISK, MLO, ARO, XIA, KUN, BBN.

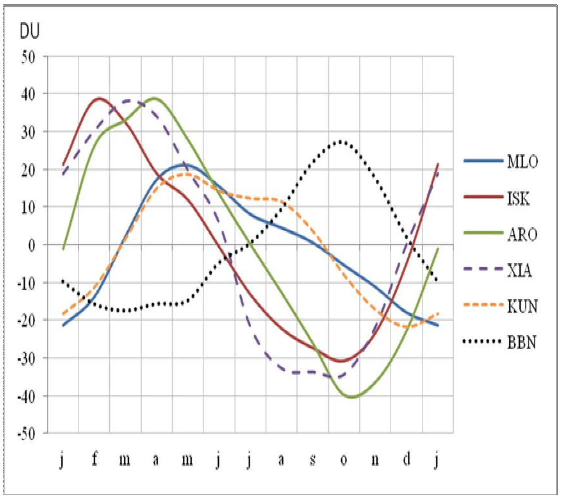


Figure 16. The relative norms of TO: ISK; MLO; ARO; XIA; KUN; BBN

To conduct a comparative analysis Fig. 17 shows the features of quasi-biennial oscillations of TO for 1980-2019 based on the data of Issyk-Kul (ISK), Xianghe (XIA), Arosa (ARO), Mauna-Loa (MLO), Brisbane (BBN) and quasi-biennial zonal wind velocity oscillations (V QBO) at the level of 20 hPa (m/s) (www.fu-berlin.de), as well as fluctuations in sunspot number (SSN) (http://www.sidc.be). The methodology for studying quasi-biennial oscillations of TO is described in [6, 9].

An analysis based on the latest data confirms the for equated conclusions [6, 8, 9], that the close relationship between QBC of TO and the velocity of the zonal wind oscillations (V QBO) is disturbed during years of abnormally high atmospheric aerosol content (volcanic activity), and during solar magnetic polarity change and high solar flare, even to a change of a sign of the correlation coefficient.

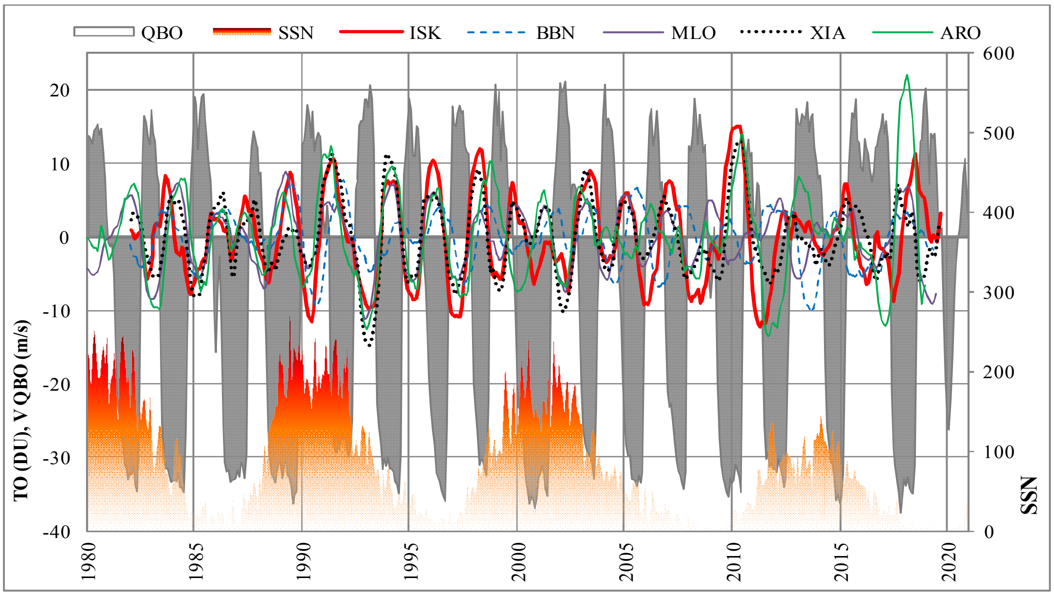


Figure 17. Comparison of quasi-biennial oscillation in TO of the station ISK, MLO, ARO, XIA, BBN in DU with quasi-biennial oscillation of the zonal wind velocity (m/s) (V QBO) at the level of 20 hPa

3. CONCLUSION

Based on the results of forty years of monitoring of climatically active atmospheric constituents at the Issyk-Kul scientific station, a bank of experimental data was obtained, which made it possible to identify some features in the variability of the ozone layer, greenhouse gases and aerosol components of the atmosphere over the mountainous region of Central Asia.

The results of monitoring, obtained at Issyk-Kul station are used:

- to expand the databases of world centers: on ozone (Issyk-Kul No. 347-WOUDC, www.woudc.org); on greenhouse gases (ISK 242 NOO WDCGG, www.ds.data.jma.go.jp); on nitrogen dioxide (NDACC - Issyk-Kul, www.ndsc.ncep.noaa.gov) and on aerosols (NASA, AERONET - Issyk-Kul, www.aeronet.gsfc.nasa.gov); to develop and adjust models for predicting the state of the ozone layer and climate change;
- for comparative analysis and validation of satellite measurements [4, 5, 13-17];
- to study the influence of fluctuations in solar and geophysical processes on interannual variations in the content of ozone and other climatically active impurities in the atmosphere in order to differentiate the contributions of natural and anthropogenic factors to the variability of the ozone layer and climate;
- for the development and adoption by international organizations (UNEP, WMO, etc.) and government bodies (Kyrgyzstan, Russia, China, etc.) of strategic programs and recommendations for preservation of the ozone layer and reducing the rate of climate change, as well as for addressing regional environmental and economic problems associated with abnormal changes in weather and climate.

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