THREE GEOMAGNETIC STORMS IN JANUARY 2005 AND THEIR IMPACT ON TOTAL ELECTRON CONTENT

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Abstract. This study presents the global and mid-latitude ionospheric response to three geomagnetic storms occurred in January 2005: the first one on 7-8 January, the second one on 17-19 January, and the last one on 21-22 January. This period has been selected, because no major sudden stratospheric warming (SSW) occurred during this month and according to many scientists this winter is represented as an example of a background reference case corresponding to a 'normal' year. Therefore, the observed ionospheric response to the considered geomagnetic storms could be attributed mainly to the external forcing. The reaction is explored by considering N(h) profiles registered by manually scaled ionosonde measurements at station Sofia (42.5°N, 25°E), which are used for calculating the total electron content (TEC) up to the F2-layer maximum (bottom-TEC). The full-TEC data are provided by the Center for Orbit Determination of Europe (CODE)-Bern, for the nearest point to Sofia. The main aim of this work is to compare in details the temporal variability of the full-TEC with bought that below (bottom-TEC) and up (top-TEC) the F2-layer maximum for each of the considered geomagnetic storms. It is found that for all investigated geomagnetic storms in January 2005 the bottom-TEC is considerably different from bought top-TEC and full-TEC. An explanation of the main mechanisms responsible for the observed difference has been proposed.

Key words: geomagnetic activity, TEC, ionospheric anomalies.

Introduction

Geomagnetic storms are associated with high-speed plasma injected into the solar wind from coronal mass ejections or coronal holes that impinges upon Earth's geomagnetic field. If the interplanetary magnetic field (IMF) Bz has southward direction then the solar wind energy enters the magnetosphere-ionosphere-thermosphere system by establishing an interconnection between the southward IMF and the Earth's magnetic field lines. As a result the geomagnetic space environment becomes strongly disturbed and a global ionospheric storm occurs (Kamide and Kusano, 2015; Mukhtarov and Bojilova, 2017). The ionospheric structure and variability are related to changes in solar radiation and geomagnetic activity, together with the subsequent response of the thermosphere-ionosphere system (Roble, 1995). The ionosphere also varies in response to neutral winds (Schunk et al., 2009), electrodynamic coupling with the overlying plasmasphere and magnetosphere (Huba et al., 2005), and dynamical coupling with the underlying atmosphere particularly effective during low solar activity conditions (Mendillo et al., 2002; Rishbeth, 2006). It is well known that during geomagnetic storms the dynamics, electrodynamics and chemistry of the atmosphere-ionosphere system are modified on a global scale and cause positive and/or negative phases of ionospheric response (Gadzhev et al., 2013). The latitude and longitude, season, as well as the both storm onset time and maximum are the main factors which define the positive/negative response (Andonov et al., 2011; Mukhtarov et al., 2013a; Mukhtarov and Bojilova, 2017).

Three main reasons have been proposed to explain the observed storm phases: thermospheric composition changes, neutral wind perturbations and the electric fields of magnetospheric origin (Mendillo, 2006). The total electron content (TEC) is one of the particularly important physical quantities of the ionosphere. The main reason for the TEC importance is that the trans-ionospheric radio signals, used by the Global Navigation Satellite Systems (GNSS), may reach quite large range errors and these errors are proportional to the integral of the electron density along the ray path, i.e. proportional to slant TEC. It is measured by TEC Unit (TECU) as one TECU is equal to 1016 electrons/m^2. Therefore the ionospheric effect has become the largest error source in GNSS positioning, timing and navigation. Wang et al., (2010) has presented clear evidence that the negative storm response observed in the TEC maps at high- and mid-latitudes is directly related to the changes in the $[O]/[N_2]$ ratio. The geomagnetic storms significantly change the ionosphere especially the electron density and its vertical distribution, as well as the total electron content (TEC). The serious problems in the ground-based HF radio communications during negative ionospheric storm are caused because the electron density and TEC decrease much below their "quiet-time" levels. The positive ionospheric storms in which electron density and TEC increase much above their "quiet-time" levels can cause serious problems in satellite communication and navigation. Because the GPS signals are used by wide range of applications, any geomagnetic storm event which makes GPS signal unreliable could have significant impact on the society. That is why a detailed study of the ionospheric response to forcing from above and below is among the important mission of the ionosphere studies.

The purpose of this study is to compare in detail the temporal variability of the full-TEC with bought that below (bottom-TEC) and up (top-TEC) the F2- layer maximum for each of the considered geomagnetic storms in January 2005. It is found that for all cases examined in this study the bottom-TEC is considerably different from bought the top-TEC and the full-TEC. An explanation of the main mechanisms responsible for the observed difference has been proposed.

Data

The geomagnetic activity is described by the planetary Kp-index and the equatorial Dst-index that are received from: https://omniweb.gsfc.nasa.gov/. The TEC values for the nearest point to Sofia are obtained by the Center for Orbit Determination of Europe (CODE) at Astronomical and Physical Institutes of the University of Bern: ftp://ftp.unibe.ch/aiub/CODE/. The reason for using the closest to Sofia point with coordinates (42.5°N, 25°E) is that the TEC data have a grid spacing of 5◦ x 2.5◦ in longitude and latitude. The N(h) profiles up to the F2-layer maximum are derived from the manually scaled ionograms (Mukhtarov et. al, 2013b) of the ionosonde station Sofia- SQ143 (42.4°N, 23.2°E). The considered quantity bottom-TEC in this paper is defined as an integral of the electron density profile while the top-TEC is the difference between the full-TEC and the bottom-TEC. The TEC response to the geomagnetic storms is described by relative deviations of the considered all three quantities (the top-TEC, bottom-TEC and full-TEC) from their stationary diurnal course and are calculated by the formula:

$$rTEC(t) = \frac{TEC(t) - TECm(UT)}{TECm(UT)}$$

where $\underline{t}$ is the current time in hours that is counted from the beginning of the period considered, while UT is the universal hour corresponding to the moment *t*. The value TECm (UT) is the median, calculated on the base of the whole month considered.

Experimental results

Three clear storms, with maximum Kp~8 occurred in January 2005. Fig. 1 shows the planetary Kp-index giving information for the global variations of the geomagnetic field. The first storm begins on 7 January and the Kp-index reaches maximum of ~7.5-8 between 21-23 UT. This storm has duration of only ~18 hours, i.e. it is a short-time one. The second storm, begins on 17 January and has a duration of a few days because the Kp-index has values larger than 5 for more than 2 days. The maximum Kp-index is observed on January 18 having a value close to 8. The recovery phase of the storm begins in the next day but is interrupted because of the appearance of a new geomagnetic disturbance on January 21. The last geomagnetic storm is a short-time one, with duration less than a day. The sharp rise of the Kp-index to values above 8 is in the evening hours on 21 January. It is worth noting that the last storm starts under not very calm conditions due to the disturbances which occurred in the previous days.

The first geomagnetic storm occurs on 7-8 January 2005 and the TEC response is presented in Fig. 2. In order to have a general idea of what the global response to this storm is Fig. 2a presents the latitude-time cross-section of the relative TEC at a longitude of 25°E for the period of 7-10 January. This storm begins in the late hours on 7 January

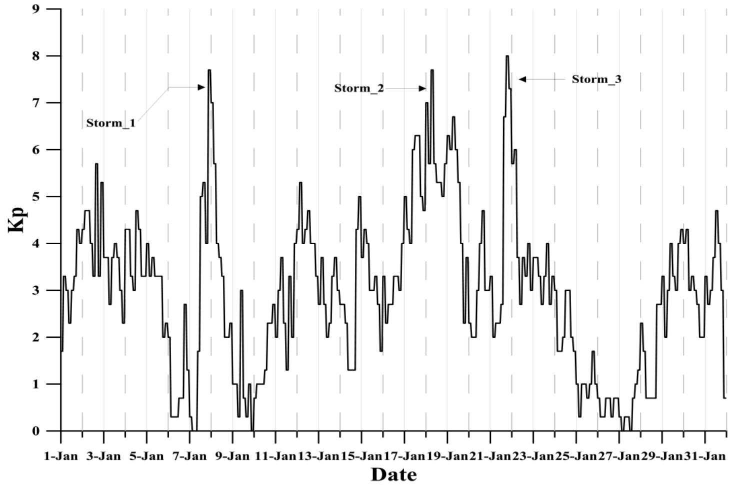

Fig. 1. Variations of the Kp-index in January 2005

and slightly after the midnight on 8 January the Kp-index reaches to ~ 7.5-8 (see Fig. 2c). Then a clear positive response is seen for all latitudes as the relative TEC is the largest at around 60°N. The summer Southern Hemisphere (SH) reacts predominantly negatively after the midnight on 8 January Fig. 2a. Such negative TEC response is typical for geomagnetic storms in summer (Pancheva et. al., 2016). The TEC response in the Northern Hemisphere (NH) is more complex (Fig. 2a). After the positive response seen at all latitudes in the late hours on 7 January it follows a negative response which can be traced only between 15°N and 50°N. At the same time a positive response is formed that is seen first at equatorial latitudes and later with some time delay it appears at mid-latitudes during the day-time on 8 January when the Kp-index is below 5 (sees Fig. 2c). While the positive response at high-mid latitudes during the late hours on 07 January is apparently associated with the direct ionization under the action of the charged particle precipitations into the night-side of the Earth's atmosphere the positive response during the day-time conditions is probably connected with electrodynamic effects. After the decay of the positive response during the afternoon hours on 8 January a long duration negative TEC reaction has been established (Fig. 2a); the latter is related to the change of the [O] / [N_2] ratio. Fig. 2b shows the relative values of the full-TEC (upper plot), top-TEC (middle plot) and bottom-TEC (bottom plot) for the period of 7-10 January. The bottom plot of Fig. 2c displays the Kp-index for the considered period. Considering the variability of the relative TEC (Fig. 2b) it is seen that all three quantities have first a positive response that is followed by a negative and then again a positive response. The largest changes of the relative values are as follow: (i) from -0.6 to +0.6 for the full-TEC; (ii) from -0.5 to +0.5 for the top-TEC, and (iii) from -0.8 to +1 for the bottom-TEC. These results clearly reveal that the bottom-TEC ionospheric changes are larger than those of both the top-TEC and the full-TEC.

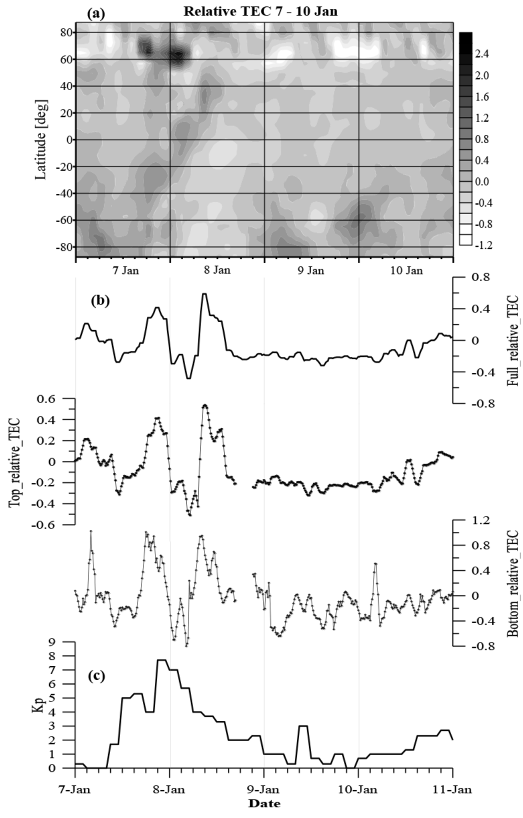

Fig. 2. (a) Global latitude-time cross section of the relative TEC; (b) temporal variability of the relative values of: the full-TEC (upper plot), top-TEC (middle plot), and bottom-TEC (bottom plot), and (c) Kp-index during the period of 7-10 January.

Fig. 3 is the same as Fig. 2 but presents the TEC response to the second geomagnetic storm; the period of 17-20 January is considered. This storm is different from the first one; it is without a sudden commencement and is significantly longer, more than 2 days. Fig. 3a shows the positive responses at latitude of 60°N during the early morning hours on 17 January when the geomagnetic activity, described by the Kp-index, is still lower than 5. Positive anomalies are seen also during the night-time hours of 17/18 and 18/19 January when the Kp-index varies between 6 and 7. It is worth noting that the large values of the night-time relative TEC at high latitudes are a result of the increase of the very low night-time TEC values in conditions close to a polar night. The relative TEC in the SH during the second half of 17 January reveals a positive response however after the midnight a negative response is observed that propagates from the polar latitudes to the equator; this is typical feature for the TEC response to the summer geomagnetic storms. The TEC response in the tropical and middle latitudes of the NH on 17 and 18 January, presented in Fig. 3a, is predominantly positive one. Two impulses of the negative response are seen during the first half of January 19, however while the first one ranges between 15°N and 50°N the second one is only between 40°N and 50°N. The stable negative response appears during the night hours of 19/20 January observing at tropical and mid-latitudes. The long duration of this storm accompanied by a significant amount of energy draw in the Earth's atmosphere together with the increased inertia (Mukhtarov et al., 2013a; Mukhtarov et al., 2018) defines a considerable time of the ionosphere recovery. The relative values of the three characteristics: full-, top- and bottom-TEC, shown in Fig. 3b, demonstrates positive anomalies on January 18 as the response is the strongest for the bottom-TEC, ~2.2 above the median one. Further, while the full- and top-TEC show two positive peaks the bottom-TEC reveals three peaks. Similarly to the first storm here also, the temporal variability of the relative bottom-TEC is quite different from those of the full- and top-TEC.

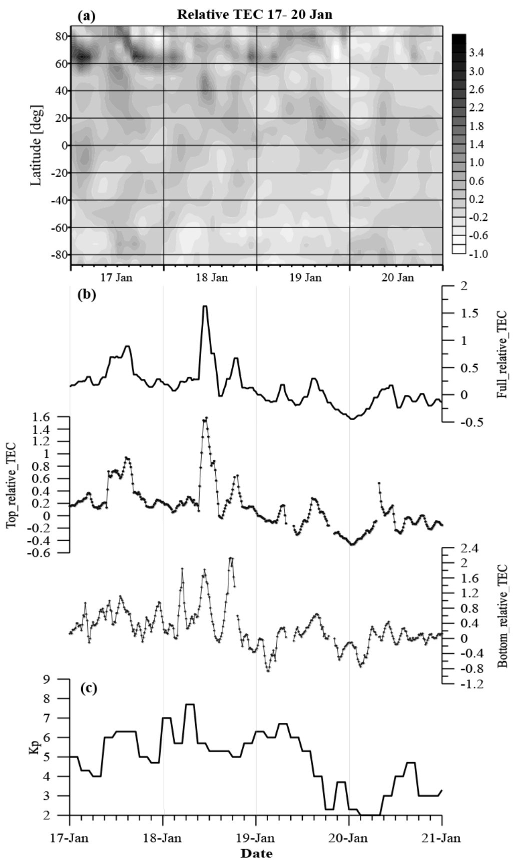

Fig. 3. The same as Fig. 2 but for the period of 17-20 January 2005

Fig. 4 presents the ionospheric response to the third geomagnetic storm that occurs on 21-22 January. This storm has approximately the same intensity as the previous two storms but has a short duration similarly to the first storm, 7-8 January. A short positive response at 60°N (Fig. 4a), coinciding with the onset of the storm, is analogous to the same phenomenon in other storms and is caused by the particle precipitations in the polar oval, i.e. direct ionization. In the SH after the evening hours on January 21 a homogeneous negative response is established. In the NH (Fig. 4a) however the TEC response strongly depends on the latitude. An initial positive response is observed at latitudes lower than 40°N while at high-mid latitudes the response is negative. After midnight all latitudes between the equator and 50°N demonstrate a negative response; only a short-term positive reaction occurs around noon. The observed complex response, particularly of the mid-latitude ionosphere, is probably related to the incomplete recovery of the previous storm leading to the overlapping of the positive and negative reactions due to different mechanisms acting simultaneously. As a result, this winter-time TEC response appears to be different from the winter-time response of the previous two storms considered in

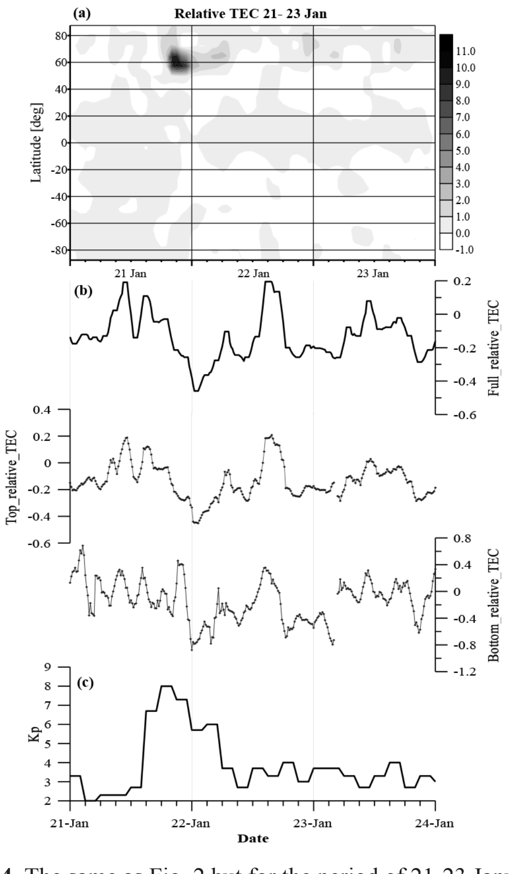

Fig. 4. The same as Fig. 2 but for the period of 21-23 January

this study, revealing strongly expressed latitudinal dependence of the reaction sign. The relative values of the full-, top- and bottom-TEC for the period of 21-23 January is shown in Fig. 4b. Similarly to the previous two storms here again the bottom-TEC reveals the largest changes (from -0.8 to 0.6) compared to the full- (from -0.5 to 0.2) and top-TEC (from -0.4 to 0.3).

Comments and conclusions

In this paper we have presented the global and mid-latitude ionospheric TEC response to three, moderate to intensive, geomagnetic storms occurred in January 2005. The following common pattern of the TEC anomalies is found: (i) there is a positive reaction in the winter during the initial phase of the storm that is most pronounced in day-time; (ii) during the storm with a longer duration (as that in 17-19 January) the positive anomaly continues over two days; (iii) the negative TEC response in the winter is observed during the recovery phase of the storms and after their completion; (iv) the response of the summer TEC is predominantly negative to the considered storms, and (v) the global distribution of the relative TEC during the tree storms considered in this work, show the greatest positive response around 60°N.

The comparison between the top- and bottom-TEC over Sofia has been presented also. It has been found that the bottom-TEC response is significantly bigger than that of the top-TEC for all three geomagnetic storms. This result raises the question: why in the winter and at mid-latitudes mostly the ionosphere below the F2-maximum reacts to the geomagnetic storms. The answer follows from the main drivers of the ionospheric response connected with the changes in the thermospheric wind system, neutral composition and temperature. The auroral heating during the geomagnetic storms can alter the mean global circulation of the thermosphere. Whereas for quiet conditions there is a general upwelling in the summer hemisphere flow toward the winter one at higher levels, and downwelling in the winter hemisphere, the storm-time heating adds a polar upwelling and equatorward flow in both hemispheres. During the winter the disturbed flow usually reverses the poleward one coming from the summer hemisphere and producing in this way two circulation cells which are situated below the F2-maximum. This process seriously affects mainly the vertical and meridional wind velocities which disturbed mainly the ionosphere below the F2-maximum. The increased downwelling at mid-latitudes moves the air into regions of increased pressure, and produces compressional heating, i.e. the neutral temperature at mid-latitudes changes and affects loss and production rates. During winter downwelling of the poleward wind from the summer hemisphere air with low concentrations of molecular species, i.e. reach of atomic oxygen, is carried downward. This leads to a decrease of the loss rate and an increase of production rate. The temperature and composition effects determine the large positive TEC response seen on 7-8, 17-18 and 22 January 2005. It is worth noting also that usually the molecular-rich air at high latitudes carried by the equatorward circulation cannot reach latitudes lower than 50°N as it has been found by (Mukhtarov and Pancheva, 2012). This is another reason explaining why the ionospheric response over Sofia in the winter is predominantly positive one.

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References

Andonov, B., Mukhtarov P., and Pancheva D., 2011. Empirical model of the TEC response to the geomagnetic activity over the North American region, Adv. Space Res., **48.6**, 1041-1048.

Gadzhev, G., Ganev, K., Miloshev, N., Syrakov, D., & Prodanova, M., 2013. Some basic facts about the atmospheric composition in Bulgaria–grid computing simulations. In International Conference on Large-Scale Scientific Computing (pp. 484-490). Springer, Berlin, Heidelberg.

Huba, J. D., Joyce, G., Sazykin, S., Wolf, R., & Spiro, R., 2005. Simulation study of penetration electric field effects on the low-to mid-latitude ionosphere, Geophysical Research Letters, **32**.

Kamide, Y., Kusano, K., 2015. No major solarflares but the largest geomagnetic storm in the present solar cycle, Space weather **13**, 365–367.

Mendillo, M., 2006. Storms in the ionosphere: Patterns and processes for total electron content, Rev. Geophys., **44**, RG4001.

Mendillo, M., Rishbeth, H., Roble, R. G., & Wroten, J., 2002. Modelling F2-layer seasonal trends and day-to-day variability driven by coupling with the lower atmosphere, J. Atmos. Sol.-Terr. Phys., **64(18)**, 1911-1931.

Mukhtarov, P., Andonov, B., Pancheva, D., 2018. Empirical model of TEC response to geomagnetic and solar forcing over Balkan Peninsula, J. Atmos. Sol.-Terr. Phys., **167**, 80–95.

Mukhtarov, P., Andonov B., and Pancheva D., 2013a. Global empirical model of TEC response to geomagnetic activity, J. Geophys. Res. - Space Physics **118.10**, 6666-6685.

Mukhtarov, P., Penov N., Pancheva D., 2013b. N(h) profiles derived from ionograms and their application for studying mid-latitude ionospheric response to geomagnetic storms, Comp. rend. Acad. bulg. Sci. **66 (9)**, 1315-1322.

Mukhtarov, P., Bojilova R., 2017. Influence of Solar and Geomagnetic Activity on the Ionosphere over Bulgaria, C.R. Acad. Bulg. Sci., **70 (9)**, 1289-1296.

Mukhtarov, P. and Pancheva D., 2012. Thermosphere-ionosphere coupling in response to recurrent geomagnetic activity, J. Atmos. Sol.-Terr. Phys., **90-91**, 132-145

Pancheva D., Mukhtarov P., Andonov B., 2016. Global structure of ionospheric TEC anomalies driven by geomagnetic storms. J. Atmos. Sol.-Terr. Phys., **145**, 10.1016/j.jastp.2016.04.015

Rishbeth, H., 2006. F-region links with the lower atmosphere? J. Atmos. Sol.-Terr. Phys, **68(3-5)**, 469-478.

Roble, R. G., 1995. Major greenhouse cooling (yes, cooling): The upper atmosphere response to increased CO2, Reviews of Geophysics, **33**, 539-546.

Schunk, R., & Nagy, A., 2009. Ionospheres: physics, plasma physics, and chemistry, Cambridge university press.

Три геомагнитни бури през януари 2005 и тяхното влияние върху общо съдържание на електрони в йоносферата

Р. Божилова

Резюме: Настоящето изследване представя глобалната и средноширинна йоносферна реакция на три геомагнитни бури случили се през януари 2005: първата буря 7-8 януари, втората на 17-19 януари и последната от 21-22 януари. Този период е избран, тъй като през избрания месец няма мажорно стратосферно затопляне (SSW) и според много учени тази зима представялва пример за т.нар. “нормална“ година. По тази причина получената реакция на йоносферата от разглежданите бури може да бъде приписана главно на външно въздействие. Реакцията е изследвана чрез разглеждане на N(h) профилите, регистрирани от йоносферна станция София (42.5°N, 25°E), които се използват за пресмятане на общото електронно съдържание (TEC) до максимума на F2-слоя и са обозначени с (bottom-TEC). Стойностите на пълния TEC (full-TEC) са получени от Center for Orbit Determination of Europe (CODE)-Bern, за най-близката точка до София. Основната задача на настоящата работа е да се направи детайлно сравнение между измененията на пълния TEC (full-TEC) с другите два подмаксимумния TEC (bottom-TEC) и надмаксимумния (top-TEC) за всяка една от разгледаните бури. Установено бе, че за всички разгледани бури през януари 2005 подмаксимумния TEC (bottom-TEC) е доста различен в сравнение с другите два top-TEC and full-TEC. Предложено е обяснение на основните механизми, отговорни за наблюдаваните различия.