Reply to Comments by Lei et al. on the paper "Poststorm Thermospheric NO Overcooling?" by A.V. Mikhailov and L. Perrone (2020)

A. V. Mikhailov[1,2] & L. Perrone[2]
[1]Institute of Terrestrial Magnetism, Ionosphere and Radio-Wave Propagation IZMIRAN, Moscow, Russia
[2]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy

Key points:

1. The "NO overcooling concept" is unable to explain the post-storm seasonal variations of neutral gas density at F_2-layer heights.

2. Contemporary F_2-layer storm mechanism adequately explains the observed seasonal differences in neutral gas density variations during the magnetic storm recovery phase.

3. The observed post-storm variations of neutral gas density at F_2-layer heights cannot be related to the process of NO cooling in the thermosphere.

Comments and Replies

Recently our paper "Poststorm Thermospheric NO Overcooling?" has been published in JGR.
Lei with colleagues (2012) who have proposed the "NO overcooling" concept have written Comments on this paper. Below is given our reply. Everywhere MP20 means the reference to the paper by Mikhailov & Perrone (2020). In the beginning to avoid misunderstanding it is necessary to stress that in MP20 we did not touch on the well-documented process of the thermosphere NO cooling (e.g. Gordiets et al. 1982; Maeda et al., 1989; Roble, 1995; Prölss, 2004, 2011; Weimer et al., 2011, Mlynczak et al., 2018) which mainly takes place in the lower thermosphere. We only explained a decrease of neutral gas density at F_2-layer heights during the recovery storm phase. The effect manifests seasonal dependence which is not explained by the "NO overcooling" mechanism.

(1) The methodology used in MP20 is questionable, and in fact, incorrect, and the results lack of proper uncertainty estimate and verification.

Comments on our method (Perrone & Mikhailov, 2018a) used in the paper are the same reported by Zhang at al. (2018) and they are repeated again. Our detailed answer was given by Perrone and Mikhailov (2018b), so there is no need to explain the method once again. Our method is not a 1-D model (as the authors of Comments call it) but a method to extract a consistent set of the main aeronomic parameters responsible for the formation of noontime F-layer at middle latitudes using observed Ne(h) distribution. This Ne(h) totally manifests the state of surrounding thermosphere and the intensity of incident solar EUV. The method was tested using CHAMP/STAR neutral gas density observations under various seasons, levels of solar and geomagnetic activity, and it was shown that the method provided statistically significant better results in a comparison to modern empirical thermospheric models. A comparison with Swarm neutral density observations was used to explain the post-storm neutral density decrease in the thermosphere (Mikhailov & Perrone, 2020). Millstone Hill ISR noontime h_mF_2 observations (as the most reliable h_mF_2 data) in 2000-2016 have been also used to test the method (Perrone et al., 2020a). The retrieved h_mF_2 values demonstrated a standard deviation close to the expected inaccuracy of h_mF_2 determination. A comparison of the retrieved EUV to observed one as well to satellite neutral gas density observations given by Perrone et al., (2020b) provides an absolutely independent check of the method as the observed EUV and neutral gas density have nothing common with the retrieval process. Figure 1 gives a comparison of June monthly median retrieved EUV flux to composite HLα (Machol, et al., 2019) and EUVAC model (Richards, et al., 1994) variations for the (1958-2020) period.

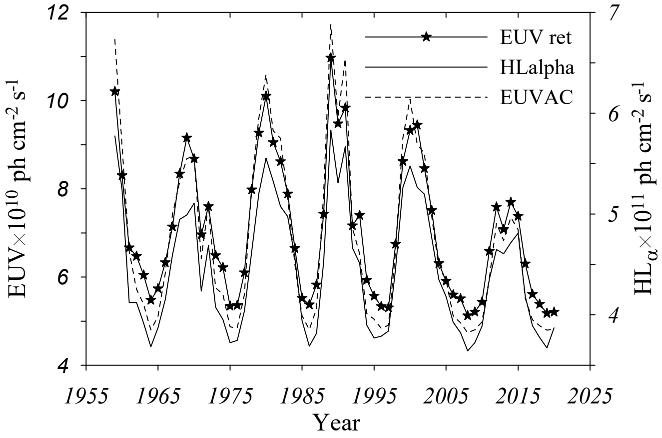


Figure 1. A comparison of June monthly median retrieved EUV flux to composite HLα and EUVAC model variations for the (1958-2020) period. The axis for HLα is shifted for better obviousness.

The correlation coefficient between the retrieved EUV and HLα variations is 0.978 ± 0.018 being significant at the 99.9% confidence level according to Student criterion. A coincidence is seen even in details – notice two-hump maxima in the even solar cycles. A comparison with the EUVAC model gives the correlation coefficient 0.987 ± 0.011 which is also significant at the 99.9% confidence level. Therefore, there are no reasons not to rely on the results obtained with this method. Anyway nobody has shown this yet.

(2) MP20's attribution of overcooling to O density reduction is problematic and physically not self-consistent.

First of all it should be stressed that MP20 gives an explanation to the observed post-storm neutral gas density decrease at F_2-region heights and the paper does not deal with the process of NO cooling in the lower thermosphere which is well-documented and does take place.

The following saying by the authors: "Memory of this composition change is widely accepted to explain the negative ionospheric storm at midlatitudes during the storm recovery phase, albeit the disturbance dynamo electric fields driven by thermospheric winds (Blanc and Richmond, 1980) can also have important contributions to negative ionospheric storms (Prölss, 1995; reference therein)" needs comments.

Prölss, (1995) has never related F_2-layer negative storms with electric fields. But he was the first who using ESRO-4 observations confirmed that F_2-layer negative storm phase was due to O/N_2 ratio decrease: "Thus a close correlation is found between magnetic storm induced changes of the O/N_2 density ratio and depletions of the ionospheric plasma" (Prölss, 1980, his Fig.8). Moreover his Fig. 9 demonstrates storm-time (October 26-31, 1973) variations of N_mF_2 (Boulder observations were used) and O/N_2 variations observed at a fixed height 260 km. On one hand a perfect association between two variations was demonstrated, on the other hand the O/N_2 ratio was strongly decreased during the recovery storm phase on October 30-31. This is exactly what is discussed in MP20. It should be reminded that namely G. Prölss using excellent ESRO-4 neutral gas density observations has experimentally grounded the F_2-layer storm mechanism.

Some comments are required in relation with the following sayings of the authors:
"As a result, [O/N_2] on a constant pressure surface that corresponds to the F_2 layer undergoes a decrease at middle and high latitudes and an increase in the lower latitudes" and "MP20 did not seem to understand the different aspects of thermospheric density change at a fixed altitude with respect to that on a constant pressure surface".

The isobaric F_2-layer concept proposed by Rishbeth & Edwards, (1989) should be considered as a rough approximation just for estimates applicable when vertical plasma drifts are small. In fact vertical drifts related to thermospheric winds shift F_2-layer from the level of constant pressure. This was shown earlier by Mikhailov et al., (1989, 1992). Therefore the statement: "The changes in peak ionospheric density N_mF_2 and changes of O/N_2 on pressure surface level 2 at 20 UT, which is close to the F_2-layer peak …" is incorrect especially during nighttime hours and under geomagnetic disturbances when the thermospheric winds (and vertical plasma drifts, correspondingly) are strong and the displacement from the constant pressure level may be large.

Any analysis of thermospheric parameter variations at a constant pressure level can be done only in computer model simulations. In reality we have satellite-born observations at fixed heights and such observations, for instance ESRO-4 (Prölss, 1980, his Fig. 2) indicate a decrease of light thermospheric species (O and He) and an increase of heavy species N_2 and Ar during storm period. This is a well-know empirical fact. It should be reminded that CHAMP and GRACE neutral gas density observations used by the authors of the "NO-overcooling" concept (Lei ,et al., 2012) were obtained at fixed heights ~ 390 and 485 km, correspondingly.

According to the F_2-layer storm mechanism the redistribution of thermospheric composition resulting in [O] decrease is due to disturbed global thermospheric circulation. We have a decrease in the total (column) atomic oxygen abundance during storm and post-storm periods and namely this is important for the mechanism of the analyzed neutral gas density decrease at the recovery storm phase.

Table 1 gives column atomic oxygen abundance variations at Rome and Juliusruh during St. Patrick storm on 17-20 March, 2015 considered in MP20.

Table 1. Daily variations of column atomic oxygen content during St. Patrick storm on 17-20 March, 2015. Noontime values in 10^{17} cm^{-2} are considered. March 16 is the pre-storm quiet reference day.

Date	Mar 16	Mar 17	Mar 18	Mar 19	Mar 20
Rome	12.00	7.09	7.40	7.21	5.17
Juliusruh	9.98	5.96	4.02	4.35	4.27

In accordance with the contemporary F_2-layer storm mechanism the total (column) atomic oxygen abundance is strongly (by more than two times) decreased during storm and post-storm periods compared to pre-storm quiet time reference values (Table 1).

The authors of Comments give TIEGCM simulations of model storm conditions to demonstrate the inefficiency (as they suppose) of the well-established F_2-layer storm mechanism. However the TIEGCM model is unable (see later) to describe storm-time variations of thermospheric and ionospheric parameters. Therefore if the authors want to support their "NO overcooling" concept by 3D model simulations they should consider a real (not artificially constructed) storm cases taken say from MP20 and to compare with available ionospheric and satellite (CHAMP, GRACE, Swarm) neutral gas density observations. If the TIEGCM model succeeds describing simultaneously the observed ionospheric and thermospheric parameter storm-time variations then results can be discussed at a serious basis. Now the presented calculations are not at this level.

Any 3D model simulations without a comparison with reliable observations should be considered as "computer games". But such attempts to compare with observations manifest not very comforting results. A comparison with Millstone Hill ISR, CHAMP and COSMIC electron density observations (Shim et al., 2011, 2012) has shown that TIEGCM occupies the 5-6th positions in the row of compared models while the empirical monthly median IRI model turns out to be one of the best. This does not mean that monthly median IRI model is a very good one - it is not designed to describe particular geophysical conditions of a given day - but this tells us that sophisticated 3D first-principle physical models are far from to be perfect. Similar results of a metrics-based assessment of current modeling capabilities in predicting the ionospheric climatology for two ionospheric characteristics, f_oF_2 and h_mF_2 have been obtained by Tsagouri et al., (2018). Further, TIEGCM in a comparison with CHAMP and GRACE neutral gas density observations has demonstrated the worst results compared to other models (Bruinsma et al., 2018, their Table 4).

Figure 1 from the Comments by Lei et al. demonstrates TIEGCM simulation results for equinoctial period with model Kp index variations. Such Kp index variations correspond to a very strong geomagnetic disturbance. However calculated ΔN_mF_2 deviations manifest positive or small negative values at middle latitudes (top right panel) but this is absolutely impossible under geomagnetic conditions used in the simulations. Small and mainly positive changes manifests atomic oxygen at 300 km during the recovery storm phase at middle latitudes (middle right panel).

To show the incorrectness of TIEGCM simulation results a similar storm on March 31, 2001 has been chosen for a comparison. That was an isolated storm during the equinoctial period with daily Ap=191 nT (Kp ~ 8), i.e. conditions were close to those used in TIEGCM simulations. Two mid-latitude ionospheric stations Juliusruh (54.6N; 13.4E) and Rome (41.8N;12.5E) were used to check the reaction to this storm.

The observed N_mF_2 variations along with ap-3 hour and Dst indices are given in Fig. 2. The selected storm presents an excellent case for a comparison with the results of model simulations. The previous day of March 30 was quiet and can be used as a pre-storm reference. Strong disturbances finished by the end of March 31, so April 01 may be considered belonging to the recovery storm phase (see Dst variations in Fig. 2). A strong negative phase with $\Delta = (N_mF_{2dist} - N_mF_{2quiet}) \sim -13\times10^5$ cm^{-3} at Juliusruh and Rome took place around noon-time hours on March 31.

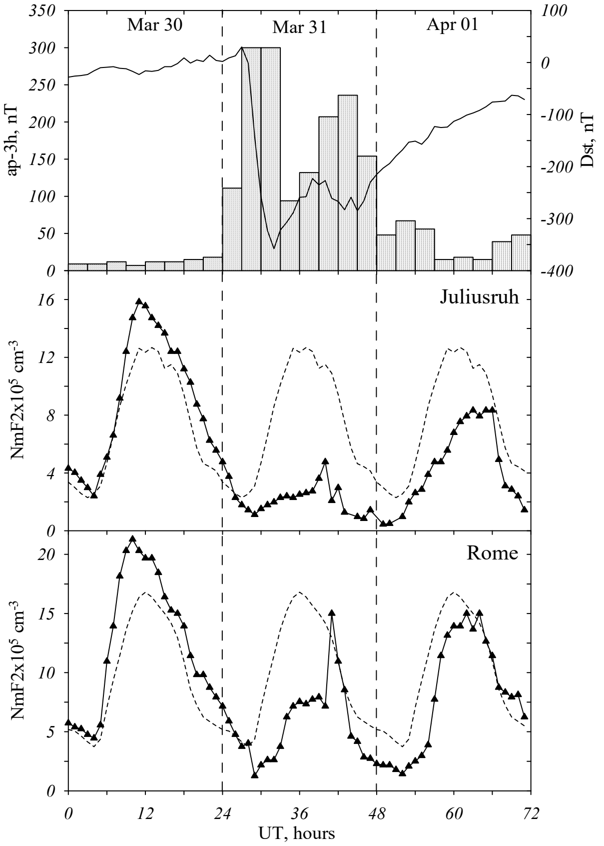
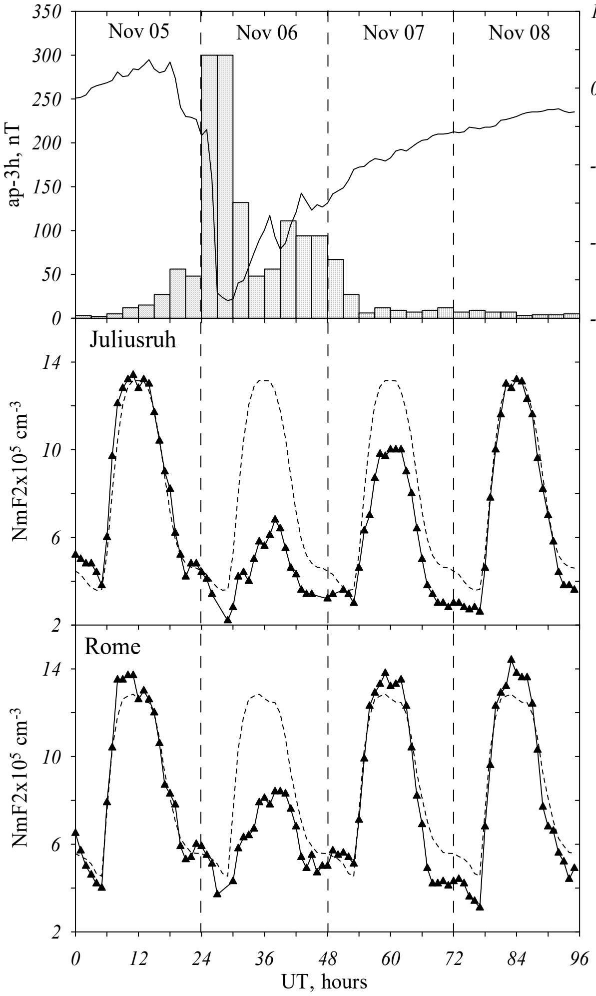


Figure 2. Observed N_mF_2 at Juliusruh and Rome along with ap-3h and Dst index variations during the severe magnetic storm on March 30-April 01, 2001. Dashes - monthly median N_mF_2 variations.

Negative N_mF_2 disturbance with less magnitude kept on April 01. This is very far from TIEGCM model simulation results when ΔN_mF_2 are around zero or even positive at middle latitudes (Fig. 1 in Comments by Lei et al.). The very fact that TIEGCM model simulation results are given for 2000 UT does not change the conclusion as strong by a factor of 2 negative N_mF_2 deviations also took place in the evening sector in Europe (Fig. 2). With such simulation results on N_mF_2 variations there is no sense to discuss TIEGCM model variations of neutral composition given in Comments. The authors may be recommended to compare TIEGCM model simulation results with real N_mF_2 observations at particular stations rather than to rely on such model calculations which may not have any real physical sense.

Zhang et al. (2019) have shown that “NO overcooling” concept is unable to explain the observed neutral gas density variations during winter magnetic storm on 20-24 November, 2003. However the observed neutral gas density storm-time variations can be explained in the framework of the F_2-layer storm mechanism as this was shown in MP20. Due to a competition between strong winter daytime poleward solar driven neutral wind and storm-induced equatorward wind the disturbed neutral composition bulge with low O/N_2 ratio is restricted to high latitudes (Prölss,1980, his Fig. 25). Therefore small changes of neutral composition and neutral gas density take place equatorward from this disturbed bulge but both are changed inside this bulge. Of course, depending on the storm intensity this boundary will shift in latitude. To demonstrate this we have selected a strong isolated winter storm on November 06, 2001 with daily Ap = 142 nT (Kp ~ 7) and $F_{10.7} = 237.4$. Juliusruh and Rome ionospheric observations were used for our analysis (Fig. 3). A quiet time day of November 05 manifests N_mF_2 variations very close to monthly median and it may be used as a reference one. November 07 formally belongs to the recovery storm phase (see Dst variations in Fig. 3 and it may be used for a comparison to November 05). The discussed dependence on latitude is clearly seen comparing N_mF_2 variations at Juliusruh and Rome on November 07. Negative daytime N_mF_2 disturbance takes place at Juliusruh while at Rome N_mF_2 are close to the pre-storm values. This means that the disturbed O/N_2 bulge covered Juliusruh but did not reach the latitude of Rome. Geomagnetic activity returned to the quiet time pre-storm level on November 07 but neutral composition remains disturbed. This effect was earlier discussed by Prölss (1995): "The idea that composition perturbations, once they have been generated, "rotate" into the daytime sector, perhaps only a first-order description. Actually, the disturbance bulge will be pushed around by winds and may move back and forth in latitude".



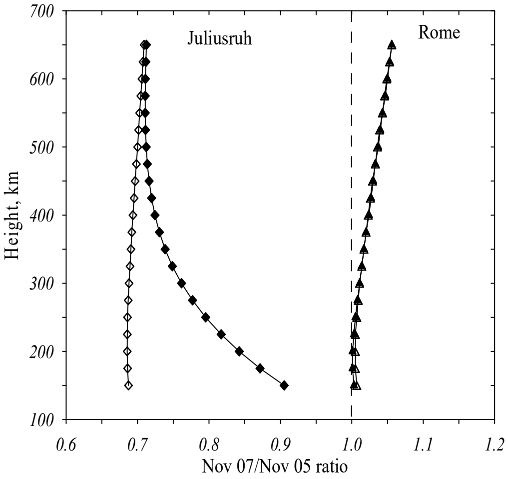


Figure 3 Observed N_mF_2 at Juliusruh and Rome along with ap-3h and Dst index variations during the severe winter magnetic storm on November 06, 2001. Dashes-monthly median N_mF_2 variations.

Figure 4. Height dependence for $O]_{dis}/[O]_{ref}$ (open symbols) and ρ_{dis}/ρ_{ref} (filled symbols) ratios at Juliusruh (diamonds) and Rome (triangles).

The retrieved thermospheric parameters confirm this difference between two stations (Fig. 4). At Rome there are practically no changes in [O] and ρ height distributions on November 07 with respect to November 05. While at Juliusruh under practically the same Tex = 1229 K on the reference day and Tex = 1238 K on the storm recovery day atomic oxygen and neutral gas density are strongly decreased by 25-30% at F_2-layer heights on November 07 (Fig. 4).

The authors of Comments state that the thermospheric overcooling in Lei et al. (2012) mainly took place during 12-20 UT on 30 and 31 October 2003, so the MP20 study is not even applicable to the observed neutral mass density changes.

On one hand, the characteristic time of neutral composition variations is much longer than 1 hour therefore the difference in 1 hour is not discussed in principle. On the other hand, Zhang et al., (2019 their Fig. 4) analyzing the same storm period of October 2003 indicate a decrease of neutral gas CHAMP density at middle 30 < lat <40 latitude during daytime 10:00 < LT < 15:00 i.e. noontime is included.

(3) Thermospheric overcooling does NOT equate to density depletion.

“In the paper of Zhang et al. (2019), however, overcooling was referred simply as density depletion which is not necessarily associated with NO cooling, and clearly what they really meant by “overcooling” is not consistent with the original concept proposed by Lei et al. 2012].”
Zhang et al. (2019) have absolutely correctly understood what was meant in the paper by Lei et al. [2012]. Open Summary of the paper by Lei et al. [2012] and read: “We emphasize here that the purpose of this study is to report the observed post-storm overcooling (**or density depletion**) in the upper thermosphere from satellite data”.

Summarizing our reply to Comments we would like to stress the key points.

1. The aim of the PM20 paper was to explain the post-storm variations of neutral gas density at F_2-region heights. The PM20 did not touch on the questions of NO cooling in the lower thermosphere which has nothing to do with neutral gas density variations at F_2-region heights during the post-storm period.

2. The authors of the “NO overcooling” concept don’t want to see and admit that this mechanism is unable to explain winter storm cases when the post-storm decrease of neutral gas density takes place in the limited high-latitude range only.

3. The “NO overcooling” concept directly relates the decrease of neutral gas density with the decrease in neutral temperature: “… the estimated decrease of thermospheric temperature is as large as 70–110 K” (Lei et al., 2012). The word “cooling” means a temperature decrease and nothing else. Maybe such cooling effect takes place in the lower thermosphere but not at the F_2-layer heights where neutral temperature is controlled by the efficiency of auroral heating during magnetically disturbed periods. October 30-31, 2003 analyzed by Lei et al. 2012 were strongly disturbed days with *ap* up to 400 nT on October 30 and *ap* up to 236 nT on October 31. All modern thermospheric empirical models like MSISE00, DTM13, JB2008 do not predict any temperature decrease for such disturbed conditions – this is absolutely impossible.

4. On the other hand, the present-day F_2-layer storm mechanism in agreement with the empirical models does not require any Tex decrease and relates the observed neutral gas density decrease with a storm-time decrease of atomic oxygen abundance in the upper atmosphere. Seasonal differences in atomic oxygen variations during the recovery storm phase manifested in corresponding N_mF_2 variations have a straight explanation in the framework of the F_2-layer storm mechanism. These seasonal differences in upper atmosphere reaction to magnetic activity are confirmed by satellite neutral gas density observations as this is shown in PM20.

Without overcoming these basic contradictions with observations the “NO overcooling” concept hardly may be considered as a plausible mechanism of the post-storm neutral gas density decrease which does take place during the recovery storm phase under specific geophysical conditions.

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Oceanic and Atmospheric Administration(NOAA) and https://www.gfz-potsdam.de/en/kp-index/ GFZ German Research Center The authors are grateful A.A. Nusinov to provide EUV data in a proper format.

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