Author's response to referee #1

We would like to thank the referee very much for their detailed consideration of the paper, including some extremely useful suggestions for interpretation of the result and with the accuracy and clarity of the interpretation. Below we respond to each specific comment.

1. To explain the observed effect, authors suggest the only mechanism, namely (Page 6, lines 24-26): "The dominant ion species in the mid-latitude ionospheric F-region is O+ whose recombination rate is temperature dependant (Rees, 1989). A rise in the background thermospheric temperature would therefore result in an enhanced loss rate, with the equilibrium between production and loss being established at a lower peak electron concentration, as observed." The equilibrium between production (q) and loss is given by: q = βne. Indeed, in the F peak region, the main ion species is O+, but their recombination rate is very low. So that the F-layer electron loss is dominated by the following two chemical reactions: O+ + N2→ NO+ + N O+ + O2 → O2+ + O After that, molecular ions (NO+ and O2+) recombine immediately. The rates of the reactions (k1 and k2, respectively) depend on the temperature, however the electron loss rate (β) depends on concentration of the molecules (N2 and O2) as well: β = k1.[N2] + k2.[02]. Authors suggest only one mechanism for the foF2 depletion, namely the temperature dependence of k1 and k2, however the thermospheric temperature increase leads also to an increase of the scale height of atmospheric gas $H_s = K_BT/mg$ (here m is mass of the molecules). Hence, concentration of N2 and O2 in the F layer peak will increase, which is a second possible reason for increasing the loss rate (β) and corresponding decrease of the plasma density. The thermospheric temperature increase may be estimated numerically as $\Delta T = Q/C_pnK_B$ where Cp ≈ 3 is the molar heat capacity, n ≈ $10^{10}cm^{-3}$ is concentration of the atmospheric gas at the F peak, k_B is the Boltzmann constant, and Q is the heat energy per volume. For 1000 metric tons of TNT, assuming the energy was uniformly distributed in the range of 1000 km at height up to 300km, we get: 1000*4.184e9J/(pi*1000km*1000km*300km)/(3*1e10cm-3*1.381e-23J/K) =11K Grandin et al. [J. Geophys. Res. Space Physics, 2015, doi:10.1002/2015JA021785] studied the ionospheric foF2 decrease caused by the solar wind high speed streams, and have shown that the thermospheric temperature increase by 20-50 K may cause the foF2 decrease of the order of 0.5-1.0 MHz. Hence, energy of the explosions during the raids could potentially cause the 0.3 MHz effect in the foF2, although the above numerical estimates are very rough.

   We are very grateful for these useful suggestions and have expanded the relevant section of our paper to include them. The text now reads;

"For the ionosphere at the altitude of the F2 region (~200-300 km) above the UK to respond to bombing raids conducted at distances up to 1000 km away, the bombing must have generated pressure waves that were capable of propagating to ionospheric altitudes. A sound wave travelling this distance in the lower atmosphere would arrive within an hour. The speed of sound is temperature dependent and the temperature decreases with altitude in the troposphere and mesosphere before increasing in the thermosphere. Since the thermosphere represents the most significant fraction of the vertical profile, it is likely that a soundwave propagating vertically as well

as horizontally would arrive even sooner. One potential mechanism therefore is of a pressure wave propagating upwards in all directions. At higher altitudes its amplitude increases until it breaks in the upper atmosphere, depositing its energy as heat. A very rough estimate of the anticipated thermospheric temperature rise can be obtained by considering the specific heat capacity of the atmosphere which can be expressed as;

$$Q = C_p n \Delta T$$

Where Q is the energy input in Joules (4.184×10^{12} for 1000 metric tonnes of TNT), Cp is the molar specific heat capacity of N_2 (~29.1 $Jmol^{-1}K^{-1}$), n is number of moles of gas m^{-3} (at ionospheric altitudes, the number density of the atmosphere is ~10^{16} m^{-3} or 1.66×10^{-8} moles m^{-3}) and ΔT is the change in temperature (K). Assuming the energy is equally distributed throughout a cylinder of atmosphere 1000km in radius and 300km in height, this gives a temperature rise of ~9K.

The dominant ion species in the mid-latitude ionospheric F-region is O^+ whose loss rate is temperature dependant (Rees, 1989). However, the dominant mechanism by which O+ ions is lost is through reaction with N_2 and O_2 molecules in the reactions;

$$O^+ + N_2 \rightarrow NO^+ + O$$

$$O^+ + O_2 \rightarrow O_2^+ + O$$

The overall loss rate, β, for O^+ ions can therefore be expressed as;

$$\beta = k1.[N_2] + k2.[O_2]$$

Where $[N_2]$ and $[O_2]$ are the concentrations of N_2 and O_2 molecules respectively and k1 and k2 are the rate coefficients for the two reactions. These rate coefficients are also temperature dependent (Rees, 1989). The combined loss rate for O^+ ions is therefore dependant on both reaction rates and the concentration of thermospheric species. Müller-Wodarg et al (1998) modelled the ionospheric and thermospheric response to localised thermospheric cooling (≤ 40K) during a total solar eclipse. They predicted an 8% increase in foF2 (~0.2 MHz) due to the contraction of the atmosphere and an increase in the [O]/[N2] ratio caused, in part, by a reduction in the concentration of N_2. It is reasonable to assume that the atmospheric expansion due to energy from localised bombing raids would have an analogous, if opposite, effect on the ionosphere and thermosphere. A rise in the background thermospheric temperature would result in an enhanced loss rate, with the equilibrium between production and loss being established at a lower peak electron concentration. Such equilibrium would be reached within minutes of perturbation, well within the resolution of the ionospheric data. Grandin et al (2015) studied the impact on foF2 of high-speed streams at Earth. They found that a thermospheric temperature increase of 20-50 K may result in a decrease in foF2 by 0.5-1.0 MHz.

If the bombing resulted in the generation of shock waves or atmospheric gravity waves, their horizontal propagation speed would need to be of the order of 300 km/hour while the vertical velocity component would need to be around 100 km/hour in order to affect the atmosphere above Slough. There is evidence that turbulence generated in the lower thermosphere by space shuttle launches can propagate 1000 km horizontally within 8 hours (Kelley et al, 2009). While this example was specific to the lower thermosphere at altitudes between 100 and 115 km, it nevertheless has a *similar time constant to that observed for the ionospheric response to bombing in the current study. Such a mechanism may therefore contribute to the observed effect."*

2. I may mention one more hypothetic mechanism for transport of N_2 and O_2, namely the turbulence provoked by the shock waves [see e.g., Kelley, et al., (2009), Two-dimensional turbulence, space shuttle plume transport in the thermosphere, and a possible relation to the Great Siberian Impact Event, Geophys. Res. Lett., 36, L14103, doi:10.1029/2009GL038362]. If authors will wish, they may consider these issues in the paper.

   Thank you for bringing this interesting piece of work to our attention. We have included the following text and reference;

   "There is evidence that turbulence generated in the lower thermosphere by space shuttle launches can propagate 1000 km horizontally within 8 hours (Kelley et al, 2009). While this example was specific to the lower thermosphere at altitudes between 100 and 115 km, it nevertheless has a similar time constant to that observed for the ionospheric response to bombing in the current study, suggesting a similar mechanism may be involved."

   We are very grateful to the referee for raising these useful points. We have expanded the discussion (and abstract) to consider these points more fully and also include a reference to modelling work of the thermospheric and ionospheric response to a solar eclipse where localised cooling also upset the local equilibrium in thermospheric composition.

3. For the case if other experts will be interested to make a more comprehensive numerical analysis, I recommend adding in Table 1 two columns showing data of the foF2 for the noon following the raids and the monthly median values.

   This is a very helpful suggestion and we have added these values to table 1 as suggested, amending the figure caption accordingly.

4. Finally, I think citation [Kurt Vonnegut (1969), Slaughterhouse-Five, or The Children's Crusade] may be very relevant in the paper.

   Thank you for this suggestion. Indeed this reference came up many times during our research. Since it is a work of fiction (albeit set in the highly relevant context of the bombing of Dresden) we are reluctant to cite it in the context of an academic paper.

5. Technical comments Page 6, line 17: "For the ionosphere (at ~ 250-350 km) above the UK to respond…" - I suppose authors assume here true height, whereas 250-350 km may be the virtual height measured by the ionosonde (it is typically higher than the true height).

   Thank you for pointing out this ambiguity. It was meant to represent an approximate altitude of the F2 peak, rather than a virtual height. While the exact values do not change the meaning of the sentence, we have amended the text to read;

   "For the ionosphere at the altitude of the F2 region (~200-300 km) above the UK…."

6. Page 6, line 24: “The dominant ion species in the mid-latitude ionospheric Fregion is O+ whose recombination rate is temperature dependant” - It is correct to say: “…whose loss rate is temperature dependant…”

   Thank you for pointing out this inaccuracy. We have amended the text accordingly.

7. Page 7, line 1: “Infrasonic waves generated by explosions are launched preferentially in a vertical direction.” - A reference or a more detailed explanation for why it is so will be very relevant here.

   We have added the following reference: Blanc, E.: Observations in the upper atmosphere of infrasonic waves from natural or artificial sources: A summary, Ann. Geophys., 3, 673– 688, 1985.