David, thank you very much for your comments and the time you took to explain us essential aspects of IRI model.

Following are our answers (in blue) to your comments (in black).

The changes in the revised manuscript which correspond to your remarks will appear in red, together with those corresponding to the comments of Reviewer #1 and Reviewer #2.

Realistically, longterm trend in the IRI can only be attributed to processes that adhere to changes in the drivers of the model themselves. As the IRI does not include a greenhouse gas-related index or driver and does not include any longterm trend parameters except solar activity, it cannot represent the impacts of that in its output. There is no multi-year term in the IRI parameterization, except solar activity, that would allow it to represent such trends even if they existed in the data used to fit the model. The IRI is just an interpolation between a low solar activity and a high solar activity map of foF2 and M3000F2, it doesn't care about the year or date outside of that.

It can, however, represent changes resulting from long term processes like the shifting of the geomagnetic field, since the IRI uses a modip or geomagnetic coordinate system (depending on the sub-model) and the magnetic field model has been updated over time. In fact, you could try to use the IRI to control against the impacts of geomagnetic field migration in search of climate change impacts, but the model output itself explicitly does not include lower atmospheric climate forcing. The impacts shown in your figures is likely entirely just the impact of the shifting magnetic field and the statistically weak solar activity over the last two cycles. If you ran the model and forced the solar activity term to be constant, you would not see anything other than the geomagnetic field migration impact. Given that you try to remove the MgII forcing later on anyway, there seems to be no reason why you shouldn't just force it to a constant to verify your hypothesis anyway.

Thank you for pointing this out to us.

As you mention, if we keep constant the solar activity index selected in IRI (IRI-Plas, IRI2016 or IRI2020), even though we run the years from 1960 to 2022, there is no solar activity variation in foF2 or hmF2, as can be seen in Figure R8. Instead there is a slow variation (or trend) which corresponds, as you also mentioned, to the Earth's magnetic field inclination angle, which is the one entering the modified dip coordinate used by IRI, and changes with years according to IGRF model. In Figure R8 we have also included foF2 and hmF2 estimated with IRI-2020 default indices (black curves), and use as an input the Rz value of the corresponding dates from 1960 to 2018 (red dashes curves), as you also suggested.

F2 parameters estimated with IRI with the default indices and by entering Rz are very similar, but not identical. We were expecting in hmF2 case to be exactly the same since hmF2 is estimated with Rz in the default option. But it is not the case.

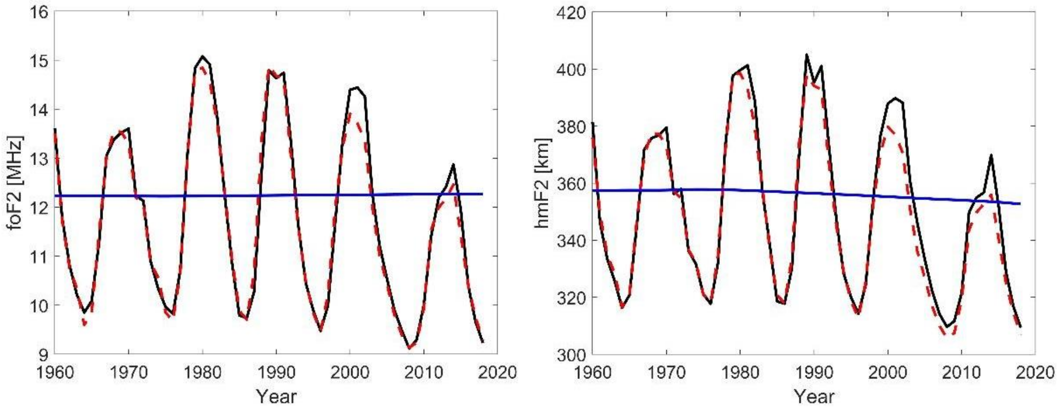

Figure R8. foF2 and hmF2 annual means, at 12 LT, 20°N-30°E, estimated with IRI2020 default parameters (IG in foF2 case and Rz in hmF2 case) (black solid line), by entering Rz for the corresponding dates (red dashed line), and keeping Rz=70 for every date (blue solid line).

Figure R9 shows the trends that we obtain if we run IRI-Plas and also IRI-2020 keeping Rz constant at 70 (that is Rz=70 for every month and year). The trend is assessed directly from the modeled data without any filtering since foF2 does not have any other variability (as seen in Figure R8, blue line), that is

foF2 = α t + β and hmF2 = α t + β

α, estimated applying least squares to the regression foF2 vs. t and hmF2 vs t, is the trend. In the case of Figure R9 the trends are estimated for annual mean values of foF2 and hmF2, so t corresponds to years.

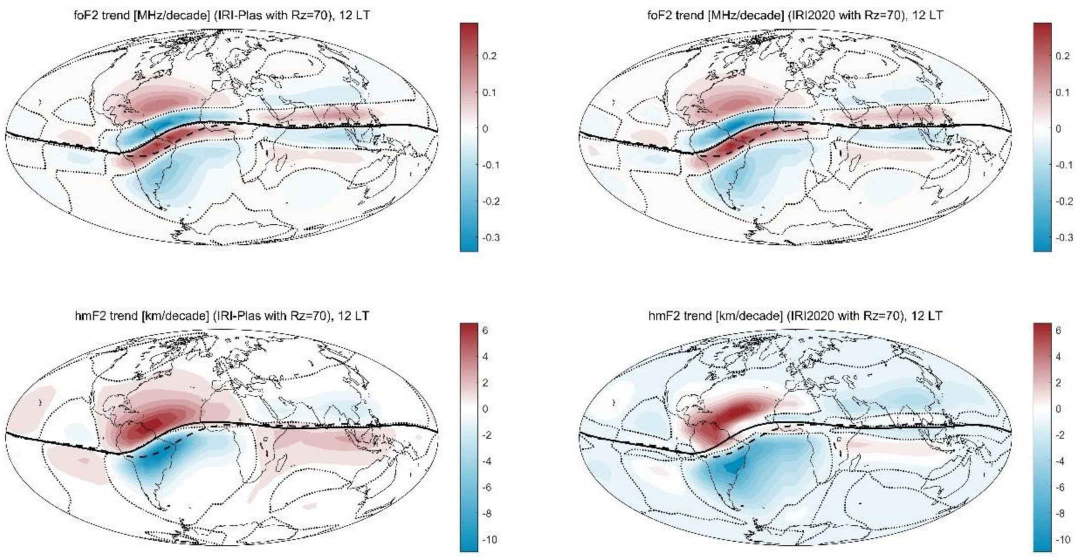

Figure R9. Trends estimated with F2 parameters obtained from IRI-Plas (left panels) and IRI2020 (right panels) keeping Rz=70 and running only the years along 1960-2018 (since IRI2020 allows until this year). Black dotted lines indicate trend=0, black dashed line the dip equator in 1960 and black solid line the dip equator in 2022.

Considering Rz fixed at 70, the global mean trends result -0.0004 and -0.0003 MHz/decade for foF2 with IRI-Plas and with IRI2020 respectively. This is almost zero compared with the trends obtained without keeping Rz constant (~-0.10 MHz/decade). In the case of hmF2, with Rz fixed at 70, the mean trends result -0.086 and -0.098 km/decade with IRI-Plas and IRI2020, respectively, that again is almost zero compared with the trends obtained without keeping Rz constant (~-2 km/decade).

This means that, globally, the trend due to the secular variation of the magnetic field inclination cancels out. This is logical since the main change here is due to the displacement of the magnetic equator which induces trends of opposite sign almost symmetrically at each of its sides along its slow displacement.

All this would point out that the trends in our work are obtained due to the filtering "method" (in agreement with our discussion), which means the following: we are filtering with MgII while the interannual time variation of the ionospheric series are determined by another proxy. This implies, as you also correctly noticed to us, that the trend obtained would have nothing to do with an external real forcing. However, in the case of foF2, the proxy determining its interannual variation in IRI is IG, which is obtained from measured foF2 data. Thus, it can be said that foF2 is obtained from measured data assimilated through IG, which is a global index, and then particularized for a location through the CCIR maps. The case of hmF2 is different, as explained in what follows.

In the default mode of IRI2020, foF2 is estimated, as already mentioned, from IG and hmF2 from Rz. This would mean that if we filter the solar activity effect from these ionospheric parameters with IG and Rz respectively, we should expect an ~100% filtering (and thus no trends) except for the effect of the magnetic field (in agreement with your comment) (and equivalent to keeping the solar proxy constant as done with Rz=70).

In the case of IRI-Plas, even though we selected MgII as the solar activity proxy, the procedures that adjust the other proxies in the subroutines ends in foF2 variability being determined by IG and hmF2 by Rz, as in the case of IRI2020, but with slight changes that depend on the proxy selected.

In addition, if we make the difference between trends estimated with MgII and trends estimated with IG in foF2 case (with Rz in hmF2 case), we should be left with the trends that are not due to the magnetic field. In this, we are making the following hypotheses:

1) foF2 ionosonde data interannual variability is composed of:
solar activity variability
+ a trend induced by the magnetic field
+ a trend induced by the greenhouse effect
+ a random noise (inherent to any non-ideal time series).

2) IG interannual variability is composed of:
solar activity variability
+ a trend induced by the greenhouse effect (since, considering that this index results from foF2 measured data from stations far from the magnetic equator, where

the secular variation of the magnetic field is extremely small, we assume that the trend induced by the magnetic field in this case is zero).

3) MgII interannual variability is composed of:
solar activity variability very close to the solar activity variability of EUV solar spectral range ionizing the F2-layer ionosphere.

The interannual variability of foF2 estimated with IRI models is forced by:

* the magnetic inclination obtained from IGRF, and

* IG, which carries with it the information of a "global" greenhouse effect and the solar activity variability effect.

So, when we filter foF2 (obtained from IRI) with MgII, or any other proxy except IG, we are left with the variability of the magnetic field and the greenhouse effect.

In the case of hmF2 instead of IG, Rz is used. And the hypothesis here is:

1) hmF2 ionosonde data interannual variability is composed of:
solar activity variability
+ a trend induced by the magnetic field
+ a trend induced by the greenhouse effect
+ a random noise (inherent to any non-ideal time series).

2) Rz interannual variability is composed of:
solar activity variability but not very close to EUV solar spectral range ionizing the F2-layer, which seems a quasidecadal cycle "falling" down along the years, as in the case of IG. The difference here is that the "falling" of IG would be due to an external forcing, possible the increasing CO2, and the "falling" in Rz we do not know. In fact, Rz would have varied very close to solar EUV until prior to solar cycle 23. After this solar cycle not anymore.

3) MgII interannual variability is composed of:
solar activity variability very close to the solar activity variability of EUV solar spectral range ionizing the F2-layer ionosphere.

The interannual variability of hmF2 estimated with IRI models is forced by:

* the magnetic inclination obtained from IGRF, and

* Rz, which does not carry with it the information of a "global" greenhouse effect. However, the solar activity variability it reflects seems to be composed of the quasidecadal well-known oscillation plus a kind of trend towards the last cycles (in particular de minimum epochs).

So, when we filter hmF2 (obtained from IRI) with MgII, or any other proxy except Rz, we are left with the variability of the magnetic field and a downward trend.

If we filter hmF2 from IRI with Rz, we would be left with "nothing".

All these reasoning is checked with Figures R10 and R11 for foF2 (assessed with IRI2020 (default setting) and IRI-Plas (with MgII) respectively) and Figures R12 and R13 for hmF2 (assessed with IRI2020 (default setting) and IRI-Plas (with MgII) respectively).

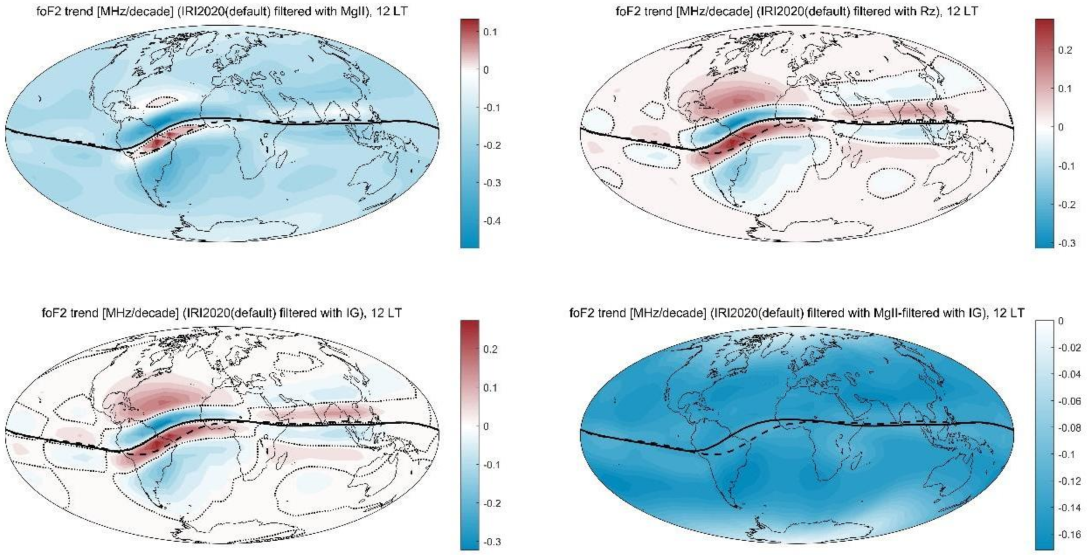

Figure R10. Trends estimated with foF2 from IRI2020 with default settings (IG for foF2 and Rz for hmF2). Solar activity is filtered with MgII in the upper-left panel, with IG in the lower-left panel, and with Rz in the upper-right panel. The lower-right panel corresponds to the difference between trends with MgII filtering minus trends with IG values, expecting to obtain trends which are not forced by the magnetic field secular variation. Black dotted lines indicate trend=0, black dashed line the dip equator in 1960 and black solid line the dip equator in 2022.

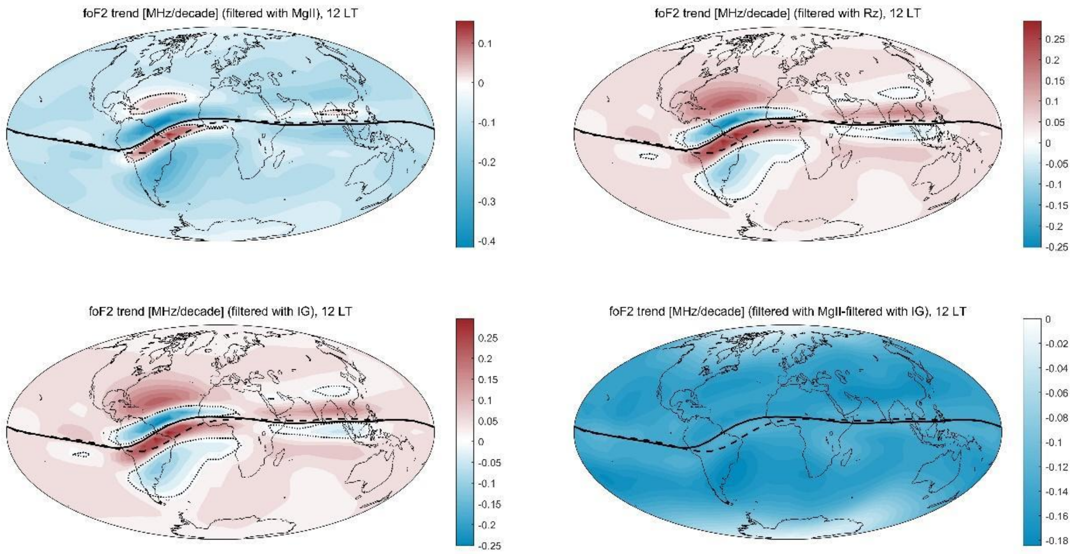

Figure R11. As in Figure R10 but using IRI-Plas with MgII as solar activity proxy.

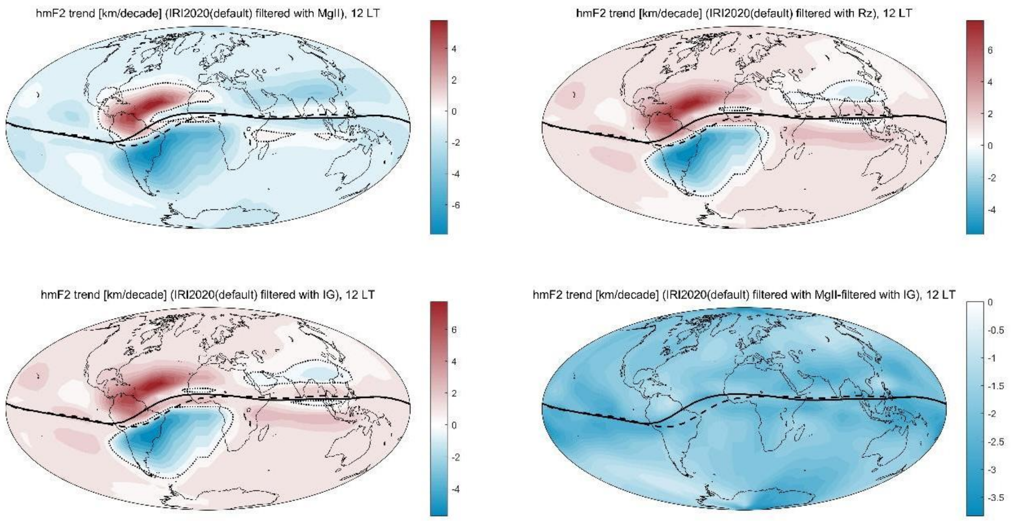

Figure R12. As in Figure R10 but for hmF2 using IRI2020.

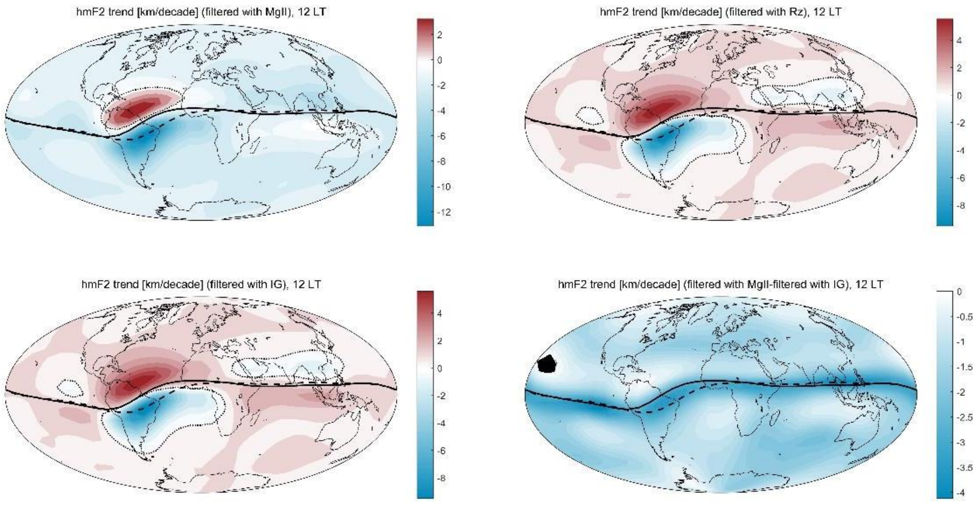

Figure R13. As in Figure R10 but for hmF2 using IRI-Plas with MgII as solar activity proxy.

We included the filtering with Rz, since it gives very similar results to those when using IG, since both have a like a "level falling" of the two last solar cycle minima. In fact, the correlation coefficients between the solar proxies are the following:

r^2	MgII	IG	Rz
MgII	1	0.950	0.954
IG		1	0.982
Rz			1

That is, IG and Rz are more similar.

The mean correlation between foF2 assessed with IRI (default indices) at 12 LT, annual time series, and each of these solar proxies is:

r^2 (global mean)	MgII	IG	Rz
foF2 (IRI)	0.961	0.998	0.980
hmF2 (IRI)	0.969	0.983	0.972

The best correlation in the case of foF2, as expected, is that with IG, since it is this proxy which determines foF2 interannual variability.

However, in the case of hmF2, the highest correlation is also with IG, even though its interannual variability is determined by Rz.

Sorry for being repetitive with all this, but we would like to add the following:

The downward trend obtained in foF2 and hmF2, statistically speaking, is due to the inter-annual time variation of these F2 region parameters that results from two time series (IG and Rz) which present the last two minima weaker than the previous four. This can be seen in Figure R14 were we plot MgII (black line) and IG (red line) annual means. It is clear that if we use MgII to filter a time series behaving like IG, we will obtain a residual with a downward trend, as also shown in Figure R14. Since IG carries the information from ionosondes, then we can expect that the trends obtained could be a reasonable approach to experimental trends.

Rz happens to vary similar to IG. That is, it presents the last two minima lower than the previous minima. This can be seen in Figure R15 were Rz original data base, Rz from SILSO and Mg II have been plot. We included the old Rz series just to notice that the new Rz has a more pronounced decrease during the last minima. We assume that this is the Rz used by IRI. It is clear also here that if we use MgII to filter a time series behaving like Rz, a downward trend will be obtained in the residuals of this regression. And this is why we obtain here a downward trend again. In this case, unlike the foF2 case, it is due to a coincidence: the downward trend of hmF2 from IRI is due to the downward trend of Rz, and that of hmF2 from ionosondes is due to the greenhouse effect (if we assume this is the main forcing). And of course, the downward trend in Rz has nothing to do with the greenhouse effect. They both just happen to be in the same direction.

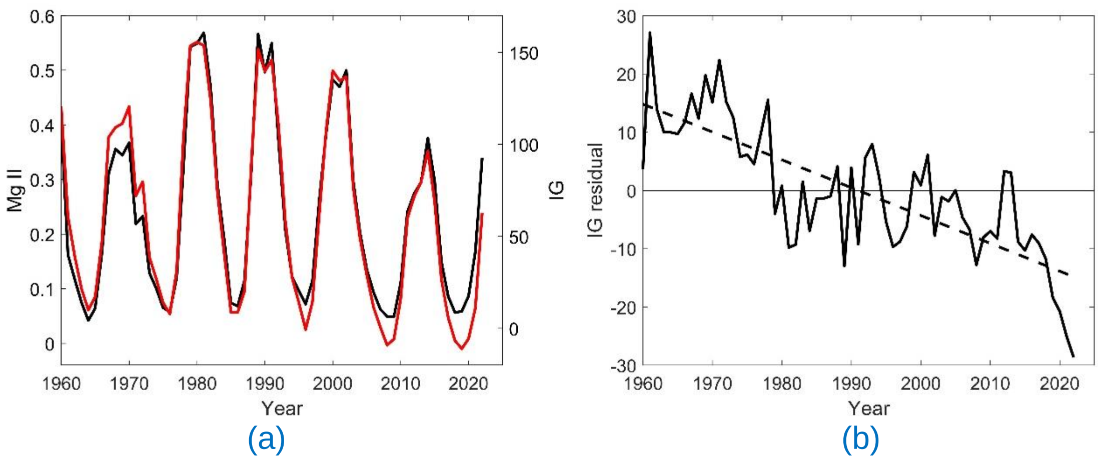

Figure R14. (a) Mg II (black) and IG (red) annual mean time series for the period 1960-2022. (b) Residuals (solid black line) from the fitted regression IG = A MgII + B, together with the residual linear trend (dashed black line).

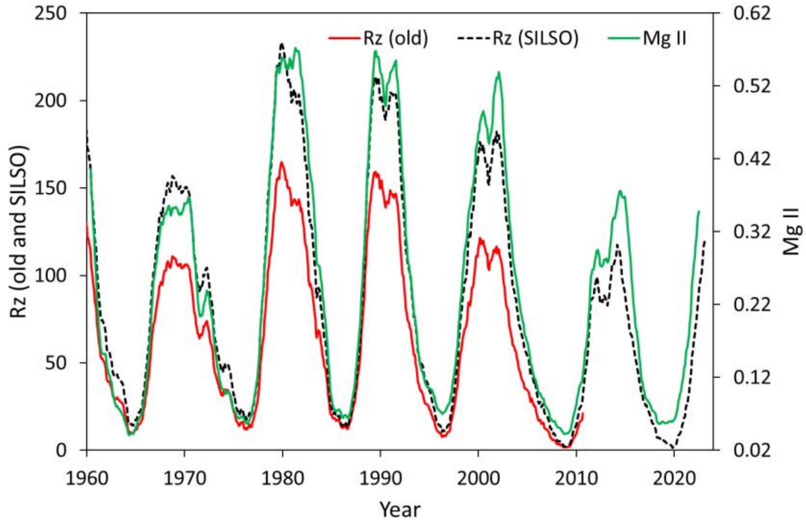

Figure R15. 12-month running mean series of Rz orginal data (red line), Rz from SILSO (black dashed line) and Mg II (green line).

One more comment. It is curious that Rz seems much better than MgII. It even contradicts the most recent results recommending MgII and F30, followed by F10.7. This is due to our series begin in 1960, while the other papers favoring MgII and/or F30 begin in 1976. However, we think this deserves another deep analysis for another work, or repeating all this considering different sub-periods.

In the revised version of our work we will include now a thorough description of how foF2 and hmF2 are estimated by IRI model, and also the interpretation of the trends will be clearly stated.

Thank you again for your observations and for having the time to meet with us to discuss about our results and their interpretation.

Hoping to meet all your requirements,

Bruno S. Zossi, Trinidad Duran, Franco D. Medina, Blas F. de Haro Barbas, Yamila Melendi, and Ana G. Elias