Modulation of Solar Irradiance on Geomagnetic Activity: An Idealized Experiment with WACCM5.

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Abstract

Interannual changes in spectral irradiance at UV wavelengths is one of sources of solar-driven decadal variability in the atmosphere and in particular in the stratosphere as most of these changes happen at UV wavelengths. In last recent years, it has been suggested that energetic electron precipitation (EEP) also contributes not only to alter the chemical composition of the middle atmosphere but also its dynamical variability through changes in stratospheric ozone. In this study we investigate the effects of the two forcings and their interactions. We employ 35-year long integrations of the atmospheric version of the Whole Atmosphere Community Climate Model version 5 with different idealized and stationary solar and geomagnetic forcing terms. Four experiments are carried out combining high (H) and low (L) solar radiative forcing and high (7) and low (3) EEP associated with geomagnetic activity: H7 (with high radiative forcing and high EEP), H3 (high/low), L7 (low/high), and L3 (low/low). We find that the extension, the seasonality, and the significance of the effects of these two forcing terms on the atmospheric variables like temperature, NOx, and ozone are dependent on the joint effects of both forcing terms. The effect of the impact on NOx, ozone and temperature was measured, on constant pressure levels, by means of a Monte Carlo test. Under minimum solar conditions EEP affects mainly the NOx field on constant pressure levels, even though vertical cross sections show statistically significant effects on temperature and ozone in the southern hemisphere during austral winter and the following spring. Under solar maximum condition the effect of EEP becomes important. Ozone depletion (augmentation) in the upper levels of the stratosphere due to more (less) NOx, produced by EEP, allows UV radiation to produce more (less) ozone in the lower levels of the stratosphere. Solar irradiance hence plays an important role in modulating the impact of geomagnetic activity on climate variables.

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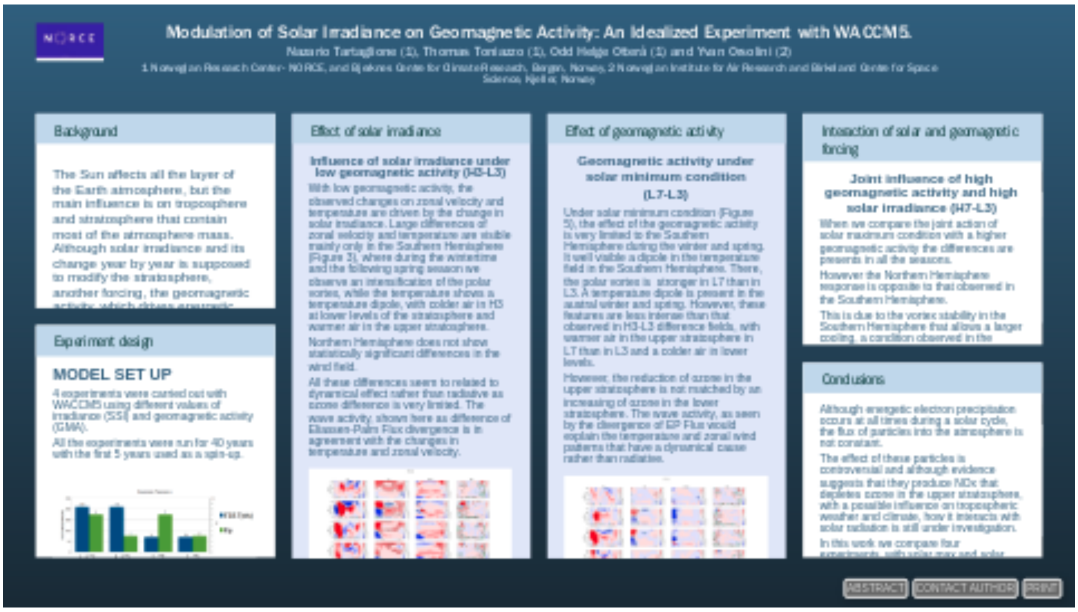

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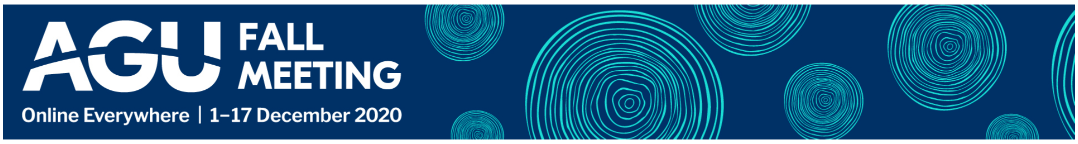
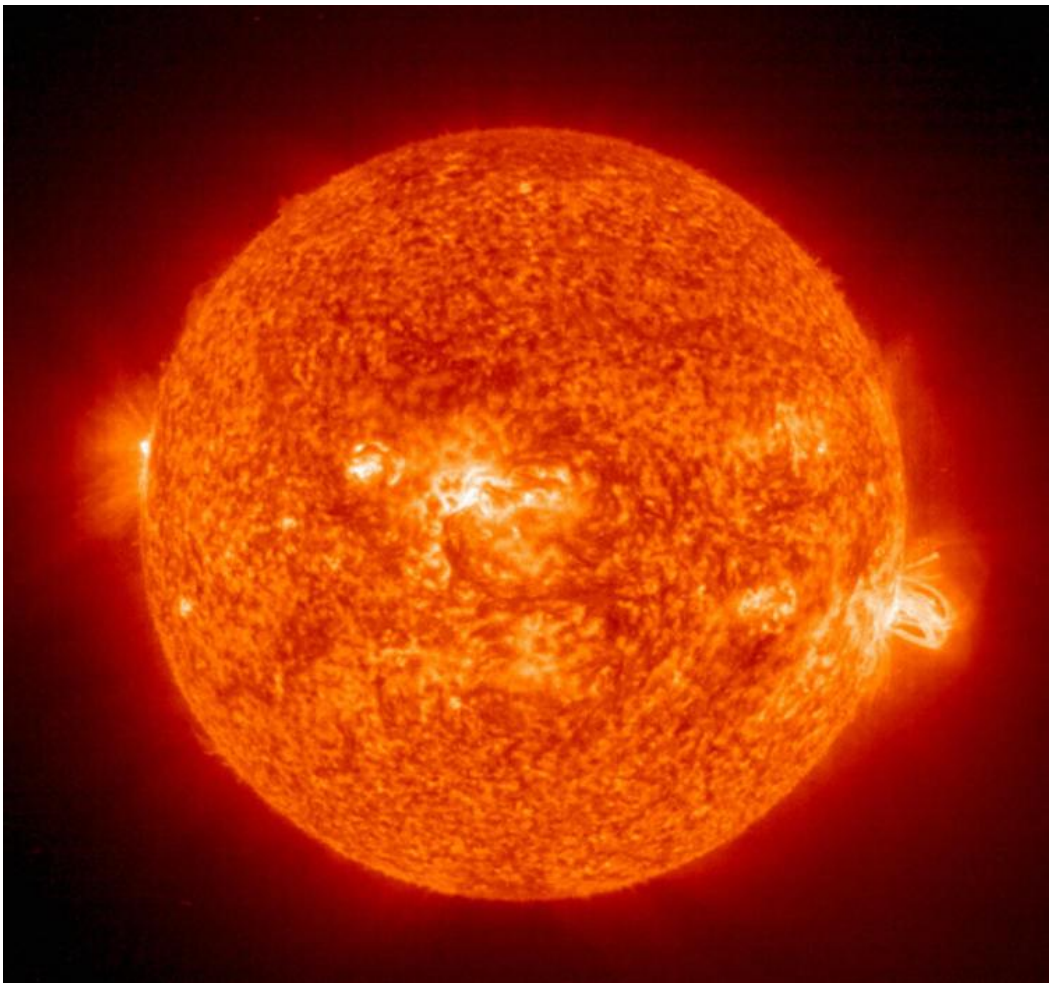


BACKGROUND

The Sun affects all the layer of the Earth atmosphere, but the main influence is on troposphere and stratosphere that contain most of the atmosphere mass. Although solar irradiance and its change year by year is supposed to modify the stratosphere, another forcing, the geomagnetic activity, which drives energetic electron precipitation, can affect the stratosphere.



For example, increasing irradiance leads to more ozone creation, but an higher geomagnetic activity should reduce ozone, at least in the upper stratosphere. However, this relationship is not that straightforward and the region of ozone production can depend on the strength of the geomagnetic activity.

This study study investigated the interaction of the irradiance, in terms of maximum and minimum solar activity,with the geomagnetic activity using the atmospheric version of WACCM5.

EXPERIMENT DESIGN

MODEL SET UP

4 experiments were carried out with WACCM5 using different values of irradiance (SSI) and geomagnetic activity (GMA).

All the experiments were run for 40 years with the first 5 years used as a spin-up.

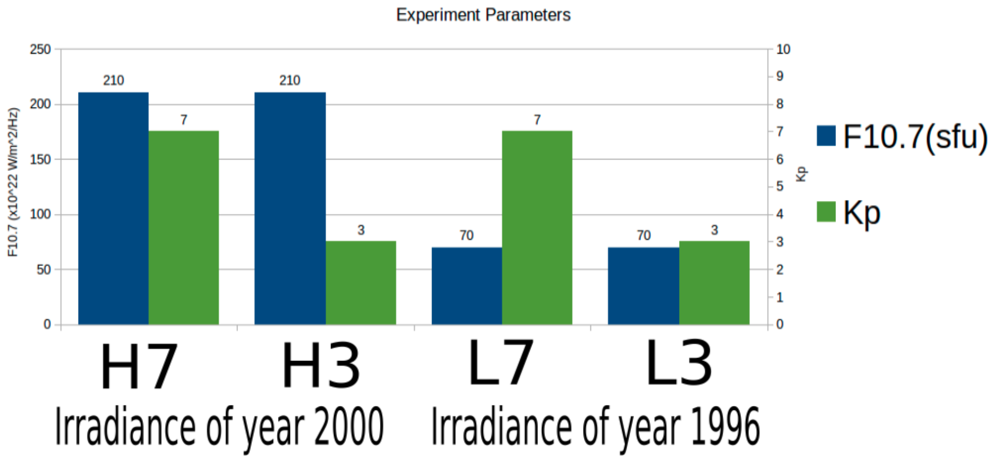


Figure 1. Experiment parameters defining the following experiments:

H7 – Solar Max – High Geomagnetic activity
H3 – Solar Max – Low Geomagnetic activity
L7 – Solar min – High geomagnetic activity
L3 – Solar min – Low geomagnetic activity

We compare differences in:

H7-L3: combined effect of SSI and GMA

H3-L3: effect of SSI under low GMA

H7-L7: effect of SSI under high GMA

L7-L3: effect of GMA under Solar min

H7-H3: effect of GMA under Solar max

SCORE DEFINITION for STATISTICAL SIGNIFICANCE

To evaluate the effect of the forcing terms on a variable, for example the 500 hPa temperature in a specific area, we first compute the mean value of the difference between two experiments (e.g. H7 and L3) on all the grid points, and we compute how many grid points in a specific domain, for example the polar region, are statistically significant. Then we perform a permutation test combining the years of a pair of experiments and rearranging these years to find the number of significant points in each rearrangement (Fig. 2).

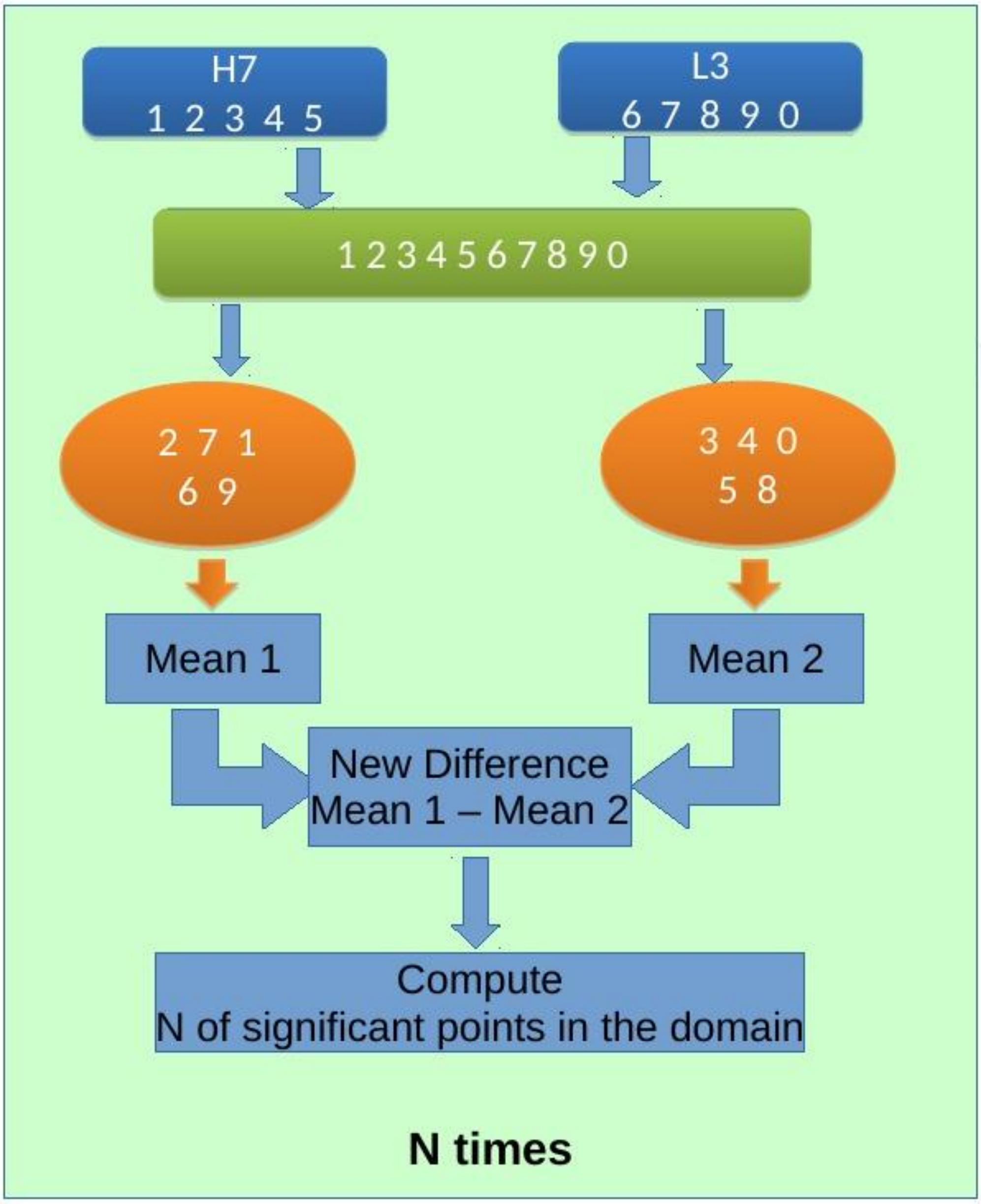


Figure 2. Algorithm used to define the distribution of number of statistically significant points within a specific region. The number of significant points of the original difference (H7-L3 in the example of the figure).

Once we have a distribution of number of significant point we compute the rank of the original number of significant points. The rank represents a score measuring the impact on large scale. When the rank is larger than 94, the effect on the region is considered statistically significant.

The choice to investigate the impact on a domain was made because when we deal with many grid points, a few of them can be statistically significant by chance.

EFFECT OF SOLAR IRRADIANCE

Influence of solar irradiance under low geomagnetic activity (H3-L3)

With low geomagnetic activity, the observed changes on zonal velocity and temperature are driven by the change in solar irradiance. Large differences of zonal velocity and temperature are visible mainly only in the Southern Hemisphere (Figure 3), where during the wintertime and the following spring season we observe an intensification of the polar vortex, while the temperature shows a temperature dipole, with colder air in H3 at lower levels of the stratosphere and warmer air in the upper stratosphere.

Northern Hemisphere does not show statistically significant differences in the wind field.

All these differences seem to related to dynamical effect rather than radiative as ozone difference is very limited. The wave activity, shown here as difference of Eliassen-Palm Flux divergence is in agreement with the changes in temperature and zonal velocity.

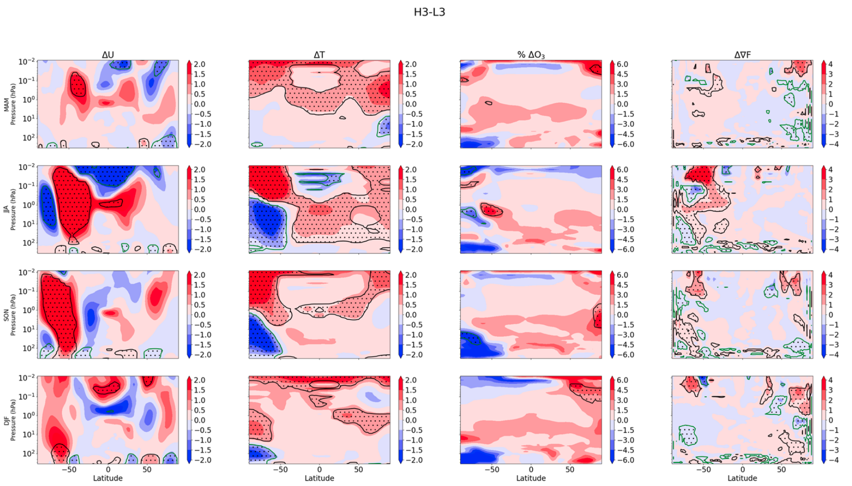


Figure 3. Zonal velocity (U), temperature (T), ozone (in percentage) and EP Flux divergence differences of experiments H3-L3 for all the seasons.

Influence of solar irradiance under high geomagnetic activity

(H7-L7)

With high geomagnetic activity the features observed in the experiments with low geomagnetic activity are no longer present in the Southern Hemisphere, although the temperature features, associated with warmer air in H7 than in L7, in the upper stratosphere are still present along almost all the latitudes (Figure 4).

Ozone in general is more abundant in H7, since the more NOx produced in the mesosphere and descending in the stratosphere because of high geomagnetic activity (present in both the experiments) depletes ozone in the upper stratosphere. However, as H7 has an higher value of irradiance more ozone in the lower stratosphere stratosphere.

The Northern Hemisphere shows larger variations in these experiments than in the experiments shown above.

However, the zonal wind is much weaker in H7 than L7 and the dipole temperature is reversed.

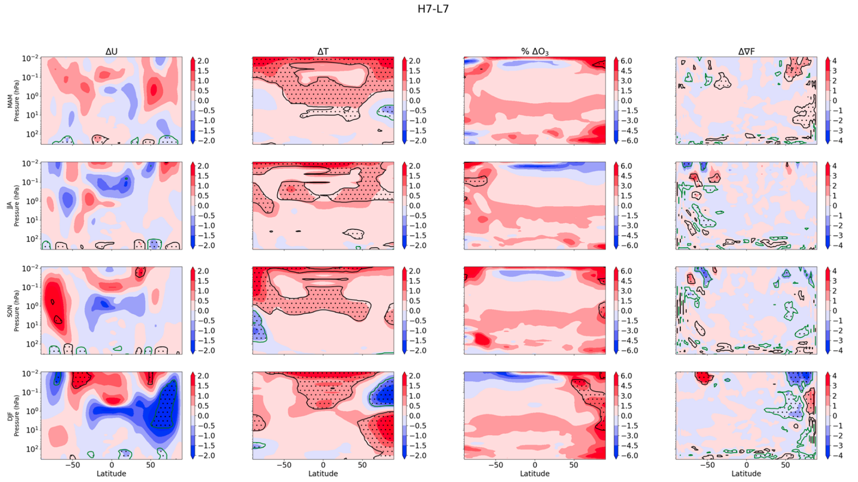


Figure 4. Zonal velocity (U), temperature (T), ozone (in percentage) and EP Flux divergence differences of experiments H7-L7 for all the seasons.

EFFECT OF GEOMAGNETIC ACTIVITY

Geomagnetic activity under solar minimum condition

(L7-L3)

Under solar minimum condition (Figure 5), the effect of the geomagnetic activity is very limited to the Southern Hemisphere during the winter and spring. It well visible a dipole in the temperature field in the Southern Hemisphere. There, the polar vortex is stronger in L7 than in L3. A temperature dipole is present in the austral winter and spring. However, these features are less intense than that observed in H3-L3 difference fields, with warmer air in the upper stratosphere in L7 than in L3 and a colder air in lower levels.

However, the reduction of ozone in the upper stratosphere is not matched by an increasing of ozone in the lower stratosphere. The wave activity, as seen by the divergence of EP Flux would explain the temperature and zonal wind patterns that have a dynamical cause rather than radiative.

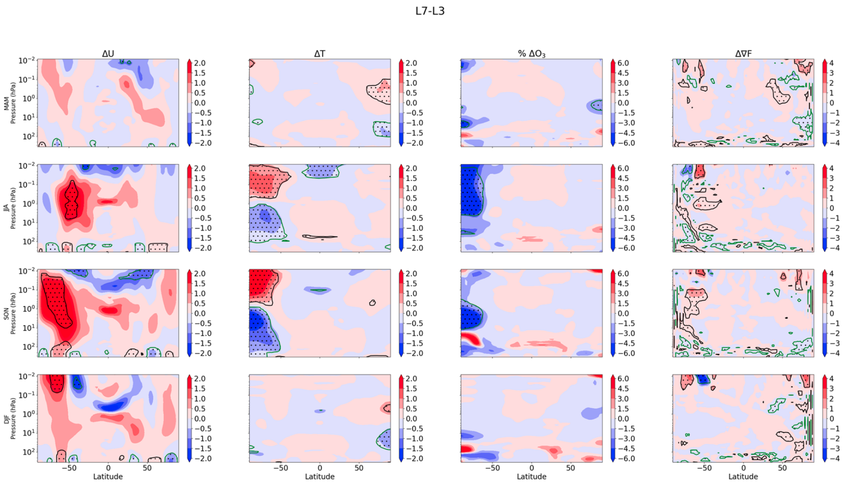


Figure 5. Zonal velocity (U), temperature (T), ozone (in percentage) and EP Flux divergence differences of experiments L7-L3 for all the seasons.

IMPACT ON TROPOSPHERIC TEMPERATURE IN POLAR REGIONS

Under solar minimum condition the score of the impact of the geomagnetic activity in the troposphere is very low (Figure 6). Low scores mean that there are more statisticaly significant points in differences obtained by chance than the experiment differences L7-L3.

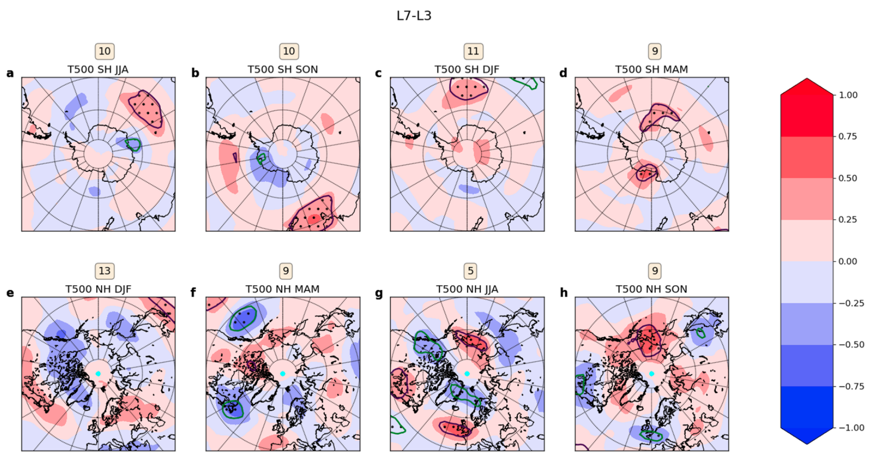


Figure 6. 500 hPa temperature L7-H3 differences. The dots indicate statistically significant points. The purple line surrounds

positive values; the green line surrounds negative values. The number over each panel indicates the significance of the statistical test over the polar region.

Geomagnetic activity under solar maximum condition

(H7-H3)

The maximum solar condition change completely the stratosphere response that is opposite to that observed in L7-L3. Moreover there are differences in the Northern Hemisphere during the wintertime.

In the Souther Hemisphere, the combination of geomagnetic activity with the maximum solar condition is responsible for the ozone dipole, as the geomagnetic activity produces more NOx and reduces ozone in the upper stratosphere. This allows to UV radiation to produce more ozone in the lower stratosphere. However the temperature dipoles have the opposite sign compared with the L7-L3 difference fields.

The zonal wind is weaker in H7 than H3, during the winter in both the hemisphere and this would suggest that in combination with high radiative forcing the geomagnetic activity would tend to reduce the polar vortex.

Again we observed temperature dipoles that are reversed compared with H3-L3 in a way like the L7-L3 differences. However the ozone distribution shows some dipoles with higher values of ozone in the lower stratosphere. Again this is caused by the geomagnetic activity that deplets ozone in the upper stratosphere allowing the production of ozone in the lower stratosphere.

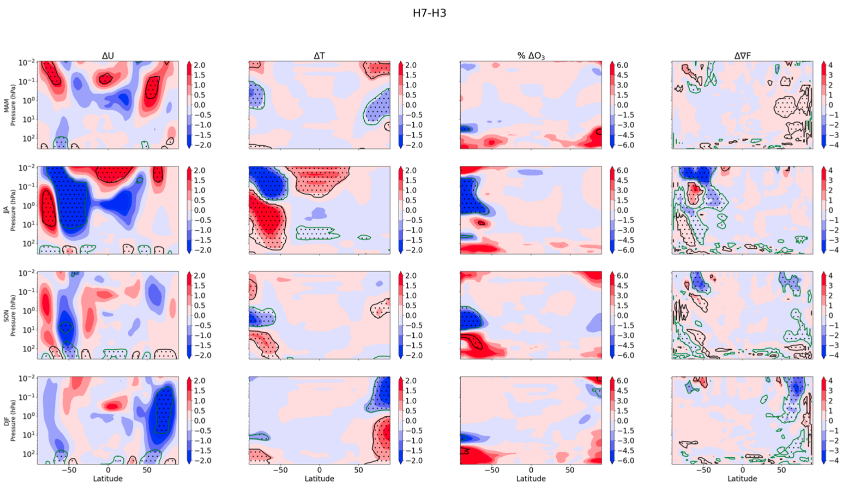


Figure 7. Zonal velocity (U), temperature (T), ozone (in percentage) and EP Flux divergence differences of experiments H7-H3 for all the seasons.

IMPACT ON TROPOSPHERIC TEMPERATURE IN POLAR REGIONS

In contrast with the features observed in L7-L3 that are not significant, the 500 hPa differences in H7-H3 show higher scores with the boreal autumn that has a score of 96, indicating the possibility that 500 hPa temperature is actually affected by geomagnetic activity. As this result appears in solar maximum condition, then solar irradiance modulates effects of the geomagnetic activity.

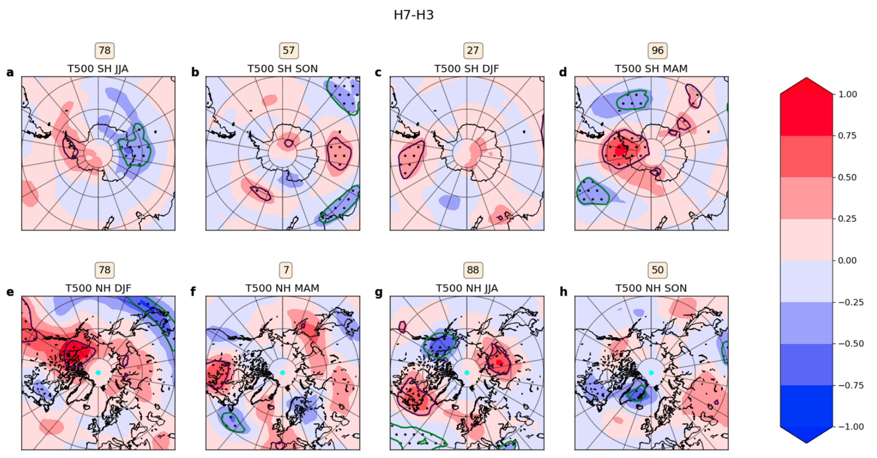


Figure 8. 500 hPa temperature H7-H3 differences. The dots indicate statistically significant points. The purple line surrounds positive values; the green line surrounds negative values. The number over each panel indicates the significance of the statistical test over the polar region.

INTERACTION OF SOLAR AND GEOMAGNETIC FORCING

Joint influence of high geomagnetic activity and high solar irradiance (H7-L3)

When we compare the joint action of solar maximum condition with a higher geomagnetic activity the differences are presents in all the seasons.

However the Northern Hemisphere response is opposite to that observed in the Southern Hemisphere.

This is due to the vortex stability in the Southern Hemisphere that allows a larger cooling, a condition observed in the experiments H3-L3 and L7-L3. This leads, in the H7 experiment, to a larger thermal wind and a larger zonal wind.

However, the experiments H3-L3 and L7-L3 do not show large variations in the Northern Hemisphere in all the seasons.

The difference fields resemble those observed in the H7-L7, showing that geomagnetic activity it is able to modulate the stratospheric response, in term of under solar maximum (compare the H7-H3).

In fact, comparing with H3-L3 differences we see that the large differences in the zonal wind is not present in H3-L3

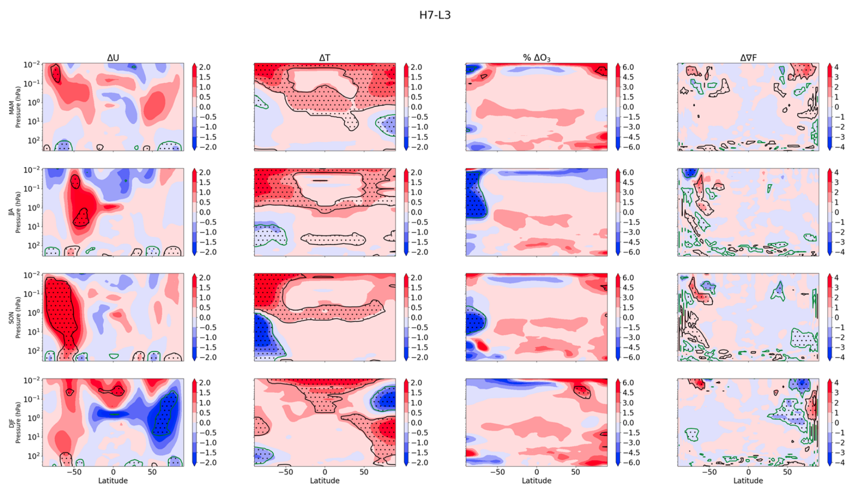


Figure 9. Zonal velocity (U), temperature (T), ozone (in percentage) and EP Flux divergence differences of experiments H7-L3 for all the seasons.

IMPACT ON TROPOSPHERIC TEMPERATURE IN POLAR REGIONS

When we look at the 500 hPa temperature differences we can observe that the impact of the irradiance and geomagnetic activity is present in the Southern hemisphere during the austral autumn (with a score of 98) and in the Northern Hemisphere during the boreal winter (with score .of 95).

There are good chance that the combination of solar irradiance and geomagnetic activity may affect the upper troposphere, even though the single forcing may not, at least in this atmospheric version of WACCM.

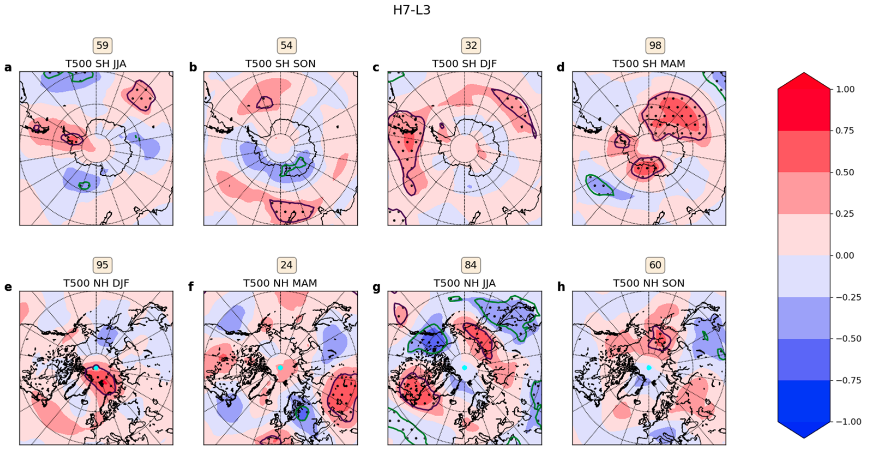


Figure 10. 500 hPa temperature H7-L3 differences. The dots indicate statistically significant points. The purple line surrounds positive values; the green line surrounds negative values. The number over each panel indicates the significance of the statistical test over the polar region.

CONCLUSIONS

Although energetic electron precipitation occurs at all times during a solar cycle, the flux of particles into the atmosphere is not constant.

The effect of these particles is controversial and although evidence suggests that they produce NOx that depletes ozone in the upper stratosphere, with a possible influence on tropospheric weather and climate, how it interacts with solar radiation is still under investigation.

In this work we compare four experiments, with solar max and solar min conditions and high and low geomagnetic activity.

We found the following results:

- With low geomagnetic activity the solar irradiance plays a key role (H3-L3), as the stratospheric temperature and zonal ind are affected by changes in solar irradiance.
- However, when the geomagnetic activity (H7-L7) is high the patterns of zonal wind and temperature are reversed compared with the equivalent experiments having low geomagnetic activity (H3-L3).
- Under solar minimum conditions (L7-L3) the geomagnetic activity hardly affects the stratospheric variables. The 500 hPa temperature has very low scores in both the hemispheres indicating that no influence of geomagnetic activity exists in the model.
- When there is a solar max condition (H7-L3) the role of the geomagnetic activity is instead stronger with changes of zonal wind, temperature and ozone, but with an opposite sign to the contribute of solar forcing term (cf H7-H3 with H3-L3).
- The joint effect of solar irradiance and geomagnetic activity (H7-L3) suggests that there is a combination of the effects that we have seen in the other experiments. For example in the Southern Hemisphere the difference patterns resemble those observed in H3-L3, whereas the features in the Northern Hemisphere resemble those observed in H7-L7.

Some of results presented here come from the following paper:

Tartaglione, N., T. Toniazzo, Y. Orsolini, O.H. Otterå (2020), Impact of solar irradiance and geomagnetic activity on polar NOx ozone and termperature in WACCM simulations, J. Atm. Solar-Terrest. Phys., Volume 209, 105398, ISSN 1364-6826,
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ABSTRACT

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In this study we investigate the effects of the two forcings and their interactions. We employ 35-year long integrations of the atmospheric version of the Whole Atmosphere Community Climate Model version 5 with different idealized and stationary solar and geomagnetic forcing terms. Four experiments are carried out combining high (H) and low (L) solar radiative forcing and high (7) and low (3) EEP associated with geomagnetic activity: H7 (with high radiative forcing and high EEP), H3 (high/low), L7 (low/high), and L3 (low/low). We find that the extension, the seasonality, and the significance of the effects of these two forcing terms on the atmospheric variables like temperature, NOx, and ozone are dependent on the joint effects of both forcing terms.

The effect of the impact on NOx, ozone and temperature was measured, on constant pressure levels, by means of a Monte Carlo test.

Under minimum solar conditions EEP affects mainly the NOx field on constant pressure levels, even though vertical cross sections show statistically significant effects on temperature and ozone in the southern hemisphere during austral winter and the following spring.

Under solar maximum condition the effect of EEP becomes important. Ozone depletion (augmentation) in the upper levels of the stratosphere due to more (less) NOx, produced by EEP, allows UV radiation to produce more (less) ozone in the lower levels of the stratosphere. Solar irradiance hence plays an important role in modulating the impact of geomagnetic activity on climate variables.

REFERENCES

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