Response of the Middle Atmosphere in the Southern Hemisphere to Energetic Particle Precipitation in the Latest Reanalysis Data

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Abstract

Research on the effects of energetic particle precipitation (EPP) on earth’s atmosphere is rapidly growing. However, these effects have not been well distinguished from those of other climate forcings. This study extracts EPP effects on the middle atmosphere in the southern hemisphere from the latest reanalysis datasets using multiple regression analysis and composite analysis. Statistically significant temperature anomalies in the summer polar upper stratosphere and lower mesosphere are found, but a simple dynamical signature explaining the anomalies is not evident. On the other hand, it is found that a negative temperature anomaly extending from the summer lower mesosphere to the midlatitude upper stratosphere in July is driven by anomalous Eliassen-Palm flux divergence in the midlatitude lower mesosphere. This result suggests that EPP effects are distinguishable from other climate forcings in the latest reanalysis data.

(Citation: Tomikawa, Y., 2017: Response of the middle atmosphere in the Southern Hemisphere to energetic particle precipitation in the latest reanalysis data. SOLA, 13A, 1–7, doi:10.2151/sola.13A-001.)

1. Introduction

Earth’s middle atmosphere (i.e., stratosphere and mesosphere) is influenced by several climate factors, such as solar activity in ultraviolet radiation, volcanic aerosols, the quasi-biennial oscillation (QBO), the El Niño-Southern Oscillation (ENSO), and greenhouse gases (e.g., Mitchell et al. 2014). Among these factors, there is a growing evidence that charged energetic particles from the sun and earth’s magnetosphere precipitating into the polar regions can significantly affect the chemistry and dynamics of the middle atmosphere. The purpose of this study is to extract the impacts of energetic particle precipitation (EPP) on the middle atmosphere from the latest meteorological reanalysis data.

Recent satellite measurements have demonstrated that reactive nitrogen (NOx = NO + NO2; Rusch et al. 1981) and hydrogen from the latest meteorological reanalysis data. Statistically significant temperature anomalies in the winter polar upper stratosphere and lower mesosphere are found, but a simple dynamical signature explaining the anomalies is not evident. On the other hand, it is found that a negative temperature anomaly extending from the polar lower mesosphere to the midlatitude upper stratosphere in July is driven by anomalous Eliassen-Palm flux divergence in the midlatitude lower mesosphere. This result suggests that EPP effects are distinguishable from other climate forcings in the latest reanalysis data.

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the value of September 2012 through the end of 2015 because there are no significant volcanic eruptions (i.e., eruptions with a volcanic explosivity index of 4 or larger) after September 2012 in the significant volcanic eruption database (https://www.ngdc.noaa.gov/hazard/volcano.shtml). A linear term with a break point at 1995 is used as a proxy for greenhouse gas and stratospheric ozone change (Seidel et al. 2016). The subsequent analysis is not sensitive to the year of break point (discussed in Section 4). In addition, the geomagnetic Ap index (obtained at ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/), which correlates well with the ozone decrease in the mesosphere and upper stratosphere due to EPP (Damiani et al. 2016), is used for a composite analysis. Figure 1 shows time series of climate predictors used for the multiple regression analysis and composite analysis in this study.

2.2 Method

In order to exclude the effects of climate factors with well-known impacts on the middle atmosphere (Mitchell et al. 2014), a multiple regression analysis is applied to time series of monthly- and zonal-mean reanalysis data (i.e., temperature and zonal wind) from 1979 to 2015 in each month. A fraction of the variance explained by the regression is large in the subtropics and in the polar mesosphere (see Fig. S1). Residuals of the regression are classified into high (Ap ≥ 15; 11 years), medium (15 > Ap ≥ 10; 13 years), and low (10 > Ap; 13 years) Ap index years based on the Ap index averaged over April–July (e.g., Lu et al. 2008; Seppälä et al. 2009). Finally, composite differences of reanalysis data between high and low Ap index years are obtained. Statistical significance of the composite difference is assessed using 1000 bootstrapped time series (e.g., von Storch and Zwiers 1999). In order to consider a time lag of 1–2 months due to the EPP indirect effect, composite figures are shown from April through September.

3. Results

Figure 2 shows latitude-pressure sections of composite differences in zonal-mean temperature between high and low Ap index years from April through September obtained from the MERRA, ERA-Interim, and JRA-55 reanalyses. The MERRA data show that a pair of negative and positive temperature anomalies exists throughout the period in the polar lower mesosphere and upper stratosphere, respectively. The negative anomalies are statistically significant from April through July. Another interesting feature is a statistically significant negative temperature anomaly extending from the polar lower mesosphere to the midlatitude upper stratosphere in July. On the other hand, a statistically significant positive temperature anomaly is seen between 10 and 0.3 hPa in the midlatitudes in August. The stratospheric part of these features is also well captured in the ERA-Interim and JRA-55 data, so we subsequently only show MERRA results.

Figure 3 shows composite differences of zonal-mean zonal wind. A statistically significant negative wind anomaly looks to be moving slightly poleward over time in the upper stratosphere and lower mesosphere. This anomaly nearly satisfies a thermal wind balance with the negative and positive temperature anomalies in the polar region shown in Fig. 2. In addition, a pair of strong positive and negative wind anomalies around the stratopause in the midlatitudes and polar region, respectively, in July is also consistent with the large temperature anomalies in July.

Figure 4a shows a time-pressure section of composite zonal-mean temperature differences at 80°S. A pair of negative and positive temperature anomalies is persistent from April through July in the lower mesosphere and upper stratosphere, respectively. The temperature anomaly in the polar region changes its sign around 3 hPa. Figure 4b shows a time-latitude section of zonal-mean zonal wind composite differences. A pair of positive and negative wind anomalies moves slightly poleward over time in the midlatitudes and polar region, respectively. These temperature and zonal wind anomalies are statistically significant from April through July, but not in August and September.

Figure 5 shows latitude-pressure sections of composite differences in zonal wind acceleration due to the Eliassen-Palm flux divergence (DF) and residual-mean vertical velocity (wP), in order to examine whether the temperature and zonal wind anomalies are dynamically driven or not using the transformed Eulerian-mean analysis (cf. Andrews et al. 1987). A DF anomaly tends to be positive and partly statistically significant at 60°S–80°S in the stratosphere from April through July, where the polar night jet is weaker (i.e., negative zonal wind anomalies in Fig. 3). Although they are roughly associated with weak positive wP anomalies on their poleward edges, they are not necessarily consistent with temperature anomalies in Fig. 2. A statistically significant positive DF

### Table 1. Specifications of reanalysis datasets used in this study.

<table>
<thead>
<tr>
<th>Reanalysis</th>
<th>MERRA</th>
<th>JRA-55</th>
<th>ERA-Interim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal resolution</td>
<td>1.25° × 1.25°</td>
<td>1.5° × 1.5°</td>
<td></td>
</tr>
<tr>
<td>Vertical levels</td>
<td>42 levels from 1000 to 0.1 hPa</td>
<td>37 levels from 1000 to 1 hPa</td>
<td></td>
</tr>
</tbody>
</table>
anomaly exists in the midlatitude lower mesosphere (i.e., above 1 hPa) in July. This is consistent with a statistically significant positive $\bar{w}$ anomaly in the upper stratosphere and lower mesosphere (i.e., between 0.5 and 10 hPa) around 60°S in July. This feature indicates that the strong negative temperature anomaly in the upper stratosphere and lower mesosphere around 60°S in July was induced by adiabatic cooling associated with strong upwelling there. A statistically significant positive DF anomaly is also observed around 50°S and 0.5 hPa in June and around 65°S and 1 hPa in August. Although they are associated with positive $\bar{w}$ anomalies on their poleward edges, their corresponding negative temperature anomalies are not necessarily evident in Fig. 2. Thus it is concluded that at least the negative temperature anomaly in the midlatitude upper stratosphere and lower mesosphere in July was dynamically driven by the positive DF in the midlatitude lower mesosphere.

Fig. 2. Latitude-pressure sections of zonal-mean temperature composite differences between high and low Ap index years from April through September for (top) MERRA, (middle) ERA-Interim, and (bottom) JRA-55. Contour intervals are 0.5 K. Negative values are dashed. Dark and light shades represent statistical significance at the confidence levels of 95% and 90%, respectively.

Fig. 3. Same as Fig. 2 except for zonal-mean zonal wind for MERRA. Contour intervals are 1 m s$^{-1}$. 
4. Discussion

This study used multiple regression analysis and composite analysis to extract EPP effects on the SH middle atmosphere from the latest reanalysis data. Their limitations and potential errors are discussed in this section.

Low Ap index years mostly occurred in the period of 2006-2015 as shown in Fig. 1. However, this bias does not have a significant effect on the results because the composite differences obtained for the period of 1979-2005 (see Fig. S2) are quite similar to those in Fig. 2 and Fig. 3.

A linear term with a break point at 1995 was used as a proxy for greenhouse gas and stratospheric ozone change following Seidel et al. (2016). Actually an amount of ozone depleting substances (ODS) at the surface changed a sign of its trend around 1995 (WMO/UNEP 2007). On the other hand, ODS has a long photochemical lifetime (i.e., more than 10 years) so that the timing of their trend change in the middle atmosphere depends on their mean age of air (i.e., how long it takes to transport the air with ODS from the tropical tropopause to the specified height and latitude; cf. Waugh and Hall 2002). It has been reported that the mean age of air in the Antarctic upper stratosphere and lower mesosphere reached 10 years (Stiller et al. 2008). Miyagawa et al. (2014) showed that assuming 10 years of age of air gave the best fit of ODS trend to ozone concentration in the upper stratosphere and lower mesosphere over Antarctic Syowa Station. Figure S3 shows the composite differences obtained by taking a break point at 2005 instead of 1995. It is nearly the same as Fig. 2 and Fig. 3. Thus it is found that the choice of the break point has little impact on the results in this study.

Composite differences based on the Ap index were acquired after excluding the effects of several climate factors including F10.7. As the Ap index correlates well with F10.7 (i.e., their correlation coefficient is 0.42), it is difficult to isolate their effects from each other (i.e., multicollinearity). This means that the extracted EPP effect based on the Ap index could be partially suppressed by the regression based on F10.7. Thus the composite differences obtained in this study might underestimate the EPP effect on the SH middle atmosphere.
Temperature and zonal wind responses to F10.7 obtained by the regression are shown in Fig. 6. They are similar to the solar signal obtained by Kuchar et al. (2015) in a similar way to this study. Comparing Fig. 6 with Fig. 2, a similar negative temperature anomaly is observed in the polar lower mesosphere. On the other hand, the solar signal is always associated with a statistically significant positive temperature anomaly in the midlatitude lower mesosphere unlike the EPP effects. The solar signal in zonal wind shows a pair of positive and negative anomalies propagating poleward and downward from the subtropical lower mesosphere to the polar lower stratosphere between June and September (i.e., in late winter; Kodera and Kuroda 2002). Although the EPP effects also show the poleward propagating zonal wind anomalies, they are dominant in the upper stratosphere and lower mesosphere from April through July (i.e., in early winter). It is difficult to eliminate the possibility that the EPP effects obtained in this study were contaminated by the solar signal because of the multicollinearity. Nonetheless, it seems that they showed the signals with different features.

A time lag for up to two months from EPP to its response in temperature and zonal wind was taken into account in this study. This captures some of the EPP indirect effect but not all. Increases in NOy transported into the lower stratosphere could survive from the previous winter to the following summer and fall (Orsolini 2001; Orsolini et al. 2003) and contribute to the ozone loss in the previous winter to the following summer and fall (Orsolini 2001; Orsolini et al. 2003). This process may have an impact on polar vortex formation during its early stage in late fall and early winter. Thus it is possible for the polar vortex to be pre-conditioned by the EPP effect from the previous winter. In addition, it is also possible for the other processes considered as predictor variables to affect polar vortex evolution from early winter in a similar way. Thus the EPP effects obtained in this study could be influenced by the EPP effect from the previous winter and by the preconditioning of the polar vortex in early winter due to the other processes. These long-lasting processes are not taken into account in this study.

The regression and composite analyses used in this study can be applied to the NH. Figure S4 shows the composite differences of zonal-mean temperature and zonal wind between high and low Ap index years in the NH from October through March. Although a negative temperature anomaly is observed in the polar stratosphere and mesosphere, its height significantly varies with month unlike in the SH. A statistical significance of the composite differences is smaller than in the SH, probably because of larger interannual variations in the NH middle atmosphere. It is compared also with the previous studies. Signs of the obtained temperature and zonal wind responses are often opposite to those of Seppälä et al. (2013) both in high and low solar activity cases. The temperature and zonal wind responses in March are also different from that of Lu et al. (2008) in their peak heights. Such a difference could occur because of the difference of used data and method. In addition, the EPP effects are expected to be smaller in the NH as mentioned in Section 1 and tend to be masked by larger interannual variations in the NH. Thus further improvement in its method is required for the study of the EPP effects in the NH.

5. Summary

In order to extract the effects of EPP on the middle atmosphere in the SH, we applied multiple regression analysis using several kinds of climate factors and composite analysis based on the Ap index to three kinds of the latest reanalysis datasets. Composite differences between high and low Ap index years showed a pair of negative and positive temperature anomalies in the polar lower mesosphere and upper stratosphere, respectively, from April through September. These temperature anomalies were associated with the zonal wind anomaly propagating slightly poleward around the stratopause over time. These anomalies were statistically significant from April through July, but not in August and September. Lu et al. (2008) derived EPP effects on temperature and zonal wind in the SH middle atmosphere by the composite analysis based on the Ap index (i.e., without a multiple regression analysis) using older reanalysis and operational analysis data. While their zonal wind anomaly in September is partly similar to that in this study, their temperature anomaly is clearly different from that in this study. On the other hand, Semeniuk et al. (2011) obtained similar EPP-induced temperature anomalies in the polar
upper stratosphere and mesosphere in a chemistry climate model simulation. They suggested that those temperature anomalies were induced dynamically rather than by radiative changes due to ozone depletion (cf. Langematz et al. 2003). However, a simple dynamical signature explaining the temperature anomalies was not evident in this study.

Another distinct signal in the composite differences was a negative temperature anomaly extending from the polar lower mesosphere to the midlatitude upper stratosphere in July. The transformed Eulerian-mean analysis showed that this temperature anomaly was induced by the strong upwelling driven by the positive DF in the midlatitude lower mesosphere and upper stratosphere. However, it is still an open question as to why the signal appeared only in July and what drove the anomalous DF.

A positive DF anomaly was also observed at 60°S–80°S in the stratosphere from April through July, where the polar night jet was weaker (i.e., negative zonal wind anomalies). However, a relationship between the weaker polar night jet and positive DF anomalies is not straightforward. If the positive DF anomalies are a cause, its effect should be stronger polar night jet. If the weaker polar night jet is a cause, smaller eastward shear would induce reduced filtering of eastward-propagating resolved gravity waves and a negative DF anomaly. In addition, the weaker polar night jet would enable more upward penetration of planetary waves considering from the Charney-Drazin theorem (Charney and Drazin 1961) and induce a negative DF anomaly. Such an inconsistency between zonal wind and wave drag anomalies will be addressed in our future work.

This study indicated that the EPP effect is distinguishable from other climate forcings in the latest reanalysis data. In addition, the obtained EPP effects are consistent between different reanalysis datasets. This result implies high reliability of the latest reanalysis data in the middle atmosphere and will accelerate further usage of the latest reanalysis data for climate studies.

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Supplement


References


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