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# Storm Track Changes in the Middle East and North Africa Under Stratospheric Aerosol Geoengineering

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**Key Points:**

- The response of storm tracks in the Middle East and North Africa to stratospheric geoengineering is investigated
- Simulations show that effects of global warming may be partially offset, through a reduced northwards shift of storm tracks. However, it involves side effect, not present in the global warming scenario
- Some of the environmental and water stresses of the region may be alleviated by stratospheric geoengineering

**Supporting Information:**

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

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**Abstract** As a potential approach to prevent dangerous climate change, stratospheric aerosol geoengineering (SAG) aims to reflect some incoming solar radiation into space and reduce temperatures. Previous modeling studies suggest that storm tracks will shift poleward due to the increases in the greenhouse gas concentrations. As a consequence of this, the Middle East, North Africa, and Mediterranean regions will most likely experience a strong precipitation decrease, increasing the pressure on the region's vulnerable environment. Our results from an Earth system model indicate that SAG can partially offset the poleward shift of the storm tracks, thus potentially soothing the environmental and water stresses of the region. However, other climatic side effects may occur, hence still motivating ambitious mitigation action to reduce emissions and impacts of global warming. The results presented may have practical implications for ongoing climate policy debates in the region.

**Plain Language Summary** As a potential approach to prevent dangerous climate change, stratospheric aerosol geoengineering aims to reflect a small percentage of incoming solar radiation into space to reduce the global mean temperature. However, regional impacts are not clear, especially in the global south. This article provides the first analysis of changes in the storm-tracks from stratospheric aerosol geoengineering in the Middle East and North Africa (MENA) region. The results of our study indicate that the poleward shift of the storm-tracks due to increases in the greenhouse gas concentration could be partially offset, and thus potentially sooth some of the environmental, in particular water, stresses. However, other side effects may occur, motivating for an ambitious mitigation pathway still.

## 1. Introduction

Slow progresses in decoupling anthropogenic emissions from economic growth is the main reason for continued increase in the global atmospheric greenhouse gas concentrations (Fuss et al., 2014; Rozenberg, David, Narloch, & Hallegatte, 2015; Sanderson, Tebaldi, & O'Neill, 2016). Even if assuming that the Nationally Determined Contributions (NDCs) would be enough to reduce emissions as promised under the 2015 Paris Agreement, this would likely not be enough to limit global temperature rise to 1.5°C or 2°C (e.g. Millar et al., 2017). This suggests that current climate pledges are not enough to avoid dangerous climate change.

As a theoretical approach to limit global warming, solar radiation management (SRM) aims to reflect a small percentage of incoming solar radiation to space, thus reducing global mean temperatures (Crutzen, 2006; Rasch et al., 2008). Among numerous approaches proposed for achieving this goal, stratospheric aerosol geoengineering (SAG) has received the most attention (e.g., Kravitz et al., 2013; Tilmes et al., 2018, and references therein). By introducing reflective sulfate aerosols into the stratosphere though deliberate injections of sulfur, SAG would reduce some amount of incoming solar radiation reaching the Earth's surface and hence mimic the cooling effect of volcanic eruptions. Although SRM is not to be considered as an alternative to emission reductions, it is the only known approach that could quickly (within a few years) slow, stop, or even reverse the increasing global temperatures. Currently, the risks of stratospheric aerosol geoengineering are uncertain, however. It remains unclear if the risks of breaking the 2°C target exceed or fall short of the risks from stratospheric aerosol geoengineering (Parker & Irvine et al., 2018; Rahman et al., 2018).

Since the early days of stratospheric aerosol geoengineering research, it has been criticized for a number of negative side effects, including not addressing ocean acidification (Lauvset et al., 2017), and stratospheric ozone losses from sulfur injections (Solomon, 1999; Solomon et al., 1996; Tilmes et al., 2008). Another point of criticism of stratospheric aerosol geoengineering has been the unequal and nonuniform regional compensation in temperature and precipitation distributions, hence creating winners and losers (Kravitz et al., 2014; Robock, 2008; Szerszynski, Kearnes, Macnaghten, Owen, & Stilgoe, 2013). To reduce some of the adverse effects, a strategically performed stratospheric aerosol geoengineering modeling exercise was performed recently (Kravitz et al., 2017). The main objective of the study was to generate a climate with minimal temperature changes compared to the present-day climate through the use of sulfur injections in the stratosphere while following the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario (Riahi et al., 2011). They show that simultaneous, multiple surface temperature objectives (maintaining global mean, equator-to-pole, and interhemispheric gradients close to 2020 level under the RCP8.5 scenario from 2020 to 2099) can be met successfully. This suggests that SAG could be done with fewer side effects and has the potential to offset some of the climate change risks, other than just global mean temperatures. In other words, it may hence be considered as complementary response to mitigation and adaptation efforts.

The Middle East, North Africa (MENA) and adjacent Mediterranean region are considered as a hot spot for climatic change. The climate model projections suggest a significant increase in temperatures, accompanied by precipitation reductions (Bucchignani, Mercogliano, Panitz, & Montesarchio, 2018; Giorgi & Lionello, 2008). The MENA region (encompassing 22 countries, from Morocco in the west to Iran in the east) is located in a sensitive climatic zone, where even relatively small changes in the atmospheric circulation and dynamics could lead to substantial climate impacts. In addition, societies here are often less resilient to the environmental changes, exacerbating the vulnerability toward the impacts of climate change. Despite of the low adaptive capacity, as well as being heavily reliant on the climate-dependent natural resources, little attention has been paid to the topic of potential SAG impacts in the region (Rahman et al., 2018). Therefore, there is an urgent need to start to fill this knowledge gap of potential SAG impacts in MENA, which we begin to explore in this study.

One of the robust responses of atmospheric circulation to anthropogenic emissions is the poleward shift of the storm-tracks (Butler et al., 2010; Yin, 2005). The change in the storm-tracks is consistent across the climate model hierarchy (Bengtsson et al., 2006; Mbengue & Schneider, 2017; O'Gorman, 2010; Yin, 2005), as well as observations (McCabe, Clark, & Serreze, 2001; Wang, Swail, & Zwiers, 2006). By transferring moisture, heat, and momentum from the source regions to remote locations, the transient eddies in the storm-tracks are indispensable elements of the synoptic meteorology in the extratropics. They also shape much of the day-to-day weather variability in the midlatitudes (Röthlisberger et al., 2016). In fact, the covariability of the variables between distant locations (due to the propagation of transient eddies in the storm-tracks) are observed, and typically referred to as atmospheric teleconnections (Branstator, 2002).

In the current study, we assess the differences in the climatology of the Rossby wave packets (RWPs) between SAG and RCP8.5 simulations using an Earth system model in order to understand how strategic geoengineering might influence storm-tracks in the MENA region. The RWPs follow the storm-tracks, which means that any changes in their location or intensity reflect changes in the storm tracks themselves (Blackmon et al., 1984; Chang, 2005; Maritus et al., 2010). A typical RWP is characterized by propagation in the zonal direction only, and within an RWP, there is a finite number of troughs and ridges (Wirth et al., 2018).

From a climate perspective, the MENA region is a transition zone that is influenced by both tropical and midlatitude processes. The possible future deployment of SAG can affect both the thermodynamics and dynamics of the Earth's major climatic zones, with possibly large socio-economic consequences. Little is known about SAG impacts on storm-tracks in the MENA region. To fill the gap, the current study is pioneering this research frontier by focusing on the effects of stratospheric aerosol geoengineering on the storm-tracks in the MENA region, by analyzing the data generated by the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project (Tilmes et al., 2018). The results might help decision-makers in area to assess any potential impacts of such forms of geoengineering, to identify and prioritize benefits and opportunities, and finally develop an action plan in partnership with regional and international stakeholders.

## 2. Data and Methods

### 2.1. GLENS Simulations

In the current study, we use model results from the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project, which is a data set composed of an ensemble of simulations aiming at identifying significant global, regional, and seasonal climate changes as a consequence of strategically performed geoengineering in the presence of internal climate variability. In the Supporting Information, we present the details of the simulations.

In this study, three ensemble members from GLENS are used to represent the current climate (the period of 2010–2030, referred to as CTL). For the future climate, the period of 2050–2070 is used from the RCP8.5 and stratospheric aerosol geoengineering simulations (referred to as SAG). The difference between RCP8.5 and stratospheric aerosol geoengineering simulations is the gradual increase in the stratospheric sulfur injections, which is initiated in 2020. The injection rate is gradually increasing, reaching 18 and 32 Tg SO2/year over the period of 2050 to 2070, during which the global surface temperature change in RPC8.5 is between 2°C and 3°C compared to Year 2020 (Figure 2 and Figure 1 in Tilmes et al., 2018). For the stratospheric aerosol geoengineering simulations, there is no change in the temperatures, as per design. The differences between individual ensemble members exist (for the global mean temperature, interhemispheric temperature gradient, and equator-to-pole temperature gradient) in both stratospheric aerosol geoengineering and RCP8.5 simulations; however, the results presented here are robust, and adding any additional ensemble members does not change our main findings on the changes of storm-tracks in the MENA region in either the RCP8.5 or stratospheric aerosol geoengineering simulations (Figures S1 and S2 in the supporting information). Hence, the mean of the three ensemble members is deemed to be sufficient to address the scope of this study.

### 2.2. Storm Track Analysis Method

In the current study, we use daily, 0.9° × 1.25° (latitude × longitude grid resolution) of meridional wind at (200 hPa), corresponding to vertical level 53 in the atmosphere model, to extract the envelopes of the RWPs. Zimin et al. (2003, 2006) proposed a powerful technique, that is a well-known method of digital signal processing known as Hilbert transforms technique, to extract the envelopes of the RWPs. The desired wavenumber component can be obtained by using the Hilbert transform technique. Since we focus on the synoptic-scale RWPs, we filter the meridional wind at 200 hPa using the Hilbert transform technique and isolate wavenumbers 4–11. Large wave packet amplitudes derived from this technique are closely tied to the storm-tracks. More details of the technique and its application in studying the regional and seasonal variation of the storm-tracks can be found in Souders et al. (2014a, 2014b). The climatology of the wave packet amplitudes (in m $s^{-1}$) for the months of January, April, July, and October are calculated for the current climate, RCP8.5, and stratospheric aerosol geoengineering simulations and compared. In addition, we calculate the composite differences (RCP8.5-CTL, SAG-CTL, and SAG-RCP8.5) and apply Student's $t$ test with 98% confidence levels to determine if the two composites are significantly different from each other.

It is also worthwhile to mention that we use the meridional wind at 200 hPa to extract the Rossby wave packets, which is different from the study of Souders et al. (2014b), who used the meridional wind at 300 hPa. The recent study of Röthlisberger et al. (2016) show that the Rossby wave initiation (RWI) occurs on the subtropical jet over the MENA region due to the interactions between extratropical and subtropical waveguides. They furthermore suggest that the meridional wind at 300 hPa is not a suitable choice to detect the RWI along the subtropical jet in the MENA region, as it often lies at a higher altitude range (200–250 hPa). Hence, no storm tracks were found in the Souders et al. (2014a, 2014b) studies.

## 3. Results

Figures 1a and 1b provide the MENA region's storm-tracks climatology from the GLENS simulation in January and April, respectively. They show the long-term “present day” (2010–2030 period) Rossby wave packet amplitudes (in m $s^{-1}$). As expected, it suggests that the storm-tracks are generally stronger in January compared to April (as representative for the winter and spring seasons, respectively). In both months, the wave packet amplitudes are larger in the Middle East compared to North Africa. However, in both months, a thin tongue of the Eurasian storm-tracks passing over the Mediterranean Sea is stronger

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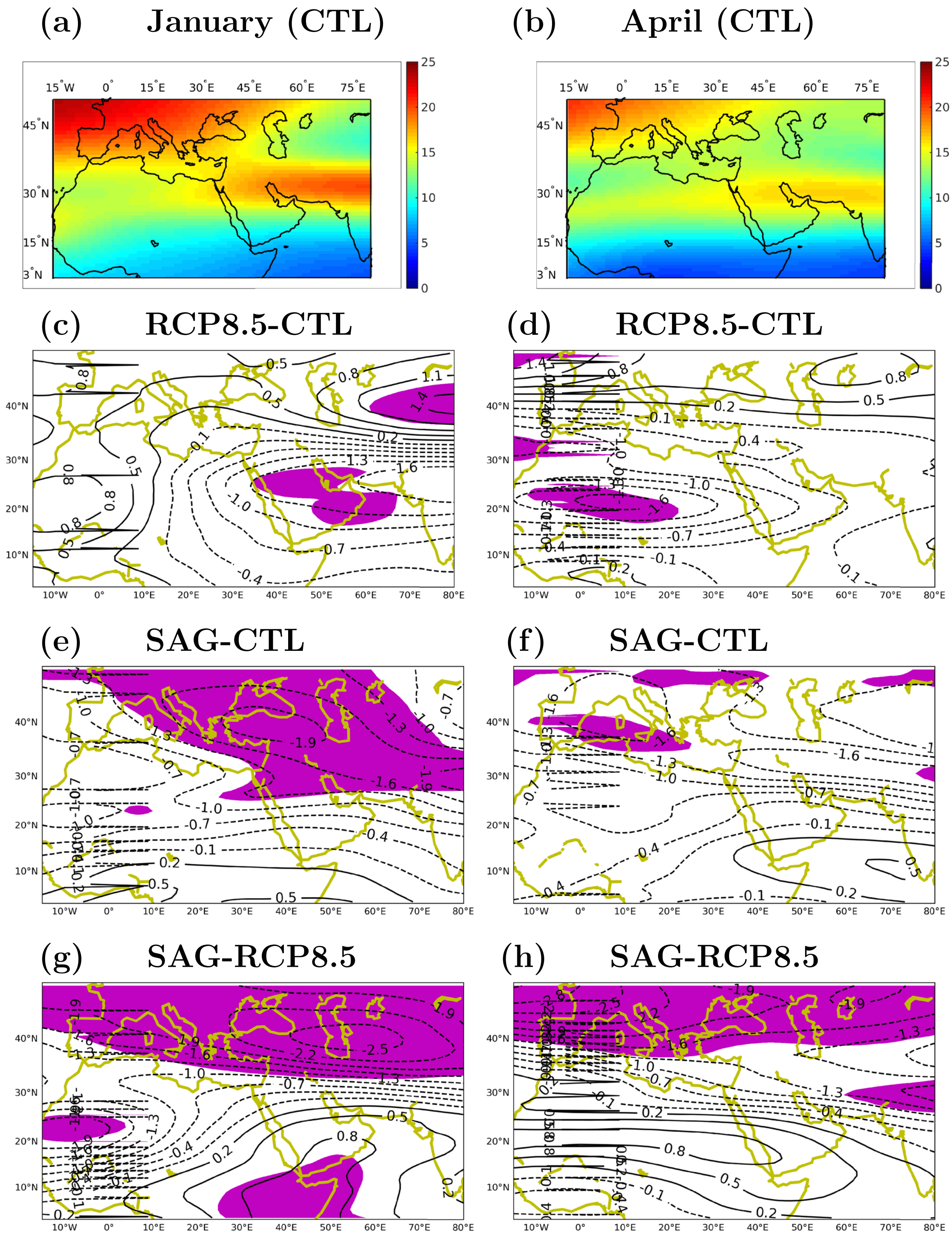


**Figure 1.** Amplitude of the Rossby wave packet in (m s$^{-1}$) representing the storm-tracks in the MENA region in January (a) and April (b). The differences in the wave packet amplitudes between high-emission scenario (RCP8.5), stratospheric aerosol geoengineering (SAG), and control (CTL) simulations for the months of January and April are presented in the left and right columns. The contours are between −4 and +4 within steps of 0.3. The shaded regions indicate regions where the differences are statistically significant at 98% confidence level according to Student's *t* test.

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than the storm-tracks in the MENA region. These features of the MENA region's storm-tracks is comparable to the reanalysis data of the National Centers for Environmental Prediction (NCEP, figures not shown), suggesting that a realistic storm-tracks climatology is provided in the GLENS simulations deeming the model suitable for the purpose of our study.

The differences of the storm-tracks intensity between high emission scenario (RCP8.5) and control simulation (CTL) for the months of January and April are provided in the second row of Figures 1c and 1d. In January, almost all parts of the Middle East, eastern part of the Mediterranean Sea, and northeastern Africa experienced a decrease in the intensity of the storm-tracks, which is statistically significant in many areas. Northwestern Africa sees a small increase in the storm-track intensity, which is not statistically significant. However, higher latitudes, especially in the eastern side of the Caspian Sea, experience an increase in the storm-tracks intensity in RCP8.5, which is statistically significant. These results, which are supported by earlier research (Butler et al., 2010), suggest that with increasing greenhouse gases concentrations, the mean position of the storm-tracks move poleward. In April, a similar response is found, with the only difference being the location of the maximum and minimum differences between RCP8.5 and CTL. Overall, a reduced intensity of the storm-track is found in most regions of the Middle East coupled with enhanced levels of the wave packet activity in the northern parts of the Mediterranean and Caspian seas.

Figures 1e and 1f show the differences of the storm-tracks intensity between the stratospheric aerosol geoengineering scenario (SAG) and control simulation (CTL) for the months of January and April, respectively. Almost all regions that show an enhancement in the level of storm-tracks activity in RCP8.5 experience a reduction in the storm-tracks activity intensity for the SAG simulation compared to the CTL simulation. More specifically, the storm-tracks activity in the northern Mediterranean and Caspian seas decreases in the SAG simulation compared to the CTL simulation. The reduced level of storm-tracks activity in the SAG compared to the CTL extends to the large area of MENA region in January. However, in April, southeastern part of the MENA region (eastern Red sea and the southern part of the Persian Gulf) indicates a positive change in the SAG simulation compared to the CTL simulation, although these positive changes are not statistically significant. The reduced level of storm-tracks activity in the SAG simulation compared to the CTL simulation are statistically significant in most regions of the MENA region and northern Mediterranean and Caspian seas.

The impact of strategic deployment of stratospheric aerosol geoengineering is best depicted by comparing the SAG simulation with RCP8.5 (Figures 1g and 1h for January and April, respectively). These figures indicate that storm-tracks activity is enhanced in the SAG scenario compared to the RCP8.5 simulation in MENA. In the northern parts of the Mediterranean and the Caspian seas, a reduction in the storm-tracks activity level is found in the SAG simulation compared to RCP8.5. This indeed suggests that the strategic geoengineering has the potential to partially offset the side effect of the increased greenhouse gases and its poleward shift of the storm-tracks.

The present day (2010–2030 period) Rossby wave packet amplitudes for the months of July and October are presented in Figures 2a and 2b, respectively. The second row of Figure 2 provides the differences of the storm-tracks between RCP8.5 and CTL simulations. In July, the north of Mediterranean and Caspian seas experiences a reduction in activity, while eastern Middle East shows an increase. In October, on the other hand, most of MENA and higher latitudes show a reduction in the storm-track activity level in RCP8.5 simulation compared to the CTL simulation. The eastern side of the Caspian Sea in October shows an increase (similar to the month of January), although in October this change is not statistically significant.

The differences of the storm-tracks intensity between SAG and CTL simulations for the months of July and October are presented in Figures 2e and 2f, respectively. In general, the negative anomalies in the activity levels of the storm-tracks in July (in RCP8.5 compared to the CTL simulation) in the northern regions of the Mediterranean and Caspian seas are offset in the SAG simulation. However, the positive anomalies in the Middle East region in July (in RCP8.5 compared to the CTL simulation) is further enhanced making the statistically significant positive responses even wider in the SAG simulation. In October, the sign of the response between SAG and RCP8.5 are opposite in the MENA region. In contrast to the reduced level of storm-tracks activity in October over vast regions of MENA region in the RCP8.5 simulation compared to CTL simulation, our analysis shows that in the SAG simulation, most of MENA has a higher level of activity compared to CTL. This is also reflected in Figures 2h and 2g, showing the differences between SAG and

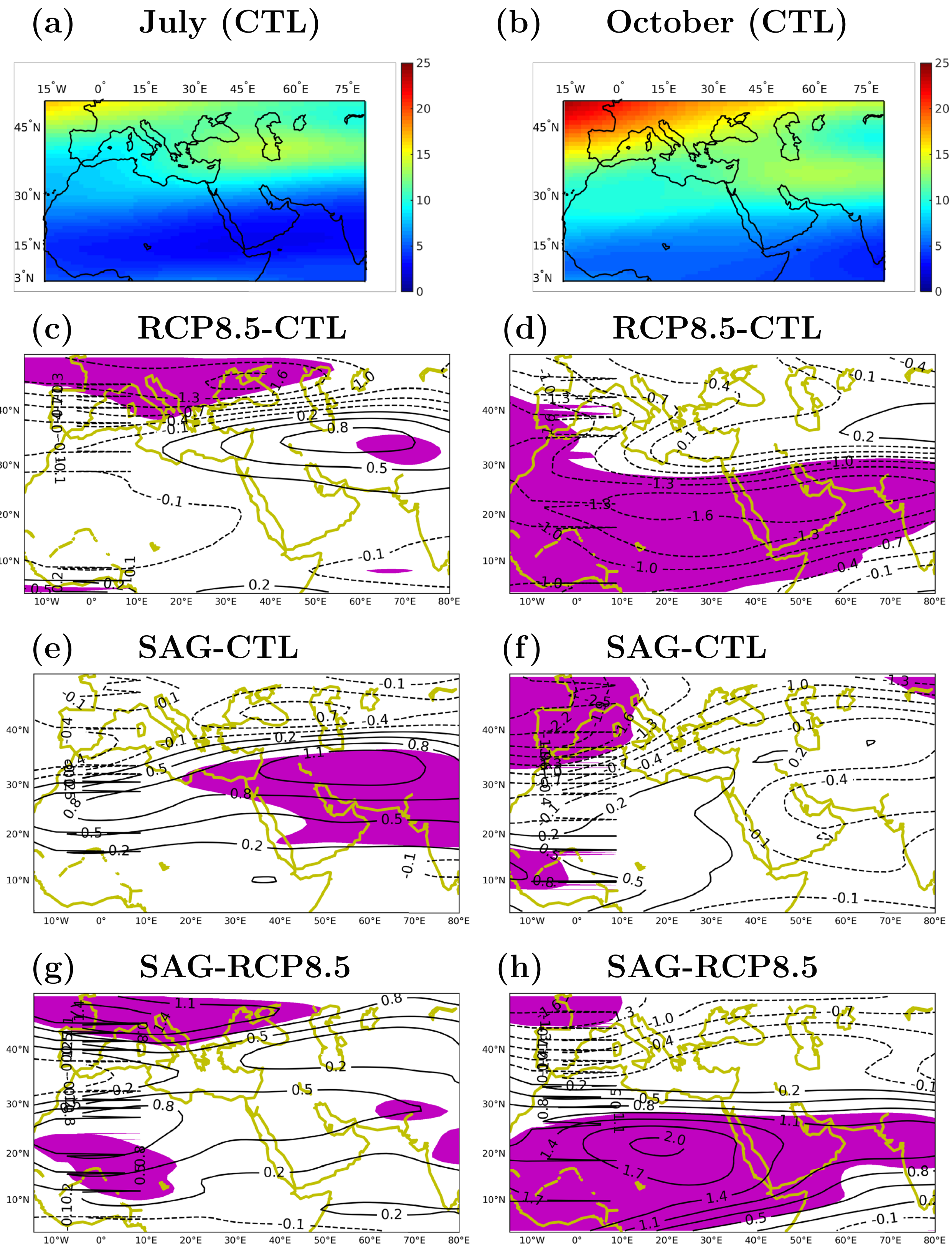


**Figure 2.** Amplitude of the Rossby wave packet (m $s^{-1}$) representing the storm-tracks in the MENA region in July (a) and October (b). The differences in the wave packet amplitudes between high-emission scenario (RCP8.5), strategic stratospheric aerosol geoengineering (SAG), and control (CTL) simulations for the months of July and October are presented in left and right columns.

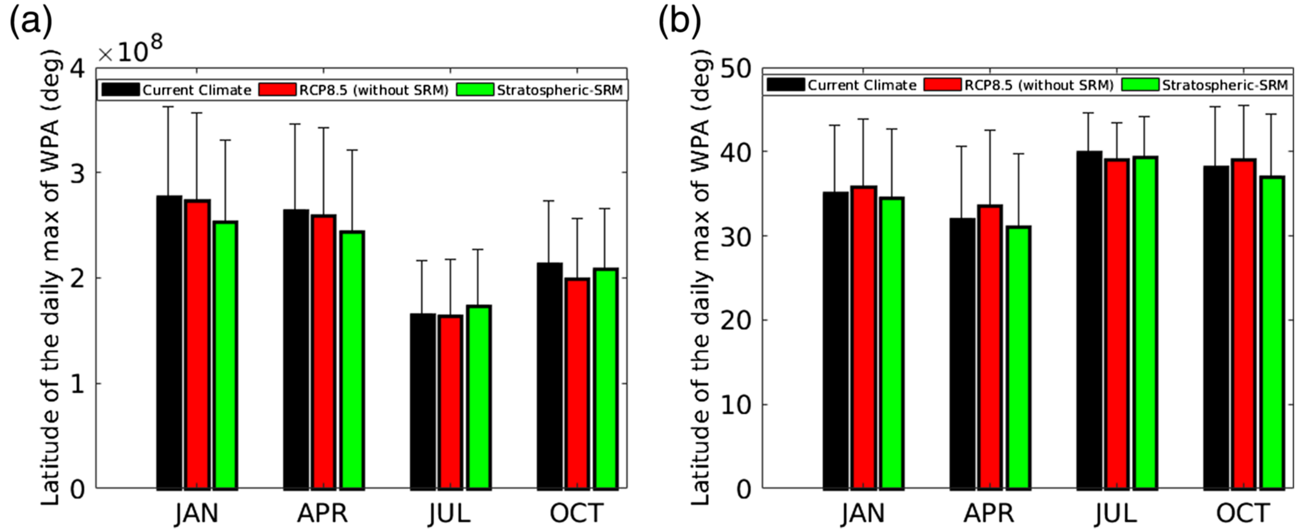


**Figure 3.** (a) Activity volume of Rossby wave packets ($km^2\ m\ s^{-1}$) and mean latitude of daily maximum of wave packet amplitudes in degrees (b). Black denotes current climate simulation, red—high-emission, and green—geoengineering simulation. The bars over the mean values show the standard deviations.

RCP8.5 in the same months. Almost the entire MENA region experiences a statistically significant increase in the level of storm-tracks activity in July, with a peak in North Africa. A similar picture is seen in October, when the largest difference is found in the northern Mediterranean and Caspian seas regions.

Figure 3a shows the activity volumes of the RWPs for the CTL, RCP8.5, and SAG simulations. The activity volume ($km^2\ m{\cdot}s^{-1}$) is defined by multiplying the area of each grid box (binned by 0.9°lat × 1.25°lon intervals between 20°N and 45°N) by the mean value of WPAs (wave packet amplitudes) in each cell. The values from CTL (black columns) show that on average, the maximum and minimum of the activity volume are found in January and July, as expected. Interestingly, in both the SAG and RCP8.5 simulations, the activity volumes are less than the CTL simulation in January. This is also the case in April. To understand this, one has to consider that in Figures 1g and 1h, the values of the wave packet amplitudes in SAG compared to RCP8.5 are larger in most regions of the Middle East. At the same time, an opposite sign in the response is found over the Mediterranean and Caspian seas, such that they actually cancel each other out. This also holds true for the activity volumes in the months of July and October. The higher activity volumes in SAG compared to RCP8.5 in both July and October are due to higher value of the wave packet amplitudes (Figures 2g and 2h, respectively). This shows that in the GLENS simulation, the strategic geoengineering is only able to preserve the activity volume of the Rossby wave packets to CTL levels in July and October. This also demonstrates that in the high-emission scenario (RCP8.5), the activity volume is reduced (compared to the CTL simulation) in all months and that SAG only offsets this in July and October. This clearly suggests that stratospheric aerosol geoengineering simultaneously controlling for three temperature targets, as done in this study, is only able to partially offset the negative side effect of the high-emission scenario.

Figure 3b demonstrates the average latitude of the daily maximum of wave packet amplitudes (in degrees) for different months and scenarios. It shows that for all months (except July), the average latitude of the daily maximum of WPAs is located more north in the RCP8.5 scenario compared to CTL scenario. This also further indicates a poleward shift of the storm-tracks during these months in the RCP8.5 simulation compared to the CTL. It also shows that in all months (except July), the SAG scenario offsets this impact and move the storm-tracks equatorward. In general, the strategic geoengineering act as an offsetting force to retain the storm-tracks location to its position closer to CTL simulation in the MENA region in all seasons.

## 4. Conclusions

In this paper, we investigated the storm-tracks response to a high anthropogenic emission scenario pathway (RCP8.5) and a strategic stratospheric aerosol geoengineering scenario (SAG) between 2050 and 2070, compared to the present-day climate (CTL) by using GLENS simulations (Tilmes et al., 2018) in the MENA region. We analyzed the differences of the amplitudes of the Rossby wave packets that are representatives of the storm-tracks in RCP8.5 and SAG simulations with CTL simulation. Our results show that increases in the greenhouse gases concentration will result in the northward (poleward) shift of the storm-tracks in all seasons, except summer when the storm-tracks in the MENA region is very weak. In the SAG simulation, most of MENA sees higher level of storm-tracks activity compared to CTL. This suggests that the strategic geoengineering has the potential to partially offset the poleward shift of the storm-tracks seen in the RCP8.5. In addition, our calculation shows that the activity volume of the storm-tracks in January and April in the SAG simulation is lowered compared to current climate simulation. Furthermore, in all months, the activity volume of the MENA storm-tracks in RCP8.5 simulation is lower than in CTL simulation. This is offset by SAG only in October and July. This suggests that the controlling three surface temperature targets with SAG as done in GLENS is only able to partially offset the impacts of the high-emission scenario on the storm-tracks in the MENA region. Since in October, the latitude of the daily maximum of the WPAs in SAG are further equatorward from the original latitude in the CTL simulation, we suggest that SAG can introduce additional (positive and negative) impacts that are not present in the RCP8.5 simulations. Such effects are in need of further investigations, beyond the scope of this study.

It is also worthwhile to mention that the information presented here should be considered with its constraints. Although the GLENS project is a first and important step in understanding the risks, uncertainties, and potential benefits of such strategic deployment of stratospheric aerosol geoengineering, here with the main objective of generating a climate with minimal temperature changes compared to the present-day climate, it has its limitations. This is the first study to address the impacts of such SAG on the storm-tracks in MENA, but the results are based on a single model and would require to be confirmed by other model studies. The results presented here does not aim at or support the large-scale deployment in the real-world but is meant to increase our understanding of the possible effects of SAG on the climate system. We also reemphasize that our results do not mean that SAG can be viewed as an alternative for emission-reductions and SAG at best should be viewed as a supplement for emission reduction policies.

## Data Availability Statement

The data from the GLENS simulations is publicly available via its website: http://www.cesm.ucar.edu/projects/community-projects/GLENS/ (DOI: 10.5065/D6JH3JXX).

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