Universiteit Utrecht

Emulating SAI Scenarios in CESM2 and the Effects on the High-Latitude Southern Hemisphere Atmospheric Circulation

Master Thesis

Simone Lingbeek
Climate Physics

Supervisors:

Dr. Claudia Wieners
Institute for Marine and Atmospheric research Utrecht (IMAU)

Dr. Michiel Baatsen
Institute for Marine and Atmospheric research Utrecht (IMAU)

Daily supervisor:

Jasper de Jong
Institute for Marine and Atmospheric research Utrecht (IMAU)

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1 Introduction

1.1 Climate change and geoengineering

In the effort of limiting the effects global climate change, eliminating fossil fuels is the most important step to take. Regrettably, the complete elimination of fossil fuels in time to prevent the most disastrous effects of climate change and limit global warming to even 2°C is becoming increasingly unlikely. Even with all currently committed climate action goals, projections show the earth warming significantly above the 1.5°C and 2°C targets from the Paris Agreement (UNFCCC 2023). With this outlook, methods to temporarily lower the earth's global temperature are looked at to buy the global community time to lower atmospheric greenhouse gases. One such method is solar radiation management with stratospheric aerosol injections (SAI).

Through injection of sulphate aerosols or their precursors at specific points in the stratosphere the earth's radiation budget is changed. At this high altitude the aerosols reflect short wave radiation, lowering the amount of sunlight reaching the earth's surface. In turn, the earth's surface temperature decreases. However, the long wave radiation emitted by the earth is absorbed by the aerosols too, resulting in warming in the stratosphere (Ammann et al. 2010). This impacts the global atmospheric circulation patterns and subsequently on precipitation patterns, making the employment of SAI not as straight-forward as appears at first glance.

1.2 Previous Research

To investigate how the earth's atmosphere responds to the employment of sulphate aersol injections, a number of model studies has been performed. The most comprehensive project to date exploring this problem is the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project (Tilmes et al. 2018). In this project the Community Earth System Model version 1 with the Whole Atmosphere Community Climate Model (CESM1(WACCM)) was used to perform simulations of a scenario that implemented SAI from 2020 onwards. The background used was the RCP8.5 emission scenario (Riahi et al. 2007). The model incorporated a feedback algorithm to adjust the sulphur dioxide (SO_2) injection amounts at four injection points to maintain 2020 temperatures, or about 1.5°C above pre-industrial levels. This included metrics related to the interhemispheric temperature gradient and the pole-to-pole temperature gradient.

In 2020 similar simulations were done using the CESM2(WACCM6) with a variety of emission and reductions scenarios, including the scenario explored in the GLENS project (Tilmes et al. 2020). The CESM2(WACCM6) is a very large model with 70 vertical layers in the atmosphere and comprehensive chemistry in the troposphere up to the lower thermosphere and it incorporates a multimodal aerosol scheme (MAM4). This makes the model exceptionally well suited for analysis of SAI schemes, but does require a lot of computing time and resources. This limits its use for ensemble projects and exploration of various SAI schemes.

1.3 Evaluating the CAM6 Emulator

One proposed solution is to use the aerosol field resulting from the CESM2(WACCM6) simulations and to prescribe this field to a smaller, less cumbersome model. This was done in Pflüger et al. (2024) with the Community Atmosphere Model version 6 (CAM6) as the atmopsheric component for CESM2. The aerosol field was adjusted using a feedforward-feedback algorithm only adjusting for GMST. The fist part of this thesis is the validation of this method and model in its use in simulating SAI scenarios based on the more comprehensive CESM2(WACCM6) results. We formulate the following research questions for the first part:

1. Does the CESM2(CAM6) succeed in maintaining global surface temperature through SAI, including spatial patterns?
2. How does the CESM2(CAM6) SAI simulation perform compared to the CESM2(WACCM6) SAI simulation it was based on?

1.4 Southern Hemisphere Atmosphere

In the second part of this thesis the CESM2(CAM6) simulation of the SAI scenario is used to investigate the effects of SAI on atmospheric dynamics in the Southern Hemisphere high latitudes. Additionally, a new scenario of rapid late-century cooling through SAI is introduced. Comparison between these scenarios can provide insight in the memory of the earth system and efficacy of rapid cooling compared to gradual cooling using SAI.

The Southern Hemisphere high latitudes are of special interest in the context of preventing climate catastrophe as large scale atmospheric dynamical changes affect the Antarctic ice sheet. Changes in temperature, precipitation and wind fields affect the surface mass balance of the ice sheet. Indirectly these changes affect the ice sheet through changes in the ocean, mainly in the rate and location of overturning circulations.

We formulate the following research quesitons for the second part:

1. How does SAI affect the Southern Hemisphere mid-level atmospheric circulation?
2. How does SAI affect the Southern Hemisphere high latitude atmospheric circulation at high altitude (Polar Night Jet)?
3. How does the late-century SAI scenario differ from the gradual SAI scenario?

ik zou heeeel graag wat feedback willen op m'n onderzoeksvragen, ik vind het goed formuleren van waar ik nou naar heb gekeken nog best lastig blijkt

Throughout this thesis, the CESM2(CAM6) configuration is referred to as CAM and the CESM2(WACCM6) configuration is referred to as WACCM. The monthly mean model output is used, resulting in 12 data entries for each model year.

Part I
Model Validation

2 Introduction Part I

2.1 Geoengineering in the Form of Stratospheric Aerosol Injections

Geoengineering can be seen as a toolbox of methods that change the earth's climate system to achieve a desired effect. Limiting global warming to 1.5-2°C is the primary goal of geoengineering. The methods of geoengineering can be divided into two basic categories, Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM) (Shepherd 2009). CDR focuses on lowering the amount of greenhouse gases in the atmosphere, by capturing CO_2 directly or enhancing and facilitating natural processes to speed up the extraction of CO_2 from the atmosphere or oceans. SRM on the other hand focuses on altering the earth's radiation budget. This can be done by increasing the amount of long wave radiation the earth emits into space. The most widely discussed approach is increasing how much short wave radiation from the sun is reflected back into space, i.e. increasing the planetary albedo. This is done for instance by making deserts more reflective or making clouds brighter.

This thesis deals with SRM in the form of stratospheric aerosol injections (SAI). Aerosols or their precursors, in this case SO_2, are injected into the lower stratosphere where they reflect some of the incoming short wave radiation from the sun. This lowers the temperature of the earth's surface at the latitudes it was injected. As atmospheric circulation carries the aerosols around the globe zonally very quickly, only the latitude and season of the injection need to be considered. This choice was found to be crucial when determining the effectiveness of SAI on the poles by Duffey et al. (2023). A more recent development in this regard started with Kravitz et al. (2017) and MacMartin et al. (2017), and then the Geoengineering Large Ensemble (GLENS) project.

2.2 The GLENS Project and Subsequent CESM2 Simulations

The GLENS project is a 20-member ensemble of gradual SAI simulations (Tilmes et al. 2018). From 2020 onwards SO_2 is injected at four injection points at ± 15°N and ± 30°N about 5 km above the tropopause. A feedback-control algorithm is used to adjust the injection amounts at each point individually based on departures from the temperature goals defined by Kravitz et al. (2016). These are the global mean surface temperature, the inter-hemispheric temperature gradient and the equator-to-pole temperature gradient. This algorithm also tunes the injection amount to the seasonal response of the model.

The GLENS project was performed using the Community Earth System Model version 1 (CESM1) (Hurrell et al. 2013), with the Whole Atmosphere Community Climate Model (WACCM) as its atmosphere component. This model uses a 0.9° latitude × 1.25° longitude rectangular grid with 70 vertical layers that reach up to 140 km, or about 10^{-6} hPa. It includes comprehensive atmospheric chemistry for the middle atmosphere, incorporating ozone chemistry and chemistry relating to stratospheric sulfate formation. A simpler chemistry scheme is used for the troposphere. Aerosol chemistry is coupled to WACCM through the three-mode version of the Modal Aerosol

Module (MAM3). past dit misschien beter in de methods, en dan voor cesm2?

After the GLENS project the method using four injection points and a feedback algorithm was further explored using the more recent Community Earth System Model version 2, also using a newer version of the WACCM, now version 6 (CESM2(WACCM6)) (Tilmes et al. 2020). WACCM6 has the same horizontal and vertical resolution, but now includes comprehensive chemistry from the troposphere up to the lower thermosphere. The MAM4 modal aerosol scheme is used for the troposphere and stratosphere. dus dit ook naar methods?

Because CESM2(WACCM) is so comprehensive in both vertical resolution and atmospheric chemistry, it is extremely well-suited to simulate SAI scenarios. However, due to this it is also a very cumbersome model, requiring a lot of computing time an resources. This limits its use in ensemble studies and studies considering a large number of scenarios.

2.3 CESM2 with CAM6 as an Emulator

To reduce the amount of resources needed, Pflüger et al. (2024) introduce a method that uses a less comprehensive atmospheric component. The same CESM2 model configuration is used as in Tilmes et al. (2020), but the Community Atmosphere Model version 6 (CAM6) is used for the atmosphere component (Danabasoglu et al. 2020). The aerosol field established in the CESM2(WACCM6) simulation is used as an external forcing. A feedforward-feedback algorithm is used to adjust the aerosol field as a whole to keep the global mean surface temperature (GMST) at 1.5°C above pre-industrial levels. So, in contrast to the CESM2(WACCM6) simulations, the temperature gradients are not adjusted for.

To assess how well this method works as an emulator, the model results for surface temperature, precipitation, potential temperature and zonal wind are compared between CESM2(WACCM6) and CESM2(CAM6). dit mag uitgebreider

To repeat, we formulate the following research questions:

1. Does the CESM2(CAM6) succeed in maintaining global surface temperature through SAI, including spatial patterns?

2. How does the CESM2(CAM6) SAI simulation perform compared to the CESM2(WACCM6) SAI simulation it was based on?

The three temperature targets are calculated for all models. The model results for reference height temperature (or 2-meter temperature), will provide additional insight into the performance of CESM2(CAM6) in regards to regulating surface temperatures. Both annual and seasonal patterns are discussed. Additionally, precipitation patterns are discussed. To assess any differences in the vertical profile between the two models, the zonally averaged potential temperature and zonal winds are compared.

3 Methods Part I

3.1 Building the Emulator for SAI simulations

The emulator for SAI simulations is introduced in Pflüger et al. (2024), it implements SAI via prescribed aerosol fields, as opposed to sulphate injections that result in aerosol fields through model physics. As per Pflüger et al. (2024), the protocol works as follows:

- Every year, observe the deviation of GMST from the target.
- Based on past GMST deviations, infer the level of SAI - expressed in terms of global mean aerosol optical depth (AOD) - which is necessary to achieve the desired target.
- Use the AOD to scale all SAI-related aerosol fields appropriately.
- Feed the scaled fields into CAM6.

The first two steps are implemented via the feedforward-feedback control algorithm as established in Kravitz et al. (2017). The control algorithm stabilises only GMST, not inter-hemispheric and equator-to-pole temperature gradients like the simulation performed by Tilmes et al. (2020).

The prescribed aerosol fields are the averaged aerosol fields from the WACCM simulation, this simulation is called the *Geo SSP5-8.5 1.5 scenario* in Tilmes et al. (2020). The fields are normalised, averaged and fit, to then arrive at an amplitude for each aersol component.

Stukje over aerosolveld hoe het eruit ziet + jaarlijkse totale massa figuren (?)

3.2 Definition of Scenarios and Time Periods for Part I

There are two simulations performed with each CESM2 configuration. The first simulation follows the historical spin-up and is continued by the SSP5-8.5 scenario. The second simulation branches from the first simulation in 2020 and from then on introduces SAI to stabilise temperatures using the SSP5-8.5 scenario as background. Here we will refer to it as the gradual SAI scenario.

Throughout this first part, three time periods are used to visualise and interpret the results from the simulations. For each period the 20-year mean is taken, unless specified otherwise. These periods are defined as follows:

- **Reference** The period 2016-2035 of the SSP5-8.5 simulation.
- **Control** The period 2080-2099 of the SSP5-8.5 simulation.
- **SAI 2020** The period 2080-2099 of the gradual SAI simulation.

misschien beter in tabelvorm

3.3 Vertical Interpolation

The atmospheric vertical levels of CESM are defined as hybrid levels. However, for ease of computation and visualisation, conversion to pressure levels is preferred. To this end, a logarithmic interpolation scheme is used, that takes the model output at hybrid levels and projects them onto the appropriate pressure levels. For CAM the model output is converted to 34 pressure levels ranging from 3.5 to 993 hPa. For WACCM the SSP5-8.5 model output was pubplished in pressure levels, 19 pressure levels ranging from 1 to 1000 hPa. The WACCM gradual SAI scenario model output is converted to those same 19 pressure levels. moet dit uitgebreider?

No interpolation is needed of the horizontal grids as these are identical in all models.

3.4 Temperature Targets

The WACCM simulations use the feedback algorithm to maintain three temperature targets in their SAI scenario. These temperature targets are defined in Kravitz et al. (2016) as the projection of $T(\psi)$ onto the first three Legendre polynomial functions of $\sin(\psi)$, resulting in

$$\begin{aligned} T_0 &= \frac{1}{A}\int_{-\pi/2}^{\pi/2} T(\psi)\, dA, \\ T_1 &= \frac{1}{A}\int_{-\pi/2}^{\pi/2} T(\psi)\sin(\psi)\, dA, \\ T_2 &= \frac{1}{A}\int_{-\pi/2}^{\pi/2} T(\psi)\frac{1}{2}(2\sin^2(\psi)-1)\, dA, \end{aligned} \tag{1}$$

where ψ is latitude, $T(\psi)$ is the zonal-mean temperature for each latitude, and A the area-weighted latitude, defined as

$$dA = \cos(\psi)\, d\psi \Rightarrow A = \int_{-\pi/2}^{\pi/2} \cos(\psi)\, d\psi = 2. \tag{2}$$

Combining Eqs. 1 and 2 we find

$$T_0 = \frac{1}{2} \int_{-\pi/2}^{\pi/2} T(\psi) \cos(\psi)\, d\psi,$$
$$T_1 = \frac{1}{2} \int_{-\pi/2}^{\pi/2} T(\psi) \sin(\psi) \cos(\psi)\, d\psi, \tag{3}$$
$$T_2 = \frac{1}{2} \int_{-\pi/2}^{\pi/2} T(\psi) \frac{1}{2}(2 \sin^2(\psi) - 1) \cos(\psi)\, d\psi\ .$$

The T_0 temperature target translates to global mean surface temperature (GMST), the T_1 is interpreted as the inter-hemispheric temperature gradient and T_2 is interpreted as the equator-to-pole temperature gradient. From the model output these temperature targets can be evaluated using Eq. 3.

Een figure van het voorgeschreven aerosolveld is handig, maar of dat hier of in de introductie moet weet ik niet goed, ik neig naar hier. Een uitgebreidere bespreking van de datasests is denk ik ook gepast, maar of dit beperkt moet blijven tot 'van wie zijn ze en waar zijn ze te vinden' of dat het uitgebreider moet weet ik ook niet goed...

Part II
Southern Hemisphere Atmospheric Circulation

4 Introduction Part II

For the second part of this thesis we consider the two CESM2(CAM6) simulations to assess the effect of SAI on the high-latitude Southern Hemisphere atmospheric dynamics. Additionally, we introduce a third simulation that employs SAI from 2080 onward to rapidly cool the earth to 1.5°C above pre-industrial levels. This scenario is used to gain insight into the effects of rapid cooling of the climate system and how this differs from gradually increasing SAI to maintain GMST.

4.1 Rapid Cooling with SAI as an Emeregency Intervention

As current climate policies are insufficient to prevent global warming of 1.5°C or even 2°C (IPCC), the proactive gradual SAI scenario is unlikely to be implemented in time as well. Employing SAI much later on after prolonged heating of the climate system is a realistic, more reactive, scenario. The earth could be cooled very rapidly, allowing the end-of-century GMST goals to be reached after the climate system has endured an even longer period of warming than it has to date. The effects of such an intervention are largely uncertain. While it is rather certain that SAI could lower GMST, it is not certain what effects of previous warming can be reversed, if at all.

Such a scenario is introduced in Pflüger et al. (2024). The SAI 2080 scenario is introduced, where SAI is employed from 2080 onwards to achieve rapid cooling to 1.5°C above pre-industrial levels. In this study the effects of SAI on ocean circulation is investigated, specifically how the rapid deployment of SAI compares to the gradual deployment of SAI.

4.2 The high-latitude Southern Hemisphere Atmosphere

The high-latitude Southern Hemisphere is of particular interest in the context of global warming and the prevention of it. The Antarctic Ice Sheet could contribute greatly to global sea level rise if it were to become unstable under global warming. Observed instabilities of the West-Antarctic Ice Sheet (WAIS) alone could contribute to significant sea level rise (IPCC WG1).

The Southern Hemisphere high stratosphere has low variability in the current climate, but any changes have far-reaching effects on the surface climate. It has been observed that SH stratospheric polar vortex weakekening contributes to climate anomalies in Australia and New Zealand, southeast Africa and southern South America. Additionally, the wind stress over the ocean around Antarctica is weakened and the Ross and Amundsen seas experience warmer climate (Domeisen and Butler 2020). There is thus a clear interaction between the atmospheric dynamics and local climate in the Southern Hemisphere.

4.3 Previous Research

The effect of SAI on the Antarctic ice sheet has been studied by McCusker et al. (2015), who found that a rapid introduction of sulphate aerosols in the stratosphere could not prevent the collapse of the WAIS. Sutter et al. (2023) found similar results. However, both studies use very simple aerosol schemes, that for instance only inject aerosols in the tropics. These types of schemes are known to lead to over-cooling of the tropics and under-cooling of the poles. As was laid out in Tilmes et al. (2020), the GLENS project aimed to implement an SAI scheme that could prevent the emergence of these patterns and was largely succesful in doing so. The CESM2(WACCM) repetition of this experiment and the CAM emulator were also largely succesful in this regard.

Understanding the consequences of this type of SAI scheme on the Southern Hemisphere is crucial to be able to make informed decisions on the deployment of SAI in the future.

4.4 ???

In this second part the effect of SAI on the high-latitude Southern Hemisphere atmospheric dynamics is investigated, both in the gradual and rapid cooling scenarios. The CESM configuration used in the emulator includes ice sheets that are non-evolving, so direct consequences to the AIS are not within the scope of this thesis. The focus here lies on atmospheric processes, as large scale circulation patterns largely dictate local climate in the Southern Hemisphere.

To repeat, we formulate the following research quesitons for the second part:

1. How does SAI affect the Southern Hemisphere mid-level atmospheric circulation?
2. How does SAI affect the Southern Hemisphere high latitude atmospheric circulation at high altitude (Polar Night Jet)?
3. How does the rapid cooling SAI scenario differ from the gradual SAI scenario?

het is nog niet een heel lopend verhaal voor mijn gevoel...

5 Methods Part II

5.1 Rapid Cooling Experiment

The rapid cooling experiment is branched from the SSP5-8.5 simulation in 2080, SAI is then deployed to restore temperatures to 1.5°C above pre-industrial levels. The control algorithm is adjusted for the first up to six years to prevent extremely high aerosol concentrations that would result in too rapid cooling.

Shown in Figure [T0T1T2tot2130] are the temperature targets from 3 for the SSP5-5.8, gradual SAI and rapid cooling SAI simulations. After a few years of SAI the T_0 target is reached and maintained, like in the gradual SAI simulation. The T_1 target stabilised after ??? years, showing ??? behaviour. The T_2 target shows ??? behaviour (un)like in the gradual SAI simulation.

[INSERT T0T1T2tot2130 FIGURE HERE]

hier moet ik het figuur nog voor maken, gewoon nog geen zin in gehad. Is een plaatje van de spatial distribution ook relevant, zoals in pt1 ook voor SAI 2020 is gemaakt?

5.2 Definition of Scenarios and Time Periods for Part II

The two simulations from Part I are referred to in the same way in this second part, namely the SSP5-8.5 simulation and the gradual SAI simulation. The simulation with the rapid cooling experiment is referred to as the rapid cooling SAI simulation.

All simulations considered in this second part were extended from 2100 to 2130. This extension provides further insight in the long-term effects of deploying SAI. Especially in the rapid cooling SAI scenario the extension provides time for the climate system to adjust to the 'shock' it experienced from SAI.

Throughout this second part, four time periods are used to visualise and interpret the results from the simulations. As in part I, for each period the 20-year mean is taken, unless specified otherwise. These periods are defined as follows:

- **Reference** The period 2016-2035 of the SSP5-8.5 simulation.
- **Control** The period 2111-2130 of the SSP5-8.5 simulation.
- **SAI 2020** The period 2111-2130 of the gradual SAI simulation.
- **SAI 2080** The period 2111-2130 of the rapid cooling SAI simulation.

misschien beter in een tabel

5.3 Thermal Wind

To calculate thermal winds from the temperature gradients, the thermal wind balance equation is used. As the vertical layers of the model are converted to pressure coordinates, the equation takes the form

$$\frac{\partial v_g}{\partial p} = -\frac{R}{p f_0}\frac{\partial T}{\partial x}; \ \frac{\partial u_g}{\partial p} = \frac{R}{p f_0}\frac{\partial T}{\partial y}, \tag{4}$$

where v_g,u_g is the geostrophic wind in meridional and zonal directions respectively, $R = 286.9$ J kg^1 K^1 is the specific gas constant, p is pressure, $f_0 = 2\Omega \sin\varphi$ is the coriolis parameter at the chosen reference latitude φ, $\frac{\partial T}{\partial x,y}$ is the layer-mean temperature gradient in zonal and meridional direction respectively. Rewriting and integrating gives us

$$\begin{aligned}\int_{p_0}^{p_1} \partial v_g &= \int_{p_0}^{p_1} -\frac{R}{f_0}\frac{\partial T}{\partial x}\partial \ln p;\\ \int_{p_0}^{p_1} \partial u_g &= \int_{p_0}^{p_1} \frac{R}{f_0}\frac{\partial T}{\partial y}\partial \ln p,\end{aligned} \tag{5}$$

where $p_{0,1}$ are the lower and upper boundaries of the model layer, respectively, so that $p_1 < p_0$. Because T is the layer-mean temperature and R and f_0 are constants, we can evaluate this integral to find the thermal wind in the layer between p_0 and p_1

$$\begin{aligned}v_T &= v_g(p_1) - v_g(p_0) = \frac{R}{f_0}\frac{\partial T}{\partial x}\ln\left(\frac{p_0}{p_1}\right);\\ u_T &= u_g(p_1) - u_g(p_0) = -\frac{R}{f_0}\frac{\partial T}{\partial y}\ln\left(\frac{p_0}{p_1}\right).\end{aligned} \tag{6}$$

To find the thermal wind at a given model layer, we take the cumulative sum of the model layers below it plus the meridional or zonal wind of the model layer below the lowest layer. We do this because the thermal wind in the lower model layers will most likely not produce stable results. To increase stability in our calculations, we assume that the thermal wind below the start of the integration is is equal to the model wind. This gives us for the thermal wind at model layer i

$$\begin{aligned}v_{T,i}(p_i) &= v_{p_{-1}} + \frac{R}{f_0}\sum_{i=0}^{i}\frac{\partial T_i}{\partial x}\ln\left(\frac{p_i}{p_{i+1}}\right),\\ u_{T,i}(p_i) &= u_{p_{-1}} + \frac{R}{f_0}\sum_{i=0}^{i}-\frac{\partial T_i}{\partial y}\ln\left(\frac{p_i}{p_{i+1}}\right).\end{aligned} \tag{7}$$

5.4 Kinetic Energy and Eddy Kinetic Energy

The CAM model woks with wind in the form of $u = \overline{u} + u^*$, $v = \overline{v} + v^*$, with u, v the total wind, $\overline{u}, \overline{v}$ the time-mean wind and u^*, v^* the deviation from the mean wind. The model output contains monthly averages $\overline{u}, \overline{v}$ and $\overline{u^2}, \overline{v^2}$.

The kinetic energy KE can thus be found from the model results directly through

$$KE = \frac{1}{2}\left(\overline{u^2} + \overline{v^2}\right). \tag{8}$$

The eddy kinetic energy EKE can be found through

$$EKE = \frac{1}{2}\left(\overline{u^{*2}} + \overline{v^{*2}}\right), \tag{9}$$

with $\overline{u^{*2}}, \overline{v^{*2}}$ found through

$$\begin{aligned}\overline{u^2} &= \overline{(\overline{u} + u^*)\,(\overline{u} + u^*)},\\ &= \overline{\overline{u}^2 + 2\overline{u}u^* + u^{*2}},\\ &= \overline{u}^2 + \overline{u^{*2}} \Rightarrow \overline{u^{*2}} = \overline{u^2} - \overline{u}^2,\end{aligned} \tag{10}$$

which can be found with the model output.

5.5 Jet Intensity Maps

The jet intensity maps are made by counting the number of times the model value of interest passes a set threshold. Each timestep and coordinate is evaluated individually, after which the set is summed over time and the vertical dimension. This result is then normalised to the number of timesteps multiplied by the number of vertical model levels included in the analysis. This results in a fraction that represents the time and vertical extent of the atmospheric jet.

To visualise the Polar night jet (PNJ), in the upper stratosphere, and the subtropical jet (STJ), in the lower stratosphere, this method is applied to the zonal wind fields. For the eddy-driven jet (EDJ), also in the lower stratosphere, this method is applied to the eddy kinetic energy fields.

5.6 Climograph

Is uitleg hiervan nodig?

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