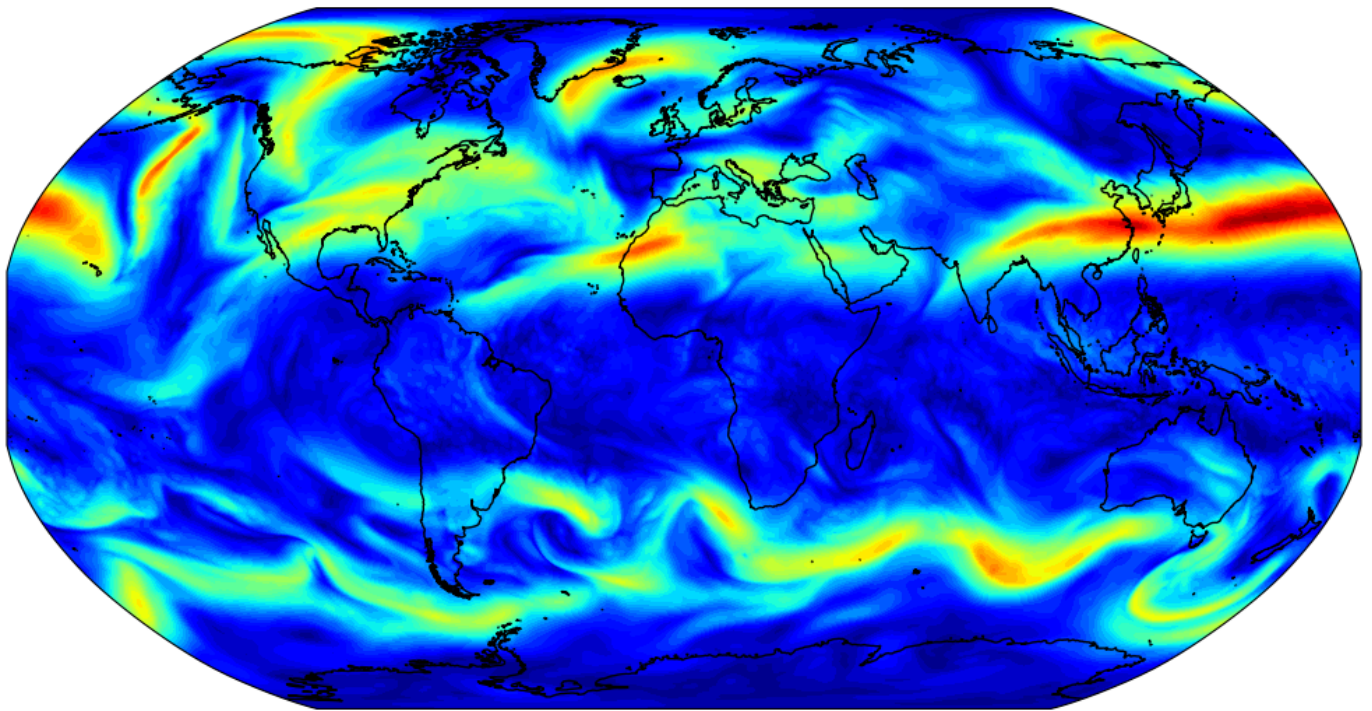


Trends in Northern Hemisphere Jet Stream Strength, Latitudinal Position and Waviness since 1940

BSc Thesis at the Meteorology & Air Quality Group of WUR

A study focused on describing the properties of the jet stream and analysing the trends in the strength, latitudinal position and waviness of the jet stream from 1940 to 2020 using the extended ERA5 reanalysis dataset.



(Copernicus, 2023)

Written by Jelmer van der Graaff

Date July 3rd, 2023

Abstract

The jet stream is a band of strong winds at an altitude of about 10 kilometres, which impacts weather patterns around the world. As the temperatures in the Arctic region are rising faster than elsewhere, it is believed that the jet stream may weaken or show more meandering. This can potentially lead to more extreme weather in the Northern Hemisphere. Yet, little is known about trends in the strength, position and meandering of this jet stream over the past decades. Not only because it is challenging to describe the properties of the jet stream properly, but also due to the limited availability of past weather data. As of March 2023, the ERA5 reanalysis dataset was extended to 1940, allowing for analysis over a longer period.

This study first of all aims to better define the properties of the jet stream, which is done by combining several methods from previous studies and verifying the outcomes. Next, the properties of the jet stream are calculated from 1940 to 2020 and a trendline is fitted to this data. The results show that a Sinuosity-index – which describes the length of the jet stream compared to the circumference of the Earth – can be optimized by making an interpolation for the latitudinal extent to account for seasonal differences in the position of the jet stream.

The trend analysis shows that the average strength of the jet stream increased significantly for all seasons from 1940 to 2020. The amount of meandering has also increased significantly, except during winter. On an annual basis and for most seasons, no significant trend in the average latitudinal position of the jet stream is seen. Only in winter, there has been a southward trend. These results do – especially during summer – indicate a trend towards a more wavy jet stream, and with that potentially more blocked weather patterns in the Northern Hemisphere. However, relating these changes to regional weather patterns and extreme weather events is difficult due to the different scales of this study (global) and these events (regional).

Preface

Well, what you are going to read now is the result of studying for almost 3 years at Wageningen University & Research. Okay, maybe not completely, as – some of you probably already know – I also like to work with meteorological data and charts in my free time. And with free time, I practically mean all the time that I am awake and don't have any appointments. But still, unknowingly following the bachelor study Soil, Water & Atmosphere at the WUR has brought me so much. Let me take you back to about three years ago when I delivered my *profielwerkstuk*, a report part of graduation from high school.

That *profielwerkstuk* was about the reason for the faster warming of the Arctic compared to the elsewhere and its potential impact on the Northern Hemisphere. If you have read the *Abstract* you will probably think: “Isn't this almost the same thing as what you have been researching now?” Well, it is indeed quite similar. When I delivered that report – consisting of a completely oversized 59 pages – I joked that I could just submit the same thing for my bachelor's thesis. Well, I am glad that I didn't do that. My supervisors probably wouldn't have liked that and the final presentation would've been quite boring.

It has been a rollercoaster, those three years in Wageningen. First of all due to a virus which completely disrupted the principle of ‘many contact hours’ the study Soil, Water & Atmosphere advertised during the Open Days. By following online courses via *Microsoft Teams* or by travelling back and forth between the university in Wageningen and home (in Rotterdam), I started gathering knowledge about the *System Earth*. Some courses were maybe more fun than others, but in the end, I fully agree that the combination of all domains – soil, water and atmosphere – makes for the best experience. Before studying at WUR, I knew that the weather was influencing many processes on Earth, but the profound and at the same time broad theory of the courses really made it clear to me what was happening, what interactions are taking place in the Earth's system every second.

Sometimes you get told, “Time flies”. Well, it does. Living barely a year on my own in Wageningen, I already had to start thinking about my thesis. Not the interesting courses on meteorology and statistics, but the thesis is by far the biggest deal of the whole study and especially the 3rd year. When I saw the possible thesis topics for the domain *Atmosphere*, I knew directly what topic to set as my first preference. Right, the one my *profielwerkstuk* was about. And not because I wanted to copy stuff to make it easier, but mainly to compare how I have advanced in terms of doing scientific research and tackling such a big project. Looking back, my *profielwerkstuk* looks like it was written by some child while this thesis research is done by a future scientist. And that is also how I feel in general. Studying at Wageningen University & Research transformed me from a teenage boy to a professional, serious and incredibly motivated future climatologist. Both mentally (in knowing how to tackle such challenges) and ‘physically’ (the knowledge of our Earth's system I have gained).

However, all of this wouldn't have been possible without the help of my friends, family, colleagues and fellow students. Please have a look at the chapter *Acknowledgements* on page 24 where I thank everyone who contributed to this thesis work directly or indirectly, and some people in particular.

That is everything I wanted to say, so here it is. My thesis “*Trends in Northern Hemisphere Jet Stream Strength, Latitudinal Position and Waviness since 1940*”. I hope you not only enjoy reading this thesis, but also learn new things about our ever-interesting *System Earth*.

Jelmer van der Graaff,

Wageningen on July 3rd, 2023

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1. Introduction

1.1. Context

Climate change is a hot topic nowadays. Global temperatures are rising steadily and extreme weather phenomena like droughts, flash floods and heat waves are occurring more frequently (IPCC, 2023). The jet stream plays an important role in the occurrence of these extreme weather events as it drives the genesis of high- and low-pressure systems. The jet stream is a band of strong winds at an altitude of approximately 10 kilometres, driven by the temperature gradient between the cold air in the polar regions and the warm air in the tropics (NWS, 2023b). When there is a big wave in the jet stream, some regions may see unusually warm and dry conditions, while other areas may face atypical cool and wet weather (Figure 1). The unprecedented heatwave in the Pacific Northwest during June 2021 – when temperatures in Canada almost reached 50°C – is a quite recent example of a big wave in the jet stream leading to very extreme weather (White et al., 2023).

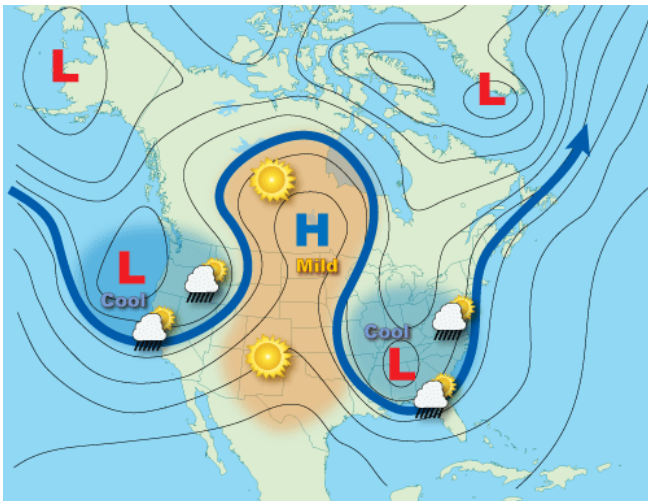


Figure 1: An example of an unusual weather pattern over North America caused by a big wave in the jet stream, coloured in blue. Unusually warm weather is occurring far north in the central part of North America, while near the East- and West-coast weather conditions are cool and wet (NWS, 2023a).

The mid-latitude jet stream is strongest during winter. During this time of year, the temperature contrast between the Arctic and the Tropics is the biggest. When in summer the temperature difference between the Arctic and the tropics is

smaller, the jet stream is generally weaker (NWS, 2023b).

Due to positive feedback mechanisms, the Arctic is warming faster than the rest of the world. This is known as Arctic amplification (IPCC, 2023). The most important positive feedback mechanism is the declining sea ice extent, which leads to more solar radiation being absorbed and consequently higher temperatures (Serreze & Barry, 2011). Arctic amplification results in smaller temperature differences between the Arctic and the tropics in the lower part of the atmosphere. However, at heights of approximately 6 to 7 kilometres and above, the temperature differences between the Arctic and the Tropics may be increasing (EUMETSAT, 2023).

1.2. Problem Description

As the strength of the jet stream depends on the temperature gradient between the Arctic and the tropics, the jet stream is believed to possibly weaken or show more meandering (Coumou et al., 2018; Francis & Vavrus, 2015; Meleshko et al., 2016). As the jet stream is a critical driver for mid-latitude weather systems, research into past and future changes in the properties of the jet stream is important. A study on the influence of Arctic amplification on extreme mid-latitude weather events found that extreme weather is occurring more frequently due to a slower progression and a more meandering upper-level flow (Francis & Vavrus, 2012). Another study found that Arctic amplification makes persistent hot and dry weather more likely during summer in the mid-latitudes (Coumou et al., 2018). Still, a lot is unknown about the behaviour of the jet stream. Not only are the outcomes of observational studies and climate model data diverging (Cohen et al., 2020), past trends in the strength, position and waviness (meandering) of the jet stream are hard to determine. Most studies on the relationship between Arctic amplification and extreme weather in the mid-latitudes do not provide a quantitative trend in the properties of the jet stream over the last decades.

A network-scheme-based study found that the strength of the jet stream decreased between 1979 and 2014 (Molnos et al., 2017). However, it found diverging trends for the latitudinal position of the polar and sub-tropical jet streams. A potential trend in the waviness of the jet stream was not studied. A recent study using reanalysis data from 1979 to 2022 contrastingly showed a positive trend in the mid-latitude zonal wind speed at about 11 kilometres height, which is a parameter relatively comparable to the jet stream strength (Simmons, 2022). Again, this study did not research potential changes in the waviness of the jet stream, and trends for the jet stream strength also vary per season.

One of the challenges is describing the properties of the jet stream. Zonal averages are used often for trend analysis, but as the jet stream has large waves, it does not follow one specific latitude around the globe. A common method to describe the meandering of a flow is by calculating its sinuosity, see Figure 2 (Fuller et al., 2013). The Sinuosity-index (SI) can also be used to analyse the meandering of the jet stream, by using a 500 hPa geopotential height isohypse to describe the approximate path of the jet stream (Cattiaux et al., 2016). This does require making arbitrary choices on the latitudinal extent used to determine the value of the isohypse. Although this study does provide a starting point for the latitudinal extent, it has not been researched whether this is actually the best extent to use. Furthermore, this study was not focused on the jet stream only, but more on upper-level flow patterns in general.

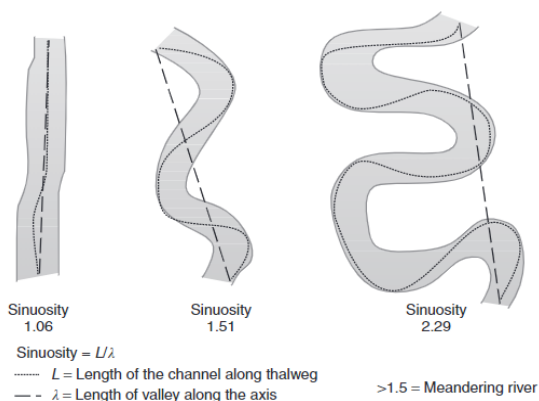


Figure 2: An illustration of the sinuosity for different flows (Fuller et al., 2013).

Another challenge was the limited availability of past weather data. Until recently hourly weather reanalysis data from the ERA5 dataset was only available from 1979 and onwards. As of March 2023, the dataset has been extended as part of the Copernicus Programme, now dating back to 1940 (Copernicus, 2023).

1.3. Research questions

This study aims to gain insights into past changes in the jet stream properties, which are: the strength, latitudinal position and waviness. Instead of researching the correlation between Arctic amplification and the frequency of mid-latitude extreme weather events, this study only focuses on trends in the three properties of the jet stream as defined above. As the weather reanalysis data of ERA5 is now dating back to 1940, trends can be determined for a total of more than 80 years. This study will take into account the period from 1940 up until 2020. In the end, knowledge of past changes in the jet stream is important when trying to say what future changes are possible. This study additionally aims to better define and describe the jet stream properties to allow for easier analysis in future studies.

To reach the aims of this study, the first goal is to define and describe the properties of the jet stream. This is the basis for the following step, namely the trend analysis. In the end, the following three research questions need to be answered:

1. How can the equation for the Sinuosity-index (SI) be adjusted to represent the actual jet stream location best?
2. How have the jet stream strength, latitudinal position and waviness changed on an annual basis from 1940 to 2020?
3. How do the trends in jet stream properties (strength, latitudinal position and waviness) from 1940 to 2020 differ per season?

The hypothesis is that to optimize the equation for the SI (see Equation 1 in section 2.2.1. *Introduction*), the latitudinal extent from which the 500 hPa geopotential height isohypse is determined needs to be shifted north. The basic SI equation uses an extent from 30° to 70°N, so centred around

50°N (Cattiaux et al., 2016). However, for the period 1979 to 2014, the average latitude of the polar jet stream core was probably closer to about 60°N (Molnos et al., 2017). In the case of large seasonal differences in the location of the jet stream, a seasonally varying latitudinal extent might be needed.

For the trend analysis, the hypothesis is that the jet stream strength shows a decreasing trend. Mainly based on the reduced temperature gradient between the Arctic and the tropics due to Arctic amplification (IPCC, 2023) and as indicated by some previous studies (Molnos et al., 2017). When using the SI to define the location of the jet stream, this results in a fixed latitudinal reference. Therefore, no significant trend in the latitudinal

position of the jet stream is expected. The waviness is hypothesized to increase due to Arctic amplification. Also, a weaker upper-level flow generally correlates with a more meandering pattern (Meleshko et al., 2016).

The decrease in the jet stream strength will likely be most significant during summer and less pronounced during winter as was found by previous studies (Molnos et al., 2017; Simmons, 2022). As an annual trend in latitudinal position is not expected because of the SI method, seasonal differences will probably also be hard to determine. The waviness is expected to increase most during summer – when the decrease in jet stream strength is most apparent – and increase the least during winter.

2. Materials and Methods

2.1. Data collection

For this study, weather reanalysis data is needed to determine the strength, latitudinal position and waviness of the jet stream in the past. Reanalysis data is sometimes referred to as ‘maps without gaps’ because the datasets are complete and consistent (ECMWF, 2020). One of the most extensive datasets available is the ERA5 reanalysis, based on the well-known ECMWF weather model. Until recently, ERA5 reanalysis data was available from 1979 to present. But as of March 2023, more years have been added to the dataset. Currently, the ERA5 reanalysis is available from 1940 (Copernicus, 2023). This allows an analysis of the jet stream for a total of more than 80 years.

The ERA5 reanalysis dataset contains hourly reanalysis of many meteorological variables worldwide (Hersbach et al., 2020). The variables needed for this study are the geopotential height at a pressure level of 500 hPa and the U- and V-components of the wind at pressure levels of 500 and 250 hPa. All ERA5 reanalysis data can be collected for free from the Copernicus Climate Data Store (Copernicus, 2023).

For the wind components at 500 hPa, only monthly averaged data is needed. This can be collected from the “*ERA5 monthly averaged data on pressure levels from 1940 to present*” dataset. The geopotential height and 250 hPa wind components data are needed with a 6-hourly interval. These are collected from the “*ERA5 hourly data on pressure levels from 1940 to present*” dataset. For the 250 hPa wind components, two extra datasets were needed for additional analysis on the zonal U-wind at 250 hPa and the uncertainty in the reanalysis. For both analyses, the selected variable is the U-component of the wind speed at 250 hPa. In the case of the zonal wind analysis, the product type “*Monthly averaged reanalysis*” is selected. The product type “*Monthly averaged ensemble members by hour of the day*” allows for the calculation of the spread between the reanalysis ensemble members. For all datasets, only data for the Northern Hemisphere is selected to reduce the file size.

The collected data for this study is stored in a shared folder on the *Anunna* server of the Wageningen University & Research (WUR), the same server on which the Python scripts for the analysis are executed and saved.

2.2. Methodology

This study consists of three main components which all require a different approach on how to tackle the challenges posed. In section 2.2.1. *Introduction*, the basis of the study and the three main components are introduced.

2.2.1. Introduction

To answer the research questions, it is important to first understand the basis of the jet stream analysis. It all starts with the determination of the approximate location of the jet stream. Whilst the jet stream is identified by a band of strong winds at a height of about 10 kilometres (NWS, 2023b), it is difficult to use this wind speed data to describe the location of the jet stream. There is namely not one constant wind speed or streamline to follow around the globe. This is necessary to determine the waviness, which is defined using the Sinuosity-index (SI), the length of a curvy line compared to a fully straight line between the same points (see Figure 2 in section 1.2. *Problem Description*). The higher the sinuosity, the wavier the flow is (Fuller et al., 2013).

A proposed solution is to use an isohypse of the geopotential height at 500 hPa to approximate the location of the jet stream core. A previous study also used this method to determine the SI of upper-atmospheric flow patterns (Cattiaux et al., 2016). In Equation 1, the formula which was used to calculate the SI from a 500 hPa geopotential height isohypse is shown.

$$SI = \frac{\text{arclength}(\overline{Z500}_{\text{lat. extent}})}{2\pi a \cos(\text{latitude})} \quad \text{Equation 1)}$$

Here, the *arclength* is the length of the 500 hPa geopotential height isohypse and *a* stands for the circumference of the Earth at the equator, which is 40,075 kilometres (Geographic, 2023). The two

remaining terms are of particular interest to this study, namely:

$$\overline{(Z500)_{lat. \text{ extent}}} \text{ and } \cos(\overline{\text{latitude}})$$

The first term represents the value of the 500 hPa geopotential height isohypse, which is defined as the spatial average 500 hPa geopotential height between a specified latitudinal extent. The study in which the SI was introduced to describe upper-level flow patterns uses a latitudinal extent of 30° to 70°N (Cattiaux et al., 2016), but more latitudinal extents will be introduced in section 2.2.2. *Latitudinal extent*. The second term is meant to calculate the circumference of the Earth at a certain latitude. Whilst the study where the SI was adapted from had a set latitude of 50°N to calculate the circumference of the Earth (Cattiaux et al., 2016), this study will use the average latitude of all coordinates along the isohypse as an input, also see section 2.2.3. *Jet stream properties*.

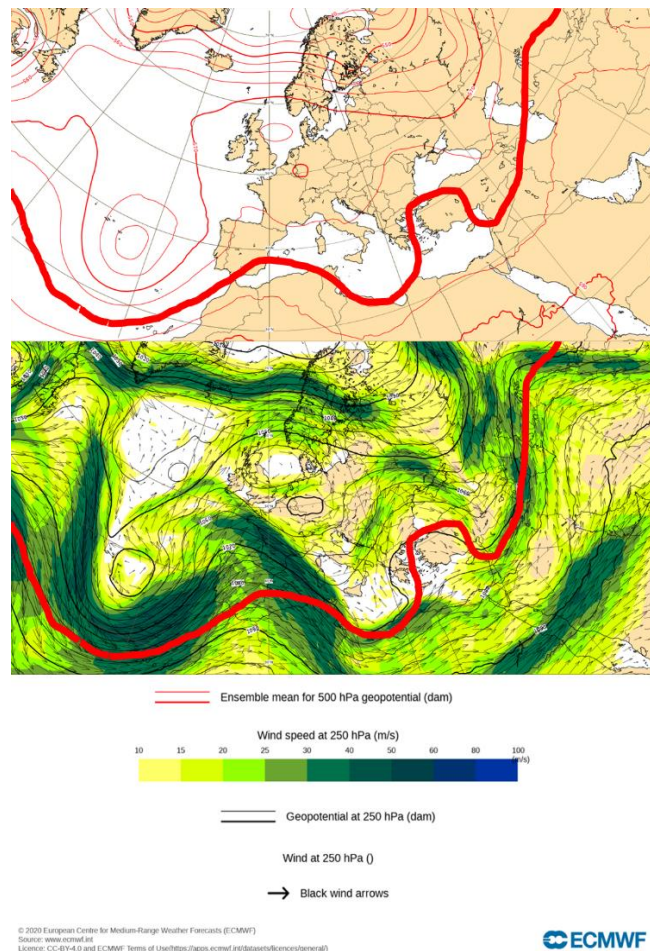


Figure 3: An example of the overlap between a 500 hPa geopotential height isohypse and the 250 hPa wind speed for June 7th, 2023 at 00 UTC according to the ECMWF weather model (Molteni et al., 1996).

In the end, the goal is to have an isohypse which describes the approximate location of the jet stream best. This can be tested by looking at the overlap between the 500 hPa geopotential height isohypse – which forms the basis of the SI – and the 250 hPa wind speed. In Figure 3, an example is shown with the thick red line representing the 500 hPa geopotential height isohypse with a value of 580 dam, drawn over from the upper plot. In the bottom plot, the overlap of this isohypse with the wind speed at 250 hPa (coloured contours) is shown.

In section 2.2.2. *Latitudinal extent*, the methodology behind the multiple latitudinal extents for the SI is explained. It also involves testing the overlap between the different 500 hPa geopotential height isohypses and the jet stream core at 250 hPa, as shown in Figure 3. Once the SI has been adjusted to best represent the location of the jet stream, the three different properties of the jet stream – the strength, latitudinal position and waviness – have to be defined. This is discussed in section 2.2.3. *Jet Stream Properties*. In section 2.2.4. *Trend Analysis*, the methods used to find trends in the jet stream properties from 1940 to 2020 are explained. Finally in section 2.2.5. *Analysis for discussion points*, the methods used for some final parts of the results and discussion are explained.

2.2.2. Latitudinal extent

To find out which latitudinal extent for the SI (see Equation 1) gives the best results, the average 250 hPa wind speed along the 500 hPa geopotential height isohypse is determined for multiple extents. In general, the jet stream core is where the highest wind speed at 250 hPa occurs. So, the latitudinal extent which results in the highest average 250 hPa wind speed along the isohypses will be used for further analysis.

The first latitudinal extent to be tested is 30° to 70°N, as used in the original study (Cattiaux et al., 2016). The other extents are based on the zonal average U-wind (west to east) at 500 hPa. More specifically, the latitudinal extent to be used for the SI is where the 500 hPa zonal average U-wind is at least half of the zonal maximum (Batelaan, 2020).

For example, when the zonal maximum U-wind speed is 10 m/s, the latitudinal extent is defined as the range of latitudes where the zonal maximum U-wind speed is 5 m/s or higher. To create an extra extent to test, this analysis is done for both the global average (all longitudes) and the Atlantic sector only, which is bounded by the longitudes from 50°W to 40°E (Cattiaux et al., 2016).

As the results of these 500 hPa U-wind analyses may vary per season, it can be useful to make a seasonal interpolation of the latitudinal extent. This means that the latitudinal extent shifts during the year. The interpolation should return a latitudinal extent based on the day of the year (DOY) from 1 to 365. When using *spline-interpolation* to get a unique daily latitudinal extent, at least six data points are needed when working with seasonal average values, preferably even some more (see the discussion in section 5.1. *Interpolation of the extent*). These are:

- One data point before the start of the year, so the previous autumn with a negative value for the DOY;
- The four seasonal average values over the year. The dates are January, April, July and October 15th, so in the middle of the season;
- One data point after the end of the year, so the next winter with a value of more than 365 for the DOY.

The x -value for the interpolation is the DOY while the y -value is the minimum or maximum latitude of the extent. The interpolation is done in Python using the *Scipy-Interpolate* module (SciPy 1.0 Contributors et al., 2020) and the results will be used as the latitudinal extent in the equation for the SI.

The calculation of the average 250 hPa wind speed along the geopotential height isohypse is done only for a subset of the full dataset to reduce the file size of the dataset and the computation time needed. To get a balanced representation of the different seasons and climatological periods, the sample dataset consists of 108 timesteps evenly spread out over the seasons and years in the whole dataset. The timesteps used are the first timestep of each

month (January 1st at 00 UTC, February 1st at 00 UTC and so on) for the first year of a decade (1940, 1950 and so on, up to 2020). The number of 108 timesteps is less than 0.1% of the total amount of data points in the time series. However, the goal is not to get an average of the jet stream properties from 1940 to 2020, but rather to see what the differences in the overlap between the isohypse and the 250 hPa wind speed are between the latitudinal extents.

The latitudinal extent which gives the on average highest 250 hPa wind speed will be considered as the closest to the jet stream core, and will therefore also be used for further analysis. For this particular analysis, the resulting geopotential height isohypse per scenario is plotted on top of the 250 hPa wind speed using the *Cartopy*-module in Python (Ari & Ustazhanov, 2014), to allow for a visual check and interpretation for the small subset of the dataset.

An example script to analyse the jet stream using the SI was provided by Thomas Batelaan-Bruggeman, who also analysed the jet stream in a quite similar way for an Aquaplanet (Batelaan, 2020). Some parts of his code were used as a starting point, mainly on the determination of the latitudinal extent from the U-wind speed at 500 hPa.

2.2.3. Jet stream properties

When the optimal latitudinal extent for the SI is determined, the jet stream properties can be analysed. A visual check of the overlap between the isohypse and the U-wind speed at 250 hPa by plotting a map for each timestep is already performed for a subset of the dataset in 2.2.2. *Latitudinal extent*, so this is not necessary anymore for the analysis of the time series. However, virtually drawing a contour line (or isohypse) is still necessary. Both to get the coordinates along the isohypse for the average jet stream strength and latitude, but also to get the length of the isohypse for the waviness using the SI. The *matplotlib*-module in Python has a built-in function to create a virtual contour line directly from an array, without the need of plotting with *Basemap* or *Cartopy* (Ari & Ustazhanov, 2014), which saves a

lot of computing power. From this virtual contour line, the coordinates are obtained and used for further processing. One small note is that using a different method compared to the analysis of the small subset as in section 2.2.2. *Latitudinal extent* might result in slightly different values for the jet stream properties. Also, see the discussion in section 5.2. *Wind speed analysis for the latitudinal extent*. The script for the time-series analysis is made in a Jupyter Notebook on the *Anunna* server of the WUR.

Jet stream strength

The jet stream strength is determined by obtaining the wind speed at 250 hPa – calculated from the U- and V-components of the wind – for all timesteps and averaging them. As the coordinates of the contour line will likely not be perfectly aligned with the grid of the reanalysis data, slicing of the data is done using the *method* ‘nearest’. This means that if a coordinate of the isohypse is not directly on a grid point, the nearest grid point will be taken as a reference.

Jet stream (latitudinal) position

The average latitudinal position of the jet stream is calculated by taking the latitudes of all coordinates and averaging them. However, the choice for a seasonally varying latitudinal extent might pose an issue for the trend analysis in particular. As during the summer, the latitudinal extent used for the determination of the isohypse is further north than in winter (also see section 3.1. *Latitudinal extents to test*), this will influence the average latitudinal position.

When using an interpolated extent with unique values for every day of the year, technically two consecutive days can not be compared directly. In this study only the same periods are compared with each other, so there is no issue. However, if further research is done with a comparison in latitude between different months or seasons, a solution is to create a normalized latitudinal position, which takes into account the latitudinal extent used. The difference between the latitudinal extent used (an extent from 30° to 70°N for example results in a latitude of 50°N) and the annual average of the

latitudinal extent will be subtracted from the calculated jet stream latitude, to create a normalized latitude.

Jet stream waviness

The waviness of the jet stream can be defined using the SI. In Equation 1 (section 2.2.1. *Introduction*), the basic SI function was given. The essence of the SI is to divide the length of a wavy path by the length of the shortest, direct path between the same points. In this study, the jet stream represents the wavy path and the most direct path is defined as the circumference of the Earth. The length of the jet stream is calculated by summing up all the distances between two consecutive coordinates along the geopotential height isohypse. This is done using the *Haversine* formula, which determines the great-circle distance between two coordinates on a sphere (Robusto, 1957). The circumference of the Earth varies depending on the latitude. At the equator, the circumference of the Earth is 40.075 kilometres. For any other given latitude, the circumference is 40.075 kilometres multiplied by the cosine of the latitude (in degrees). In this case, the latitude is the average latitude of the jet stream (see *Jet stream (latitudinal) position* in section 2.2.3. *Jet stream properties*).

2.2.4. Trend analysis

For all 6-hourly timesteps between January 1st, 1940 at 00 UTC and December 31st, 2020 at 18 UTC, the jet stream properties are calculated as explained in section 2.3. *Jet Stream Properties*. The 6-hourly data are resampled per season and year with the module *Pandas* in Python (McKinney, 2011). Using the *Statsmodels*-module, an OLS (Ordinary Least Squares Regression) is carried out (Seabold & Perktold, 2010). From the results of the OLS, the coefficient of the dependent variable and the related P-value will be retrieved. If the P-value is lower than 0.05, it means that the coefficient of the dependent variable is significantly different from the null hypothesis and the trend is significant. With the module *Matplotlib*, a scatter plot is created together with the trendline and its 95% confidence interval (Ari & Ustazhanov, 2014).

2.2.5. Analysis for discussion points

Following the results of the trend in jet stream properties, three additional analyses are carried out, namely:

- To see if there is a correlation between an anomaly in the jet stream strength and the waviness;
- To check if the trend in average latitudinal position is the same using the SI and zonal averages;
- To say whether uncertainty in the reanalysis data can influence the results of the trend analysis.

Residuals plot

The residuals of both the jet stream strength (wind speed) and waviness are plotted against each other in a scatter plot using *Matplotlib* (Ari & Ustazhanov, 2014), to find out whether there is a relationship between them. The residuals – the value minus the trendline – are chosen as the goal is to compare year-to-year anomalies instead of a long-term trend. The coefficient of determination (R^2) is calculated using the sum of squared errors. This coefficient can tell whether there is a significant correlation between the two variables.

Zonal average wind speed

As this study uses a specified latitudinal extent to describe the approximate location of the jet stream, the trend analysis for the average latitudinal

position may give a somewhat distorted result (see section 2.2.1. *Introduction*). The trend found using the SI analysis can be compared to the trend in the latitude of the zonal maximum U-wind speed at 250 hPa. For this, a separate dataset with monthly averaged values is downloaded (see section 2.1. *Data collection*) and analysed. Using the *Pandas* module in Python, the monthly data is resampled to yearly zonal averages (McKinney, 2011). With *NumPy*, the latitude at which the maximum zonal average 250 hPa U-wind speed occurs is determined. Finally, a scatter plot including the yearly latitude of the zonal maximum and the related trendline including the 95% confidence interval is created using the same method as explained in section 2.2.4. *Trend analysis*.

Uncertainty in the reanalysis data

Although the reanalysis data are based on past observations, there is still some uncertainty. In general, the fewer observations, the more uncertain the reanalysis data gets (Hersbach et al., 2020). To see if the uncertainty in the reanalysis data could have a significant impact on the determined trend, plots of the spread in the 10-member reanalysis ensemble are created for different periods. These periods can be based on the results of the trend analysis, i.e. if a series of years show very anomalous values. In Python, the average standard deviation between the ensemble members can be determined and plotted on a map using the *Cartopy*-module (Ari & Ustazhanov, 2014).

3. Description of Jet Stream Properties

3.1. Latitudinal extents to test

One method to determine the latitudinal extent of which the average 500 hPa geopotential height is taken, is by looking at the average 500 hPa U-wind speed, see section 2.2.2. *Latitudinal Extent*. The extent over which the zonal mean wind speed in the U-direction is at least half the maximum wind speed can be used as a starting point for the latitudinal extent (Batelaan, 2020). In Figure 4, the absolute zonal average U-wind speed at 500 hPa over the period 1940 to 2020 is shown per season. In winter, the zonal average U-wind speeds are at least half of the maximum between 20 and 55 degrees north and in summer between 34 and 59 degrees north, see Table 1. The annual average has a minimum latitude of 24°N and a maximum of 60°N. Note that this average is not based on the average of the seasonal latitudinal extents, but rather on the annual average U-wind at 500 hPa as plotted in Figure 4. For different climatological periods (1941 to 1970 and 1991 to 2020), there is no significant difference in both the maxima of the zonal average U-wind speed and the latitudinal extent derived from this maximum (see Figure 5).

Table 1: Latitudinal extents over which the zonal average U-wind speed is at least half of the maximum, per season.

Season	Minimum latitude	Maximum latitude
Winter	20°N	55°N
Spring	21°N	58°N
Summer	34°N	59°N
Autumn	30°N	62°N
Annual	24°N	60°N

Interestingly, these results differ significantly from the latitudinal extent previous studies used. These are mainly centred around 50°N (Cattiaux et al., 2016) or even 60°N (Molnos et al., 2017). The dominance of the strong subtropical jet stream over Asia and the Pacific may be responsible for this rather southerly extent (Simmons, 2022). The other two studies may be more focused on only the polar jet stream instead of a combination.

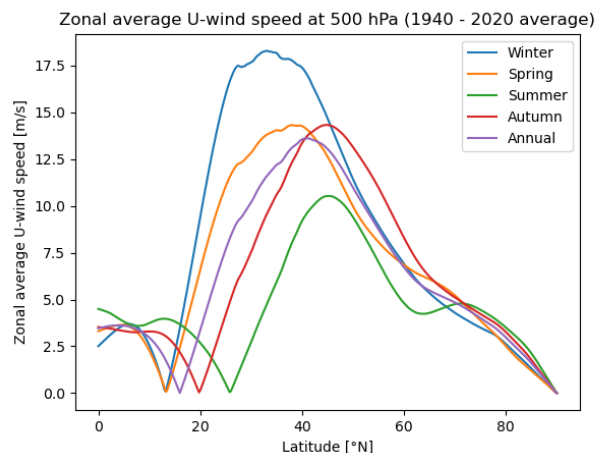


Figure 4: Zonal average U-wind speed at 500 hPa for the different seasons.

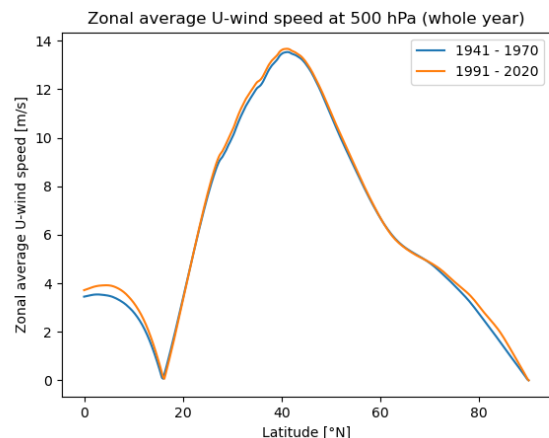


Figure 5: Annual zonal average U-wind speed at 500 hPa for different climatological periods.

Most previous studies have used a constant latitudinal extent for the whole year (Cattiaux et al., 2016), however, the results in Table 1 show that there are substantial differences per season. Using the year-round values for all seasons poses the risk of having a 500 hPa geopotential height isohypse which is too far north in summer and too far south in winter. By using *spline-interpolation*, a latitudinal extent can be specified for every day of the year, thus considering the seasonal cycle, see section 2.2.2. *Latitudinal extent*. The y-values (latitudes) used for the interpolation are the seasonal values as in Table 1. The resulting interpolation for all days in a year is shown in Figure 6.

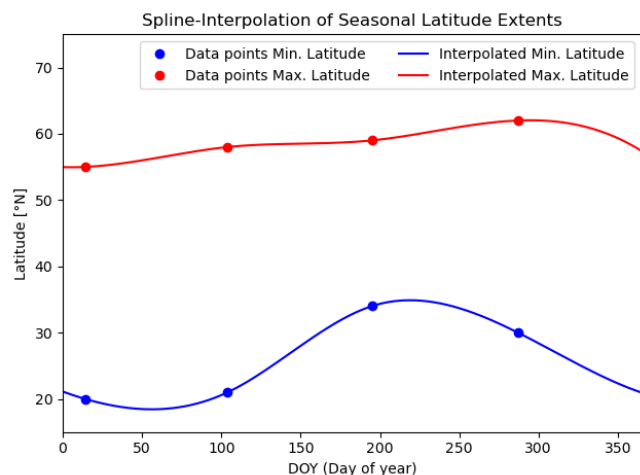


Figure 6: Visualisation of the spline-interpolation to get varying latitudinal extents based on the day of the year.

As said, the average latitudinal extent is quite far south, probably because of the relatively strong and southerly sub-tropical jet above the Pacific. A scenario in which this part of the jet is ignored can be by only looking at the 500 hPa U-wind component for the Atlantic sector. Above the Atlantic, there is usually a rather pronounced polar jet stream. The study from which the basic SI is modified already has divided the globe into four different sectors (longitudinal extents), one of which is the Atlantic sector with longitudes between 50°W to 40°E (Cattiaux et al., 2016). For this sector, the same analysis of the latitudinal extent based on the global average 500 hPa U-wind component is done, but only for the longitudes within the Atlantic sector, see section 2.2.2. *Latitudinal extent.* The results are shown in Table 2. Again, the seasonal differences are quite large. To account for this, a seasonally varying latitudinal extent will be created using *spline-interpolation*, as also done for the results of the 500 hPa U-wind method for the whole northern hemisphere.

Finally, also the latitudinal extent of 30° to 70°N as in the original study will be analysed as a comparison (Cattiaux et al., 2016).

Table 2: Latitudinal extents over which the average U-wind speed at 500 hPa for the Atlantic sector is at least half of the maximum, per season.

Season	Minimum latitude	Maximum latitude
Winter	16°N	68°N
Spring	18°N	76°N
Summer	32°N	61°N
Autumn	27°N	78°N
Year-round	22°N	78°N

3.2. Wind speeds for different scenarios

There are in total 5 scenarios for which the average jet wind speed is analysed. These are:

1. Global Yearly: 24° to 60°N, based on the 500 hPa U-wind method for all longitudes;
2. Atlantic Yearly: 22° to 78°N, based on the 500 hPa U-wind method for the Atlantic sector only;
3. Cattiaux et al.: 30° to 70°N, based on the extent used in the previous study on the SI;
4. Global Seasonal: A variable extent with interpolated values for all days of the year as in Figure 6, for all longitudes;
5. Atlantic Seasonal: A variable extent with interpolated values for all days of the year similar as shown in Figure 6, but only for the Atlantic sector.

In Figure 7, the 250 hPa wind speed and contour of a specified 500 hPa geopotential height isohypse for January 1st, 1970 at 00 UTC are plotted five times. As described in section 2.2.2. *Latitudinal extent*, the value for the geopotential height of this isohypse is calculated dynamically for every single time step by taking the mean of the geopotential height within a certain latitudinal extent. For subplots *a* to *c*, the extent is based on a constant value, while for subplots *d* and *e* they are calculated based on an interpolation of the seasonal values.

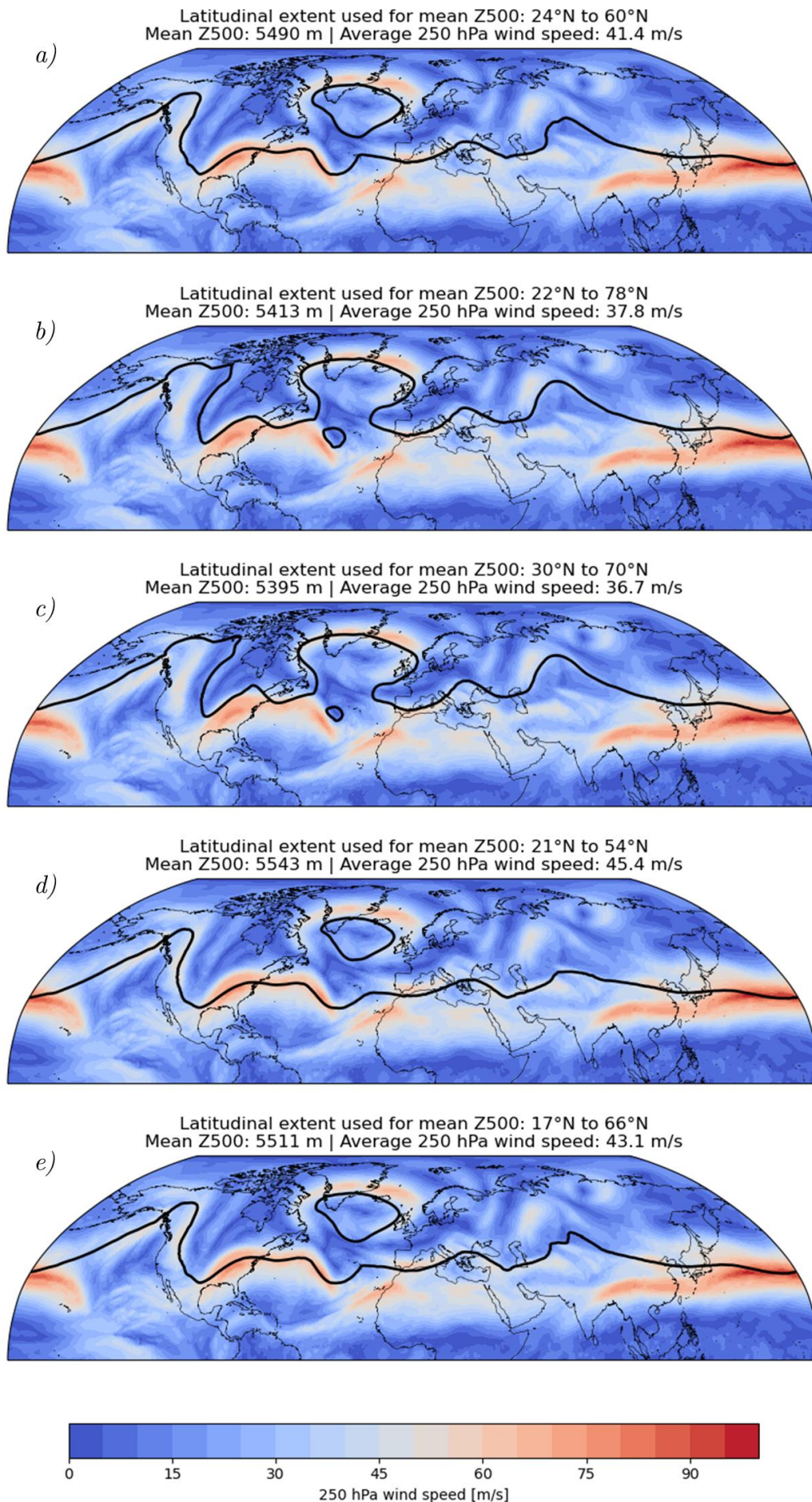


Figure 7: 250 hPa wind speed and the contour line of the average Z500 over a specified latitudinal extent on January 1st, 1970 at 00 UTC. For subplots a, b and c, the latitudinal extent are constant values for all timesteps of respectively 24°N to 60°N (Global – Yearly), 22°N to 78°N (Atlantic – Yearly) and 30°N to 70°N (Cattiaux et al.). For subplots d and e, the latitudinal extent was derived using an interpolation of the seasonal values, resulting in an extent of respectively 21°N to 54°N (Global – Seasonal) and 17°N to 66°N (Atlantic – Seasonal).

As can be seen in Figure 7, using different latitudinal extents results in another 500 hPa geopotential height isohypse which should approximate the actual location of the jet stream. Therefore, also the overlap with the jet stream – indicated by the more reddish colours – is different. In the caption of the subplots in Figure 7, the average 250 hPa wind speed along the isohypse is shown, as well as the value of the 500 hPa geopotential height isohypse which is followed, valid for January 1st, 1970 at 00 UTC.

For this specific timestep, the *Global – Seasonal* scenario (subplot *d*) has the highest average 250 hPa wind speed along the isohypse with 45.4 m/s, and would therefore be preferred for further analysis. The *Cattiaux et al.* scenario has the lowest average wind speed at 250 hPa for this specific timestep with 36.7 m/s.

As explained in section 2.2.2. *Latitudinal extents to test*, this analysis is done for a total of 108 timesteps. On average, the *Global – Seasonal* scenario has the highest average wind speed at 250 hPa on an annual basis (see Table 3). Also in winter and spring the 250 hPa wind speed along the isohypse is on average the highest using this scenario. Although in summer and autumn, using the fixed 22° to 78°N extent (*Atlantic – Yearly*) gives the highest average 250 hPa wind speed, on an annual basis the *Global - Seasonal* scenario still performs better. Therefore, the seasonally interpolated extent based on the global zonal U-wind at 500 hPa will be used for further analysis.

Table 3: Average 250 hPa wind speed in m/s along the isohypse of the 500 hPa geopotential height per season and for 5 different latitudinal extents. Underlined numbers indicate the scenario with the highest average wind speed.

Period	250 hPa Wind speed [m/s]				
	Global - Yearly	Atlantic - Yearly	Cattiaux et al.	Global - Seasonal	Atlantic - Seasonal
Winter	42.9	40.0	38.7	<u>44.3</u>	43.2
Spring	39.9	38.2	37.8	<u>40.1</u>	39.4
Summer	29.9	<u>31.2</u>	31.1	30.8	31.1
Autumn	35.8	<u>38.5</u>	38.3	37.7	38.3
Year	37.1	37.0	36.5	<u>38.2</u>	38.0

In Figure 8, the overlap of the 500 hPa geopotential height isohypse and the jet stream is shown for January 6th, 2010 at 00 UTC. This was a date highlighted in the original paper where the original SI was introduced (Cattiaux et al., 2016). Subplot *a* shows that with a latitudinal extent of 30° to 70°N as used in that study, a very wavy pattern would be recognized. However, in certain parts of the Northern Hemisphere – for example, over the Atlantic Ocean and above Asia – the isohypse does not follow the main branches of the jet stream. With the adjusted extent (*Global – Seasonal* scenario), the isohypse is less wavy but closer to the main branches of the jet stream, see subplot *b*. This is more relevant, as this study focuses solely on the strength, position and waviness of the main jet stream branches.

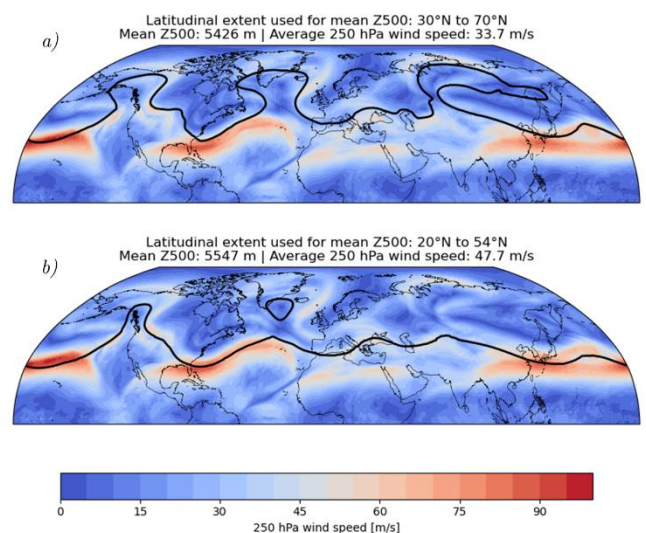


Figure 8: Wind speed at 250 hPa and the mean Z500 based on the original 30° to 70°N extent (Cattiaux et al., 2016) in subplot *a*) and the optimized, varying latitudinal extent for January 6th, 2010 at 00 UTC.

Something to note is that the isohypse in subplot *a* is not completely the same as the isohypse shown in a plot of the original study (see Figure 19 in Appendix B), even though the underlying method and the timestep are the same. A potential explanation for this is the use of a different dataset. This study uses the updated ERA5 reanalysis dataset, while the plot from Cattiaux et al. was based on the ERA-Interim reanalysis dataset with a lower resolution and fewer observations.

3.3. Description of jet stream strength, latitudinal position and waviness

As the best latitudinal extent to use is now researched, the properties of the jet stream can be determined. In section 2.2.3. *Jet Stream Properties*, the underlying methods are described. In Figure 9, two plots with 250 hPa wind speed and the determined 500 hPa geopotential height isohypse are shown, one for January 1st (subplot *a*) and August 1st, 2020 (subplot *b*). Both of these dates are part of the small subset of timesteps used for the verification of the average wind speed at 250 hPa along the isohypses for different latitudinal extents.

On January 1st, the isohypse is located further south and the 250 hPa wind speeds along the isohypse are generally higher than on August 1st. Both plots show roughly the same amount of waviness; the length of the isohypse divided by the circumference of the Earth at the average jet stream latitude.

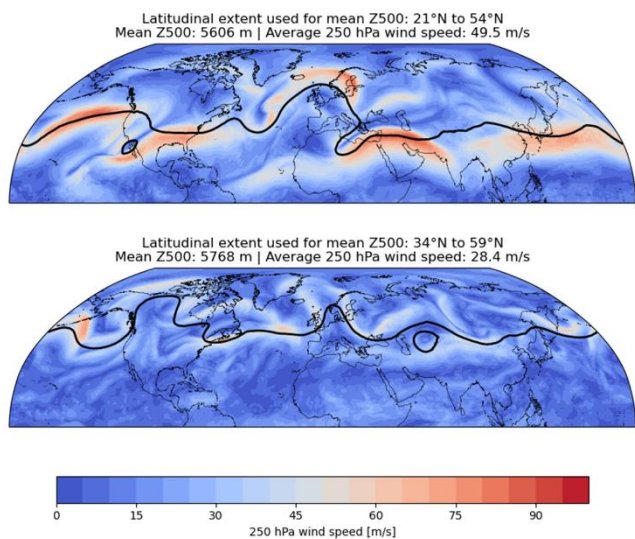


Figure 9: 250 hPa wind speed and isohypse plots for January 1st (top) and August 1st, 2020 (bottom).

In Table 4, the calculated jet stream properties for the two dates (January 1st and August 1st, 2020) are shown. As described in section 2.2.3. *Jet stream properties*, the standardized latitude is added to allow for a better comparison by filtering out seasonal differences in the latitudinal extent used. As the extent used to determine the isohypse is further south during winter, the standardized latitude is higher than the original latitude. For the summer, the opposite holds. To calculate the waviness, the circumference of the Earth at a certain latitude is needed. In contrast to the original study where the SI was introduced, this is done dynamically by taking the average latitude of the jet stream, also see section 2.2.3. *Jet stream properties*.

Table 4: Calculated jet stream properties (strength, latitudinal position and waviness) for January 1st and August 1st, 2020.

Variable	January 1st, 2020	August 1st, 2020
Wind speed	49.5 m/s	28.4 m/s
Latitude	39.6°N	50.2°N
Standardized latitude	44.5°N	46.1°N
Waviness/SI	1.31	1.38

4. Trend analysis

4.1. Annual trends

With the properties of the jet stream being defined, the strength, (normalized) latitudinal position and waviness are analysed for the period starting on January 1st, 1940 at 00 UTC and ending on December 31st, 2020 at 18 UTC. As described in section 2.2.4. *Trend analysis*, the data is averaged per season and year. In Figure 10, the annual averaged wind speed, latitude and waviness of the jet stream are plotted, together with the trendline and its 95% confidence interval.

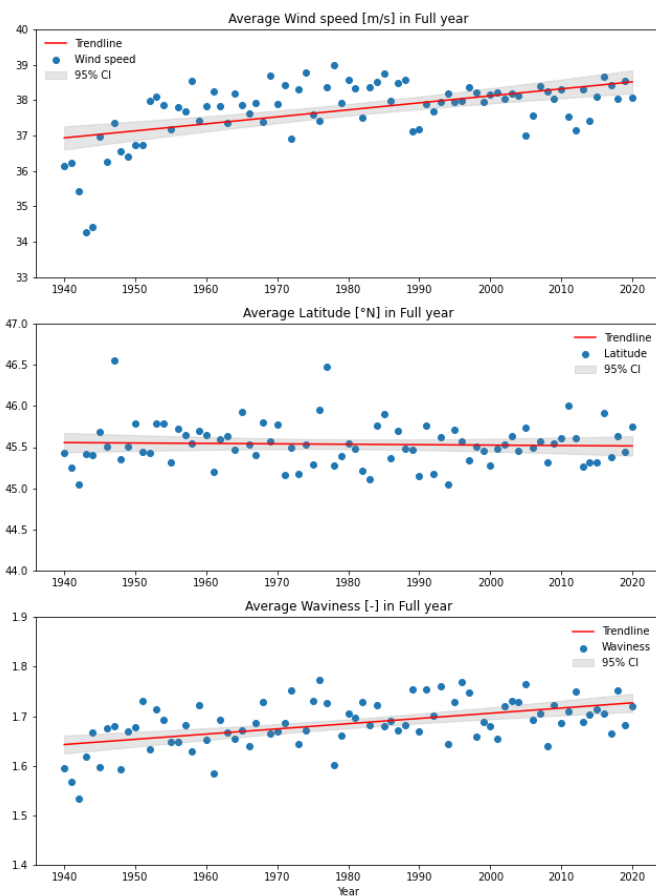


Figure 10: Scatter plots for the annual averaged wind speed, latitude and waviness of the jet stream from 1940 to 2020, including the trendline and its 95% CI.

The average jet stream strength and waviness show an increasing trend of respectively +0.2 m/s and +0.011 per decade. The average latitudinal position of the jet stream shows a slight southerly trend of -0.01°N per decade. Based on the P-value for the coefficient of the trendline, the trends for the jet stream strength and waviness can be considered *statistically significant* ($\alpha = 0.05$) on an annual

basis, see Table 5 in section 4.2. *Seasonal trends*. The trend for the average (latitudinal) position between 1940 and 2020 is not statistically significant with a P-value of 0.69. Something to note is that the annual average jet stream wind speed is heavily deviating from the trendline in the first 5 years of the analysis (1940 to 1944). This may to some extent impact the trendline for the average jet stream strength with a more pronounced upward trend. In section 5.5. *Uncertainty in the reanalysis data*, it is discussed whether this strong deviation is due to natural variability, or that uncertainty in the reanalysis data possibly explains these deviating values.

The average jet stream strength and waviness interestingly both show an increasing trend, which is contrary to the general hypothesis of a weaker jet stream resulting in more meandering (Francis & Vavrus, 2012), see section 1.2. *Problem Description*. To see if both properties are correlated on a year-to-year basis, the residuals of the two variables are plotted against each other in Figure 11 as explained in section 2.2.5. *Analysis for discussion points*.

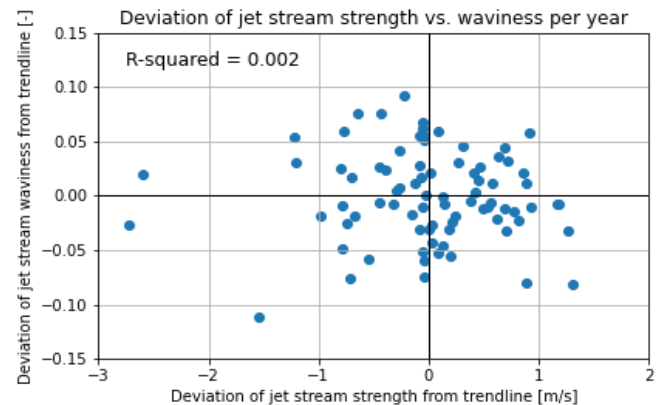


Figure 11: Scatter plot of the correlation between the annually averaged residuals for the jet stream strength and waviness including the coefficient of determination.

The results show that there is no significant correlation between the deviation in the jet stream waviness and strength on a year-to-year basis, with an R^2 value of only 0.002. This is despite both variables showing an increasing trend in the long term.

As described in section 2.2.3. *Jet stream properties*, one artefact of the SI is that finding a potential trend in the average latitudinal position is quite difficult. This method namely uses a set latitudinal extent which does not change over the years. The latitude of the jet stream will always be somewhere in the middle of this specified extent, making it less likely to find a trend in the latitudinal position.

A solution is to do the same trend analysis for the latitudinal position, but using the zonal mean 250 hPa U-wind speed, also see section 2.2.5. *Analysis for discussion points*. The latitude at which the highest zonal mean occurs is taken as a reference for the latitudinal position of the jet stream. In Figure 12, it can be seen that the trendline shows a slightly decreasing trend for the average latitudinal position of -0.04°N per decade. However, the trend is far from significant with a P-value of 0.66 for the coefficient of the trendline. For further discussion, see section 5.3. *Comments on trend analysis*.

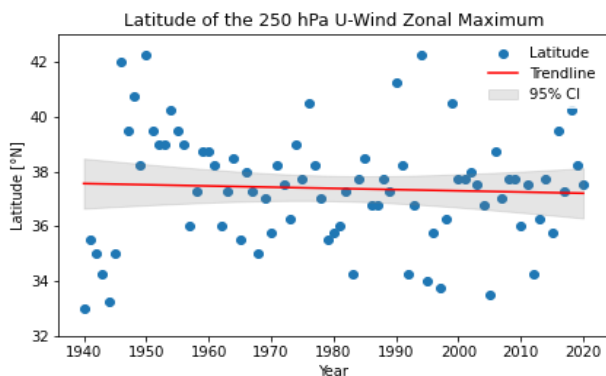


Figure 12: Scatter plot for the latitude of the zonal maximum average U-wind speed at 250 hPa from 1940 to 2020, including the trend line and its 95% CI.

4.2. Seasonal trends

In Table 5, the seasonal trends are listed with both the coefficient of the trendline for the dependent variable and its significance. The jet stream strength has increased significantly in all seasons, although the most pronounced increase is during winter and the least during summer. A significant increase in the waviness of the jet stream was found for all seasons except during winter. The latitudinal position shows no significant trend for most seasons, except during winter when there is a trend towards a more southern position of the jet stream, see

Table 5. Scatter plots with the jet stream properties per season, including trendlines and 95% confidence intervals (similar to Figure 10) can be found in *Appendix A* on page 27.

Table 5: Coefficient of the dependent variable for the trends in jet stream properties from 1940 to 2020 and the significance of these coefficients, with bold values indicating a P-value of <0.05 (statistically significant).

Season	Strength [m/s]		Latitude [$^{\circ}\text{N}$]		Waviness [-]	
	Trend/decade	$P> t $	Trend/decade	$P> t $	Trend/decade	$P> t $
Winter	0.37	<0.01	-0.07	0.01	-0.002	0.53
Spring	0.17	<0.01	0.03	0.12	0.012	<0.01
Summer	0.10	0.02	0.02	0.41	0.022	<0.01
Autumn	0.14	0.01	-0.01	0.66	0.011	<0.01
Annual	0.20	<0.01	-0.01	0.69	0.011	<0.01

4.3. Comparison with previous studies

Although not too much is known about trends in the jet stream properties over the last decades, some studies did address changes in the average latitudinal position and strength of the jet stream.

4.3.1. Network-based analysis of the polar and subtropical jet stream

A network-based study looked at the changes in jet stream strength and position for both the polar and subtropical jet streams from 1979 to 2014 (Molnos et al., 2017). As in this study using the SI method no distinction was made between the polar and subtropical jet stream branches, comparing the results from the previous network-based study to the results in Table 5 is difficult. However, when averaging the results for the polar and subtropical jet stream from the network-based study, the average strength decreased between 1979 and 2014 on an annual basis. Regarding seasonal differences, the results showed a decrease in jet stream strength – averaged for the polar and subtropical jet – for all seasons, except during winter (Molnos et al., 2017).

A positive (northward) trend was found for the subtropical jet stream and a negative (southward) for the polar jet stream by the network-based study. The average of both results shows no trend or a slight northerly trend for the spring and summer. During autumn and winter, there is a bit more pronounced southerly trend (Molnos et al., 2017).

Although the results of this study (see Table 5) show an increase in the jet stream strength for all seasons, the relative differences between the seasons are quite comparable. The relatively strongest positive trend in the jet stream strength occurs during winter while in summer the trend is lower (more negative or less positive). Also, the results of this study show a slight northward trend in the average latitudinal position during spring and summer (although not significant) and a southward trend during winter. This is also in line with the results of the network-based analysis from the previous study (Molnos et al., 2017).

4.3.2. ERA5 analysis since 1979

A study using ERA5 data from 1979 to 2022 generally showed a positive decadal trend in the 200 hPa wind speed in the northern hemisphere

above approximately 35°N, the only exception being an area above the Pacific (Simmons, 2022). In Figure 13, four plots of this study are shown with the least squares linear trend of the 200 hPa zonal wind speed for the different seasons. The green lines are placed at the average latitude of the jet stream per season, found in this study. Visually, it looks like the strongest positive trend in the 200 hPa zonal wind speed along the average latitude is found for the winter. Although there are no exact numbers available from this study, the plots do indicate that the results of the previous study with ERA5 reanalysis data on the average jet stream strength are likely quite comparable with the results of this study (see Table 5).

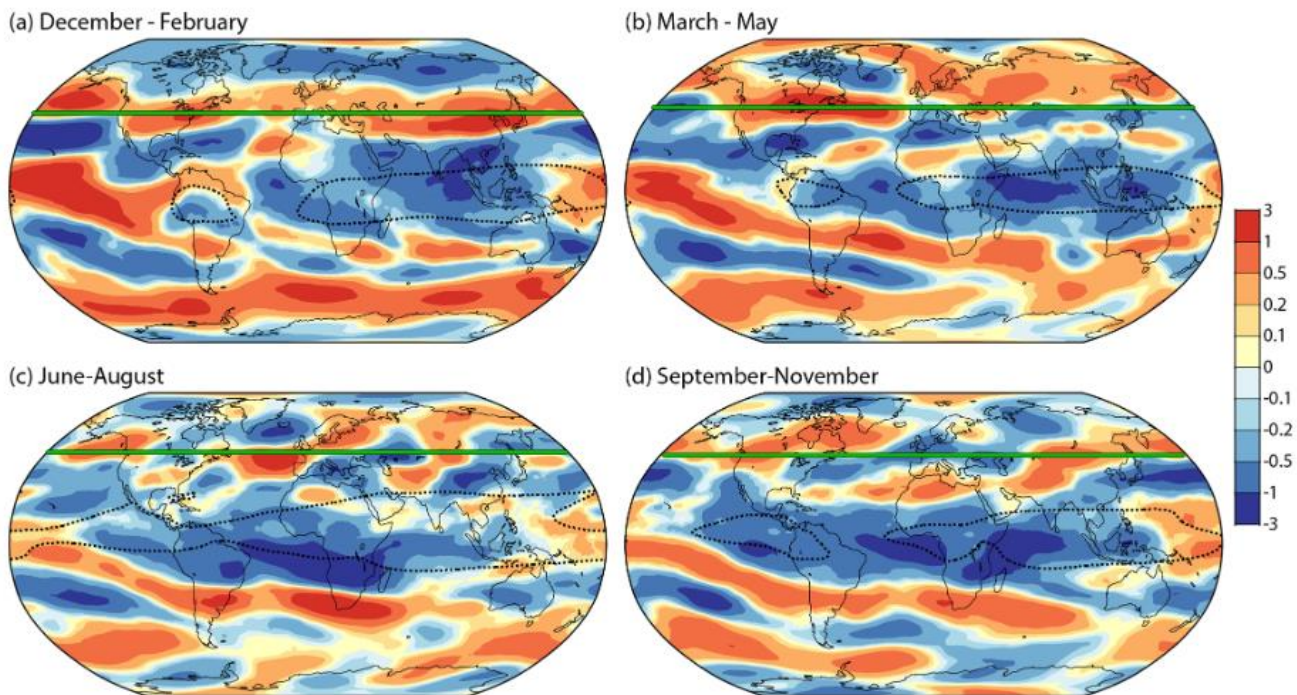


Figure 13: The least squares linear trend (m/s per decade) in 200 hPa ERA5 seasonal-average zonal winds for (a) DJF, (b) MAM, (c) JJA and (d) SON from MAM 1979 to DJF 2021/22 based on the 2022 study (Simmons, 2022). The green lines are the seasonal average jet stream latitude found in this study.

5. Discussion

5.1. Interpolation of the extent

For the determination of the jet stream properties, a variable extent has been used as input for the SI. The variable extent was calculated using four seasonal values – based on the 500 hPa U-wind speed – and interpolated afterwards. This interpolation causes a very smooth variable extent over the year (see Figure 6 in section 3.1. *Latitudinal extents to test*), but it is questionable whether this is representative of reality. There might for example be more of an abrupt shift during a certain period rather than a very smooth shift. An option is to calculate an extent for every single day using the 500 hPa wind speeds, but this is beyond the scope of this study.

Another thing to note for the interpolation is that the values for the maximum latitude at the end of the year may be a bit too low, as not in hindsight enough data points have been added outside of the seasonal cycle. Only one seasonal value was added before the start of the year (autumn) and only one after day-of-year 365 (winter), see section 2.2.2. *Latitudinal extent*. This error was only discovered later when the data analysis already had started. The impact should be limited as the difference is not that large; the ‘sudden’ jump from December 31st to January 1st is about 2°N for the maximum latitude and neglectable for the minimum latitude of the extent. However, for future studies, the interpolation should be done using at least two seasonal values before the start of the year (summer and autumn) and after the end of the year (winter and spring).

5.2. Definition and computation of the jet stream properties

The determination of the best latitudinal extent to use was based on the average 250 hPa wind speed along the isohypse for a small subset of timesteps. This average wind speed was based on the coordinates retrieved from the isohypse plotted with the *Cartopy*-module in Python. For the time-series analysis, it was chosen not to use *Cartopy* to make a plot for all timesteps, as this would

drastically increase computation time. Instead, a virtual isohypse was drawn using the *Matplotlib*-module directly from the dataset array. The coordinates retrieved using *Matplotlib* are however divided slightly differently along the isohypse due to the different projections (a *Mercator* projection when using *Matplotlib* and a *Robinson* projection with the *Cartopy*-module). This results in a slight inconsistency between the average wind speed values for the sample calculations and time-series analysis. As the difference in wind speeds is generally small (less than 1 m/s), on average this would likely not have changed the outcome of the results for the most optimal latitudinal extent based on the sample data. Also, in the unlikely case that another latitudinal extent would have been selected, the time-series analysis still would have been possible. The goal is namely to find trends between 1940 and 2020, for which is it most important to use the same latitudinal extent consistently for all time steps.

For the normalization of the average latitude during the year, it was chosen to make a correction based on the average latitude of the extent for the specific DOY, see section 2.2.3. *Jet stream properties*. This would have been a useful property to compare the normalized latitude between different times of the year. However, in the end, this metric was not necessary for the results of this study as only the same periods (four seasons and annual data) were compared to each other. This property can still be used for future research.

5.3. Comments on trend analysis

Where on an annual basis and for almost all seasons the trends in jet stream strength and waviness were significant, this was not the case for the average jet stream latitude (see table 5 in section 4.1. *Annual trends*). One potential reason for the lack of a significant trend might be that the chosen extent more or less determines the location of the isohypse which represents the jet stream, also see section 2.2.1. *Introduction*.

As the variable extent only depends on the day of the year and not the year in the time-series, it is to be expected that the annual average latitudinal extent will remain relatively constant. This study did find evidence for a lack of a trend in the latitudinal position of the jet stream using other methods. As described in section 3.1. *Latitudinal extents to test*, there were no significant differences in the latitudinal extent to be used for two different climatological (1941 to 1970 and 1991 to 2020). Furthermore, the additional analysis done in section 4.1. *Annual trends* for the zonal average U-wind speed at 250 hPa showed no significant trend in the latitude of the zonal maxima occurring. Both of these outcomes would support a lack of a significant trend in the annual average latitude, however, this drawback of using the SI method should be considered in future research.

5.4. Comparison of the results with previous literature

Not too much is known about trends in the properties of the jet stream yet. In section 4.3. *Comparison with previous studies*, the results of this study were compared with the outcomes of two previous studies. However, both of these studies did not look into a potential trend in the waviness of the jet stream. One study that did research the waviness of the jet stream is of course the one from which the basic SI was taken and adjusted. However, the results presented were only focused on regional trends at different time scales and on upper atmospheric flow patterns in general rather than the jet stream core (Cattiaux et al., 2016). Therefore, no clear comparison could be made on trends in the waviness of the jet stream.

5.5. Uncertainty in the reanalysis data

Another potential issue is the quality of the reanalysis data. In Figure 10 (section 4.1. *Annual trends*), it can be seen that the first five years of the time-series (1940 to 1944) show an annual average jet stream strength well below the trendline, deviating more than almost all of the other years. The ERA5 reanalysis data is based on historical observations (Hersbach et al., 2020), which were less abundant at the start of the reanalysis. A lack

of observations increases the chance of differences between the reanalysis data and reality.

To investigate the uncertainty in the ERA5 reanalysis data, the standard deviation of the 250 hPa U-component of the wind speed between the 10 reanalysis ensemble members is plotted in Figure 14 for three different periods. Averaged over the years 1940 to 1944 (subplot a), the spread in the 250 hPa U-wind speed was about 0.2 to 0.5 m/s over the Pacific Ocean and 0.1 to 0.2 m/s over Europe and North America. This is not only significantly higher than the last years of the reanalysis (average from 2015 to 2019, subplot c) but also compared to only 15 years later (1955 to 1959 average, subplot b). This shows that during the first few years of the reanalysis dataset, the uncertainty was indeed relatively large. However, it is questionable whether the heavily deviating values of the annual average wind speed during those years (up to 2 or 3 m/s lower than the trend) can be explained by this. The standard deviation in the data is namely in the order of 0.1 to 0.5 m/s and by averaging over many timesteps the average deviation should be reduced towards zero. It can not be ruled out that there might be a bias in the U-wind speed data at 250 hPa for these years, but this can't be determined from the dataset itself.

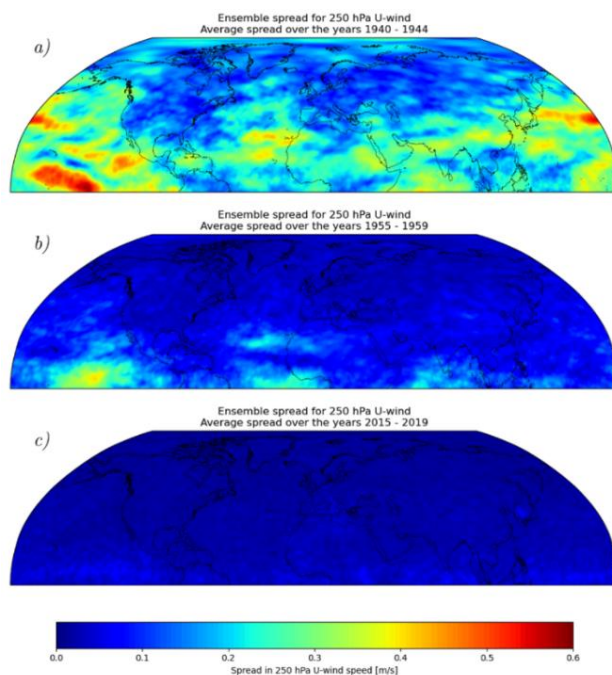


Figure 14: 10-member reanalysis ensemble spread for the U-component of the wind speed at 250 hPa, averaged over the years a) 1940 to 1944, b) 1955 to 1959 and c) 2015 to 2019.

6. Conclusion

The goal of this thesis work was to answer the following three research questions:

1. How can the equation for the SI be adjusted to let the 500 hPa geopotential height isohypse represent the actual jet stream location best?
2. How have the jet stream strength, latitudinal position and waviness changed on an annual basis from 1940 to 2020?
3. How do the trends in jet stream properties (strength, latitudinal position and waviness) from 1940 to 2020 differ per season?

The first research question was addressed in Chapter 3. *Description of Jet Stream Properties*. By combining the SI and its application to upper-atmospheric flow patterns, a basic formulation to describe the jet stream's location was obtained. For five different latitudinal extents, the overlap between the 500 hPa geopotential height isohypse and the 250 hPa wind speed was tested, as the jet stream core is identified by the highest wind speeds at 250 hPa. In the end, the latitudinal extent chosen was based on the average zonal U-wind speed at 500 hPa and interpolating seasonally averaged values (*Global – Seasonal* scenario). The 250 hPa wind speed along the isohypse was on average the highest for this scenario. Testing multiple latitudinal extents to describe the jet stream position using the SI is also advised for future studies on the jet stream.

The second research and third question were answered by determining the average 250 hPa wind

speed along the isohypse, the average latitude and the total length of the isohypse (for the SI) for all timesteps in the dataset, so every 6 hours from January 1st, 1940 at 00 UTC to December 31st, 2020 at 18 UTC. On an annual basis, both the average waviness and strength of the jet stream have increased significantly from 1940 to 2020, whilst no trend in the average latitude was found.

For the meteorological spring, summer and autumn, the same trends were found between 1940 and 2020; a significant increase in the jet stream strength and waviness whilst the average latitude did not change significantly. During the meteorological winter, a significant increase in jet stream strength was also found. However, the average jet stream latitude has decreased significantly (southerly trend) and no change in waviness was found during winter. The relative seasonal differences in average jet stream strength and latitudinal position are comparable to previous studies.

Important to note is that although these results can give an idea of the past trends for the different jet stream properties, relating these trends to changes in regional weather patterns and extreme weather events is difficult. First of all, because the scale of the jet stream analysis (a global average) is different from the scale of the weather patterns and extreme weather events (local to regional impacts). Furthermore, it is not fully known how the different properties of the jet stream (strength, latitudinal position and waviness) exactly impact these weather patterns and extreme weather events.

Acknowledgements

Now that the end of this thesis work is near, it is time to thank everyone who has helped me through the past two and a half months of brainstorming, writing, discussing and presenting. As enthusiastic as I was about the topic, the results and the whole ‘challenge’ itself, I shared many thoughts and ideas with my friends, family, colleagues and fellow students. Not only did this give some useful insights, but it also helped me to stay immensely motivated for all the 16 weeks I have worked on this project. I am also thankful to the *Copernicus Programme* of the European Union, as they provide a ton of (historical) data which can be used for these kinds of meteorological studies for free.

There are some people I explicitly want to thank for their significant contribution to this project. First of all, my first supervisor Chris Weijenborg. Chris, although I had not really met you in any course before this thesis started, from the first meeting I knew you were a great supervisor. Not only were you able to provide content-related help such as collecting the terabytes of data needed, giving comments on the proposed methods and discussing the results, but you also found the perfect balance between closely assisting me process-wise and leaving other responsibilities for myself to decide on. In the beginning, I probably wanted to do too much work, while you were trying to limit the proposed amount of work a bit too much for my liking. In the end, we converged on a great proposal with the right amount of workload to be done within two half-periods. And instead of strongly following the topic as given in the thesis project description, we together agreed on slightly changing the approach which worked out great.

Furthermore, I want to thank Thomas Batelaan-Bruggeman. Thomas, it may just have been a coincidence that you came along during one of the first meetings I had with Chris, but I am very grateful for that. First of all, because your Master's Thesis was a great starting point for my research and you were able to clearly explain the essentials of the methods to me. But probably I am most thankful for the fact that you were present at practically every single meeting I had with Chris, even though you were not at all obligated to come or provide information in any way. I believe the input you gave in terms of discussing the proposed methodology and the results took my thesis to a higher level. Without your contribution, I would probably have missed several points for discussion and additional results.

I also want to thank Bert Heusinkveld, Antonija Rimac-van Heerwaarden and Arnold Moene. Bert, you – as my second supervisor – may not have been involved a lot in this thesis work, I know that you would have been there for me in case Chris was not able to help due to unforeseen circumstances. Antonija, you have been very busy with organising everything around the thesis work for all Soil, Water & Atmosphere students. Even though we have only seen each other during the introductory lecture, I want to thank you for organising all of what was necessary. From the on-campus symposia to the digital learning environment with lots of documentation on writing skills and being available for all thesis-related questions. And finally, Arnold, as the programme director of the BSc Soil, Water & Atmosphere, I want to thank you for offering this wonderful bachelor's study at the Wageningen University & Research together with all of your colleagues. I was already convinced this would be the best study to follow as a future climatologist beforehand. Now that I am almost finished, I can confirm this.

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Appendix A: Scatter- and trendline plots

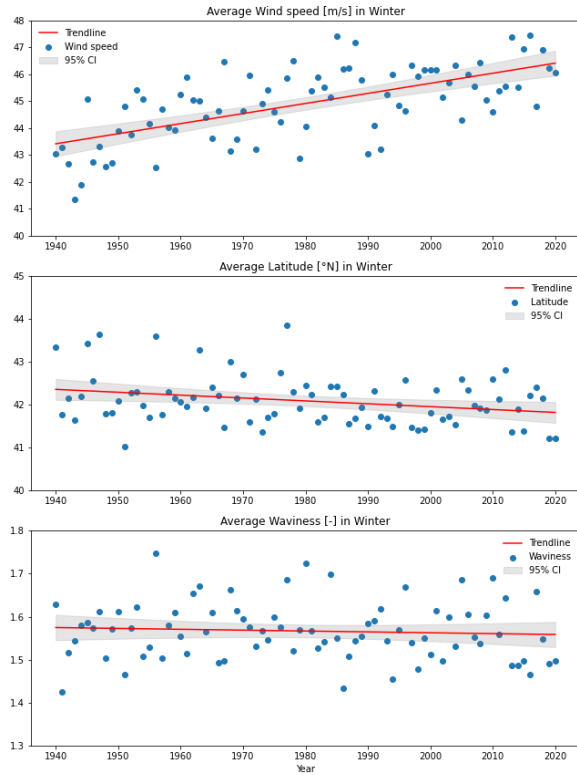


Figure 15: Scatter plots for the average wind speed, latitude and waviness of the jet stream in winter from 1940 to 2020, including the trendline and its 95% CI.

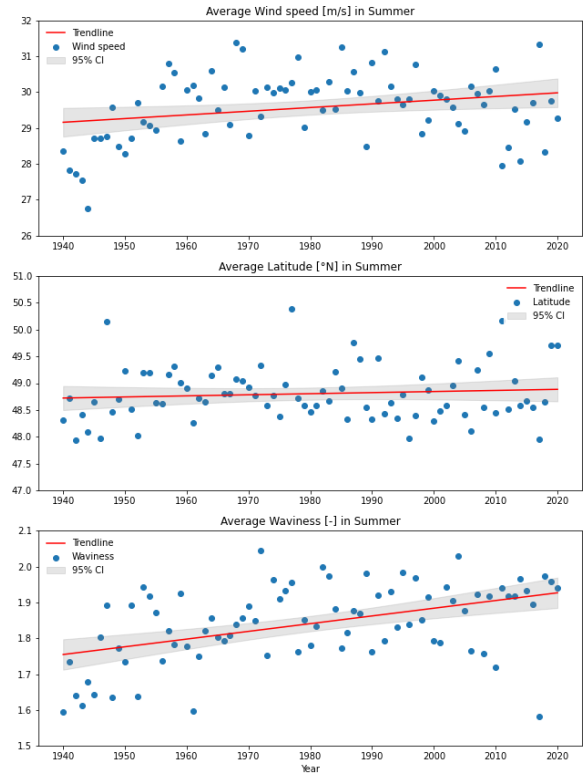


Figure 17: Scatter plots for the average wind speed, latitude and waviness of the jet stream in summer from 1940 to 2020, including the trendline and its 95% CI.

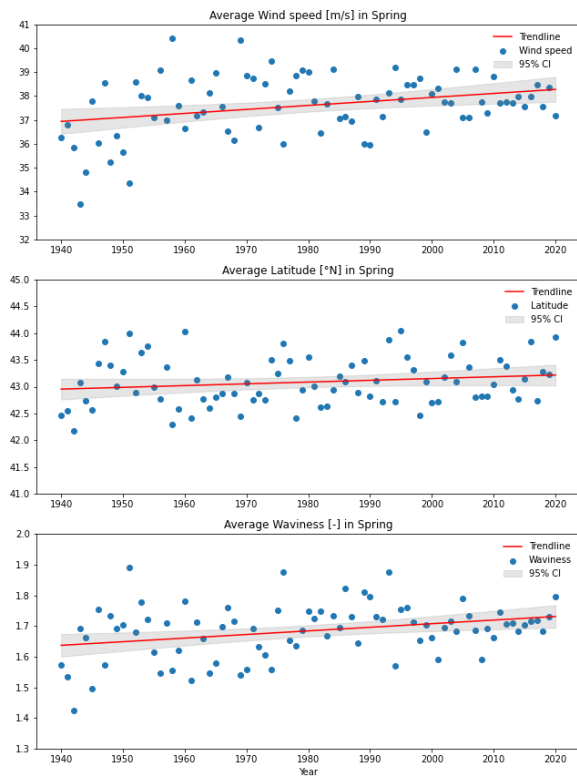


Figure 16: Scatter plots for the average wind speed, latitude and waviness of the jet stream in spring from 1940 to 2020, including the trendline and its 95% CI.

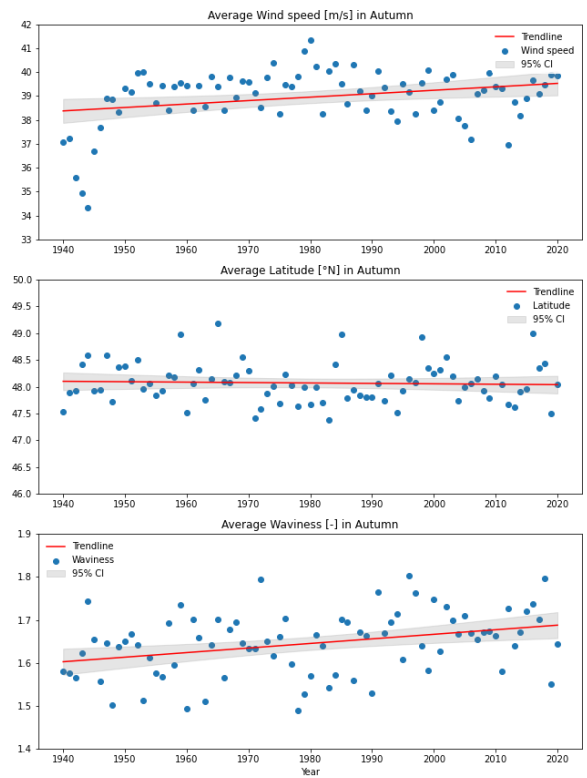


Figure 18: Scatter plots for the average wind speed, latitude and waviness of the jet stream in autumn from 1940 to 2020, including the trendline and its 95% CI.

Appendix B: Plot from Cattiaux et al.

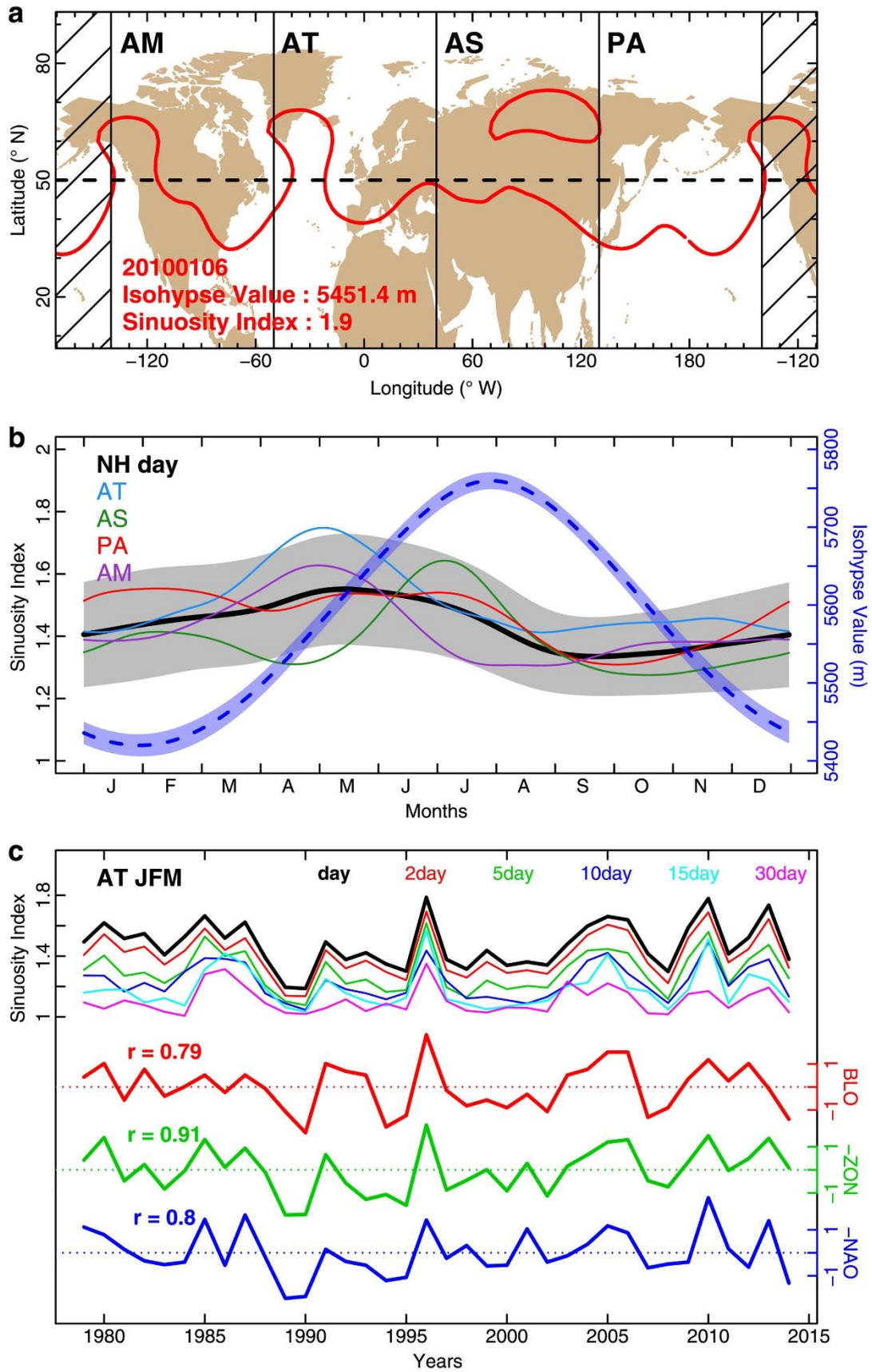


Figure 19: Plot from Cattiaux et al. with in subplot a) the 500 hPa geopotential isohypse used for the Sinuosity-index (SI) on January 6th, 2010.