High-/Midlatitude Interaction in Arctic Amplification

meteorologisches Seminar

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Chapter 1

Introduction

This seminar report is based on the paper "Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves" by Russell Blackport* and James A. Screen.

1.1 Motivation

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Over the next decades, the climate will change inevitable. Therefore, the Arctic amplification will increase as well. To improvingly forecast the dangers and risks of climate change, the causal-chaine between the Arctic amplification and the waviness of the atmosphere is going to be examinated.

The Arctic amplification is the phenomenon of the Arctic (northern of 60 °N) warming up faster and stronger than the rest of the globe. There are some positive feedbacks, that make the Artic amplification increase, as well as the temperature gradient decrease more and more. The feedbacks in themselves are not part of this report.

On average there is an easterly wind in the atmosphere. If the wind deviates from this direction, air masses are transported meridionally from south to north or from north to south. The waviness of the atmosphere describes the characteristics of these meridional transports. If the waviness is highly developed, it can lead to extreme weather events such as cold snaps and heat waves.

Chapter 2

Methods

2.1 Waviness Metrics

The waviness can be observed in all heights of the free atmosphere. In this study the 500 hPa level is used, because it is the middle of the atmosphere (divided by mass). Here, mainly the Local Wave Activity (LWA) is used. In order to represent and estimate the waviness correctly, the LWA is compared with the Meridional Circulation Index (MCI, chapter 2.1.2) and the sinuosity of the atmosphere (chapter 2.1.3).

2.1.1 Local Wave Activity

The Local Wave Activity is a metric for the waviness, which can be formed for every day at every point on earth (or every grid point of the data).
First, the equivalent magnitude (Φ_e) is determined for every day and every geopotential level (z_c) on the 500 hPa level (equation 2.1). The equivalent latitude is the latitude at which the area enclosed poleward of the equivalent latitude corresponds to the area that has a lower geopotential height.
Φ is the magnitude and λ the geopotential height.

$$\Phi_e(z_c) = sin^{-1}\left(1 - \frac{\iint_{z \leq z_c} \cos\Phi \, \mathrm{d}\lambda \, \mathrm{d}\Phi}{2\,\pi}\right) \tag{2.1}$$

Following, for each equivalent latitude and each geographic Longitude, the anti-cyclonic (LWA_A) and the cyclonic (LWA_C) LWA is calculated (equation 2.2). In the equation, $\hat{z}z - z_c$ is the difference between the geopotential height

z at the grid point and the geopotential height of the equivalent magnitude z_c and a is the radius of the earth.

$$LWA_A(\lambda, \Phi_e) = \frac{a}{\cos\Phi_e} \int_{\hat{z}\geq 0,\, \Phi\geq\Phi_e(z_c)} \hat{z}(\lambda, \Phi)\, \cos\Phi\, \mathrm{d}\Phi \tag{2.2}$$

$$LWA_c(\lambda.\Phi_e) = -\frac{a}{\cos\Phi_e} \int_{\hat{z}\leq 0,\, \Phi\leq\Phi_e(z_c)} \hat{z}(\lambda, \Phi)\, \cos\Phi\, \mathrm{d}\Phi \tag{2.3}$$

The absolute local wave activity results from the addition of the cyclonic and anticyclonic LWA of all equivalent latitudes.

2.1.2 Meridional Circulation Index

The meridional circulation index (equation 2.4) indicates the ratio between meridional and total wind speed at each grid point at 500 hPa. Therefore, daily averaged wind speeds at each grid point between 40 °N and 60 °N were used.
This results in the same spatial and temporal resolution for the MCI as for the LWA.

$$MCI = \left| \frac{v * |v|}{u^2 + v^2} \right| \tag{2.4}$$

2.1.3 Sinuosity

The sinuosity is a more simple metric for the waviness of the atmosphere. The averaged geopotential height of the 500 hPa level between 30 °N and 70 °N is calculated for each day.
The daily averaged length of the isohypse with identical geopotential height on the 500 hPa area (including cut off highs and lows) indicates the sinuosity. It is therefore a measure of the meandering of the mean geographic height of the 500 hPa area. However, it does not allow spatial resolution like the LWA and the MCI.

2.2 Metric for Arctic Amplification

The Arctic amplification is shown in the near-surface air temperature (SAT). In some cases, the SAT is given as a function of the geographical latitude (averaged over the longitude).

In other Cases, the difference between the SAT of the middle latitudes (30 °N to 50 °N) and the high latitudes (65 °N +) is considered. The difference is abbreviated as ΔSAT, which shows the gradient of the surface temperature.

2.3 Datasets

Since the exact state of the atmosphere cannot be measured with adequate resolution, ranalysis data are used for the observations. The data come from the reanalysis model ERA-Interim (ERA-I), which contains a global reanalysis of the weather from 1997 to 2018.

The model data used are from four different models: CESM1, CanESM2, GFDL-CM, HadGEM2. All four models contain feedbacks between the atmosphere, oceans, sea ice and land surface.

The first three models start in different years (CESM1 1920, CanESM2 1950, GFDL-CM 1920) and simulate historically forced greenhouse gas concentrations. The initial conditions are slightly varied for the individual model runs in order to form a spectrum. The model data are considered from 1979 onwards (like the reanalysis data). At that point in time, the individual model runs have already released themselves from the starting conditions and are in equilibrium.

The model HadGam2 ist used in a different way. It allows major interventions in the initial and boundary conditions and is therefore used to force certain scenarios.

Chapter 3

Observations

3.1 Trends from 1979 to 2018

First, the trends from 1979 to 2018 were considered (Figure 3.1).
In the plots **A** and **C**, the Arctic amplification is clearly visible in October-November-December (OND) as well as in January-February-March (JFM). In the midlatitudes, the SAT increases by a few tenths of a degree, in the high latitudes SAT increases by more than one degree.

In the plots B and D, on the other hand, we do not see a significant increase in LWA from 1979 to 2018. Dotted areas represent the significance in the 95 % confidence interval.

3.2 Trends of various years

Since the figure 3.1 only includes the years 1979 and 2018, they do not allow any reliable statements. That is because of the values for SAT and LWA being varified by natural fluctuations. In figure 3.2 the trends of SAT and LWA are therefore plotted with different intervals.
ΔSAT in plots A and B shows a negative trend throughout. With the end years of the time period 2010 and later, the trend becomes significant regardless of the start year, in OND already with 2005 and later as end years.
For the LWA, the stagnation action from the previous plot is confirmed. Even though there is partly an increase in the LWA in OND, the increase is only significant from 1989/90 to 2005 or 2010. This represents an outlier that becomes significant for a short time, although the overall data does not reflect this increase.
In JFM, on the other hand, there are statistically significant outliers in the

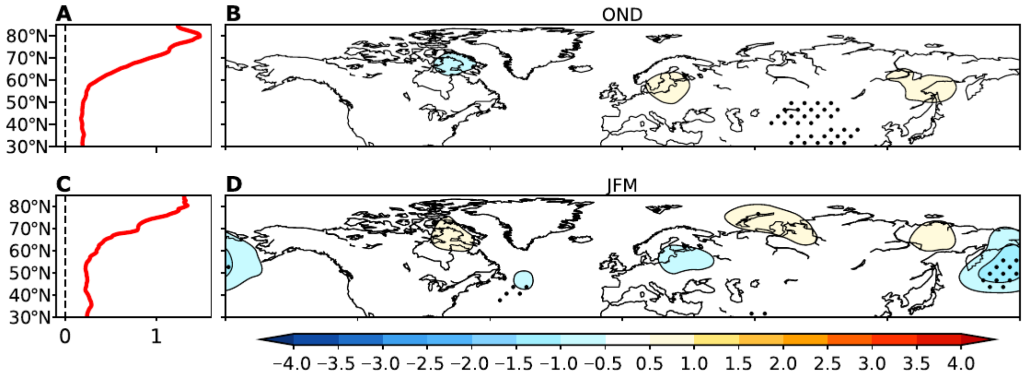

Fig. 3.1: **Observed trends in near-surface temperature and waviness.** (**A**) Trends in zonal mean SAT (°C per dacade) as a function of latitude during OND from 1979 to 2018 in ERA-Interim reanalyses. (**B**) Observed trends in LWA (10^7 m^2 per decade) during OND from 1979 to 2018. Stippling indicates trends that are significant at the 95% confidence intervall level. (**C** and **D**) As in (A) and (B), but for JFM.
Blackport and Screen, 2020

other direction from 1980 to 2002.

Overall, even with a more precise differentiation of the start and end years, there is a significant trend in ΔSAT, which is the Arctic amplification. With the LWA, on the other hand, the non-trend remains even with the differentiation.

3.3 Comparisson of Waviness Metrics

In order to avoid further systematic errors in the analysis, the different measurement variants of the waviness were compared (Figure **??**). The months April-May-June (AMJ) and July-August-September (JAS) were also included.
From 1979 to 2018, there are no significant trends in any of the seasons or in any of the three metrics for waviness. In all variants, the 95 % interval crosses the line of constant waviness, so that there is not a single statistically significant increase or decrease in waviness.

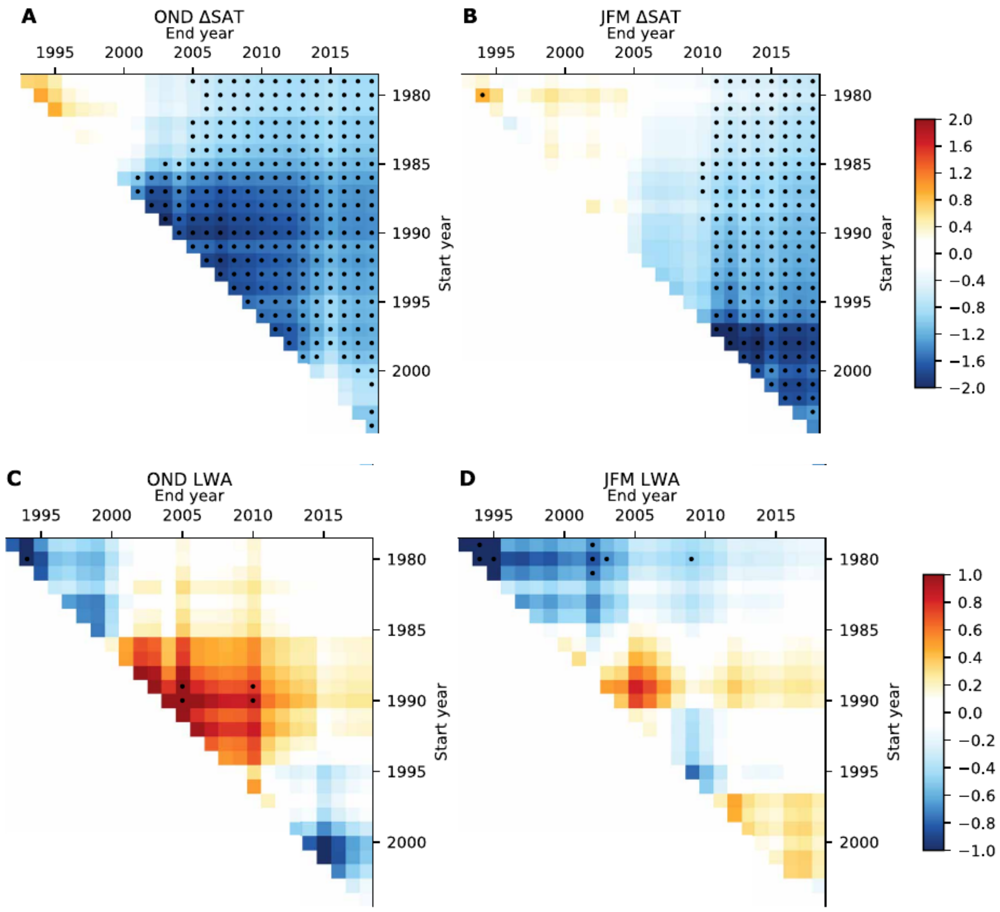

Fig. 3.2: **Observed trends in the meridional near-surface temperature gradient and waviness as a function of start and end year.** (**A**) Trends in ΔSAT (°C per decade) during OND as a function of satr year (vertical axis) and end year (horizontal axis). Only trends of greater than 15 years in length are plotted. Stippling indicates trends that are statistically significant at the 95% confidence interval level. (**B**) As in (A), but for JFM. (**C**) As in (A), but for the LWA (SDs per decade) aberaged over 40° to 60 °N. (**D**) As in (C), but for JFM.
Blackport and Screen, 2020

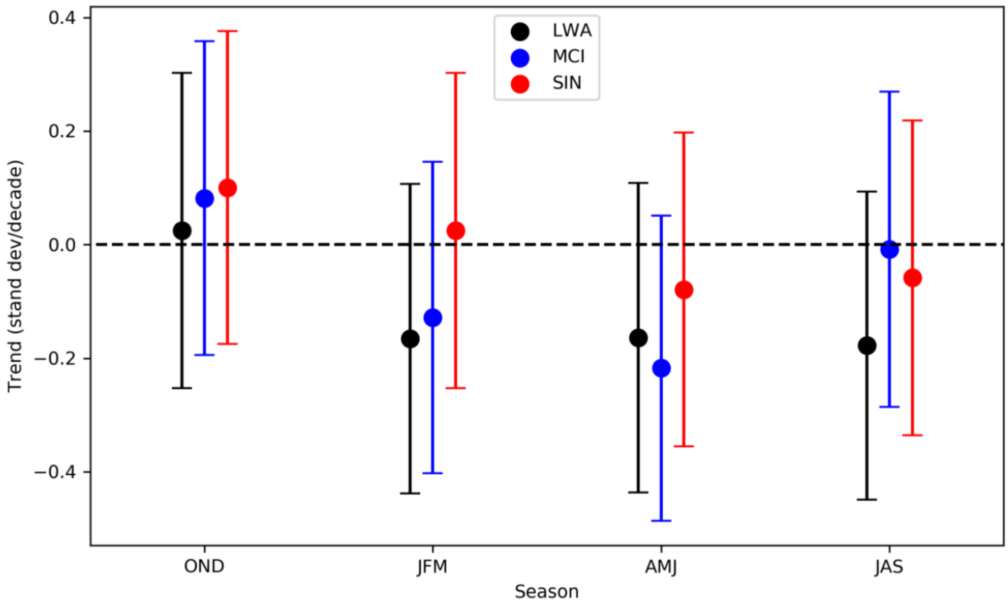

Fig. 3.3: **Observed trends in waviness from additional metrics across all seasons.** Observed trends in LWA (black), MCI (blue) and sinuousity (red) calculated from 1979 to 2018 for each season. All trends have units of standard deviations/decade. Error bars represent the 95% confidence interval.
Blackport and Screen, 2020

Chapter 4

Model data

4.1 Comparison of Reanalyses with model data

To check the quality of model data, they were compared with reanalysis data. For this purpose, the trends from 1979 to 2018 from ΔSAT and LWA were considered. In figure 4.1 the trends of the reanalysis data as well as the trends of three climate models (section 2.3) are plotted.
The trends of the analysis data are given with the significance limits of the 95% confidence interval. The different model runs are each marked with an "x", in addition there is the mean value of the respective model.

For the trends of ΔSAT in OND (plot **A**) is the variation of the model runs for each model greater than the confidence interval of the reanalysis data. The mean values of the models CESM1 and CanESM2 are in the error range of the reanalysis data, the mean value of the model GFDL-CM3 shows a stronger trend. But even with this model there are runs that are in the error range of the reanalysis data, therefore they do not contradict each other.
For the trend in JFM of ΔSAT (plot **B**) the mean value of GFDL-CM3 (as well as CanESM2) is in the error range of the reanalysis data. Here the mean value of CESM1 is at a slightly weaker trend than the confidence interval of the reanalysis data. However, some model runs also cover the error range of the reanalysis data, they do not contradict each other either.
The models thus agree with the reanalysis that from 1979 to 2018 the meridional temperature gradient ΔSAT decreased, therefore the Arctic amplification increased.

The trend of LWA in OND (part **C**) is close to zero, the error interval

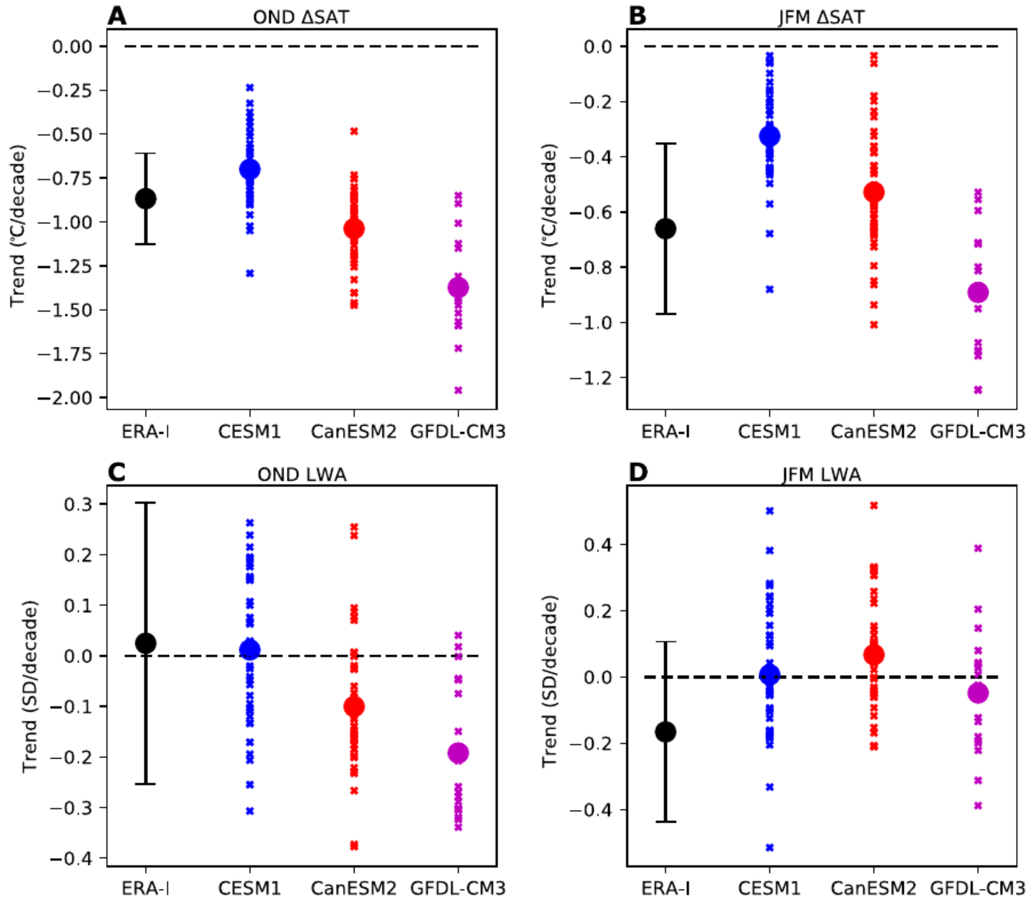

Fig. 4.1: **Comparison of observed and simulated trends in meridional near-surface temperature gradient and waviness.** (**A**) Trend in ΔSAT (°C per decade) during OND from 1979 to 2018 in ERA-Interim reanalysis (black) and the three models (blue, red, and magenta). Error bars for ERA-Interim indicate the 95% confidence interval. For the models, the small crosses indicate the trends in individual ensemble members, and large dots indicate the trend of the ensemble mean. (**B**) As in (A), but for JFM. (**C**) As in (A), but for LWA (SDs per decade). (**D**) As in (C), but for JFM.
Blackport and Screen, 2020

range from the positive to the negative area. The model runs of all models also cover both areas (positive and negative). For the mean values of the model runs, the mean value of the GFDL-CM3 model differs the most from the reanalysis. But it is still in the confidence interval of the reanalysis data. In JFM the trend of LWA of the reanalysis data deviates further from 0 than in OND (plot **D**). However, the error intervals also cross the zero line, so that no trend is visible. The models here again confirm the reanalysis. The mean values of the three models are even closer to zero than the reanalysis and the individual model runs show trends in both directions.
Thereby, the models agree with the reanalysis that the waviness of the atmosphere did not change significantly from 19979 to 2018.

4.2 Correlation of Waviness and Temperature Gradient

Over the span of 40 years it has been found that there is no correlation in the long-term trends between LWA and ΔSAT. However, the question still remains, whether the two quantities exist without feedbacks between each other or whether they influence one another on shorter time scales. For this purpose, correlations were examined in annual and overlapping 15-year trends in the models and the reanalysis data. The 15-year trends were linearly detrended in order to compensate for the deviating long-term developments. To the annual correlation, the model HadGem2 was added as well.

4.2.1 Interannual Correlation

The correlation of the annual variation of LWA and ΔSAT in OND (Figure 4.2, part **A**) is more pronounced in the reanalysis data than in the mean values of the model runs. Thereby, the reanalyses as well as all models show a slight negative correlation. There are only a few model runs that contain a very weak or no correlation.
A similar picture emerges in JFM (plot **B**). Here the mean values of the model runs are closer to the correlation of the reanalysis data. The correlations of the individual model runs are further away from zero.
Following, a low meridional temperature gradient occurs more often together with increased waviness. With a stronger temperature gradient, on the other hand, there is less waviness.

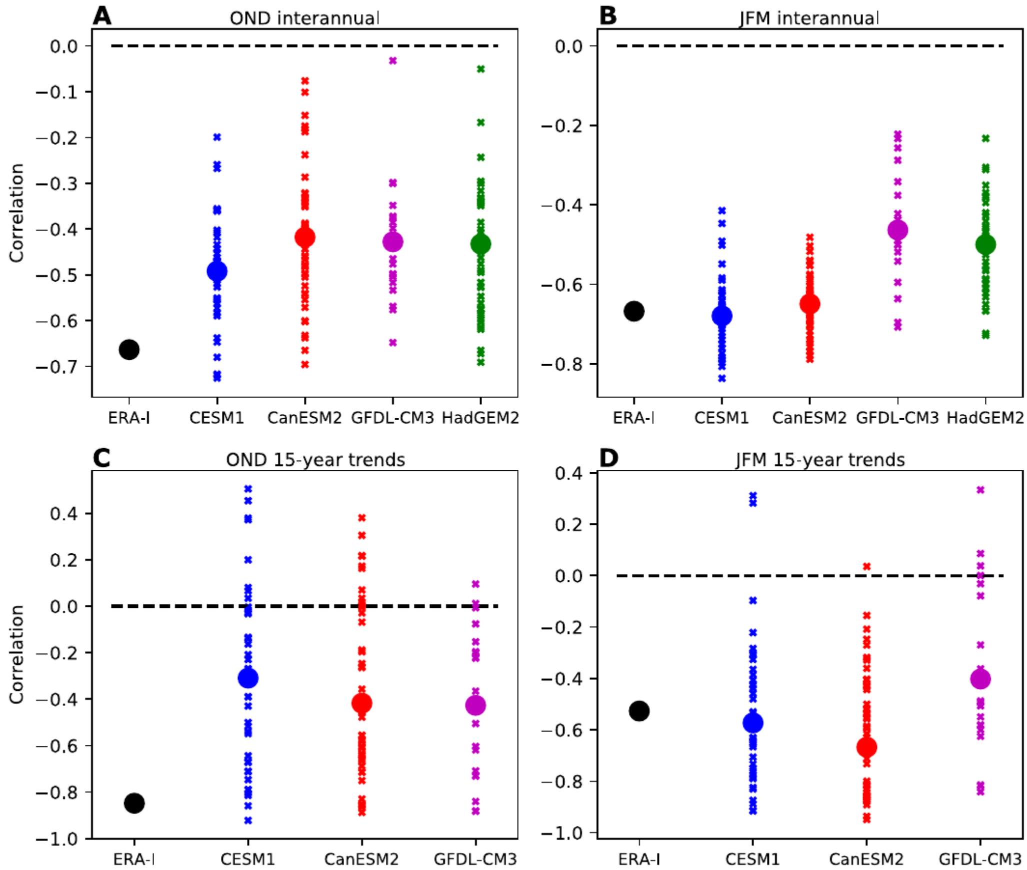

Fig. 4.2: **Correlation between the meridional near-surface gradient and waviness in internal variability.** (**A**) Correlation between ΔSAT and LWA in interannual variability during OND for ERA-Interim reanalysis (black) and the four models (blue, red, magenta, and green). For the models, the small crosses indicate the correlation in individual ensemble members, and the large dots indicate the correlation in individual ensemble members, and the large dots indicate the correlation for concatenated time series of all ensemble members. (**B**) As in (A), but for JFM. (**C**) As in (A), but for correlations of 15-year overlapping trends. (**D**) As in (C), but for JFM.
Blackport and Screen, 2020

4.2.2 Correlation in 15-Year-Trends

When correlating the detrended overlapping 15-year trends, the result is not as clear.
In OND (Figure 4.2, plot **C**) the most pronounced correlation is shown in the reanalysis data. However, the mean values of the correlations of the models are significantly lower. The correlations of the individual model runs range from the correlation of the reanalysis data to opposing (positive) correlations.
In JFM (part **D**) the mean values of the models are again closer to the reanalyses, which again shows a less strong correlation. Occasionally, model runs also show an opposite correlation, but significantly less than in OND.
Overall, the result is confirmed that LWA and ΔSAT correlate negatively over shorter periods of time. Even though, the correlation is much more pronounced within a year than it is over 15 years.

4.3 Regression of Waviness and meridional Temperature Gradient

Next, regional differences were examined. For this, the regression of the zonally averaged temperature and the regression of the LWA on the meridional temperature gradient *Delta* SAT were implemented. Before the regression, all parameters were linearly detrended again. The results would not change without the detrending over the years, but they would not be as pronounced... The regressions are plotted with the opposite sign, so that a positive regression represents an inverse proportion.

4.3.1 in Reanalyses Data

First, the regressions were carried out with the reanalysis data (Figure 4.3). The regression of the zonally averaged SAT on the temperature gradient ΔSAT is the same in both OND (part **A**) and JFM (part **G**). In the middle and higher latitudes are opposing effects, the effect of the higher latitudes is much more pronounced. However, the middle latitudes are significantly larger and underrepresented in comparison with zonal averaging.
In the midlatitudes the surface temperature is lower with a weakened ΔSAT, so there is a cooling as long as there is a lower temperature gradient. In the higher latitudes, the regression is reversed. With a weakened ΔSAT, the temperature increases in the high latitudes / the Arctic.

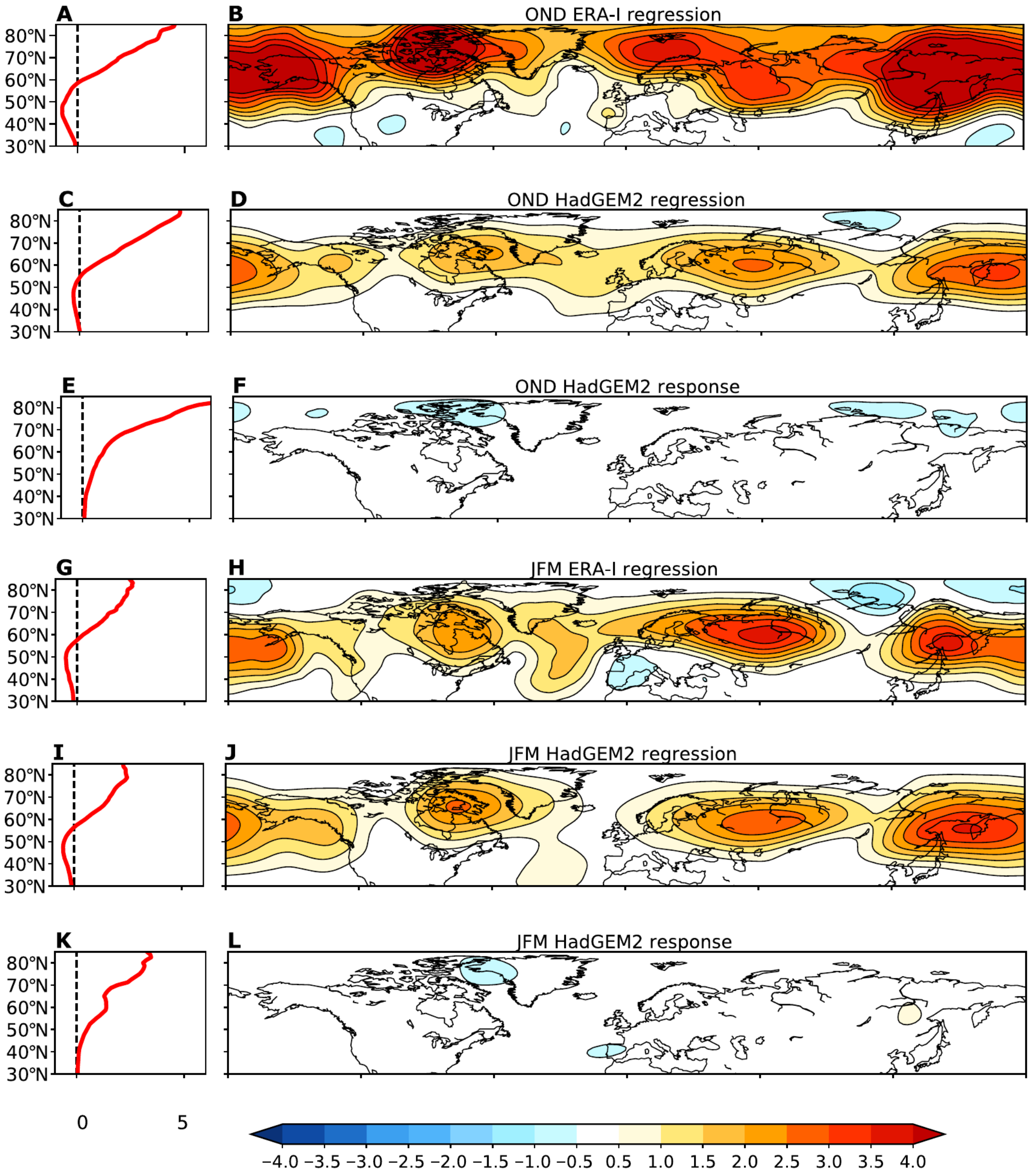

Fig. 4.3: **Links between the meridional near-surface temperature gradient and waviness in internal variability versus the forced response.** (**A**) Zonal mean SAT (°C) regressed onto ΔSAT during OND for ERA-Interim. (**B**) LWA (10^7 m^2) regressed onto ΔSAT during OND for ERA-Interim. (**C** and **D**) As in (A) and (B), but for the HadGEM2 model. (**E** The zonal mean near-surface temperature (°C) response to Arctic amplification in HadGEM2. (**F**) Response of LWA (10^7 m^2) to Arctic amplification in the HadGEM2 simulations. (**G** to **L**) As in (A) t0 (F), but for JFM. The magnitudes of the regression coefficients are scaled by the ΔSAT response in the experiments forced with Arctic amplification (3.06° and 2.17 °C in OND and JFM, respectively)
Blackport and Screen, 2020
All regressions (A, B, C, D, G, H, I, J) are calculated with the reserved sign of ΔSAT.

A larger difference can be seen in the regression of the LWA onto ΔSAT. In OND (plot **B**) there is a very strong regression in the higher latitudes. In contrast, no correlations can be observed in midlatitudes. The regression between Canada and Greenland as well as in eastern Russia is particularly pronounced. In JFM (plot **H**) the regression is not quite as pronounced as in OND. The most pronounced part is over the Ural Mountains. In small parts of the Arctic, the regression is in the opposite direction, but overall it corresponds to the regression in OND.
At higher latitudes, the waviness of the atmosphere increases with a reduced temperature gradient. The further south, the more the effect decreases; in OND it can no longer be observed further south of 40 °N.

4.3.2 in Model Data

The regressions with the HadGEM2 model (Figure 4.3) behave similar to the regression with the reanalysis data. In the regression of the zonally averaged temperature on ΔSAT in OND (plot **C**), in contrast to the corresponding regression with the reanalysis data, the deflection in the midlatitudes is missing. Therefore, there is no visible regression in the midlatitudes. However, in the higher latitudes the strong correlation is confirmed. With a weaker temperature gradient, the higher latitudes are significantly warmer than with a more pronounced gradient. However, in JFM (plot **I**) the warming of the midlatitudes is still visible as long as there is a weakened gradient.

In the regression of LWA on ΔSAT, the plots in OND (plot **D**) and JFM (plot **J**) are more similar to each other than in the regression with the reanalysis data. In both cases, the regression does not extend completely into the Arctic, but is rather between 50 °N and 75 °N. Again it is strongly pronounced over the Ural Mountains, Eastern Russia and Canada. With a weakening of the meridional temperature gradient there is an increase in the waviness too.

Overall, the data of the HadGEM2 model reflect the results of the reanalysis data well. They are just not that pronounced.

4.4 Forced Response of Waviness and meridional Temperature Gradient

After considering the spatially resolved relationship of the meridional temperature gradient ΔSAT to the zonally averaged SAT and the waviness, the

causal relationship between ΔSAT and LWA is still unclear. Because of that, the model HadGEM2 was used to precisely determine the influence of ΔSAT on LWA.
For this purpose, 400 model runs were calculated from 2008 to 2012. After withdrawing the first year of each model run, there is a total of 1600 years with our current climate conditions.
For comparison, 400 other runs were calculated from 2008 to 2012. This time Arctic amplification was forced by reducing the sea ice. This results in a much weaker temperature gradient ΔSAT.
The difference of the zonally averaged SAT and the LWA between the two run-throughs are shown in figure 4.3. For the SAT (plot **E** in OND and plot **K** in JFM), there is a clear warming in the higher latitudes. This proves that the forced Arctic amplification worked. The LWA did not change, except for small regional weaknesses, as for example between Greenland and Canada. Overall, however, the waviness did not react to the Arctic amplification.

Chapter 5

Summary and Discussion

Overall it became clear that the waviness of the atmosphere is not going to change in the course of the arctic amplification. Even though the waviness is related to the meridional temperature gradient in short time scales, it is not dependent on it. With increased waviness, the meridional transport of air masses increases. The meridional temperature gradient could decrease through increased mixing of the air masses. In order to specify whether the waviness on short time scales directly influences the temperature gradient or whether both depend on a third variable would have to be examined more closely. In the paper of Russell Blackport* and James A. Screen, it was only shown that the waviness is not influenced by the temperature gradient.
On longer time scales, the correlation between the short-term trends disappears completely, even if internal variability is big enough to reach into the 95% confidence interval in separate years.

Chapter 6

Literature

Russell Blackport, James A. Screen: Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves, Science Advances, 6(8), 1-8, doi: 10.1126/sciadv.aay2880, 2020