Master Thesis

Rossby wave breaking in the global climate model ECHAM5
The dynamic capabilities of a GCM at different model resolutions

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Rossby Wave Breaking in the Global Climate Model ECHAM5

The Dynamic Capabilities of a GCM at Different Model Resolutions

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Abstract

Equatorward Rossby Wave Breaking (RWB) describes the irreversible deformation of undulations of the tropopause and subsequent stratosphere-troposphere exchange. These events usually occur near the jet exit region, where they have severe implications for atmospheric dynamics and trigger heavy precipitation events and strong convection.

Whether state-of-the-art Global Climate Models represent Rossby Wave Breaking well is essential in order to assess their value for the prediction of altered atmospheric dynamics in a warmer climate. This study evaluates three ECHAM5.5-HAM model simulations in triangular spectral resolutions of T42 (2.8°×2.8°, 19 vertical levels), T63 (1.875°×1.875°, 31 vertical levels) and T106 (1.125°×1.125°, 31 vertical levels). All three simulations use the same datasets of prescribed sea-surface temperatures and radiative forcings. Our approach detects individual RWB events produced in these simulations using a contour-based approach which identifies highly deformed portions of the dynamical tropopause on an isentropic surface. Climatologies of the locations and sizes of these events during the winter season (DJF) are compared to the ERA-40 dataset on the 310K and 330K isentropes over the northern hemisphere. In addition, the accuracy of the ECHAM5 climatological jet stream and average low-level baroclinicity is evaluated.

The RWB frequency maxima in ECHAM5 show an eastward bias of about 10° at T42 and T63 resolution on the 310K isentrope. The model underestimates the overall RWB frequency on this level by 36% at T42 and by 12% at T63. On the 330K isentrope, there is a south-easterly shift of streamer maxima in all simulations. As on 310K, the location shift is most pronounced over the Pacific. On 330K, the model underestimates the overall RWB frequency by about 50% in the T42 simulation and by 3% at T63. On both levels, there is a positive bias of 7% in the T106 simulation. The ECHAM5 jet stream shows less split-jet configurations than ERA-40 over the Atlantic, and it is also located farther south (approx. 5°), broader, and faster than in the ERA-40 dataset. An equatorward jet bias of similar structure is present in all three simulations, both on the 310K and 330K isentropes.
Chapter 1

Introduction

1.1 Motivation

Global Climate Models are increasingly used to assess the impacts of Climate Change on severe weather conditions. Some of the considered events are strongly influenced by synoptic-scale flow features referred to as Rossby waves. When these waves break at the end of their life cycle, they produce elongated intrusions of stratospheric air into the troposphere, forming so-called Potential Vorticity (PV) streamers. The formation of a Potential Vorticity streamer is irreversible: A full-fledged PV streamer will unavoidably break up and exert substantial influence on the dynamics in the nearby range of the streamer. The range of altered processes includes:

- Convection in the Eastern tropical Pacific (e.g. Funatsu and Waugh, 2008, see their schematic in Fig. 1.1)
- Heavy Precipitation on the Alpine south side, which often occurs when a stratospheric PV streamer is present over the Alps (e.g. Massacand et al., 1998, Massacand and Davies, 2001)
- Stratosphere-Troposphere Exchange, which is enhanced by PV streamer breakup and the vertical circulation surrounding a PV streamer (e.g. Sprenger et al., 2007)
- Large-Scale teleconnection patterns on the northern hemisphere (PNA, NAO) are influenced by PV streamers (e.g. Benedict et al., 2004, Franzke et al., 2004)
- The maintenance of atmospheric blockings (Altenhoff et al., 2008)

The above list is far from being comprehensive. The wide range of processes vividly illustrates that it is pivotal to understand the dynamics of PV streamers in Global Climate Models (GCMs), as this will help us to assess changes in dynamics in a warmer climate. Currently, the accuracy of GCMs with respect to these processes is hotly debated. Some analyses on the quality of ECHAM5 dynamics have already been performed. For example, Bengtsson et al. (2006) analyse the capabilities of the ECHAM5 model regarding storm tracks and cyclone activity. They state that "the overall impression
Chapter 1. INTRODUCTION

Fig. 1.1: Schematic of the influence of a Potential Vorticity Streamer on convection. The streamer being advected from the left induces upward vertical motion along the downwind flank and downward vertical motion in its lee by bending the underlying isentropic surface upwards. This facilitates the formation of a convective cloud along the downstream flank of the streamer. From Funatsu and Waugh (2008), Fig. 1.

is that the performance of the model compares very well with the reanalysis of ERA-40”. They find good agreement between modeled and observed storm tracks, especially on the northern hemisphere. Pinto et al. (2009) extend this analysis, which is based on cyclone tracking, to include the role of the North-Atlantic Oscillation (NAO) and its effects on cyclones on the northern hemisphere.

The reliability of Regional Climate Model output fundamentally depends on the quality of the forcings at its domain boundaries, which are usually given by a GCM like ECHAM5. Therefore, the quality of the representation of large-scale atmospheric flow is also of high importance to regional climate modeling approaches. By analysing the Potential Vorticity Streamers in the model, we hope to cover a range of dynamically relevant processes going beyond the numbers and tracks of extratropical cyclones. This approach circumvents parameterizations of subgrid-scale processes because the features we investigate are resolved by the grids.

1.2 Aims of this Study

This study aims at exploring the capabilities of the ECHAM5 climate model to adequately represent stratospheric Potential Vorticity streamers and isentropic wind fields in the northern hemisphere. An assessment of the climatological wind and baroclinicity fields in the model complements the analysis of streamers. The PV streamers in the model are considered in terms of their size, location, and frequency. As a baseline for comparison, we use the 40-year reanalysis dataset (ERA-40) provided by the European
1.2. AIMS OF THIS STUDY

Center for Medium-Range Weather Forecasts (ECMWF). A major goal of this thesis is to help assessing whether the ECHAM5 model can be used to examine changes in weather and extreme event patterns in a changing climate.

The thesis is structured as follows: Chapter 2 discusses the datasets which form the basis for this study. Chapter 3 gives an overview of the various tools used in this analysis, like the Potential Vorticity variable and the algorithms used. It also discusses the sensitivity of the detected streamers to algorithm parameters and model resolution. The Results section (Chapter 4) starts out with a display of the heights of near-tropopause isentropes in the model and the reanalysis. Then, I show wind velocities on these isentropes, followed by a brief discussion of low-level baroclinicity. In section 4.4, PV streamer frequency on near-tropopause isentropes is shown, and the annual cycle of the number of PV streamers per day is displayed immediately afterwards. Key results are then summarized in Chapter 5, followed by an outlook onto further research in Chapter 6.
Chapter 2

Datasets

This section briefly introduces the ERA-40 dataset and the ECHAM5 model simulations used for our analysis. Data is available for the period 1958-2002 for all model datasets and the ERA-40 reanalysis. This 44-year time period has therefore been chosen as reference period for the intercomparison study.

2.1 The ECHAM5 Model

Three transient climate simulations performed with the ECHAM5.5 climate model form the core data for this study. The ECHAM5 model runs were calculated at the Institute for Atmospheric and Climate Science at ETH to test a new cloud microphysics parameterization for the model. The simulations use an identical model set up, but differ in horizontal and vertical resolution. The dynamical core of the model is based on an earlier version of the ECMWF operational model and has been adapted for climate projections at the Max Planck institute for Meteorology in Hamburg (Roeckner et al., 2003). The model configuration includes the Hamburg Aerosol Module (HAM) (Stier et al., 2005), which is coupled to cloud microphysical processes to account for the cloud formation and cloud lifetime effects of aerosols (Lohmann et al., 2007).

The model is forced by the ENSEMBLES sea-surface temperature dataset. The horizontal resolutions of the simulations in spectral notation are T42, T63, and T106. The corresponding resolution in degrees and km is given in Table 4.1. While the T42 simulation was calculated with only 19 vertical levels, the T63 and T106 simulations use 31 vertical levels. The uppermost level is located at 10 hPa in all model configurations.

Sensitivity experiments by Roeckner et al. (2004) show that an increase of the vertical resolution to more than 19 levels fails to improve the representation of the zonal wind. This supports our choice of 19 vertical levels for the T42 simulation.

The scenario A1B from the IPCC Special Report on Emissions Scenarios is used for simulation of future climates. This scenario is “a balanced mix of technologies and supply sources, with technology improvements and resource assumptions such that no single source of energy is overly dominant” ((Nakicenovic
and Swart, 2003, chap. 4.3.1)). The A1B scenario is used to circumvent claims to be overly pessimistic (A2 scenario) or optimistic (B1 scenario).

2.2 The ECMWF 44-year Reanalysis Dataset (ERA-40)

Modern climatological research applies the ERA-40 dataset to a broad range of analyses. Many model validations use ERA-40 as their baseline, and lots of research was based on the ERA-40 data themselves. There are some well-known deficiencies of the ERA-40 dataset, like the quality of the upper-air data and the data on the southern hemisphere, where observations are sparse (especially in the pre-satellite period). On lower levels and on the northern hemisphere, the dataset is the best reanalysis currently available. A detailed description of the quality of ERA-40 is given in Uppala et al. (2005), where the effects of the introduction of satellite data to the observing system in the 1970s is also discussed in more detail. The original horizontal resolution of the dataset is T157. A version interpolated to a regular 1° × 1° latitude-longitude grid is used for this study. The top boundary of the reanalysis is at 1 hPa, with 60 vertical levels below. 47 of these are lower than 10 hPa, which is the top boundary for the ECHAM5 simulations. We use monthly mean fields of wind velocity on the isentropic surfaces at 310 K and 330 K from ERA-40 as a baseline for assessing the ability of ECHAM5 to reproduce the sub- and extratropical jet stream. In addition, ERA-40 is used as an input to the PV streamer detection routine described in the following chapter. The appendix contains plots of wind velocity and streamer frequency on the 350 K isentrope.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Resolution Gridpoints</th>
<th>Resolution Degrees</th>
<th>Resolution [km at 45° N]</th>
<th>Vertical Levels</th>
<th>Top Boundary [hPa]</th>
<th>Output Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHAM T42</td>
<td>128×64</td>
<td>2.8°×2.8°</td>
<td>220</td>
<td>19</td>
<td>10</td>
<td>24 h</td>
</tr>
<tr>
<td>ECHAM T63</td>
<td>192×96</td>
<td>1.875°×1.875°</td>
<td>150</td>
<td>31</td>
<td>10</td>
<td>12 h</td>
</tr>
<tr>
<td>ECHAM T106</td>
<td>320×160</td>
<td>1.125°×1.125°</td>
<td>90</td>
<td>31</td>
<td>10</td>
<td>6 h</td>
</tr>
<tr>
<td>ERA-40</td>
<td>360×180</td>
<td>1°×1°</td>
<td>79</td>
<td>60</td>
<td>1</td>
<td>6 h</td>
</tr>
</tbody>
</table>
Chapter 3

Tools and Methods

This chapter describes the methodology used in this thesis. First, the concept of Potential Vorticity is introduced, followed by a description of the programs used to compute the Potential Vorticity streamers. Subsequently, the sensitivity of the detected PV streamers to important parameters is discussed and the definitions of RMSE and relative bias are shown.

3.1 Potential Vorticity

Ertel’s Potential Vorticity (PV) is a powerful concept for studying atmospheric dynamics. Potential Vorticity is defined as a product of a thermodynamic variable (static stability) and a kinematic variable (absolute vorticity). The definition of PV in an isentropic coordinate system is defined as follows (Ertel, 1942):

\[ PV = (\zeta_\theta + f) \left(-g \frac{\partial \theta}{\partial p}\right) \]  

(3.1)

The first factor in Eq. 3.1 consists of the vertical component of relative vorticity \( \zeta_\theta \) and the Coriolis parameter \( f \), and is the definition of relative vorticity. The second factor is the definition of static stability, which is proportional to the vertical derivative of potential temperature (\( \theta \)). PV is usually measured in ”Potential Vorticity Units” (PVU), which provide a convenient scale for investigating PV fields. One PVU is defined as \( 10^{-6}K s^{-1}kg^{-1}m^2 \). The 2 PVU isosurface defines the location of the dynamical tropopause: Air parcels with PV values below this threshold are deemed tropospheric, while PV values above 2 indicate stratospheric air.

In addition to the importance of PV streamers in various dynamic processes, PV also has very useful mathematical properties which can be harnessed in the analysis of atmospheric flow fields (Hoskins et al., 1985). These are:

- Invertibility of the PV field
  The invertibility principle states that important aspects of the flow field, such as wind speed and temperature, can be recovered from the scalar PV distribution provided that boundary conditions
Chapter 3. TOOLS AND METHODS

of the selected variable are available. Therefore, if PV is the prognostic variable in a forecasting system, wind velocity and temperature can be diagnosed from PV using the state of these variables in the previous timestep as boundary conditions.

- Conservation of PV
  
  PV is conserved in adiabatic 2D-flow on surfaces of constant potential temperature $\theta$.

- The partition principle
  
  Individual features of the PV field add together linearly to produce the observed wind fields.

Generation and destruction of PV can occur from diabatic processes, like heating due to solar radiation, and from friction on the ground.

3.2 Algorithms used for the Analysis

3.2.1 Determination of the 2 PVU - Contour

PV and wind velocity data are used as an input to the PV contour identification algorithm presented in Wernli and Sprenger (2007). The PV contour is stored as an ASCII file containing the geodetic coordinates of each point on the 2 PVU contour. The points have a distance of about 30 km, independent of the resolution of the input data.

3.2.2 Identification of Stratospheric PV Streamers

After the 2 PVU contour has been identified, it is analyzed for strong curvature, which indicates the presence of a PV streamer. The analysis begins with the identification of so-called “close encounters”, which are points on the contour with a great-circle distance of less than 1500 km. This distance is an important parameter determining the algorithm’s output. Corresponding sensitivity experiments were performed and are shown in section 3.3.1. Subsequently, the distance between the two points along the contour is measured (length $l$ in Fig. 3.2.2) and checked to be larger than 2000 km and smaller than 15000 km. The former threshold excludes small waves on the contour, and the latter prevents large, highly deformed PV bodies from being classified as streamers. In addition to these criteria, the distance along the contour needs to be at least twice as long as the close encounter distance (length $d$ in Fig. 3.2.2). A maximum of 80 percent of the 2 PVU contour is allowed to be attributed to streamers, in order to minimize high streamer occurrence due to highly distorted stratospheric bodies, which are sometimes seen on lower isentropic levels. Structures qualifying for all criteria are stored in a binary field on a regular latitude-longitude grid.

In its most recent version, the PV streamer detection algorithm creates an additional output file “corners”, in which the tip of the streamer and the two base points are saved. This file allows computing the streamer orientation in a further postprocessing step. This option was not available for the ERA-40
3.3 SENSITIVITY ANALYSIS

dataset, for which streamers had already been computed.

3.2.3 Calculation of Streamer Area and Orientation

Using the binomial streamer field and the locations of the streamer’s ”corners” as an input, a novel post-processing code computes the area and orientation of each individual streamer. For the area calculation, cosines of the latitude of the streamer’s grid points are summed and multiplied by the area of one grid box at the equator:

\[ A = \sum_{i=1}^{N} A_{eq} \cos(lat_i) \]

The streamer orientation is calculated by the use of trigonometric functions. It is defined as the angle created by the meridian with the connecting line between the streamer tip (the southernmost point of the streamer) and the base point (cf. Fig 3.2.2). Spherical corrections to the trigonometric functions are omitted in this step.

In addition, the weighted sum of grid point locations is used to calculate the center of mass of the streamer:

\[ \text{lat}_{mean} = \frac{1}{N} \sum_{i=1}^{N} \text{lat}_i \cos(lat_i) \quad \text{lon}_{mean} = \frac{1}{N} \sum_{i=1}^{N} \text{lon}_i \cos(lat_i) \]

3.3 Sensitivity of Potential Vorticity Streamers in the ECHAM5 Model

This section describes how the streamers detected by the PV streamer routine change when two important parameters vary. These are: (1) the “close encounter” parameter, which defines a maximum distance between two points on the PVU contour in order to initiate the search for a PV streamer, and (2) ECHAM5 model resolution.

![Fig. 3.1: Schematic of a Potential Vorticity Streamer illustrating the meaning of CEP (length d), the streamer base point and the streamer tip. Modified from Wernli and Sprenger (2007), Fig. 1.](image-url)
3.3.1 Sensitivity towards the “Close Encounter” Parameter

The “close encounter” parameter (CEP from here on) is an important value when using the PV streamer detection routine developed by Wernli and Sprenger (2007). The choice of CEP determines the locations on the 2 PVU contour where PV streamer detection is initiated, as the search for a “close encounter” is the first step in the detection algorithm. Figure 3.2 presents an example from the T106 simulation which illustrates several effects of changing CEP on the detected streamers.

For example, the algorithm catches the large PV streamer over Northern America only if CEP > 1250 km. This streamer gradually breaks up over the following three days, a period where it grows thinner and smaller with each timestep (see Appendix for the development of this case over the following three days). We decided that this type of streamer is dynamically relevant and should be detected by the code, and concluded that CEP should be greater than 1250 km.

The effect of increasing the CEP can be observed well by the changes induced in the streamer which can be seen over the Pacific near the dateline. The algorithm identifies two streamers if the CEP is less than or equal to 1500 km, but only finds one merged feature if CEP is set to 2000 km. This classification is incorrect, as the features soon separate and develop into two distinct PV streamers. A comparable case can be found over the Arabian Peninsula for the same period, although the identification of a single feature seems to be correct in this case. However, this streamer will have a minor effect on the flow field because it is smaller. Based on this and similar cases, we decided to choose a value of 1500 km for CEP. This has made the criterion more stringent, thereby producing more of the small PV streamers and less of the large ones.

3.3.2 Sensitivity to ECHAM5 Resolution

Model resolution was expected to have a strong effect both on the climatological distribution and the individual shape of the PV streamers. Here we compare the shapes of the 2 PVU contour and the detected PV streamers under similar large-scale atmospheric circulations. The three examples from the 330K isentrope in Fig. 3.3 all show a PV streamer hovering over the African and European coastline.

The PV fields from the three simulations differ most significantly in their wealth of small-scale structures, which is due to the finer gridding at higher model resolution. In addition, the smaller distance between grid points results in a considerably smoother PV contour at higher resolutions. As a result, the identified streamers have a more elegant contour with fewer kinks. The higher variability of the PV field at higher model resolutions indicates that the mixing between stratospheric and tropospheric air is modeled with more detail, and presumably higher accuracy, when model resolution increases.

3.4 Selection of Isentropic Levels

We have confined our analysis to isentropic levels between 300 and 350 K, as this is the range of potential temperatures which are relevant to near-tropopause investigations. Levels below 320 K will only be
3.5 Calculation of Root-Mean-Squared Error and Model Bias

Apart from a visual inspection of the dynamically relevant variables, we also give numerical evaluations of the differences between reanalysis and model. We use the Root-Mean-Squared Error accuracy measure (RMSE) because of its straightforward definition and its widespread application to maps of climatological variables. Wilks (2006, chap. 7.6.3) gives a standard definition of the RMSE. We slightly adapt this
Fig. 3.3: Streamer distributions for similar large-scale configurations from the three different model resolutions on the 330 K isentrope. The colors indicate PV in PVU, the blue line is the demarcation of the 2 PVU - contour. Green diamonds illustrate the “corners” of the streamer, while red and white diamonds are used for the streamer’s center of mass.

Another relevant measure is the relative bias, which shows whether the modeled values are on average higher or lower than the ERA-40 baseline. The definition used to calculate the relative bias in Tables 4.3 and 4.3 is as follows:

$$B = \frac{\sum_{i=1}^{N} (y_i - o_i) \cos(lat_i)}{\sum_{i=1}^{N} o_i \cos(lat_i)}.$$ 

Notes/scratch: As there is a high PV gradient between the troposphere and the stratosphere, regions of high PV surrounded by air with tropospheric (less than 2 PVU) PV values are indicative of the mixing of stratospheric air into the troposphere.

This can lead to the development of isolated blobs of high PV surrounded by lower PV values, a structure commonly termed a "PV cutoff". This study only analyses PV streamers and does not take PV cutoffs into account.
Chapter 4

Results

In this chapter, we compare 44 years of ERA-40 and ECHAM5 present-day (1958-2002) data from the DJF winter season on the northern hemisphere. First, variations in the heights of the isentropic levels are discussed, followed by the spatial distributions of wind velocity and low-level baroclinicity. Thereafter, the results on PV streamer frequency, size and annual cycle are presented. A section on wavenumber 1-3 components of the potential vorticity field concludes this chapter. Most results are shown for the 330 K and 310 K isentropes only, which are representative for sub- and extratropical dynamics during winter, respectively.

4.1 The Height of Isentropic Levels

When conducting analyses of any variable on an isentropic surface, it is important to bear in mind that the height of this surface is not constant in the course of the year due to the annual temperature cycle of the troposphere. Consequently, different processes occur on an isentrope throughout the year, which adds complexity to the interpretation of the results. The point where an isentrope intersects the dynamical tropopause is of particular importance to the dynamics displayed on this level. Liniger and Davies (2004) emphasize the importance of this intersection latitude in PV streamer climatologies, and assume isentropes which intersect at similar latitudes (e.g. 45°N) to show comparable dynamic events throughout the year.

We have compared the heights of the 315 K, 330 K, and 350 K isentropic surfaces and the 2 PVU-surface, which defines the dynamical tropopause, in the ERA-40 dataset and the ECHAM5 model simulations. The result is shown in Fig. 4.1. The colored lines in Fig. 4.1 show the height of the 315 K, 330 K, and 350 K isentropes in the ECHAM5 and ERA-40 datasets. The intersection of the isentrope and the dynamical tropopause is highlighted by a colored circle. In the T42 simulation, the dynamical tropopause intersects the isentropic surfaces at lower latitudes than in ERA-40 (about 3°, cf. Table 4.1). However, this distance is on the order of magnitude of the grid spacing T42 resolution, and thereby the method to identify the intersection point will influence its location. The intersection latitudes are comparable.
to ERA-40 for the T63 and T106 simulations. The intersection altitudes for these simulations, however, are found to be higher than in the ERA-40 dataset (cf. table 4.2). This is true for all the isentropes considered. The relative importance of intersection latitude and altitude is not entirely clear, but we consider the intersection latitude to be of higher dynamic relevance. From this perspective, the T63 and T106 simulations are expected to model the position of the intersection well enough to permit further comparisons.

Fig. 4.1 can also be used to compare the steepness of the "tropopause jump" in the ERA-40 reanalysis and the ECHAM5 simulations. In an instantaneous picture, the jet stream usually flows at the latitude where the tropopause is steepest. This connection is usually preserved in the climatological mean. The steepness of the tropopause in the ECHAM5 model is slightly lower than in ERA-40, in particular in between 30°N and 45°N. This is indicated by the deviation of the ECHAM5 tropopauses away from the black ERA-40 tropopause north of 30°N. At latitudes below 30°N, ECHAM5 and ERA-40 tropopauses are almost parallel, with only the T42 tropopause deviating substantially from the other surfaces. This is the first hint at slightly different jet positions in ECHAM5 and ERA-40. Fig. 4.1 also points towards possible differences in jet speed, as a steeper tropopause usually causes a stronger jet stream.

Fig. 4.1: Height of isentropic surfaces on 315, 330 and 350 K and of the 2 PVU contour in hPa for the three ECHAM runs and the ERA-40 dataset.
4.2. WIND VELOCITY

Table 4.1: Zonal mean intersection latitudes between the 2 PVU surface and the isentropic levels in the ERA-40 dataset and the ECHAM5 model simulations.

<table>
<thead>
<tr>
<th>Isentropic level</th>
<th>ECHAM T42</th>
<th>ECHAM T63</th>
<th>ECHAM T106</th>
<th>ERA-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>315 K</td>
<td>45.7</td>
<td>48.6</td>
<td>47.9</td>
<td>48.9</td>
</tr>
<tr>
<td>330 K</td>
<td>33.7</td>
<td>36.0</td>
<td>35.7</td>
<td>35.8</td>
</tr>
<tr>
<td>350 K</td>
<td>28.1</td>
<td>30.0</td>
<td>29.9</td>
<td>30.8</td>
</tr>
</tbody>
</table>

Table 4.2: Zonal mean intersection heights [hPa] between the 2 PVU surface and the isentropic levels in the ERA-40 dataset and the ECHAM5 model simulations.

<table>
<thead>
<tr>
<th>Isentropic level</th>
<th>ECHAM T42</th>
<th>ECHAM T63</th>
<th>ECHAM T106</th>
<th>ERA-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>315 K</td>
<td>280</td>
<td>277</td>
<td>278</td>
<td>298</td>
</tr>
<tr>
<td>330 K</td>
<td>236</td>
<td>235</td>
<td>231</td>
<td>249</td>
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<tr>
<td>350 K</td>
<td>185</td>
<td>185</td>
<td>178</td>
<td>196</td>
</tr>
</tbody>
</table>

4.2 Wind Velocity

This section compares the wind velocity fields on the 330 K and 310 K isentrope in ECHAM5 and the ERA-40 reanalysis on the northern hemisphere. Wind velocity maxima on these levels are found at the climatological position of the jet stream. The location of the jet stream is relevant for sub- and extratropical dynamics, as it is linked to the location of Rossby Wave Breaking and other dynamically relevant processes.

4.2.1 The Subtropics

Average wind velocities on the 330 K isentrope show the climatological position of the subtropical jet stream. A 44-year-average of DJF wind speed is shown in Fig. 4.2. On this level, wind velocity maxima are found over the Western Pacific, the Western Atlantic and over the Arabian Peninsula in the ERA-40 dataset. The Pacific maximum is strongest, with wind speeds of up to 60 m/s, followed by the Atlantic maximum (45 m/s) and the Arabian maximum (40 m/s).

The wind velocity biases from the model simulations and the ERA-40 dataset are shown in Fig. 4.3. The most prominent feature in these fields is a southerly shift of the wind maxima in the ECHAM5 data with respect to ERA-40, which creates the four north-south dipoles discernible in in the bias fields. These dipoles are located over the western and eastern Pacific (south of Japan and off California, respectively), over the central Atlantic (west of the Azores), and over north-western Africa. The relative importance of these dipoles varies with model resolution, but the errors in the Atlantic and the eastern Pacific usually exceed those over the western Pacific and Africa. In particular, a reduction of error by nearly 50% in the western Pacific and over the central Atlantic occurs when model resolution increases from T42 to T63. Over the western Pacific, there is further improvement when resolution increases to T106. Over the Atlantic, model performance is best at T63 resolution in terms of horizontal wind.

In contrast to the improvements over the central Atlantic and the western Pacific, errors over the eastern Pacific and Africa persist in simulations with higher horizontal resolution. The errors near the Californian coast even increase when going from T42 to T106 resolution. However, this decline in performance at
the edges of the jet maxima goes together with a better representation of the maximum values of the average wind fields. Apparently, increasing horizontal model resolution mainly reduces errors in the wind maxima. Errors in the shape of the jet (that is, its length/width ratio) are present independent of the model’s resolution.

Apart from the length-width ratio, ECHAM5 also struggles with the representation of the spiral wind field structure found in ERA-40 (compare Fig. 4.2 d). Instead of the spiral, a more annular pattern is found in the ECHAM5 wind field. This can be observed clearly off the coast of Europe, where the separation between the Arabian and Atlantic wind velocity maxima is too small in the ECHAM5 simulations, especially at higher resolutions. Koch (2004) discusses the spiral wind field structure in the ERA-40 reanalysis and its dynamic relevance. It is related to double-jet configurations over the Atlantic, which could be less frequent in the ECHAM5 simulations than in the ERA-40 dataset.

Table 4.3: Root-Mean-Squared Error, Absolute and relative bias of the wind fields for the three ECHAM5 model simulations on the 330 K level.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>RMSE [m/s]</th>
<th>Relative bias [% of ERA-40]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHAM T42</td>
<td>2.84</td>
<td>5.8</td>
</tr>
<tr>
<td>ECHAM T63</td>
<td>2.61</td>
<td>6.4</td>
</tr>
<tr>
<td>ECHAM T106</td>
<td>2.38</td>
<td>5.6</td>
</tr>
</tbody>
</table>

4.2.2 The Extratropics

The wind velocity on the 310 K isentrope represents the extratropical jet stream. On the 310 K level, maxima of average wind velocity are found over the Pacific and Atlantic ocean (Fig. 4.5), where it reaches up to 40 m/s and 35 m/s, respectively. In addition to being slightly stronger, the Pacific jet also exceeds the Atlantic jet in zonal extent: the area with velocities above 30 m/s spans over about 90° of longitude for the Pacific jet, while the Atlantic jet only covers around 60° of longitude.

Three error dipoles can be observed in the bias fields displayed in Fig. 4.4: One over the eastern Pacific (off California), one over the central Atlantic (west of the Azores), and a weaker one over the Caspian region. In general, the errors are smaller than on the 330 K level, as average wind speeds are lower on the 310 K isentrope. As on 330 K, the errors over the Atlantic decrease significantly when model resolution surpasses T42, but simultaneously increase in the eastern Pacific.

Areas where the bias is very high represent locations where the 310 K - isentrope intersects the Earth’s surface during boreal winter, like central Africa, the Himalayas, and the Rocky Mountains. These biases are artifacts of the bias calculation.
After having discussed differences and similarities of the wind fields in ERA-40 and ECHAM5, we now examine potential temperature $\theta$ on the 850 hPa level together with its northward gradient. This field represents the baroclinicity in the middle tropopause, which might cause the observed wind patterns via the thermal wind relation. Fig. 4.6 shows the spatial distribution of $\theta$ (lines) and its meridional gradient in the ECHAM5 simulations and the ERA-40 reanalysis.
Some of the location shifts mentioned in section 4.2 reoccur in the baroclinicity field. For example, the positive wind velocity bias over the eastern Pacific is paralleled by a southward shift of the baroclinic zone over the eastern Pacific. The southward shift of the baroclinic zone is stronger in models of higher resolution, which might explain the stronger positive bias in wind velocity over the Pacific at higher resolutions.

Over the western Atlantic the situation is slightly more complicated as the baroclinic zone is both smaller and richer in small-scale features. In the ERA-40 dataset, high values of baroclinicity are found over
4.3. LOW-LEVEL BAROCLINICITY

Fig. 4.5: Wind velocity [m/s] in the ECHAM5 model simulations on 310 K in a DJF mean. The contour lines in panels a-c indicate the values from the ERA-40 reanalysis for easier comparison. Only the area with wind velocities above 20 m/s on the northern hemisphere is shown.

the Appalachians, with a "tongue" extending into the western Atlantic. Similar patterns are found in the ECHAM5 simulations, but the difference between Appalachian baroclinicity and baroclinicity over the ocean is less distinct. This could be connected to the representation of the Appalachian topography in ECHAM5. Most simulations show the same baroclinicity over the mountains and the ocean, and a baroclinic zone extending further south into the Atlantic. This increased southward extent parallels the existence of the positive bias of wind speed over the Atlantic near 30°N.
Fig. 4.6: Potential temperature $\theta$ [K] and its northward gradient ($\nabla\theta$ [K/1000 km]) in the ECHAM5 model simulations and ERA-40 baseline. Black lines indicate the contours of $\theta$, colors show the main baroclinic areas, where $\nabla\theta$ is high. The areas where the 850 hPa surface intersects the ground (Rocky Mountains, Himalayas, Greenland) show chaotic contour lines due to the averaging process.

### 4.4 PV Streamer Frequency

This section describes the climatological distribution of PV streamers on the northern hemisphere during boreal winter (DJF) on the 330K and 310K isentropes in the ERA-40 reanalysis and in the ECHAM5 model. Streamers on these levels are relevant for sub- and extratropical dynamics, respectively. Martius
(2005) discusses a PV streamer climatology obtained from the ERA-40 reanalysis. It highlights the
general features of the ERA-40 PV streamer climatology, like the climatological position of the streamers
on various isentropes. In the present study, a similar dataset is used as a baseline for the assessment of
ECHAM5 model performance. The slightly different streamer detection criterion used for the ERA-40
dataset, which has been mentioned in the section 3.3.1, might influence this analysis. However, first
investigations on the effect of the criterion suggest that this influence is minor.

4.4.1 The Subtropics

PV streamers on the 330 K isentrope influence convection and severe weather events in the subtropical
region (Funatsu and Waugh, 2008). Fig. 4.7 maps the streamer occurrence frequency for a climatological
DJF mean onto the northern hemisphere. It shows two maxima of streamer occurrence, one over the
Californian coast and one north of the Canary Islands. In the ERA-40 reanalysis these two maxima
are of similar shape, but there are more streamers north of the Canary Islands. The spatial extent of
the streamer frequency maximum can be approximated by the area where streamer frequencies exceed
5%. This area (colored in Fig. 4.7) is considerably smaller in the T42 simulation than in the ERA-40
dataset. As resolution reaches T63, the representation of the spatial extent of the maximum improves
considerably: While the zonal extent of the Atlantic maximum is overestimated by 15° at T63 and 30°
at T106 at its easterly edge, its meridional extent is very close to the one observed in ERA-40, with
errors on the order of one degree.

Fig. 4.8 shows absolute biases of streamer frequency. The T42 simulation produces about 33 % fewer
streamers than ERA-40 over the Atlantic, and over California negative biases exceed 50%. This negative
bias reduces almost to zero for the Atlantic maximum, and to about 33 % for the Californian maximum
in the T63 simulation. The representation of streamers over California further improves in the T106
simulation, but the modeling of the Atlantic streamer maximum by the T106 model is inferior to that
of the T63 simulation: streamer frequencies over the Atlantic basin are again underestimated by about
10%.

There are positive biases at the southeastern edges of the two streamer frequency maxima in the T63
and T106 simulations. Together with the concomitant negative biases over the northwestern edges of
the maxima, they indicate a south-easterly shift of the streamer frequency maxima in the model
simulations. A hint to this dipole can also be found in the bias field of the T42 resolution at the
southeastern edge of the Atlantic maximum. Also note the positive bias of the T106 simulation over
Central Asia and the Himalayas. In these regions, no streamers are found in the ERA-40 reanalysis.

Apart from the spatial distribution of PV streamers, it is also instructive to examine the size of the
individual streamers. A histogram of the PV streamer sizes illustrates this aspect of PV streamers in
the model (Fig. 4.9). Information on PV streamer size allows speculations on the cause of the observed
differences between ECHAM5 and ERA-40. Possible explanations are an increasing abundance of small
streamers, a slight increase in the number of modeled large streamers, a shift of the complete size
distribution to lower or higher values, or shifts in location only. The positive bias of the T106 simulation over Central Asia is apparently due to an increased number of small streamers in the model: Streamers with an area of less than $10^6 \text{ km}^2$ are overestimated by more than a factor of 2 in this dataset. This makes them a strong candidate for the positive bias over central Asia. We also observe that larger streamers apparently are easier to model: Streamers with sizes above $3 \times 10^6 \text{ km}^2$ show only a small positive bias, both in T106 and T63 resolution. In the T42 simulation the number of streamers is underestimated in all size categories. This creates the large negative bias discussed above and shown in figure 4.8. The number of small PV streamers increases with model resolution, a result that follows the rationale of more small-scale features at higher resolution. However, the negative bias in the T42 simulation is found across all sizes and might illustrate dynamical errors in the model, not only the effect of grid spacing.

4.4.2 The Extratropics

Extratropical cyclone and heavy precipitation activity is strongly influenced by PV streamers on the 310K isentrope (e.g. Massacand et al., 1998). Three maxima of streamer occurrence can be seen in Fig. 4.10: One each over the North-Eastern Pacific, Eastern Canada, and Eastern Europe. In the ERA-40 dataset, the maximum over Eastern Europe is strongest, followed by the Canadian streamer maximum. In the T42 run the streamer frequency maxima are located in the correct position, but the amplitude of the maxima is generally underestimated by 40%. As on the 330K isentrope, the streamer occurrence in T42 resolution does not match the distribution found in the ERA-40 reanalysis extremely well. The bias plots of streamer occurrence shown in Fig. 4.11 show a negative bias of up to 10% in T42 resolution at the western edge of the Pacific maximum and at the northern edge of the European occurrence maximum. This negative bias is substantially smaller at higher resolutions. The frequency maximum over Europe is modeled particularly well (∼3% negative bias) by the T106 simulation, while an underestimation of streamer frequency over the northern Pacific also persists at high resolutions.

The location of the Pacific streamer maximum seems to be more difficult to model than the Atlantic and European maxima, as there is a pronounced south-easterly bias in its location in all model datasets. Consequently, an error dipole develops in the Pacific and dominates the bias field of the T106 simulation (Fig. 4.11). This observation is in accordance with the south-easterly shift of the Eastern Pacific baroclinic region discussed in the previous section and the concomitant shift of the jet stream over the eastern Pacific discussed in section 4.2.2. These bias regions overlap with the positive streamer bias seen in Fig. 4.11. Streamers usually occur in the jet exit region, which is why a co-location of a streamer bias and a jet bias can be expected: as the jet extends farther to the east, the PV streamers occur in a more easterly position as well.

This point is emphasized by the small values of relative wind bias for the T63 and T106 simulations shown in Table 4.4: Overall mean deviation from ERA-40 is below 7% for these simulations. To interpret the above location shift, the size distribution of the PV streamers (Fig. 4.12) is helpful. It illustrates that the frequency of streamers in all size bins is underestimated by the T42 simulation on the 310K
Fig. 4.7: Absolute streamer occurrence in the ECHAM5 model simulations and ERA-40 baseline on 330 K during boreal winter (DJF). The contour lines in panels a-c indicate the values from the ERA-40 reanalysis for easier comparison. The plots show the area with non-zero values on the northern hemisphere.

The T63 and T106 simulations show streamer size distributions similar to the one extracted from the ERA-40 dataset, with a slight bias towards smaller streamers. As the size distributions are similar, we can infer that the negative biases discernible in Fig. 4.11 (b) and (c) are mainly due to location shifts, and not the result of a general lack of streamers in the model. This has implications for efforts to further improve the representation of PV streamers in ECHAM5: The modeled PV streamers are to the ones in ERA-40 in terms of their frequency (especially at T63 resolution). However, their location
Chapter 4. RESULTS

(a) T42L19  
(b) T63L31  
(c) T106L31

Fig. 4.8: Absolute bias of streamer occurrence in the ECHAM5 model simulations on 330 K during boreal winter (DJF). Contour lines indicate the area with streamer frequencies above 5 % in the ERA-40 dataset.

Fig. 4.9: Histogram of streamer sizes on 330 K in a DJF mean for the three ECHAM simulations, each with the ERA-40 baseline plotted in blue.

could be improved, in particular over the Pacific.

4.5 The Annual Cycle in PV Streamer Frequency

A graphic representation of the annual cycle of the number of detected PV streamers on an average day is presented in Fig. 4.13. For an explanation of the plotted values, compare Fig. 3.3 in the Methods section, which shows winter days with two PV streamers from the different ECHAM5 simulations. The panels for the T63 and T106 simulations in Fig. 3.3 correspond to a value of 2 in Fig. 4.13.

Fig. 4.13 clearly shows that all the simulations either over- or underestimate streamer counts with respect to the ERA-40 dataset. In general, the simulations using 31 vertical levels produce too many streamers, while the T42 simulation, using only 19 vertical levels, lacks more than 50% of streamers throughout the year. This observation extends our results found for the 330K and 310K isentropes to most of the near-tropopause isentropes.

On higher levels and during summer, a positive bias of up to a factor of 2 is found for the T63 and
4.5. THE ANNUAL CYCLE IN PV STREAMER FREQUENCY

Fig. 4.10: Absolute streamer occurrence in the ECHAM5 model simulations and ERA-40 baseline on 310K during boreal winter (DJF). The contour lines in panels a-c indicate the values from the ERA-40 reanalysis for easier comparison. The plots show the area with non-zero values on the northern hemisphere.

T106 simulations. This agrees with the magnitude of the Atlantic streamer maximum in the T63 and T106 simulations, which is shown in Appendix 7.4. On lower isentropic levels, the mid-summer break in streamer events is relatively well-represented by all simulations, but the mid-summer streamer break reaches too far upwards during July and August. In winter and on lower levels, agreement of the ECHAM5 simulations with ERA-40 is better, but there is a positive bias of streamer frequency at all levels below 330K in the T63 and T06 simulations.
Chapter 4. RESULTS

(a) T42L19  
(b) T63L31  
(c) T106L31

Fig. 4.11: Absolute bias of streamer occurrence in the ECHAM5 model simulations on 310 K during boreal winter (DJF). Contour lines indicate the area with streamer frequencies above 5 % in the ERA-40 dataset.

(a) T42L19  
(b) T63L31  
(c) T106L31

Fig. 4.12: Histogram of streamer sizes on 310 K in a DJF mean for the three ECHAM simulations, each with the ERA-40 baseline plotted in blue.

4.6 Fourier Decomposition of the PV Field

A decomposition of the Potential Vorticity field of ECHAM5 and ERA-40 into wavenumber 1-3 components was also performed. A Fast Fourier Transformation (FFT) calculated the contributions of these frequencies to the Potential Vorticity field. Section 7.5 in the Appendix shows the positive components of these fields. Here, I only present the amount of variance in the different wavenumbers (Table 4.5).

Apparently, the PV values in ECHAM5 are too high, as there is an overestimation of the field average (wavenumber 0) contribution. In wavenumber 3 , which is supposed to show the effects of orography on the Potential Vorticity field, the T42 overestimates the variance in this wavenumber, while the 31-level simulations (T63 and T106) show a smaller contribution of this wavenumber.
4.6. FOURIER DECOMPOSITION OF THE PV FIELD

Table 4.4: Root-Mean-Squared Error, absolute and relative bias of the streamer frequency fields for the three ECHAM5 model simulations on middle-world isentropes.

<table>
<thead>
<tr>
<th>Isentropic Level [K]</th>
<th>Resolution</th>
<th>RMSE [frequency * 100]</th>
<th>Relative bias [% of ERA-40]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T42</td>
<td>1.14</td>
<td>10.04</td>
<td></td>
</tr>
<tr>
<td>T63</td>
<td>1.03</td>
<td>-18.77</td>
<td></td>
</tr>
<tr>
<td>T106</td>
<td>1.05</td>
<td>-18.78</td>
<td></td>
</tr>
<tr>
<td>T42</td>
<td>2.47</td>
<td>-36.20</td>
<td></td>
</tr>
<tr>
<td>T63</td>
<td>1.32</td>
<td>-11.86</td>
<td></td>
</tr>
<tr>
<td>T106</td>
<td>1.33</td>
<td>7.32</td>
<td></td>
</tr>
<tr>
<td>T42</td>
<td>2.00</td>
<td>-42.35</td>
<td></td>
</tr>
<tr>
<td>T63</td>
<td>1.17</td>
<td>-11.20</td>
<td></td>
</tr>
<tr>
<td>T106</td>
<td>0.99</td>
<td>13.47</td>
<td></td>
</tr>
<tr>
<td>T42</td>
<td>1.52</td>
<td>-49.46</td>
<td></td>
</tr>
<tr>
<td>T63</td>
<td>0.88</td>
<td>-3.12</td>
<td></td>
</tr>
<tr>
<td>T106</td>
<td>0.80</td>
<td>6.87</td>
<td></td>
</tr>
<tr>
<td>T42</td>
<td>1.33</td>
<td>-44.04</td>
<td></td>
</tr>
<tr>
<td>T63</td>
<td>0.84</td>
<td>9.12</td>
<td></td>
</tr>
<tr>
<td>T106</td>
<td>1.06</td>
<td>6.56</td>
<td></td>
</tr>
<tr>
<td>T42</td>
<td>1.11</td>
<td>-33.26</td>
<td></td>
</tr>
<tr>
<td>T63</td>
<td>0.93</td>
<td>35.62</td>
<td></td>
</tr>
<tr>
<td>T106</td>
<td>1.15</td>
<td>31.62</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5: PV in different wavenumbers of the Fourier decomposition of the Potential Vorticity Field relative to the values in ERA-40.

<table>
<thead>
<tr>
<th>Wavenumber</th>
<th>ECHAM T42</th>
<th>ECHAM T63</th>
<th>ECHAM T106</th>
<th>ERA-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (mean)</td>
<td>1.47</td>
<td>1.44</td>
<td>1.46</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>1.14</td>
<td>1.13</td>
<td>1.12</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>1.06</td>
<td>0.99</td>
<td>1.04</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>1.31</td>
<td>0.86</td>
<td>0.97</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Fig. 4.13: Annual cycle of the average number of detected streamers per day in the ECHAM simulations and in the ERA-40 dataset.
Chapter 5

Summary and Discussion

In this chapter, we discuss the most relevant results from Chapter 4 and mention some caveats of our approach at examining the dynamics of ECHAM5. The most relevant results are repeated and some differences are reported more quantitatively. Wind velocity and baroclinicity are discussed first, followed by the PV streamers in the model. An account of the limitations of our approach ends this chapter.

5.1 Wind Velocity and Baroclinicity

The wind velocity fields from different simulations (section 4.2) suggest that increasing model resolution of ECHAM5 enhances the model’s capabilities to represent spatial wind fields. The dynamics of ECHAM5 show patterns similar to ERA-40 in most regions, especially at higher resolutions. Roeckner et al. (2004), who examine the sensitivity of ECHAM5 model output to horizontal and vertical resolution, conclude that the zonal mean wind in ECHAM5 agrees well with ERA-40, especially at higher resolutions. Our analysis underlines the positive effect of higher horizontal and vertical model resolutions, as we find similar results for mean wind velocities mapped onto the northern hemisphere.

An equatorward shift of the jet stream on the northern hemisphere is found in the present study. It is most prominent over the Atlantic and European sectors, where the position of the wind speed maximum on the 310K isentrope is shifted by about 3°S at all tested model resolutions. The 20 m/s isotach deviates by up to 10°S at T42 resolution. While the width of the jet is represented better at T63 and T106, the southerly shift in the jet maximum persists. This explanation is not readily available for the T63 and T106 simulations, where the 310 and 330K isentropes intersect the tropopause at latitudes comparable to ERA-40.

In addition to the southerly shift, there is a general eastward bias of the sub- and extratropical wind maxima by about 4°E and 2°E, respectively. This longitudinal shift could only be detected when inspecting horizontal cross-sections of wind velocity, as zonal averaging prohibits the detection of longitudinal shifts. The observed shift might be explained by the south-easterly shift of the main baroclinic zone in the eastern Pacific of ECHAM5. At higher model resolutions, the shift of the main baroclinic
zone is more pronounced, and might foster the positive wind bias at the eastern edge of the Pacific jet by means of the thermal wind (Fig. 4.4). Over the Atlantic, the picture is less conclusive because the smaller scales of the baroclinic zone and the Appalachian orography influence the baroclinicity in this region. To clarify the origin of the wind biases of ECHAM5 over the Atlantic, further analyses of the wind fields are therefore necessary. These should take the state of the North-Atlantic Oscillation in the model into account, as it strongly influences wind fields over the Atlantic.

5.2 PV Streamer Frequency

Turning to the climatological distribution of PV streamers, we conclude that smaller deviations than initially expected have been found. Both in ECHAM5 and ERA-40, the streamers are found near the climatological jet exit regions. Similar results have also been presented for the NCEP reanalysis by Peters and Waugh (1996). Waugh and Polvani (2000) use a different method to identify streamers in their PV streamer climatology, and also find that the streamer events usually occur in regions where the jet position is highly variable.

We also find some pronounced differences between the ERA-40 and ECHAM5 streamer distributions. A hot spot for streamer errors is the Eastern Pacific, where a shift in jet stream and baroclinic zone location have also been observed. The overlap between the wind and streamer bias fields emphasizes the physical connections between these variables. On the 310K level, a positive bias of about 25% (relative to the Pacific streamer frequency maximum in ERA-40) is found over the eastern Pacific in the T106 simulation, together with a negative bias of similar magnitude over the western Pacific (Fig. 4.11). A south-easterly shift of the Pacific PV streamer frequency maximum by about 10° in the T106 simulation produces this error dipole. This shift is a substantial model error.

Only the T106 simulation overestimates the magnitude of the streamer frequency maximum over the Pacific, but a location shift can be found both in the T63 and the T42 simulations. This suggests that a south-easterly shift of the Pacific streamer maximum with respect to ERA-40 is a robust feature of the ECHAM5 model.

The PV streamer distribution on 330K presents a similar picture, but the location shift is smaller and there is no overestimation of the frequency maximum.

5.3 Limitations of the approach

Some limitations of our approach of identifying PV streamers and jet biases in the ECHAM5 model dynamics demand discussion. The first caveat of the analysis is the different nature of the datasets as far as the non-atmospheric forcings are concerned. Greenhouse gas concentrations, solar irradiance, sea-surface temperature (SST) and land-use change all are prescribed for the ECHAM5 model. Aerosols are calculated with the Hamburg Aerosol Module (HAM), which is coupled to ECHAM5. The model
forcings contain a statistic variability of Sea-Surface Temperatures generated by the Hadley Centre Atmosphere-Ocean Coupled GCM. This dataset does not contain the rise of the NAO index throughout the 1990’s observed in the ERA-40 dataset. Therefore, there might be a bias towards more split jet configurations and more storms over central Europe in the ERA-40 dataset during the last decades of the 20th century. Simulations using observations as boundary conditions, rather than randomized forcing, would be useful to examine whether this type of error is the origin of some of the jet and streamer biases found. Alternatively, years with positive and negative NAO indices in ECHAM5 could be analyzed for their streamers, which would allow to find out about the connection between NAO and PV streamers in ECHAM5. Comparing climatologies across years with positive and negative NAO separately will be helpful to find out whether the observed biases are due to modeling deficiencies or due to different forcings.

One possible reason for the large increase in model performance when going from a T42 model to a T63 model is the smaller number of vertical levels used in the T42 simulation. In the first step towards identifying PV streamers, Potential Vorticity has to be calculated from static stability and relative vorticity. As the definition of static stability contains the derivative of potential temperature with respect to pressure, a model with 19 vertical layers will almost necessarily show less exact values for static stability than a 31-layer model. As the difference between the 19-layer model and the 31-layer models is very large for all PV streamer frequency plots, this might be one source of pronounced difference.

As far as the choice of the "close encounter" parameter (CEP) is concerned (see section 3.3.1), we can say that the influence on the climatological fields of PV streamer occurrence is minor, but that the streamer sizes vary significantly with the choice of this parameter. We possess data on streamer frequencies from the ERA-40 dataset with CEP=1500 km and CEP=2000 km. While the PV streamer frequency plots are fairly similar for the two datasets, there is a shift to smaller streamer sizes and higher streamer numbers when the CEP is reduced to 1500 km. Histograms, streamer frequency plots and the annual cycle in streamer number for the old CEP value of 2000 km are shown in Appendix 7.6 for the ERA-40 dataset. From this comparison we conclude that the PV streamer frequency distribution is fairly robust with respect to the CEP, but that streamer sizes and numbers are influenced by it.
Chapter 6

Conclusions and Outlook

This study aimed at examining the dynamic capabilities of the Global Climate Model ECHAM5 in the light of Potential Vorticity streamers it produces and wind biases it shows. We examined to which degree the Potential Vorticity streamers in ECHAM5 are comparable to those in the ERA-40 dataset, thereby also assessing its value for providing boundary conditions to smaller-scale models.

We conclude that the ECHAM5 model is good at capturing important dynamical features at spectral resolutions of T63 and T106. Apart from this general conclusion, the core results of this study are:

- Northern hemisphere jets in the ECHAM5 GCM show a southeasterly bias compared to the ERA-40 dataset
- PV streamer location is represented significantly better in the T63 and T106 simulations than in the T42 simulation
- All ECHAM5 simulations show a south-easterly shift of PV streamer frequency over the Pacific, while the Atlantic streamers are represented well by the T63 and T106 simulations

PV streamer climatologies provide a useful aggregate measure of model output quality from the dynamic viewpoint, and therefore are useful for the assessment of climate models. An extension of this study to other GCMs would therefore be desirable when evaluating model differences. The next step in this project will be to extend this analysis to the full time period available from the ECHAM5 runs, which extends until 2049. By doing so, we hope to forecast extreme precipitation events in the Alpine region during the next decades. Also, a streamer climatology taking the different lifecycles of baroclinic waves into account will be helpful to examine the effects of the streamers on precipitation events on the northern hemisphere.
Acknowledgements

References


Chapter 7

Appendix

7.1 Temporal development of a streamer over North America in the ECHAM T106 simulation
Fig. 7.1: Breakup of a large PV streamer over North America over four consecutive days in the ECHAM5 T106 simulation.
7.2 RMSE and Relative Bias of Wind Velocity

Table 7.1: Root-Mean-Squared Error, absolute and relative bias of the wind velocity fields for the three ECHAM5 model simulations on middle-world isentropes. Large values of RMSE on the low isentropes are the result of NaN values at locations where the isentrope frequently intersects Earth’s surface.

<table>
<thead>
<tr>
<th>Isentropic Level [K]</th>
<th>Resolution</th>
<th>RMSE [frequency * 100]</th>
<th>Relative bias [% of ERA-40]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>T42</td>
<td>102.43</td>
<td>-0.08191</td>
</tr>
<tr>
<td></td>
<td>T63</td>
<td>110.31</td>
<td>0.63252</td>
</tr>
<tr>
<td></td>
<td>T106</td>
<td>86.311</td>
<td>0.48945</td>
</tr>
<tr>
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7.3 Wind Velocity on the 350 K Isentrope
Fig. 7.2: (a)-(d): Wind velocity [m/s] in the ECHAM5 model simulations on 350 K in a DJF mean. The contour lines in panels a-c indicate the values from the ERA-40 reanalysis for easier comparison. The plots show the area with values above 20 m/s on the northern hemisphere. (e)-(g): Absolute bias of wind velocity [m/s] in the ECHAM5 model simulations and ERA-40 baseline on 350 K in a DJF mean. A contour line indicates the area with wind velocities above 20 m/s in ERA-40.
7.4 PV Streamer Frequency on the 350 K Isentrope
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Fig. 7.3: (a)-(d): Absolute bias of streamer occurrence in the ECHAM5 model simulations on 330 K during boreal winter (DJF). Contour lines indicate the area with streamer frequencies above 5% in the ERA-40 dataset. (e)-(g): Absolute bias of streamer occurrence in the ECHAM5 model simulations on 330 K during boreal winter (DJF). Contour lines indicate the area with streamer frequencies above 5% in the ERA-40 dataset.
7.5 Decomposition of the PV field by FFT transformation

Fig. 7.4: Positive components of the wavenumber 1 contributions in a Fourier Decomposition of the mean DJF Potential Vorticity field in ECHAM5 and ERA-40.
Fig. 7.5: Positive components of the wavenumber 2 contributions in a Fourier Decomposition of the mean DJF Potential Vorticity field in ECHAM5 and ERA-40.
Fig. 7.6: Positive components of the wavenumber 3 contributions in a Fourier Decomposition of the mean DJF Potential Vorticity field in ECHAM5 and ERA-40.
Fig. 7.7: Mean DJF Potential Vorticity field in ECHAM5 and ERA-40.
7.6 Streamer frequency on 330 K and Annual Cycle of streamer number for the choice of CEP = 2000 km in the ERA-40 dataset
Fig. 7.8: Plots from the ERA-40 PV streamer climatology using the old CEP value of 2000 km.