Atmospheric circulation regimes and climate change

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Abstract

The Earth's atmosphere is expected to warm in response to increasing atmospheric concentrations of greenhouse gases (GHG). The response of the Earth's complex and chaotic climate system to the GHG emissions is, however, difficult to assess. In this thesis, two issues of importance for the assessment of this response are studied. The first concerns the magnitude of the natural and anthropogenic emissions of CO_2. An atmospheric transport model is used, combined with inventories of anthropogenic CO_2 emissions and estimates of natural emissions, to compare modelled and observed variations in the concentration of CO_2 at an Arctic monitoring site. The anthropogenic and natural emissions are shown to exert approximately equal influence on Arctic CO_2 variations during winter.

The primary focus of this thesis is the response of the climate system to the enhanced GHG forcing. It has been proposed that this response may project onto the leading modes of variability. In the present thesis, this hypothesis is tested against the alternative that the spatial patterns of variability change in response to the enhanced forcing. The response of the atmospheric circulation to the enhanced GHG forcing as simulated by a specific coupled global climate model (CGCM) is studied. The response projects strongly onto the leading modes of present-day variability. The spatial patterns of the leading modes are however changed in response to the enhanced GHG forcing. These changes in the spatial patterns are associated with a strengthening of the waveguide for barotropic Rossby waves in the Southern Hemisphere. The Northern Hemisphere waveguide is however unchanged.

The magnitude of the global mean responses to an enhanced GHG forcing as simulated by CGCMs vary. Moreover, the regional responses vary considerably among CGCMs. In this thesis, it is hypothesised that the inter-CGCM differences in the spatial patterns of the response to the enhanced GHG forcing are partially explained by inter-CGCM differences in zonal-mean properties of the atmospheric flow. In order to isolate the effect of these differences in the zonal-mean background state from the effects of other sensitivities, a simplified model with idealised forcing is employed. The model used is a global three-level quasi-geostrophic model. The sensitivity of the stationary wave pattern (SWP) to changes in the zonal-mean wind and tropopause height of similar magnitude as those found in response to the enhanced GHG forcing in CGCMs is investigated. The SWP in the simplified model shows a sensitivity of comparable magnitude to the analogous response in CGCMs. These results indicate that the CGCM-simulated response is sensitive to relatively small differences in the zonal-mean background state. To assess the uncertainties in the regional response to the enhanced forcing associated with this sensitivity, ensemble simulations of climate change are of great importance.

Contents

List of Papers

This thesis consists of a summary and the following four papers, which will be referred to by their Roman numerals:

I **Anthropogenic and biogenic winter sources of Arctic CO2 - a model study.**

J. Brandefelt and K. Holmén

Tellus, **53B**, 10-21, 2001.

II **The response of the Southern Hemisphere atmospheric circulation to an enhanced greenhouse gas forcing.**

J. Brandefelt and E Källén

J. Clim., **17**, 4425-4442, 2004.

III **The response of the Northern Hemisphere atmospheric circulation to an enhanced greenhouse gas forcing.**

J. Brandefelt

Report DM–95, 2005.

IV **The sensitivity of the Northern Hemisphere stationary wave pattern to the background state.**

J. Brandefelt

Manuscript.

Chapter 1

Introduction

Greenhouse gases, such as water vapour, carbon dioxide (CO_2), and methane (CH_4), are natural components of the Earth's atmosphere. The absorption of long wave radiation by these gases makes a difference of more than $+30^oC$ for the mean temperature at the Earth's surface. The atmospheric concentrations of these gases exhibit large amplitude variations over all timescales, from day-to-day variations up to the age of the planet. However, to find the equivalent of the magnitude of the CO_2 increase during the last two centuries as well as the relatively high concentration of today, we have to go back more than 400,000 years in time (Petit et al. 1999). There is a broad agreement today on the cause of these changes, i.e. that man-made (anthropogenic) emissions of CO_2 are the cause of the increase during the twentieth century (IPCC 2001).

The global mean surface temperature has increased by about 0.6^oC during the twentieth century (IPCC 2001). Further, in response to the increasing atmospheric greenhouse gas concentrations, the global mean surface temperature is expected to rise by 1.4–5.8°C over the period 1990–2100 (IPCC 2001). This estimate is obtained from integrations with different numerical models of the atmosphere-ocean system and with different scenarios for the future CO_2 emissions. These coupled global climate models simulate the response of the climate system to an increasing radiative forcing. The forcing originates from different estimates of the future atmospheric concentrations of greenhouse gases and, in some cases, for the predicted future concentrations of aerosols. This thesis deals with two issues of importance for an improved assessment of the effects of the increasing GHG forcing on the Earth's climate, viz. the magnitude of the emissions of CO_2 (Paper I), and the response of the climate system to an increasing GHG forcing (Papers II-IV).

1.1 Emissions of CO_2

The atmospheric concentrations of greenhouse gases are not only dependent on the anthropogenic emissions of these gases. Release of CO_2 from soils as well as deforestation and uptake of CO_2 by the oceans as well as growing plants are important in connection with the anticipated increases of CO_2 due to increased anthropogenic emissions. However, measurements of the rates of photosynthesis, respiration and decomposition made throughout the year and over large areas are sparse. Different approaches to this problem exist. Fung et al. (1987) derive the seasonal exchange of CO_2 between the atmosphere and the terrestrial biosphere using satellite measurements of radiance and field data of soil respiration. Another approach is to use existing measurements to parameterise the exchange of CO_2 between the atmosphere and the terrestrial biosphere. This parameterisation can be coupled to an atmospheric general circulation model to obtain the net flux from the terrestrial biosphere.

In Paper I, a three-dimensional atmospheric transport model is used to compare modelled and observed variations in the concentration of CO_2 over synoptic timescales at Mt. Zeppelin, Ny-Ålesund, Spitsbergen. Inventories of anthropogenic CO_2 emissions and estimates of biogenic emissions are used to investigate the impacts of these emissions on Arctic CO_2 variations during four winter months. This type of investigation can help to quantify the exchange of CO_2 between the atmosphere and the terrestrial biosphere. The possibility of weaknesses in the anthropogenic emission inventories, indicated by earlier results (Engardt and Holmén 1999), is also considered.

1.2 Climate system response

The atmospheric circulation and its possible changes due to an increasing GHG forcing is the focus of Papers II-IV. The effects of increased concentrations of aerosols are less well known, and thus this thesis mainly deals with the effects of the increasing concentrations of atmospheric greenhouse gases. To assess possible GHG-induced changes in the atmospheric circulation we need to take into account the interaction of the atmosphere and its boundaries, viz. the land and ocean surface. The state of these boundaries is partially determined by the state of the lower atmosphere, e.g. by the temperature, but also by internal processes in the oceans (including sea ice) and in soils, glaciers, etc. Thus, in order to assess GHG-induced changes of the atmospheric circulation it is essential to take all these interactions into account. Coupled global climate models (CGCMs) attempt to model the present-day climate and the response to changes in the forcing of the climate system, taking the interactions between the various components of the climate system into account. In these models, the equations of atmospheric and oceanic motion are discretized and coupled to parameterisations of physical processes (e.g. clouds).

The IPCC (2001) estimate of the expected increase in the global mean surface temperature is based on simulations with a number of such CGCMs. These simulate the effects of an increased radiative forcing which originates from different estimates of the future atmospheric concentrations of greenhouse gases and, in some cases, of the future concentrations of aerosols. The uncertainty interval in the global mean warming is a consequence of both uncertainties in the future emissions and of differences between models forced with the *same* GHG concentration changes. The origin of these differences in the simulated response to a particular forcing scenario is thus found both in the internal variability of the climate system and in model differences.

Regional climate changes can be much larger than the global-mean responses and are therefore likely to have larger consequences. Unfortunately, the regional responses in different CGCM simulations vary even more than the global mean responses. In order to improve the assessment of the climate system's response to enhanced GHG forcing, a better understanding of the dynamics of the change is needed. The stronger forcing affects the mean state and the variability of the climate system, the latter quantity being physically coupled to the mean state and hereby responding to changes in the mean state. The aim of this thesis is to try to establish physically-based connections between the mean-flow response and the regional response, with focus on the mid-latitudes.

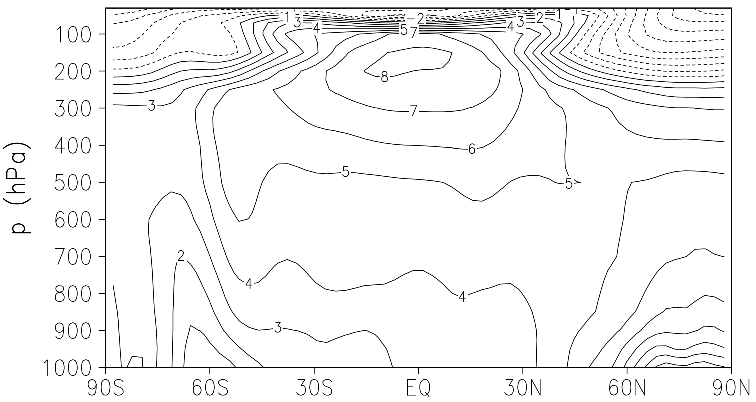
1.3 The mean response

A specific transient greenhouse warming integration is studied in Paper II-IV. The increase of the global mean temperature in this simulation is close to the mean of those in current CGCM simulations. To investigate connections between the mean-flow response and the regional response in mid-latitude variability, it is necessary to define what is meant by "the mean flow response".

The zonal-mean temperature response for NH winter (December–February), as simulated by this CGCM, is shown in Figure 1.1. The direct effect of the enhanced GHG forcing is a heating of the climate system due to the absorption of the increased thermal radiation. This increased thermal radiation is mainly absorbed at the Earth's surface, where the heating is larger over land than over ocean. The heating at the surface is redistributed by dynamical processes in the atmosphere (and oceans) such as convection, baroclinicity, winds and ocean currents. The larger warming over land than over ocean results in a zonal-mean meridional gradient in the heating response with a minimum over the Southern Ocean. This means that the surface temperature gradient is increased north of 60°S in the Southern Hemisphere (SH) and *decreased* in the Northern Hemisphere (NH). In the upper levels however, the pole-to-equator temperature gradient is increased for both hemispheres. This is associated with an increase in the upper-level wind (also shown in Figure 1.1) in agreement with the thermal-wind balance. In the SH, the zonal-mean wind maximum is shifted towards the pole throughout the troposphere and lower stratosphere. However, in the NH, the response of the zonal-mean wind is confined to the upper levels.

In CGCM simulations this increase in the zonal-mean upper level wind and temperature gradient is a common signature of the response to an enhanced GHG forcing (Räisänen 2003). Increases in tropospheric GHG concentrations and decreases in stratospheric ozone are expected to result in a heating of the troposphere and a cooling of the stratosphere (Hoskins 2003). Since the tropopause height decreases from the subtropics to high latitudes, the temperature gradient at a particular pressure level is therefore expected to increase. As a further result, a heightening of the tropopause level during the 21st century is expected (Santer et al. 2003). Increases in tropopause height are also identified in observations over the past decade (Hoinka 1998, Seidel et al. 2001, Randel and Gaffen 2000, Highwood et al. 2000). These results indicate that the zonal-mean response in CGCMs is more robust

a. zonal mean temperature



b. zonal mean wind

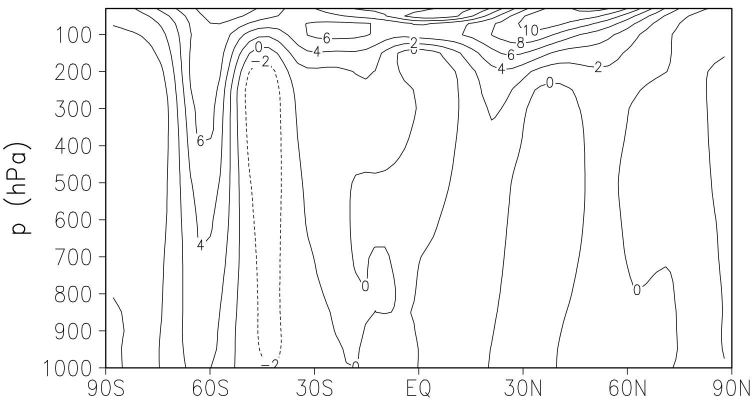


Figure 1.1: Zonal mean (a) temperature and (b) wind response (years 2070–99 minus years 1860–89) in a transient integration with the ECHAM4/OPYC3 CGCM for NH winter. Units are (a) Kelvin and (b) ms^{-1}.

than the regional response (which varies widely among CGCM simulations with the same forcing). Therefore, in this thesis, the response to the enhanced GHG forcing is decomposed into the zonal mean and deviations from the zonal mean, whereafter physical connections between the zonal-mean response and the spatial patterns of the response are sought.

The zonal asymmetries in the large-scale atmospheric circulation are of great importance for the regional climate. Therefore, focus is on the spatial patterns of the response of the large-scale atmospheric circulation to the enhanced GHG forcing. In mid-latitudes, the large-scale flow is primarily determined by the geostrophic balance between the pressure gradient force and the Coriolis force. The response in the wind and the pressure (or geopotential height) are therefore tightly linked. In Paper II–IV, the response in geopotential height is studied. The spatial pattern of the zonally asymmetric component of the response to the enhanced GHG forcing in geopotential height is more or less unchanged with altitude in both winter and summer in both hemispheres in the CGCM simulation. The response at high altitude

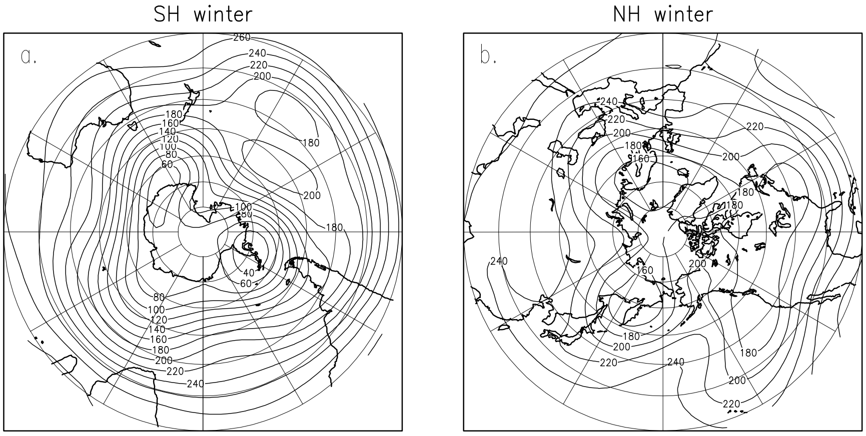


Figure 1.2: The mean response in the (a) SH winter and (b) NH winter response in the geopotential height at 200 hPa. Units are geopotential meters.

is stronger and more significant.

The response in the geopotential height at 200 hPa is shown for SH winter (June–August) and NH winter (December–February) in Figure 1.2. The SH response in the geopotential height has a zonal wave number equal to 3. The NH response also exhibits a strong zonally asymmetric component. Possible physical connections between the zonal-mean component and the zonally asymmetric component of the response to the enhanced GHG forcing in the SH (Paper II) and in the NH (Paper III) are sought. In Paper IV, an investigation of the importance of differences in the zonal-mean state for the spatial patterns of the response to the enhanced GHG forcing is undertaken. In order to isolate the effects of differences in the zonal-mean state of the atmosphere from the effects of other inter-CGCM differences (such as differences in the parameterised physical processes) a simplified model with idealised forcing is used.

Chapter 2

Sources of Arctic CO_2

In order to assess possible changes in the Earth's climate forced by the expected increase in CO_2, a good understanding of the carbon cycle is necessary. CO_2 is emitted to the atmosphere, not only due to fossil fuel and biomass burning, but also as release from soils and deforestation. Other natural processes, such as uptake by growing plants and the oceans, also affect the atmospheric CO_2 concentration. The natural (biogenic) emissions and uptake of CO_2 are not well known.

In Paper I of this thesis, biogenic and anthropogenic emissions of CO_2 in winter are studied. The aim is to study the relative importance of these emissions for the observed atmospheric concentration of CO_2 at an Arctic monitoring station (Mt. Zeppelin, Spitsbergen). The station is located approximately 1000 kilometres from the nearest human activities of size, in a location characterised by glaciers and sparse vegetation. The observed CO_2 levels may therefore be considered representative of background conditions. The study is performed using a three-dimensional atmospheric tracer transport model in combination with inventories of anthropogenic emissions and estimates of biogenic emissions of CO_2. In this rather indirect way, the validity of the estimates of the winter biogenic emissions may be judged.

2.1 Atmospheric tracer transport

To simulate paths taken by the CO_2 from the primarily continental areas of emission to the Arctic monitoring station, the regional tracer transport model MATCH (1999) is used. The relatively high horizontal resolution of this model makes it feasible to study sources and sinks of CO_2 on regional and continental scales. The model makes use of the assimilated atmospheric circulation fields during the period when the observations were made. In this sense, an off-line model has an advantage as compared to on-line models, which determine their own atmospheric flow. Further, due to the chaotic nature of atmospheric flow, on-line models without continuous data assimilation should not be used for long simulations.

A complementary way of using archived atmospheric circulation fields to assess the path taken by air masses that arrive at, or depart from, a given location at a given time is three-dimensional trajectories. These may be used to provide an indication of the path taken by a particular air parcel. In Paper I, five-day back-trajectories arriving at the Arctic monitoring station (McGrath 1989), are used to indicate the source of the air arriving at the station.

2.2 CO_2 emissions

The synoptic variations of CO_2 at Mt. Zeppelin are modelled using two different estimates of biogenic emissions and three different inventories of anthropogenic emissions. Two of the anthropogenic source functions describe CO_2 emissions (Andres et al. 1996; Olivier et al. 1996). The third is obtained from a linear scaling of a global distribution of anthropogenic sulphur (sulphur dioxide and sulphate; SO_x) emissions (Benkovitz et al. (1996)). In an earlier study, Engardt and Holmén (1999) used the MATCH model to determine which anthropogenic sources are important for the observed CO_2 at Mt. Zeppelin. They used this scaling of the sulphur emissions to test the influence of the geographical distribution of the emissions in the Andres et al. (1996) inventory. Engardt and Holmén (1999) found that the amplitude of the modelled CO_2 variations is consistently too low, as compared to the observations, and two alternative explanations for this discrepancy are explored in Paper I; weaknesses in the anthropogenic emission inventory and omission of biogenic CO_2 emissions.

2.3 Results

The main conclusions of Paper I are well summarised in Figure 2.1, where the observed and modelled concentration of atmospheric CO_2 at Mt. Zeppelin are shown for February 1993. The modelled concentrations from anthropogenic and biogenic emissions are shown separately. The biogenic sources account for 61% of the variations in the concentration during this month. As noted by Engardt and Holmén (1999), the Ob-Norilsk region plays an important role for the variations during this month when the scaled SO_x emissions are used. However, using the inventories of anthropogenic CO_2 emissions, this region accounts for only 1% of the total modelled anthropogenic CO_2.

The variations in the modelled CO_2 concentration at Mt. Zeppelin due to biogenic and anthropogenic emissions are well correlated. This can be explained by the similarities of the source regions and the strengths of these emissions. In the absence of major local sources, the Arctic CO_2 concentration is primarily determined by the transport to this region of CO_2 emitted elsewhere. Also shown in Figure 2.1 is the number concentration of condensation nuclei. Due to the covariation between CO_2 of anthropogenic and biogenic origin, the covariation between anthropogenic variations of CO_2 and the aerosol particle scattering coefficient (used by Engardt and Holmén 1999) or the number concentration of condensation nuclei can not be used to exclude biogenic sources of the variations in the observed CO_2 concentration.

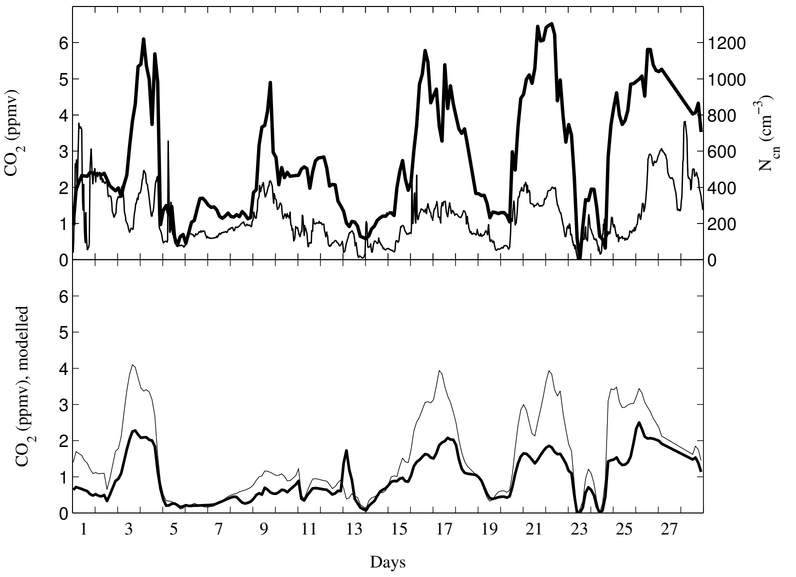


Figure 2.1: February 1993. Upper panel: The observed CO_2 concentration (heavy line) and the number concentration of condensation nuclei (weak line). The background variation of the observed concentration has been subtracted from the observed concentration. Bottom panel: The modelled concentration of CO_2 using anthropogenic emissions (heavy line) and biogenic emissions (weak line).

We conclude that the biogenic emissions of CO_2 affect the Arctic CO_2 concentration during winter. We further conclude that the dominating anthropogenic source region for the synoptic variations of CO_2 at Mt. Zeppelin is Europe, and find no indications of the lower-Ob area having a large impact on Arctic CO_2 concentration. The sum of the anthropogenic and biogenic emissions used in this study yield an amplitude of the same order as that observed at Mt. Zeppelin, and generally the timing is remarkably good. This shows that the model, used together with the anthropogenic and biogenic source functions, is a useful tool for investigating the transport of CO_2 from lower latitudes into the Arctic.

Chapter 3

The leading modes of variability

The atmospheric circulation is governed by a set of non-linear partial differential equations. Due to the non-linearities the system is chaotic, i.e. starting from two almost identical initial states the system evolves into two completely different states given sufficient time. For the atmospheric circulation the limit beyond which the circulation is inherently unpredictable is approximately two weeks (Lorenz 1969). However, the climatological state does not suffer from this "weakness" and is therefore predictable on long timescales, a results that makes it possible to use CGCMs to assess the response of the climate system to an enhanced GHG forcing.

The enhanced GHG forcing affects the mean state and the variability of the climate system. The variability is physically coupled to the mean state and may respond also to changes of the mean state. Using various statistical methods, the leading modes of variability may be determined. These modes represent characteristic spatial patterns of deviations from the mean state in e.g. sea level pressure or surface temperature. The first modes of variability in the NH and SH sea level pressure are what are known as the Arctic and Antarctic Oscillations. These are often referred to as the annular modes (Limpasuvan and Hartmann 1999) due to their significant zonal-mean components. Several papers have reported trends in the behaviour of the Antarctic Oscillation (AAO; Thompson et al. 2000; Marshall 2003) and the Arctic Oscillation (AO; Thompson et al. 2000; Feldstein 2002; Frauenfeld and Davis 2003; Ostermeier and Wallace 2003) over the past few decades. The trends indicate a change in the frequency of occurrence of the spatial patterns of these modes. The observed trends further lends support to the argument that the spatial patterns of the response to anthropogenic forcing may project onto modes of natural climate variability (Palmer 1999).

A trend in the AAO is also found in many transient greenhouse warming integrations (Fyfe et al. 1999; Kushner et al. 2001; Stone et al. 2001; Cai et al. 2003). For the NH, the modelled response of the AO in transient greenhouse warming integrations varies between different CGCMs. Selten et al. (2004) use an ensemble of 62 climate model simulations over the period 1940–2080 based on the same model. They find that the trend in the NAO during the past decade is largely an expression of a random, internal climate variation. Kuzmina et al. (2005) compare the trend in the AO from twelve CGCMs participating in the CMIP2. Contrary to Selten et al. (2004), they find that the recent trend in the North Atlantic Oscillation (NAO; the leading mode of variability for the North Atlantic sector, where it resembles the AO) lies beyond the natural variability in the control integrations (i.e. integrations where the GHG forcing is held constant).

The hypothesis that the response to anthropogenic forcing projects onto modes of natural variability implies that the modes of variability do not themselves change in response to the forcing. The alternative to this hypothesis of unchanged flow regimes is that the geographical structure of the flow patterns is altered in response to the forcing. Changes in the mean climate in response to anthropogenic forcing may entail changes in the geographical structure of the flow patterns.

The response of the NH and SH atmospheric circulation to an enhanced GHG forcing is studied in Paper II and III of this thesis. The aim of these studies, using a transient integration of a coupled global climate model (CGCM), is to try to establish physically-based connections between the mean flow response to an enhanced GHG forcing and the response of extratropical variability. The possibility that the response to anthropogenic forcing projects onto modes of natural variability is evaluated. In particular the plausible inference that the spatial patterns of the leading modes remain unchanged is evaluated. The results of this evaluation are briefly presented here, possible physically-based explanations for these results are presented in chapter 4.

3.1 The leading modes of variability in a changing climate

The leading modes of variability are determined using Empirical Orthogonal Function (EOF) analysis (i.e. principal component analysis). This is a statistical method used to determine the most frequent spatial patterns representing the largest amounts of variability around the mean. In Paper II, the SH response to the enhanced GHG forcing is shown to project strongly onto the leading modes of variability. However, inspection of the spatial patterns of these leading modes of variability shows that the spatial patterns of the modes change in response to the enhanced GHG forcing. The first and second EOF of SH winter (June–August) inter-weekly variability in geopotential height at 200 hPa is shown in Figure 3.1 for the unperturbed (1860–89) and perturbed (2070–99) period. The spatial patterns of the EOFs of geopotential height at 200 hPa for the years 2070–99 are similar to those of the EOFs for the years 1860–89 over the southern Pacific and the southwestern Atlantic Oceans. However, the patterns differ substantially in the Eastern Hemisphere. The spatial patterns of the EOFs resemble large-scale Rossby waves and therefore the explanation for the changes in the spatial patterns of the leading modes is sought in Rossby wave theory. This is discussed in chapter 4.

The spatial patterns of the leading modes of NH winter (December–February) variability are also changed in response to the enhanced GHG forcing. Again, the spatial patterns of the EOFs resemble large-scale Rossby waves and therefore the explanation for the changes in the spatial patterns of the leading modes is sought in Rossby-wave theory.

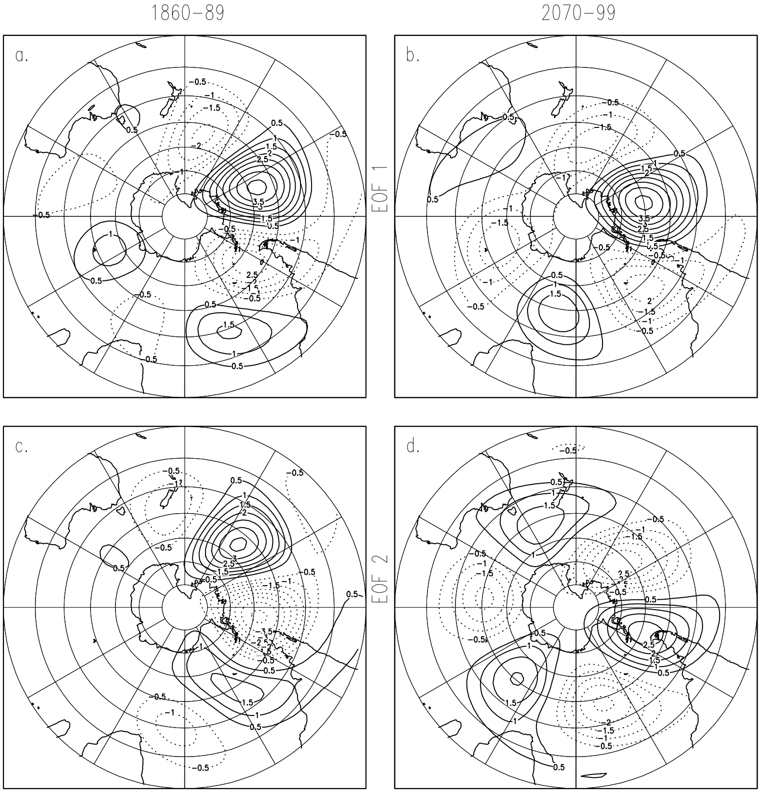


Figure 3.1: The (a,b) first and (c,d) second EOF of inter-weekly variability in SH winter geopotential height at 200 hPa for the years (a,c) 1860–89 and (b,d) 2070-2099.

The results shown in Paper II and III indicate that not only the frequency of occurrence of the leading modes of variability, but also the spatial patterns of these modes can change in response to an enhanced GHG forcing. The hypothesis that the response to anthropogenic forcing projects onto modes of natural variability is based on the results from studies of non-linear systems with a few degrees of freedom. The number of degrees of freedom characterising the Earth's climate system is, however, many orders of magnitude larger. In order to interpret the results of CGCM simulations of this complex, chaotic system, simplifications (from theory and less complex models) are necessary. The ideas that emerge from studies of "simple" non-linear systems are appealing and provide a means of interpreting CGCM results. However, we must look at climate change as simulated by the CGCMs from different angles to get a more complete picture.

Chapter 4

Rossby wave dispersion

The spatial patterns of the EOFs of geopotential height at 200 hPa in the SH (Fig. 3.1) and NH resemble large-scale Rossby waves. Therefore, the explanation for the changes in the spatial patterns of the EOFs is sought on the basis of Rossby-wave theory. These changes are similar to those in the stationary wave pattern found in a study with a far less complicated model than the CGCM used here. Yang et al. (1997) present results from a study of the existence of spherical resonance i a two-layer, high-resolution, quasi-geostrophic model forced by a single isolated mountain. They find that a modest change in the shape of the zonal-mean wind yields a dramatic change in the shape of the stationary wave forced by the mountain, a result which is coupled to the stationary Rossby wave number. According to Hoskins and Ambrizzi (1993), the degree to which the time mean zonal-mean flow may act as a potential waveguide for barotropic Rossby waves may be estimated. The basis of the underlying analysis is the dispersion relation for plane barotropic Rossby waves in a meridionally varying flow. Hoskins and Ambrizzi (1993) show that for stationary solutions the total wavenumber (K_s) for the perturbation can be interpreted as a refractive index for the Rossby wave perturbation. If the group velocity of the Rossby waves is considered, it may be shown that Rossby rays are always refracted towards latitudes with larger K_s (Hoskins and Ambrizzi 1993). This stationary Rossby wave number is determined by the ratio of the meridional gradient of absolute vorticity on the sphere and the zonal-mean wind.

The time mean zonal-mean K_s at 200 hPa is shown for eight 30-yr periods of the transient integration (1860–89, ..., 2070–99) in Figure 4.1. A local maximum in K_s, indicating a potential waveguide, is found at mid-latitudes in all graphs. In response to the enhanced GHG forcing, this waveguide gradually becomes more distinct. The resulting change in the dispersion properties for barotropic Rossby waves is a probable explanation for the changes in the spatial patterns associated with the leading modes of variability and for the zonal wave number 3 in the mean response to the enhanced GHG forcing. The possibility that the changes in the spatial patterns of the NH leading modes of variability can also be explained on the basis of the changes in the dispersion properties for barotropic Rossby waves is evaluated in Paper III. The NH mean atmospheric flow is zonally asymmetric,

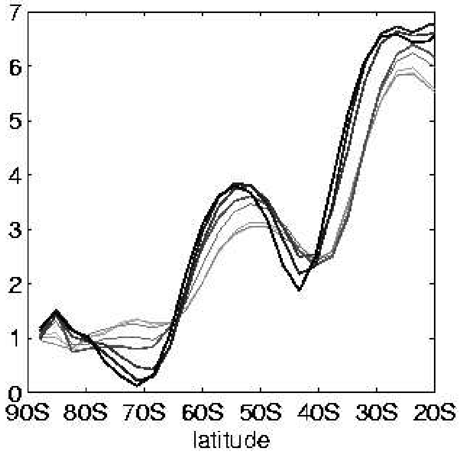


Figure 4.1: The zonal-mean stationary Rossby wave number (K_s) for SH winter (Jun-Aug). K_s is shown for eight consecutive 30-yr periods in the transient integration (1860–89, ..., 2070–99) with individual curves ranging from light gray (1860–89) to black (2070–99).

and thus the stationary Rossby wave number is determined as a function of longitude and latitude. Changes in K_s in response to the enhanced GHG forcing occur over Southern North America. The scale of this change is, however, small and not clearly separated from the scale of the large-scale Rossby wave in EOFs 1 and 2.

To investigate the importance of these changes in the mean flow for the propagation of large-scale Rossby waves, Rossby rays are determined. These are the paths traced following the group velocity of plane Rossby wave perturbations to a slowly varying basic state flow. Following Karoly (1983), ideas originating from ray tracing in geometric optics and wave propagation in a slowly varying medium are applied to Rossby wave propagation in a barotropic atmosphere. The results from applying this method indicate that K_s may be interpreted as a refractive index for barotropic Rossby waves if the basic state is zonally symmetric or large-scale. However, for smaller-scale features in the basic state, stationary Rossby waves may very well propagate through a region where K_s is undefined, and which in principle should act as a barrier for the wave.

Thus, the change in the spatial patterns of the leading modes in the NH can not be explained by changes in the dispersion properties for barotropic Rossby waves.

Chapter 5

Stationary waves

Regional climate changes can be much larger than the global-mean responses and are therefore likely to have larger consequences. Unfortunately, the regional responses in different CGCM simulations vary considerably. The regional responses are dependent upon changes in the atmospheric circulation. A common signature in CGCM simulations to the response to an enhanced GHG forcing is an increase in the zonal mean upper level wind (Räisänen 2003). This increase results from an increased pole-to-equator temperature gradient at upper levels. Increases in tropospheric GHG concentrations and decreases in stratospheric ozone are expected to result in a heating of the troposphere and a cooling of the stratosphere. Since the tropopause height decreases from the subtropics to high latitudes, the temperature gradient at a particular pressure level is expected to be enhanced. As a further result, a rise of the tropopause during the 21st century is expected (Santer et al. 2003). Increases in tropopause height have also been identified in observations spanning the past decade (Hoinka 1998, Seidel et al. 2001, Randel and Gaffen 2000, Highwood et al. 2000).

In Paper IV, physical explanations for the inter-CGCM differences in the regional responses to an enhanced GHG forcing are sought, particularly as regards the inter-CGCM differences in the spatial patterns of the response to the enhanced GHG forcing. As described above, the zonal-mean response in CGCMs is more robust. Therefore, the response is decomposed into the zonal mean and deviations from this quantity (the stationary wave pattern; SWP). Inter-CGCM differences in the SWP are hypothesised to be partially explained by the analogous differences in zonal mean properties of the atmospheric flow. Räisänen (2003) discusses inter-CGCM differences in the zonal mean wind in present-day simulations and in the response to enhanced GHG forcing among the CGCMs used in the second phase of the Coupled Model Intercomparison Project (CMIP2; Meehl et al. 2000). He finds the differences among present-day simulations to be of the same order of magnitude as the response to the enhanced forcing. In Paper IV, it is hypothesised that these inter-CGCM differences explain part of the inter-CGCM differences in the response in the SWP (and thus the regional response). In order to isolate the effects of differences in the zonal mean background state from effects of other CGCM-differences, a simplified model with idealised forcing is used.

5.1 The global quasi-geostrophic model

The model used (Marshall and Molteni 1993) is a spectral, three-level quasi-geostrophic model with global domain and pressure as vertical coordinate (henceforth denoted G3QG). A zonally symmetric forcing is applied to the model. The only zonal asymmetry in the model is provided by an orography consisting of two isolated mountains. The distance between the mountains is 160°of longitude, i.e. roughly corresponding to the distance between the Himalayas and the Rockies.

5.2 Three cases

Three cases are set up in order to test the sensitivity of the SWP in G3QG to differences in the zonal mean wind and the tropopause height. The cases are designed to represent an unperturbed (years 1860–89; case 1) and perturbed (years 2070–99; case 2 and 3) period in the ECHAM4/OPYC3 CGCM transient simulation discussed in Paper II and III. In case 2, the thermal wind is increased as compared to case 1, and, in case 3 the thermal wind as well as the tropopause height are increased as compared to case 1.

The zonal-mean wind at the upper (200 hPa) and lower (800 hPa) level is shown in Figure 5.1, which also includes the zonal mean wind at these levels from the CGCM. The jet is centred around 30°N in the CGCM. The quasi-geostrophic model used is not capable of describing the dynamics of the NH winter westerly wind at the equator. Therefore we choose to centre the wind around 45°N in all three cases. Consequently, the mountains are centred at 45°N in G3QG as compared to around 35°N in reality.

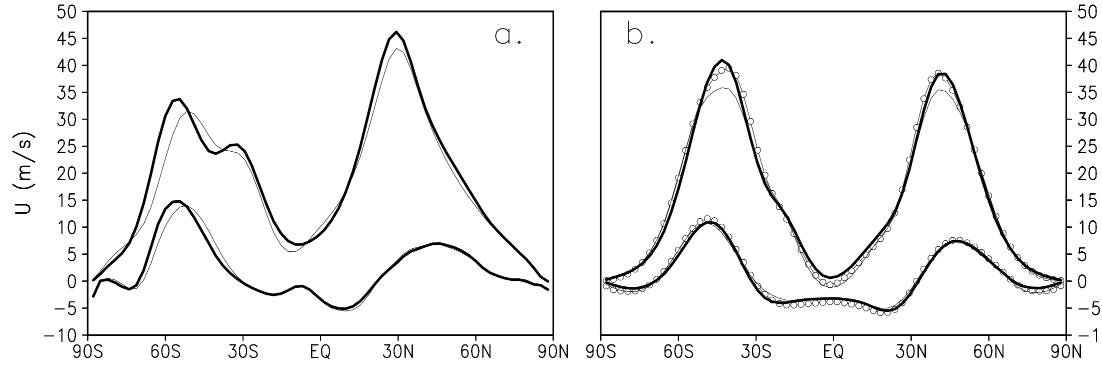


Figure 5.1: Zonal mean wind at 200 hPa and 800 hPa in (a) the CGCM and (b) G3QG. The period 1860–89 in the CGCM is shown with a weak line and the period 2070–99 with a heavy line. For the G3QG integrations, case 1 is shown with a weak line, case 2 with a heavy line and case 3 with a weak line with rings (o).

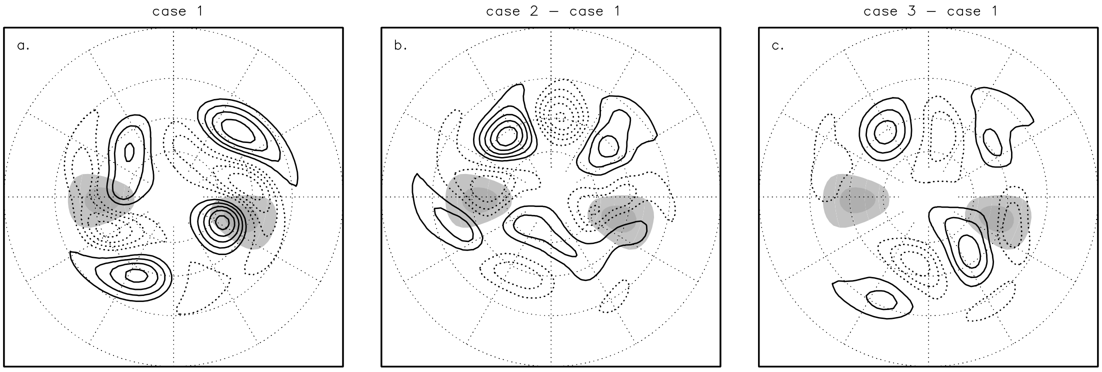


Figure 5.2: G3QG vertical mean SWP for (a) case 1, (b) case 2-case 1 and (c) case 3-case 2. The contour interval is $2 \cdot 10^6 m^2 s^{-1}$ in (a) and $5 \cdot 10^5 m^2 s^{-1}$ in (b) and (c). The zero contour is omitted in all panels. The orography is shaded.

5.3 Sensitivity to the background state

Figure 5.2 shows the reference-case results for the vertical mean SWP, defined as the deviation from the time and zonal mean. The difference between the two perturbed cases (case 2 and 3) and the reference case is also shown. The vertical mean SWP in the G3QG model is of comparable amplitude to the NH winter vertical mean SWP in the ECHAM4/OPYC3 CGCM (not shown). Further, the amplitude of the "response" to the changes in the zonal mean background state are comparable to the CGCM response to the enhanced GHG forcing. It is interesting to note that not only the amplitudes but also the spatial patterns of the two responses in G3QG are quite different.

The relative importance of barotropic and baroclinic dynamics for the difference in the SWP between the perturbed cases and the reference case is diagnosed. This is done by studying the balance for the time-mean barotropic state, which primarily is a balance between advection of barotropic relative vorticity and planetary vorticity. The difference in the SWP between the perturbed cases and the reference case is mainly explained by a difference in this balance. The terms associated with baroclinic and transient processes are of smaller magnitude than the barotropic advection terms, but the relative response of these terms is large and could play an important role for the balance.

Chapter 6

Concluding remarks

The aim of the work presented in this thesis is to increase our understanding of the response of the climate system to an enhanced GHG forcing. For a good assessment of future climate change quantifications of both natural and man-made emissions of greenhouse gases are necessary. Further, the large uncertainties in the modelled response must be understood.

In Paper I, a rather indirect approach is taken to quantifying present day natural and man-made emissions of CO_2. Combining measurements of CO_2 at a remote Arctic site and simulations with a three-dimensional atmospheric transport model, the accuracy of current estimates of the natural emissions of CO_2 could be assessed. The natural emissions of CO_2 used in this study do not agree with measurements from Europe and Siberia. More measurements of natural fluxes in CO_2 in winter are therefore called for.

Papers II and III deal with the response of the Southern and Northern Hemisphere atmospheric circulation as simulated in a specific CGCM. The zonal mean response to the enhanced GHG forcing is assumed to be more robust than the deviations from this mean. Therefore, the response is decomposed into the zonal mean and deviations from the mean. Note however, that this decomposition is not entirely uncontroversial, in particular when the NH circulation is discussed. Zonal asymmetries at the Earth's surface break the zonal symmetry of the atmospheric flow imposed by solar radiation. Orography and continents have a stronger influence on the NH than on the SH extratropical circulation.

In Paper IV, a simplified model with idealised forcing is used to investigate the sensitivity of the orographic stationary wave pattern to differences in the zonal-mean properties of the flow.

Some of the main results from the present thesis are:

- Natural emissions of CO_2 affect the Arctic CO_2 concentration also during winter. The natural emissions are comparable in magnitude to those of anthropogenic origin.
- The spatial patterns of the leading modes of variability change in response to the enhanced greenhouse gas forcing in a simulation with the ECHAM4/OPYC3 CGCM.

These results indicate that the response of the climate system is different to that of non-linear dynamical systems with only few degrees of freedom.

- The changes in the leading modes are associated with a strengthening of the Southern Hemisphere waveguide for barotropic Rossby waves, whereas the Northern Hemisphere waveguide remains unchanged.
- The topographically forced stationary wave in a simplified model with idealised forcing is sensitive to changes in the zonal-mean wind and tropopause height. The imposed changes of these quantities are of similar magnitude as the response to the enhanced forcing in the ECHAM4/OPYC3 CGCM. The resulting sensitivity in the stationary wave is of similar magnitude as the response in the stationary wave in the CGCM. These results indicate that a substantial part of the CGCM-differences in the spatial pattern of the response to an enhanced GHG forcing may be attributed to inter-CGCM differences in the zonal-mean flow and zonal-mean thermal structure.

6.1 Outlook

In Paper IV, a possible explanation for the inter-CGCM differences of the regional response is indicated by the idealised experiments. The magnitude of the sensitivity found in the three-level quasi-geostrophic model is quite large. Sensitivity tests with a primitive equation model (including the full dynamics, but still excluding the effects of parameterised physical processes) would thus be highly useful for clarifying this issue.

The results presented in this thesis indicate that the uncertainty in the model response of the climate system to increasing greenhouse gas emissions is partially due to differences in the simulations of the mean state. Since no model gives (and never will give) a perfect description of the climate system, differences in the mean climate of this magnitude may be regarded as inevitable sources of uncertainty. In simulations of the climate system, the future climate evolution is also sensitive to the initial state and to the model formulation. To assess all these uncertainties in the future climate evolution, ensemble simulations of climate change are necessary. Stainforth et al. (2005) have carried out a multi-thousand-member grand ensemble experiment to explore both the chaotic climate variability and model response sensitivity in a state-of-the-art model consisting of an atmospheric model coupled to a mixed-layer ocean. They find model versions as realistic as other state-of-the-art climate models, but with climate sensitivities ranging from less than 2K to more than 11K, i.e. twice that reported in the IPCC (2001) report. They also find that model versions with similar sensitivities often show differences in regional details of the response to the enhanced GHG forcing. In order to assess the range of possibilities for future climate evolution, especially that of the regional climate, further investigations of this type are required. In particular, a fully coupled model should be used in order to determine a more complete range of sensitivity.

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Finally, in spite of all my doubts, this thesis is actually finished!

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