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Long-term changes in the mesosphere (LOCHMES)

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1 Introduction

During the last decade the middle atmosphere (∼10 to 110 km) has been recognized as an essential part of the climate system. The natural internal variability of the troposphere (∼0 to 10 km) and its sensitivity to perturbations can only be understood when the middle atmosphere is taken into account (Shindell et al., 2001; Sigmond et al., 2008; Shaw et al., 2009). The mesosphere (∼50 to 100 km) is of particular importance because long-term variations exceed those in the troposphere by an order of magnitude (Fig. 1). Furthermore, in the upper part of the stratosphere (∼10 to 50 km) and in the mesosphere, variations in high-energetic solar radiation alter the ozone chemistry and subsequently the radiation budget. This affects the entire atmosphere through dynamical interactions. The role of the mesosphere as an indicator for climate change has long been discussed (Thomas et al., 1989), not at least because of the presence of peculiar noctilucent ice clouds at about 85 km altitude in polar summer. These clouds have been observed since more than hundred years and can now be analyzed with regard to decadal, interannual, and intraseasonal variability (DeLand et al., 2007; Karlsson et al., 2007; Lübken et al., 2009). Nevertheless, the mechanisms by which the mesosphere reflects, or even influences, any long-term changes in the troposphere are by far not understood. A comprehensive understanding of the coupling mechanisms between the lower and middle atmosphere has not been acquired yet, but is necessary for taking advantage of observations in the mesosphere in order to better distinguish between natural and anthropogenic climate variability.

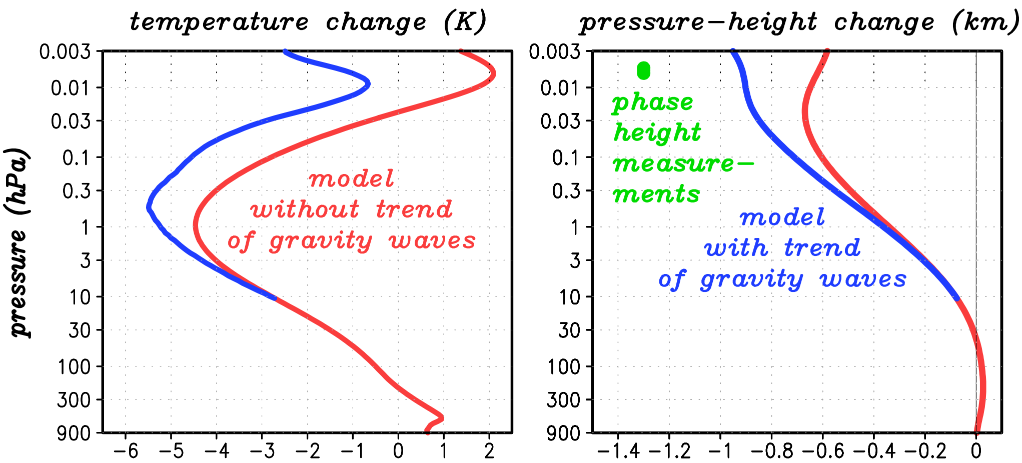

Figure 1: Long-term changes of temperature and pressure heights in summer. The simulation without trend of gravity waves (red curves) corresponds to results obtained with the Whole Atmosphere Community Climate Model (Garcia et al., 2007) for the period from 1950 to 2003 and has been mimicked here using a one-dimensional radiative-convective-equilibrium version of the KMCM (see Sec. 3). For the blue curves, the temperature change above 10 hPa (30 km) is completed by the effect of stronger gravity wave activity according to Becker (2009). The green dot indicates phase-height measurements at the IAP for the period from 1959 to 2003 according to Bremer (2005), implying a mesospheric cooling much stronger than can presently be explained with complex climate models.

2 Motivation and main aim

In general the climate is subject to large temporal and geographical variations. This internal variability is superposed by an increased greenhouse effect in the troposphere and enhanced radiative cooling in the middle atmosphere due to anthropogenic influences. Such influences can in turn alter the internal variability similar to other external perturbations like the solar cycle. Therefore the anthropogenic climate signal is often hard to detect.

On the seasonal and interannual scale the internal variations show up as global modes of variability. Prominent examples are the Northern and Southern Annular Mode (NAM and SAM). The lower tropospheric branch of the NAM is also known as the Arctic Oscillation and is particularly relevant for Europe because of its center of action associated with the North Atlantic Oscillation (Wallace, 2000). The NAM and SAM are usually considered for the troposphere and stratosphere while their role in the mesosphere has long been ignored. Another prominent natural variability mode is the Quasi-Biennial Oscillation (QBO). Even though the QBO concentrates in the tropical stratosphere, it has global effects throughout the middle atmosphere. In particular, the QBO gives rise to a strong modulation of the stratospheric branch of the NAM (Holton and Tan, 1980). However, this modulation is not well understood and, moreover, depends crucially on the 11-year solar cycle (Labitzke, 2003). The vertical extent of the NAM and SAM into the upper mesosphere has recently been established as Interhemispheric Coupling (IC) since the variability pattern reaches from the winter troposphere all the way to the upper mesosphere above the summer pole (Becker et al., 2004; Becker and Fritts, 2006; Karlsson et al., 2008; Körnich and Becker, 2010). The IC shows profound signals in the summer polar mesopause region such that variations in ice clouds and associated radar echoes correlate to variations in the winter troposphere and stratosphere (Karlsson et al., 2009).

The importance of the mesosphere to detect and understand long-term changes is twofold. First, at some locations a long-term temperature decrease over the past decades is observed that is about one order of magnitude stronger than the global warming (20 K cooling around 60 km in summer over the past 40 years versus 0.5 K warming close to the surface; Keckut et al., 1995; Ramaswany et al., 2001; Bremer et al., 2005). This trend can only partly be attributed to increased radiative cooling (Garcia et al, 2006; see Fig. 1). Therefore, other processes must cause a substantial cooling. We note that the middle atmosphere is dynamically controlled by all kinds of atmospheric waves with tropospheric origin and amplitudes growing exponentially with height. Hence, weak dynamical variations at low altitudes can create strong signals higher up (Becker, 2009). Another way of describing this coupling is in terms of the aforementioned modes of internal variability (e.g. Körnich et al., 2006). Second, variations in the middle atmosphere, induced by the solar cycle, modified trace-gas concentrations, or upward propagating waves feed back on the troposphere (Gabriel et al., 2007). Spectacular natural examples are sudden stratospheric warmings in northern hemispheric winter. During such an event, a complete reversal of the zonal circulation propagates downward from the upper mesosphere to the troposphere (Hoffmann et al., 2007; see Fig. 2). The onset of the event in the upper mesosphere is not understood yet (Manney et al., 2008). Nonetheless, the strong statistical evidence of downward propagation of circulation patterns from the stratosphere to the troposphere (Baldwin and Dunkerton, 2001) has inspired developers of weather forecast models to place the model top at 80 km height (see ECMWF newsletter, No. 120, 2009).

How the internal atmospheric variability extends into and interacts with the mesosphere and, particularly, how the overall patterns respond to external perturbations like the solar cycle or trends in trace-gas concentrations is very poorly understood. For example, the aforementioned strong temperature trends in the mesosphere cannot be explained yet. In the present project we focus on the dynamically controlled internal variability and its sensitivity to solar and anthropogenic perturbations. Our goal is to considerably improve our understanding of the mesosphere as an indicator for natural variability and climate change.

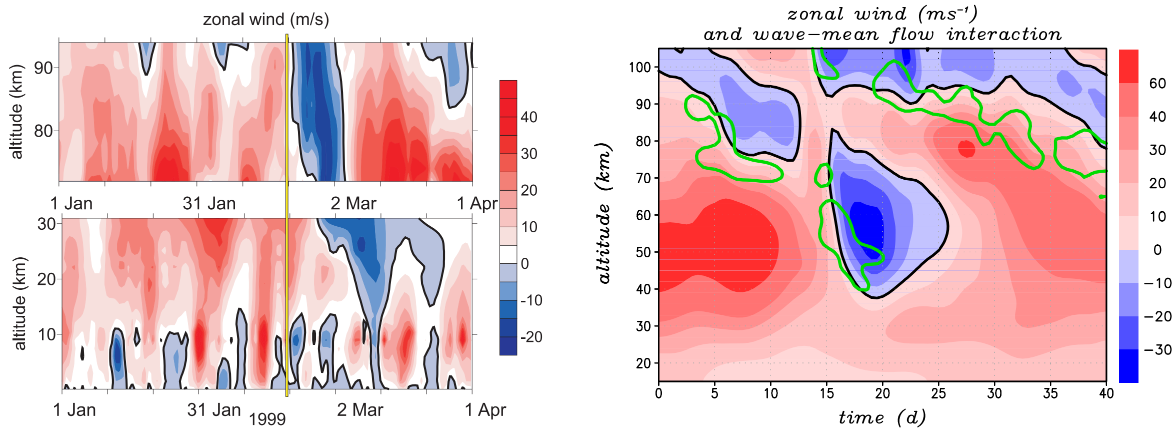

Figure 2: Left: Downward propagation of the reversal of the zonal wind during the sudden stratospheric warming in February 1999 at the site of Andenes (69°N) in radar observations (upper panel) and analyses from the European Center for Medium Weather Forecasting (lower panel). Right: Simulation of a sudden stratospheric warming with the KMCM (see Sec. 3). Here we show the zonal-mean zonal wind averaged for the latitude band from 50° to 70°N. The -50 m s^{-1} d^{-1} contour of the Eliassen-Palm flux divergence is indicated by a green contour. It propagates downward synchronously with the wind reversal indicated by black contours in each panel.

3 Work packages

Modeling and data base

Our methods rest on a unique combination of models and analysis of observational records. We employ the Kühlungsborn Mechanistic general Circulation model (KMCM), which is the only presently available global model that yields an explicit simulation of the gravity-wave effects (momentum deposition, turbulent diffusion and dissipative heating) in the upper mesosphere (Becker 2009), as well as a thermodynamically closed Lorenz energy cycle, i.e., zero radiative forcing in the climatological mean (Becker 2003). These properties are due to a combination of a standard spectral dynamical core with high spatial resolution and a sophisticated turbulence model. For conventional resolutions, gravity waves are parameterized by a novel version of the Doppler-spread parameterizations (DSP, Becker and McLandress, 2009). The KMCM has recently been extended by an idealized new radiation scheme which includes the surface heat budget by means of a swamp ocean and extends continuously up to 120 km. These features are unique among middle atmosphere models. The radiation is computed with prescribed trace-gas concentrations. An idealized treatment of the tropospheric hydrological cycle along the ideas of Frierson and Held (2006) will be implemented, including full orography and land-sea contrasts for our purposes. The KMCM is complemented by the MEsospheric Chemistry Transport Model (MECTM) and a Langrangian model for ice particles called LIMA/ice. These models have successfully been used in several previous studies (Grygalashvyly et al., 2009; Lübken et al., 2009) and will be driven with the dynamical fields obtained with the KMCM. We furthermore take advantage of simulations already performed with the HAMburg Model of the Neutral and Ionized Atmosphere (HAMMONIA; Schmidt et al., 2006, 2009).

On the observational side, the IAP has access to several unique long-term data sets like the 50-year-spanning phase height observations (Bremer, 2005), upper mesospheric wind measurements with MF-radars which now cover almost 20 years (e.g., Keuer et al., 2007), lidar and radar observations of mesospheric ice clouds over more than one solar cycle (Fiedler et al., 2009; Bremer et al., 2009), as well as other unique but shorter data sets which are available for case studies like temperature and ice-cloud observations at 54°N (Gerding et al., 2007, 2008), Doppler lidar observations of mesospheric winds (Hildebrand et al., 2009), and meteor radar measurements of winds and temperatures (Singer et al., 2004). Where necessary for a proper interpretation, these

IAP-owned observations will be complemented by satellite observations like the publicly available SABER and MLS temperature data sets.

WP 1: Solar cycle and trends in variability modes of the middle atmosphere

The KMCM will be used with conventional resolution and short-wave radiation conditions that correspond to a permanent minimum of the solar cycle. Conditions corresponding to La Nińa in the tropical Pacific are implemented by means of prescribed oceanic heat fluxes. The model will be integrated for several years in order to simulate the QBO, the Semi-Annual Oscillation (SAO), the NAM and SAM, and the IC. From this control simulation we shall analyse how the modifications introduced to the Doppler-spread parameterization of gravity waves (DSP) affect the simulations of the QBO and SAO. The Holton-Tan mechanism by which the QBO modulates the NAM, but also the SAM in late southern winter, will be revisited using an accurate Eliassen-Palm flux diagnostics and estimates of refractive indices for planetary Rossby waves. Finally, the modulation of the IC by the QBO through the interactions of gravity waves, planetary waves, and the mean circulation will be analyzed.

The long-term simulation is then repeated for perturbed conditions: (1) short-wave radiation for permanent solar maximum, (2) oceanic heat fluxes corresponding to El Nińo conditions, (3) doubling of the CO_2 concentration, and combinations of (1)-(3). These simulations provide a set of representative dynamical regimes that will allow to understand in detail why the Holton-Tan effect is reversed during solar maximum (Kodera and Kuroda, 2002) and how the IC changes in the course of the solar cycle. They will furthermore illuminate how these variations in the mesosphere respond to the El Nińo/Southern Oscillation variability mode and to an increased CO_2-concentration. The aforementioned radar and lidar measurements and other observational data sets will be analyzed and combined with the modeling results. Our aim is to establish a comprehensive picture of mesospheric variability in the mean winds and temperatures, as well as in planetary Rossby waves and thermal tides. These results will furthermore be validated against simulations with the complex climate model HAMMONIA with regard to the solar cycle (Schmidt et al., 2010) and increased CO_2-concentrations (Schmidt et al., 2006), as well as against meteorological analyses for the troposphere and stratosphere.

WP 2: Solar-cycle effects and trends in gravity waves.

Due to the many simplifying assumptions that must be made in gravity-wave schemes (e.g., quasi linear and stationary dynamics, single-column approximation), they are among the most uncertain parameterizations in complex climate models. Gravity waves can be resolved when a high spatial resolution is applied and gravity-wave breakdown is treated appropriately by a corresponding parameterization of turbulence. Such a novel concept has already proven successful in the KMCM (Becker, 2009). For instance, it has been shown that reduced static stability in the lower troposphere, as is the case due to global warming, leads to intensifications of both the Lorenz energy cycle and the extratropical dynamical gravity sources. The remote effect in the polar summer mesosphere is a dynamically induced cooling by several degrees. Such effects, as well as the fully nonlinear coupling between gravity waves and all larger scales are excluded when a conventional model concept is employed. Therefore the aforementioned simulations will be repeated with resolved gravity waves. An ambitious modelling task in this context is the self-generation of the QBO by convectively excited gravity waves in the tropics.

The main scientific questions in this package are again the dependence of the IC on the QBO, as well as the sensitivity of the IC to the solar cycle and an increased CO_2 concentration. However, the emphasis is now on the differences to the conventionally obtained results from WP1. Due to having both radiative and all dynamical effects included in our simulations, we expect to give a satisfactory interpretation of the aforementioned strong cooling of the mesosphere over Europe during the last decades. The interpretation likely requires the combination of enhanced radiative cooling (Schmidt et al., 2006) with 1) enhanced dynamical cooling due to an increased gravity-wave drag in summer (Becker, 2009) and 2) changes in quasi-stationary Rossby waves in winter (Gabriel and Peters, 2007).

To complete the picture and to validate the simulations, the radar and lidar data sets will be analyzed with regard to such important parameters like the altitude of particular pressure levels (from phase-height observations), gravity waves, and even turbulence.

WP 3: Effects of the IC, solar cycle, and trace-gas variations on temperatures and ice layers in the mesosphere

Mesospheric ice layers known as NLC or PMC[1] have been considered to be sensitive indicators for climate change for many years (Thomas et al., 1989). Roughly speaking, NLC depend on low enough temperatures and large enough water vapor concentrations which are both potentially affected by anthropogenic activities. First observations and altitude measurements of NLC are reported from more than 120 years ago. Since this is probably the oldest data record from the MLT region and because ice particles are extremely sensitive to temperatures, NLC are presumably an ideal tool to study long-term trends at mesopause levels. It has been noted, though, that the mean altitude of NLC has not changed significantly over the last 120 years which imposes a major constraint on simulations of trends in the MLT (Lübken et al., 2009). Observations of PMC from satellites have only recently been demonstrated to show significant long-term variations (DeLand et al., 2007). Still, some critical issues are not yet solved satisfactorily, e. g., a potential bias due to local time dependence of the observations.

Lidars provide the most comprehensive measurement of ice cloud parameters, although at a single station only. The IAP owns the largest data record on NLC now covering more than a solar cycle (Fiedler et al., 2008). We plan to study in detail the solar cycle signal in various NLC parameters and the potential implications for satellite observations.

It has been speculated that NLC extend further equatorward due to climate change, but corresponding observations of NLC or physical processes involved have not yet been investigated. The IAP lidars at Kühlungsborn (54°) occasionally detect NLC at the latitudinal edge of their appearance (Gerding et al., 2007). Since 2009 the IAP runs a new microwave spectrometer to measure H_2O in the mesosphere. Within this proposal we aim to better explore the physical conditions during the appearance of NLC at mid latitudes (i.e., at Kühlungsborn) and the implications for long-term changes.

Large radar echoes called PMSE[2] originate from (charged) ice particles in the summer mesopause region. The physics behind PMSE has only recently been unraveled so that they can now be used to study long-term changes (see review by Rapp & Lübken, 2004; Bremer et al., 2009). PMSE are easy to observe and have been applied to detect IC signatures (Goldberg et al., 2004). On the other hand, PMSE depend on plasma properties and turbulence (apart from ice particles) which complicates the interpretation. We plan to study solar cycle and coupling processes applying PMSE observations at various geographical locations.

The LIMA/ice model has successfully been used for ice layer studies in the summer MLT region (Berger and Lübken, 2006). For example, it was shown recently that stratospheric cooling alone significantly contributes to observed PMC trends in the mesosphere (Lübken et al., 2009). We plan to study the implications of solar cycle and greenhouse gas trend effects in the background conditions of the summer mesosphere (temperatures, mean circulation, gravity waves) for NLC,

[1] NLC=noctilucent clouds ; PMC=polar mesospheric clouds

[2] Polar Mesosphere Summer Echoes

PMC, and PMSE. This includes also feedback mechanisms since the ice-layer model computes water vapor internally. For example, freeze-drying may redistribute water vapor in the ice layer domain, which in turn modifies the capability of solar Ly_α radiation to destroy H_2O by photo dissociation. The simulated dynamical fields from WP1 and WP2 are used to drive both the LIMA/ice model and the MECTM. This allows us to study in detail the variations of ice layers and trace gases with the Interhemispheric Coupling (IC) and other large-scale dynamical pattern such as the QBO and SAO. Such effects have indeed been detected from satellite observations (Karlsson et al., 2007, 2009).

4 Cooperations

The project will be carried out in cooperation with

- Prof. Dr. Kirstin Krüger (IFM-GEOMAR, Kiel), regarding: evaluation and interpretation of model simulations and analyses with regard to QBO, solar cycle, and long-term changes in trace gases; advice in parameter settings for the different simulations with the KMCM
- Dr. Heiner Körnich (MISU, Stockholm), regarding: analysis of variability modes in model simulations and analyses; advice in statistical analysis of observational data.

5 WGL line of funding

The WGL line of funding for the proposed project LOCHMES is '**Qualitätssicherung'**.

The Leibniz Institute of Atmospheric Physics at the Rostock University (IAP) was evaluated in May 2008 and the final report was issued in August 2008.

In Section 1 (pages B-2 and B-3) of its report the committee acknowledges that the IAP has made substantial contributions to our understanding of the mesosphere with regard to its relevance for climate variability. The committee mentions that the contributions of the IAP in the field of gravity waves are even excellent.

In the course of the proposed project we plan to further develop and broaden our expertise in these areas in order to make substantial progress in understanding the role the mesosphere for climate change. The project will thus further strengthen activities of already excellent research at the IAP.

6 Milestones

	2011	2012	2013
WP1	implement and validate the KMCM version with conventional resolution (moisture cycle, self-generated QBO by means of the Doppler-spread gravity-wave parameterization); analyse radar and lidar observational data with regard to mean winds, mean temperatures, planetary waves and tides	perform long-term simulations for minimum and maximum solar activity; perform diagnostics of the QBO, the Holton-Tan effect, and the IC; extract QBO and IC signals in radar and lidar measurements; validate results against HAMMONIA simulations and analyses	repeat simulations for El Nińo conditions and for doubling of the CO_2 concentration: interpret and publish results
WP2	develop and validate the KMCM version with a self-generated QBO due to resolved gravity waves; perform long-term simulation for solar minimum conditions; analyse radar and lidar observational data with regard to gravity waves and turbulence	perform long-term simulations for solar minimum and maximum; apply diagnostics as in WP1; analyse gravity-wave amplitudes and turbulence; extract QBO and IC signals in gravity-wave amplitudes and turbulence obtained from radar measurements	repeat simulations for El Nińo conditions and doubling of the CO_2 concentration; explain mesospheric cooling over Europe; interpret and publish results
WP3	perform simulations with the MECTM and LIMA/ice driven by the dynamical fields from WP1 and WP2; derive variability of trace gases and ice clouds with regard to the IC and its modulation by the QBO; estimate the role of mixing due to resolved gravity waves	perform long-term simulations for solar maximum; analyse solar-cycle effects on trace gases and ice clouds and the role of explicit simulation of gravity waves	repeat simulations for El Nińo conditions and doubling of the CO_2 concentration; assess long-term variations of trace gases and ice clouds and compare results to observational records; interpret and publish results

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