the generation of misfit dislocations and the cracking of AlGaN layers with higher aluminum content.

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The stratosphere as a puppeteer of European winter climate

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The depletion of the stratospheric ozone layer and the increase of greenhouse gas concentrations have led to changes in the climate of the stratosphere, the atmospheric layer between about 10 and 50 km. Stratospheric climate change currently receives wide attention among environmental physicists, because it will likely influence the speed of recovery of the ozone layer, and it may induce climate change in the troposphere, the atmospheric layer between the earth's surface and the stratosphere. Recent studies indicate that a significant part of the European winter warming observed in the past and predicted for the next decades might be due to changes in the climate of the stratosphere. To some extent the troposphere and the stratosphere might be regarded here as puppet and puppeteer, respectively. Unusually, the puppet's weight is about ten times that of the puppeteer.

Stratospheric ozone depletion

The ozone layer has been depleted due to human emissions of ozone-depleting gases containing chlorine and bromine. The ozone depletion is largest, about 50%, over Antarctica in winter-spring. This annually recurring "ozone hole" is due to special (photo)chemical ozone destruction reactions at very low temperatures that only occur in winter-spring over Antarctica and, to a lesser extent, the Arctic. Over the Arctic the depletion is up to about 20%, and is more variable than over Antarctica. Also at middle latitudes the ozone layer has been depleted, by about 5% between 1980 and 2000. As a result of international regulations, the total abundance of the ozone-depleting gases in the atmosphere has begun to decrease in recent years. Natural chemical and transport processes limit the rate at which these gases can be removed from the stratosphere. Model predictions indicate a recovery of the ozone layer to pre-ozone hole conditions by the middle of the 21st century. For more information about stratospheric ozone depletion see, e.g., Fahey *et al.* (2003).

Stratospheric global cooling

The ozone depletion leads to less absorption of solar radiation in the stratosphere and, consequently, to colder stratospheric temperatures. Also the increased greenhouse gas concentrations lead to colder stratospheric temperatures, which can be understood as follows. Greenhouse gases emit radiation at their local temperature, and absorb radiation that is emitted by the surrounding air, most of which is at lower altitudes. The emission increases with increasing temperature, according to Stefan-Boltzmann's law. Since in the stratosphere the temperature increases with altitude, the cooling by the emission at the local temperature exceeds the warming by the absorption of the radiation that is mainly emitted at the lower temperatures of the altitudes below. Thus in the stratosphere an increase in greenhouse gases will lead to more radiative cooling and,

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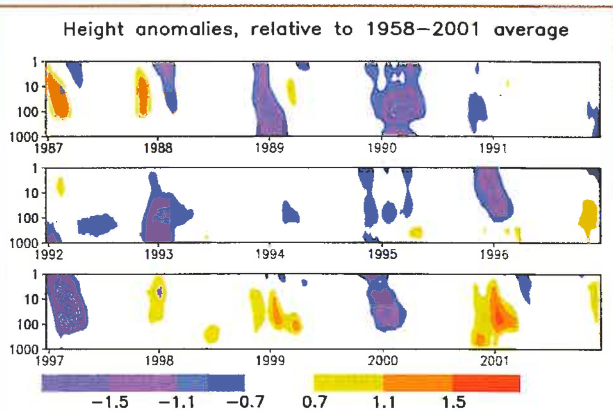
consequently, lower temperatures. In the troposphere, where the temperature decreases with altitude, the emission is less than the absorption, and a greenhouse gas increase will cause higher temperatures. Although the climate change due to increased greenhouse gases is often called 'global warming', for the stratosphere the term 'global cooling' would be more appropriate. Temperature observations in the lower stratosphere (15-20 km) show a cooling trend of ~0.6 °C/decade since 1980. The strongest cooling occurs in the polar lower stratosphere during winter-spring (~3 °C/decade). The observed cooling in the upper stratosphere (30-50 km) is 1-2 °C/decade since ~1970, with the magnitude increasing with altitude. Model simulations of the climate response to ozone depletion and increasing greenhouse gases show an increase of the equator-to-pole temperature gradient and a corresponding increase of the westerly wind in the lower extratropical stratosphere, which are also observed (Ramaswamy *et al.*, 2001; Langematz *et al.*, 2003).

European winter warming

In the past decades the surface temperature has increased almost globally (IPCC, 2001). The warming is largest over the Northern Hemisphere (NH) winter continents. A part of this warming may result from the sharp increase in the positive phase of the wintertime Arctic Oscillation (AO) since about 1970. The AO is the dominant geographical pattern of surface pressure variability in the NH. It is basically a dipole with opposite signs north and south of ~60 °N, representing the latitudinal swings of air mass. In the positive phase of the AO the surface pressure at lower latitudes is larger, and the surface pressure at higher latitudes is smaller than the climatological mean value. Since the climatological mean surface pressure at lower latitudes is larger than that at higher latitudes, a positive phase of the AO also corresponds to an enhanced difference in surface pressure between lower and higher latitudes. This enhanced pressure difference leads to enhanced westerly winds, which, in turn, lead to cold winters downstream of the cold winter continents, e.g. over the north-west Atlantic, and warm winters downstream of the relatively warm oceans, e.g. over Europe and Siberia. Thus, a positive phase of the AO corresponds to relatively warm winters in Europe. The observed increase in the positive phase of the wintertime AO accounts for ~30% of the warming of the NH as a whole, and ~50% of the warming of the Eurasian continent (Thompson *et al.*, 2000).



▲ Fig. 1: Height anomalies at pressure levels (in hectoPascal, hPa) from the surface (1000 hPa) to the top of the stratosphere (1 hPa), for all seasons during the period 1986-2001. The height has been averaged over the area north of 60°N. The anomaly for each day is relative to the 1958-2001-average for that calendar day, and has been scaled by the standard deviation of the anomaly's timeseries for all days of 1958-2001. To put emphasis on seasonal timescales, the daily height data have been low-pass-filtered using a 91-day running average. In clear regions (most of which occur in summer) the absolute value of the height anomaly is less than 0.7 times the standard deviation. Red shading corresponds to high temperatures in the area north of 60°N, weak westerly winds, and a negative phase of the Arctic Ascillation (AO); blue shading corresponds to low temperatures, strong westerly winds, and a positive phase of the AO.

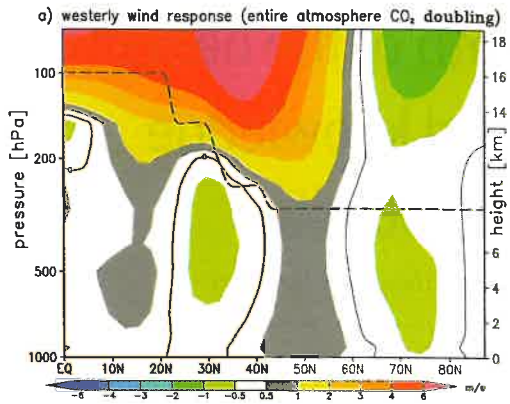
Stratosphere-troposphere coupling

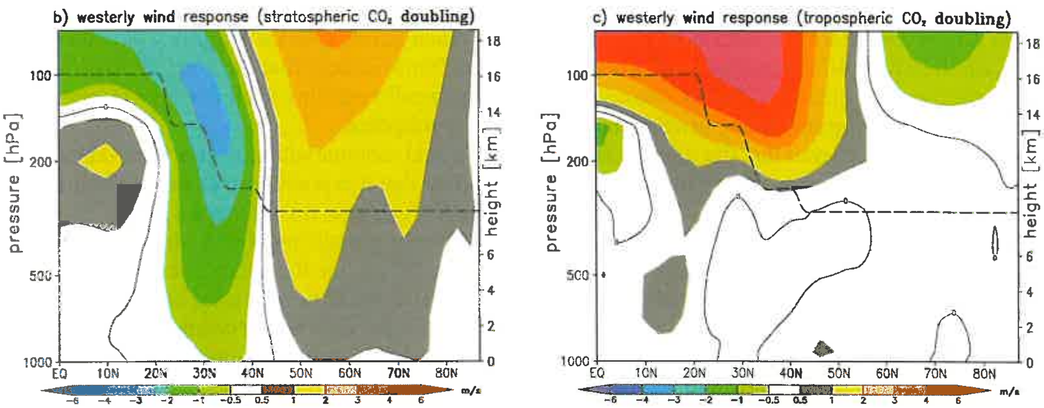
Observations show that there exists at seasonal time-scales a strong relation between the surface pressure pattern and the circulation pattern throughout the troposphere and the stratosphere. In particular, a positive phase of the AO corresponds to enhanced westerly winds in the area north of about 45 °N in both the troposphere and the stratosphere. This is illustrated in Figure 1, which shows anomalies of the height in the polar region at pressure levels from the surface to the top of the stratosphere, for the period 1986-2001 (environmental physicists use height as a function of pressure, rather than pressure as a function of height). We have averaged the height over the area north of 60°N. The anomaly for each day is relative to the 1958-2001-average for that calendar day, and has been scaled by the total time series' standard deviation. This scaled anomaly is a proxy for the strength of the AO. To put emphasis on seasonal timescales, a 90-day low-pass filter has been applied. The data have been obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis project. A negative height anomaly corresponds to a positive phase of the AO. The anomalies are largest in winter, and comprise both the troposphere and the stratosphere, suggesting a coupling between the stratosphere and the troposphere. An important observation is that anomalies in the stratosphere often precede those in the troposphere, suggesting that variations in the surface AO are often 'driven' by variations in the stratosphere. The anomalies are predominantly negative, i.e. the height values are generally smaller than the 1958-2001-average, which is in line with the observed increase of the positive phase of the AO. In summary, the European winter warming of the last decades can for a large part be explained by an increase in the positive phase of the AO, which in turn might be induced by stratospheric climate change due to ozone depletion and increased greenhouse gas concentrations. More information about the relation between stratosphere-troposphere coupling and climate change is given, e.g., by Hartmann *et al.* (2000). The question whether stratospheric climate change indeed induces an increase in the positive phase of the AO has motivated us to perform idealized experiments with a global climate model comprising both the troposphere and the stratosphere.

A simulation of the separate climate effects of stratospheric and tropospheric CO_2 doubling

Our climate simulations show an increase of the tropospheric westerlies (associated with an increase in the positive phase of the AO) in NH winter middle latitudes in response to uniform CO_2 doubling (Figure 2a). This increase corresponds to an increase in the positive phase of the AO. To address the question to what extent the increase in the positive phase of the AO is caused by stratospheric and by tropospheric climate change, two additional experiments have been performed in which the CO_2 concentration has been separately doubled in the stratosphere and the troposphere. The sum of the separate responses to tropospheric and stratospheric CO_2 doubling is in most regions approximately equal to the uniformly doubled CO_2 response. This implies that the

▶ Fig. 2: Latitude-altitude distribution of the simulated Northern Hemispheric winter longitudinally averaged westerly wind response to a) CO_2 doubling in the entire atmosphere, b) CO_2 doubling in only the stratosphere, and c) CO_2 doubling in only the troposphere. Units are m/s. The climate simulations have been performed with a climate model including the troposphere and the entire stratosphere. The results shown are computed as the difference between 30-year simulations of the doubled CO_2-climate and of the actual climate with present-day CO_2 concentration. The dashed line denotes the position of the tropopause, separating the troposphere and the stratosphere. Positive values denote an increase in the westerly wind relative to the actual climate simulation, negative values denote a decrease.





(rather artificial) separation of the climate response into a response to stratospheric and a response to tropospheric CO_2 doubling is physically meaningful. The NH middle latitude tropospheric westerlies strengthen in response to stratospheric CO_2 doubling (Figure 2b), but do not significantly change in response to tropospheric CO_2 doubling (Figure 2c). These results suggest that the increase of tropospheric westerlies in response to uniform CO_2 doubling can be attributed mainly to the stratospheric CO_2 doubling. Since the stronger westerly winds correspond to a stronger positive phase of the AO, the results confirm the suggestion that the observed increase in the positive phase of the wintertime AO is caused by climate change in the stratosphere.

Whereas normally a pupetteer has more than one puppet, the European climate change has probably more than one puppeteer. Recent studies suggest that also changes in tropical sea surface temperatures might have induced an upward trend in the AO. Identifying and understanding the strings between these stratospheric and tropical puppetteers and the European climate change puppet is a major challenge of current studies in environmental physics in the next decade.

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