Inter-annual variability of high-latitude stratospheric ozone from satellite observations and model calculations

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Abstract.   It has been shown that the inter-annual variability of total ozone in the polar regions of both hemispheres is highly correlated with the flux of planetary waves into the stratosphere. In order to estimate the relative importance of transport and chemistry on the inter-annual variability of high latitude ozone, we use a chemical transport model (CTM) together with observations from the Global Ozone Monitoring Experiment (GOME) and the Total Ozone Mapping Spectrometer (TOMS). We find that the expected inter-annual variability of total ozone in the northern hemisphere in the absence of polar ozone depletion is not significantly different from the observed variability, in contrast to the southern hemisphere, where chemical ozone depletion is the dominant effect. However, the large uncertainty of the planetary wave flux in current meteorological analyses is a limiting factor for modeling the inter-annual variability of total ozone.

Introduction

During the last decade there has been substantial chemical ozone depletion during individual cold Arctic winters, with the loss in total ozone comparable to that in the Antarctic ozone hole [e.g., *Sinnhuber et al.*, 2000; *Sinnhuber et al.*, 2003]. Nevertheless, the inter-annual variability of Arctic ozone is to a large extent due to inter-annual variability in dynamics and transport [*Chipperfield and Jones*, 1999]. The increase of total ozone between fall and spring is largely controlled by the Eliassen-Palm (EP) flux of planetary waves into the stratosphere [*Fusco and Salby*, 1999; *Randel et al.*, 2002]. Recently, *Weber et al.* [2003] have shown that the inter-annual variability of the fall-to-spring ozone increase in polar regions of both hemispheres is well correlated with the inter-annual variability in the EP flux (see Figure 1 below). Here we use a chemical transport model (CTM) to separate the contributions of transport and polar ozone depletion in forming the observed correlation between EP flux and total ozone.

Data and Model

In this study we focus on the inter-annual variability of the total ozone increase between September and March in the northern hemisphere (NH) and between March and September in the southern hemisphere (SH), averaged between 50° and the pole. We use data from the Total Ozone Mapping Spectrometer (TOMS, version 7) onboard the Nimbus 7, Meteor 3 and Earth Probe satellites, together with data from the Global Ozone Monitoring Experiment (GOME, version 3.0) onboard ERS-2. While TOMS and GOME data agree generally very well, averaged total ozone values for recent years show differences between TOMS and GOME of up to 20 DU, possibly related to a degradation of both instruments.

We correlate the ozone increase with the eddy heat flux at 100hPa, which is proportional to the vertical component of the EP flux. The heat flux is calculated from analyses of the United Kingdom Met Office (UKMO) [*Swinbank and O'Neill*, 1994], averaged between 40° and 70° of the individual hemispheres and averaged between September and March (NH) or March and September (SH). For comparison we also use the eddy heat flux calculated in the same way from analyses of the European Centre for Medium Range Weather Forecasts (ECMWF).

The CTM used in this study is the same as described by *Sinnhuber et al.* [2003]. It is forced by temperatures and wind fields from UKMO analyses. The model was initialized in October 1991 from an ozone climatology and integrated until present (spring 2004 so far). The model uses isentropic levels as vertical coordinates. Transport on isentropic levels is calculated from UKMO wind fields. Vertical transport is derived from interactively calculated diabatic heating rates. The model uses 24 levels between 300 and 3000 K (about 10 to 55 km) with a horizontal resolution of 2.5° by 3.75°. For this study we use a simple linearized ozone chemistry [*McLinden et al.*, 2000]. This linearized ozone chemistry does not include any representation of polar ozone loss as a result of chlorine activation on polar stratospheric clouds (PSC). The model results thus provide the expected inter-annual variability of ozone in the absence of polar ozone loss due to PSC processes.

Results and Discussion

Our CTM calculations of the total ozone increase between fall and spring for both hemispheres are shown against the UKMO heat flux in Figure 2. The ozone increase follows a linear correlation with the heat flux. In particular, northern hemisphere and southern hemisphere data lie on the same slope. A linear fit to the model results is shown as a dashed line in Figure 2, indicating an additional increase of total ozone of about 20 DU for an increase of the heat flux by 1 K m/s.

We compare this modeled relation between heat flux and ozone increase with the TOMS and GOME observations in Figure 1. The modeled relation describes well the observed inter-annual variation in the northern hemisphere. The southern hemisphere observations, on the other hand, are about 20 to 50 DU lower than what is predicted by the model in the absence of polar ozone depletion. This difference in the southern hemisphere thus provides an estimate for the reduction of total ozone due to polar ozone depletion in the Antarctic ozone hole. Somewhat surprising may be the fact, that the observed correlation between EP flux and ozone increase in the northern hemisphere follows the same correlation as the model without polar ozone depletion. However, this does not say, that polar ozone depletion is not important in individual years in the northern hemisphere. E.g., for the Arctic winter of 1999/2000 the model without polar ozone depletion predicts much higher total ozone than observed (compare Figures 1 and 2), indicating significant chemical ozone loss in agreement with
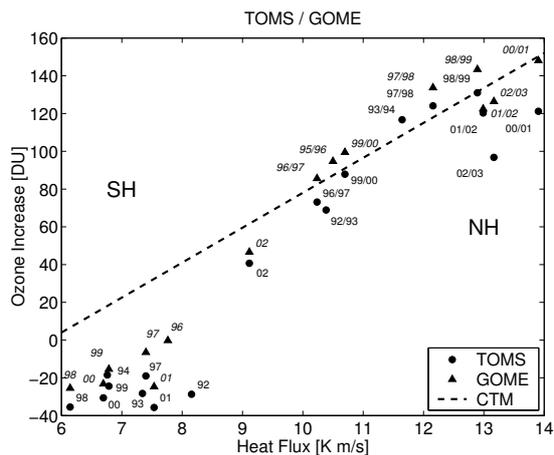
Figure 1. Correlation between 100 hPa eddy heat flux and total ozone increase between fall and spring from TOMS and GOME observations. The heat flux is calculated from UKMO analyses and averaged between September and March (NH) or March and September (SH). Total ozone differences are March-September (NH) or September-March (SH). Also shown (dashed line) is the best fit straight line to the CTM model results (Figure 2).
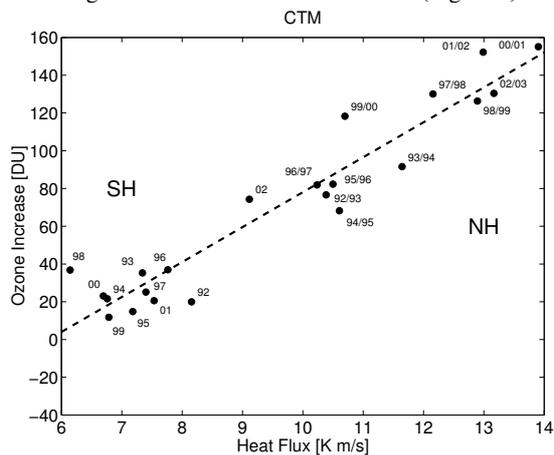
Figure 2. As Figure 1, but for total ozone from the chemical transport model. The dashed line shows the best fit to combined NH and SH data.
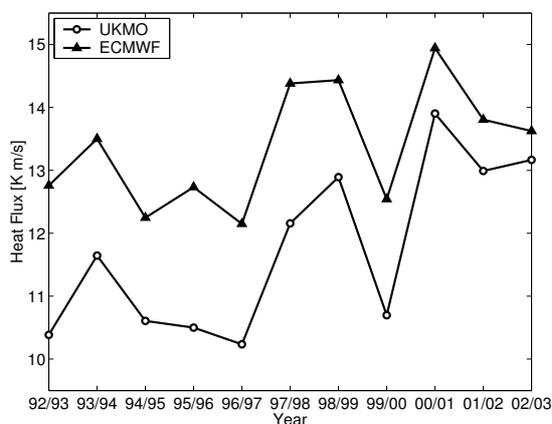
Figure 3. Time series of northern hemisphere heat flux at 100 hPa from UKMO and ECMWF analyses. In addition to the systematic difference between the two analyses, there is a trend of (2.9 K m/s) / (decade) in UKMO heat fluxes that is about twice as large as the trend in ECMWF heat fluxes.

previous studies [e.g., *Sinnhuber et al.*, 2000].

It should be noted, however, that it is difficult to compare directly individual years from the CTM with observations, as the modeled total ozone shows a positive trend in the northern hemisphere over the 12 years of model integration. This trend in modeled total ozone is consistent with a trend in the UKMO EP flux of 2.9 K m/s per decade (Figure 3). From our empirical correlation between heat flux and total ozone – both modeled and measured – this trend in the EP flux would correspond to a total ozone increase of more than 50 DU per decade!

Conclusions and Outlook

Our 12 year CTM calculation reproduces the previously found correlation between total ozone and EP flux. By comparing the modeled and observed correlations between EP flux and fall-to-spring total ozone increase, we find that the expected inter-annual variability of total ozone in the northern hemisphere in the absence of polar ozone depletion is not significantly different from the observed variability. This is in contrast to the southern hemisphere, where polar ozone depletion significantly lowers total ozone by about 20 to 50 DU relative to values expected from transport alone. However, a quantification of the relative influence of transport and chemistry is limited by the uncertainties in planetary wave flux in current meteorological analyses [*Newman and Nash*, 2000], as seen in the large differences between UKMO and ECMWF analyses (Figure 3). We are currently planning to rerun the CTM with ECMWF ERA-40 analyses for comparison.

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