ESA O_3-CCI Project (Phase 2)

Climate Assessment Report (CAR) – final version (30 March, 2017)

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1. Introduction, purpose and scope of the CAR

Europe has the responsibility to perform long-term measurements of Essential Climate Variables (ECVs) and to evaluate and investigate the ECVs, to meet obligations regarding the monitoring of international agreements, in particular the protocols of Montreal and Kyoto. Therefore, it is one of the highest priority tasks for European and national agencies (e.g. ESA, research funders) and the scientific community to work on the creation and maintenance of ECV records. The implementation of appropriate missions and programs are technically and scientifically challenging. It is becoming increasingly clear that monitoring of atmospheric composition and other relevant climate variables is essential, to detect and enable investigations of short- and long-term variations including possible trends, and to provide a better understanding of atmospheric mechanisms driving the climate system. This is absolute essential aiming to enhance the scientific knowledge of the relevant physical, dynamical and chemical processes in Earth atmosphere and gaining deeper insights of their interactions. For example, it is necessary to investigate in detail the chemistry-climate feedback mechanisms. In this respect, process-oriented studies using numerical modelling support such scientific investigations. They help to identify weaknesses of our atmospheric models and to correct adequately the description of atmospheric behavior. This is the most important foundation for robust predictions of climate change and modifications of the chemical composition of the atmosphere. For instance, the expected recovery of the stratospheric ozone layer in the next decades has to be checked and investigated, including the evolution of tropospheric ozone in a future climate. It is expected that there will be significant regional differences regarding the timing of the recovery (or return to 1980-levels) of the ozone layer.

Comprehensive global long-term data sets of ECVs with high quality standards are required to provide the foundation for a complete description of the current status of Earth climate and the evolution in the recent decades, in particular allowing an adequate reproduction of the Earth climate system with our numerical model systems. One important task of atmospheric models is to project future evolution of climate change and possible risks. In the face of outstanding great challenges regarding effects of climate change and modifications of our environment, mitigation and adaptation strategies have to be investigated using a robust database. Therefore, necessary requirements for ECV data sets are long-term stability, precision, characterization of errors, continuity; we need further continuation of observations, i.e. monitoring of ECVs. It is not only necessary to perform measurements, but also to provide high quality derived data products (from Level 0 to Level 3+) that permit respective scientific examinations. We need long time series to identify trends in a statistic manner.

ESA-CCI has enabled ESA and European scientists to contribute significantly to coordinated international actions on climate observations from space. Establishing and working with the ESA ECVs enables the European community to strengthen its international leadership and visibility in comparison to the USA and others, increasing scientific excellence in this area.

European scientists play vital parts in international climate research programs (such as WCRP) and in recent assessment reports, in particular ESA-CCI has made valuable contributions to IPCC's 5th Assessment report and the recent UNEP/WMO Scientific Assessment of Ozone Depletion: 2014; the CCI has and will further help to increase the visibility of European research and researchers in this field.

As already mentioned before, such an ECV database is crucially important, supporting the goals of protecting Earth climate and the environment in the international context. In this connection, the ECV "ozone" is one of the most important climate agents. It is well known that the stratospheric ozone layer protects the Earth surface from ultra-violet radiation. Beyond that the extreme ozone loss over Antarctica in spring has obviously changed surface climate significantly (see Chapter 4 in WMO, 2014). Recently clear indications were presented of connections of Arctic stratospheric ozone extremes to Northern Hemisphere surface climate (Ivy et al., 2017).

The generation of homogeneous, high-quality long-term (multi-year/-decadal) data sets, which allow the investigation of relevant processes and how processes are changing in space and time are still needed. Recent data sets have to be combined together in a consistent manner to enable a uniform picture of recent fluctuations and changes. This is one prerequisite to add new future measurements allowing identification and investigation of short- and long-term fluctuations and trends.

Scientists need high quality data sets to support excellent scientific investigations of atmospheric fluctuations and changes and of the processes involved. The usefulness of the data products have to demonstrate that they are helping to answer climatically relevant questions. In particular in the Ozone_cci project substantial community building has taken place to strengthen the relationship between satellite data product developers and climate scientists. Ozone_cci has produced long, consistent time series (currently 1995-2016) of total ozone column and ozone vertical profile measurements from multiple nadir and limb sounding instruments. Consistency between these European data sets and other ozone data products (derived from US instruments, e.g., TOMS, SBUV, OMPS, HALOE, SAGE, MLS, IASI) has been investigated (future plan: merged data sets, to extend the length of the data series). Some of these results are discussed in the following.

2. Scientific tasks and current investigations

Consistent, multi-year data sets are still needed for scientific research. In particular for the ECV ozone there are some outstanding questions which have to be investigated in the coming years. There is need for extending the CCI scientific program and to continue with the monitoring of the stratospheric ozone layer. Available long-term data sets (e.g. multi-decadal observations of total ozone; see the recent WMO Scientific Assessments of Ozone Depletion, 2007, 2011, and 2014) have demonstrated impressively their usefulness; it is obvious that a continuation of these data series is required.

Regarding ozone, the current scientific challenges, questions and tasks are:

- Continuous monitoring of the consequences of the Montreal Protocol and its amendments, in particular
- Detection of ozone return/recovery in the next 5 to 10 years, i.e., identifying the reversal point in time where stratospheric ozone decline stalls due to the regulation of CFCs and the ozone layer will start to recover. It has to be investigated if the recovery of ozone in the upper stratosphere is consistent with our expectations based on Cl_y, temperature, and other factors; and
- Further monitoring of the ozone layer change over the 21st century (including in respect of atmospheric changes from, sudden stratospheric warmings, the accelerated Brewer Dobson circulation, etc.) is necessary, in particular detecting higher stratospheric ozone values as an indicator of climate change.
- A multi-year comprehensive 4D-ozone data base is the foundation for understanding of dynamical and chemical processes and their feedback (coupling) affecting the ozone layer.
- A comprehensive data base is needed to check the abilities of Chemistry-Climate Models (CCMs) to reproduce observed features and short- and long-term variability.
- CCM simulations are used to predict the future evolution of the stratospheric ozone layer in a changing climate, determining the dependence of ozone recovery in space (latitude and altitude) and time, especially investigating the evolution of the ozone layer in polar regions (ozone hole) as well as the tropics and its impact on surface climate.
- How important is climate change for the future evolution of the tropospheric ozone (e.g. Stratosphere-Troposphere Exchange, STE)? How will ozone concentrations develop in the troposphere depending on the assumed RCPs and the expected emissions of ozone precursors? I.e., examination of the importance of STE processes for tropospheric ozone and the impact of climate change on STE; what is expected for the future? How strong will they affect the total ozone column?

- Investigation of the importance of increasing tropospheric ozone as a hemispheric pollutant and climate forcer related to ozone precursor emissions.
- Working on the importance of (changes in) troposphere-stratosphere transport, e.g. in the Asian monsoon region for the evolution of the ozone layer.
- Examination of the importance of ozone-radiative and ozone-dynamical interactions in the lower stratosphere and the impact of climate change on these interactions.
- And, last but not least making an attempt getting boundary layer ozone and mid-upper tropospheric ozone concentration distributions and trends worldwide (probably best achieved through reanalysis that uses the full integrated observing system).

3. Examples of new ozone analyses and current status of knowledge

In this section a short review of recent and ongoing scientific work regarding atmospheric ozone and in particular which is related to Ozone_cci CAR will be presented. The Ozone_cci Climate Research Group is working on a number of aspects. Examples are given in the following.

3.1 Highlights of the recent WMO ozone assessment and open question

The current status of knowledge regarding the evolution of the stratospheric ozone layer is summarized in the last UNEP/WMO Scientific Assessment of Ozone Depletion (2014). Some of the most outstanding statements are:

- The sum of the measured tropospheric abundances of substances controlled under the Montreal Protocol continues to decrease, and therefore they are enabling the return of the ozone layer toward 1980 levels.
- Measured stratospheric abundances of chlorine- and bromine-containing substances originating from the degradation of Ozone-Depleting Substances (ODSs) are decreasing (i.e. by about 10-15% from the peak values of ten to fifteen years ago).
- Total column ozone declined over most of the globe during the 1980s and early 1990s (by about 2.5% averaged over 60°S to 60°N). It has remained relatively unchanged since 2000, with indications of a small increase in total column ozone in recent years, as expected.
- The Antarctic ozone hole continues to occur each spring, as expected for the current ODS abundances.
- Total column ozone will recover toward the 1980 benchmark levels over most of the globe under full compliance with the Montreal Protocol. This recovery is expected to occur before midcentury in mid-latitudes and the Arctic, and somewhat later for the Antarctic ozone hole.
- As controlled ODSs decline, the evolution of the ozone layer in the second half of the 21st century will largely depend on the atmospheric abundances of CO_2, N_2O, and CH_4. Overall, increasing carbon dioxide (CO_2) and methane (CH_4) elevate global ozone, while increasing nitrous oxide (N_2O) further depletes global ozone.
- In the tropics, significant decreases in column ozone are projected during the 21st century. Tropical ozone levels are sensitive to circulation changes driven by CO_2, N_2O, and CH_4 increases.

More detailed descriptions and explanations are discussed in the following with respect to the evolution of the global and polar ozone layer and how it is connected with climate change.

Ozone-depleting substances (ODSs) were the dominant driver of global ozone decline in the late 20th century. As controlled ODS concentrations decline, CO_2, N_2O, and CH_4 will strongly influence ozone evolution in the latter part of the 21st century through chemical and climate effects. Uncertainties in future emissions of these gases lead to large differences in ozone projections at the end of the century.

It is evident that climate change is not only affecting the troposphere (the greenhouse effect leads to a warming) but is also modifying the stratosphere (leading to a cooling). In this connection important questions are: (i) How are the interactions between climate change and modifications of the circulation and chemical composition of the stratosphere? (ii) How is climate change influencing the stratospheric ozone layer? Due to lower stratospheric temperatures, ozone chemistry is directly affected. For example the content of ozone (O_3) in the middle and upper stratosphere is globally enhanced due to reduced ozone depletion by slower homogeneous gas phase reactions, while in the polar lower stratosphere the enhanced probability of polar stratospheric clouds intensify ozone depletion.

With this respect, therefore one of the major bullet points in the WMO ozone assessment is:

"Changes in concentrations of CO_2, N_2O, and CH_4 will have an increasing influence on the ozone layer as ODSs decline."

As controlled ODSs decline, the evolution of the ozone layer in the second half of the 21st century will largely depend on the atmospheric abundances of greenhouse gases. Overall, increasing CO_2 and CH_4 elevate global ozone while increasing N_2O further depletes global ozone (**Figure 1**).

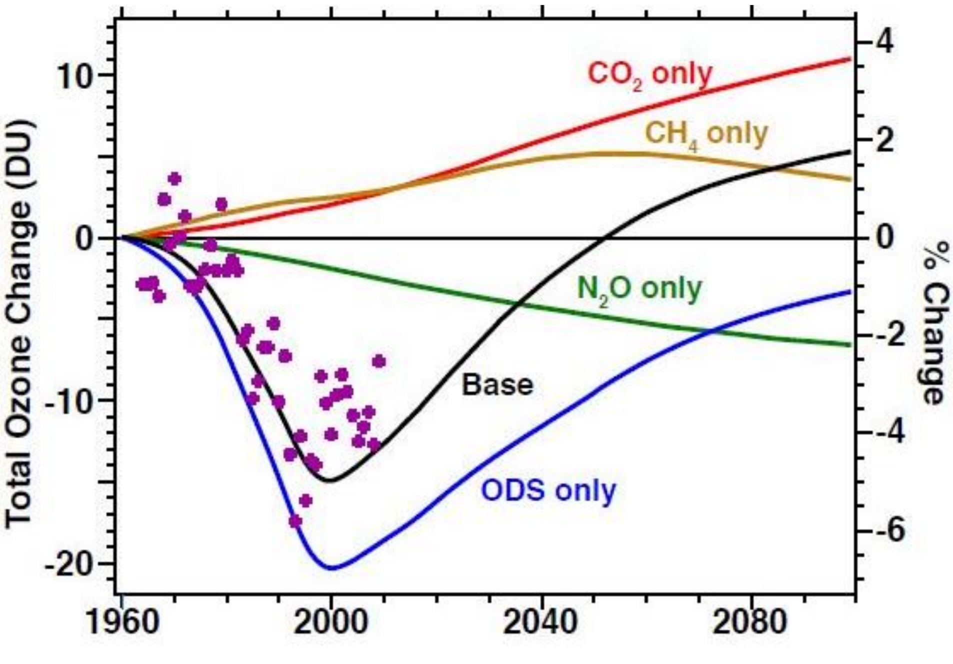

Figure 1: Model-simulated global/annual averaged total ozone response to the changes in CO_2 (red line), CH_4 (brown line), N_2O (green line), and ODSs (blue line). The total response to ODSs and greenhouse gases combined is shown as the black line. The responses are taken relative to 1960 values. Ground-based total ozone observations (base-lined to the mid-1960s) are shown as magenta cross symbols (figure taken from WMO, 2014).

In the tropics, significant decreases in column ozone are projected during the 21st century. Tropical ozone levels are only weakly affected by the decline of ODSs. They are sensitive to circulation changes driven by CO_2, N_2O, and CH_4 increases.

There are several indications that the ozone layer is beginning to recover from ODS-induced depletion. Tropical ozone has not been strongly affected by ODSs; its future changes will be dominated by enhanced greenhouse gas concentrations.

The projected future evolution of tropical total column ozone is strongly dependent on future abundances of CO_2, N_2O, and CH_4 (e.g., as in Representative Concentration Pathways (RCPs)), and is particularly sensitive to changes in the tropical upwelling and changes in tropospheric ozone. Except for RCP 8.5, which specifies large increases in methane, significant decreases in total column ozone are projected during the 21st century (**Figure 2**).

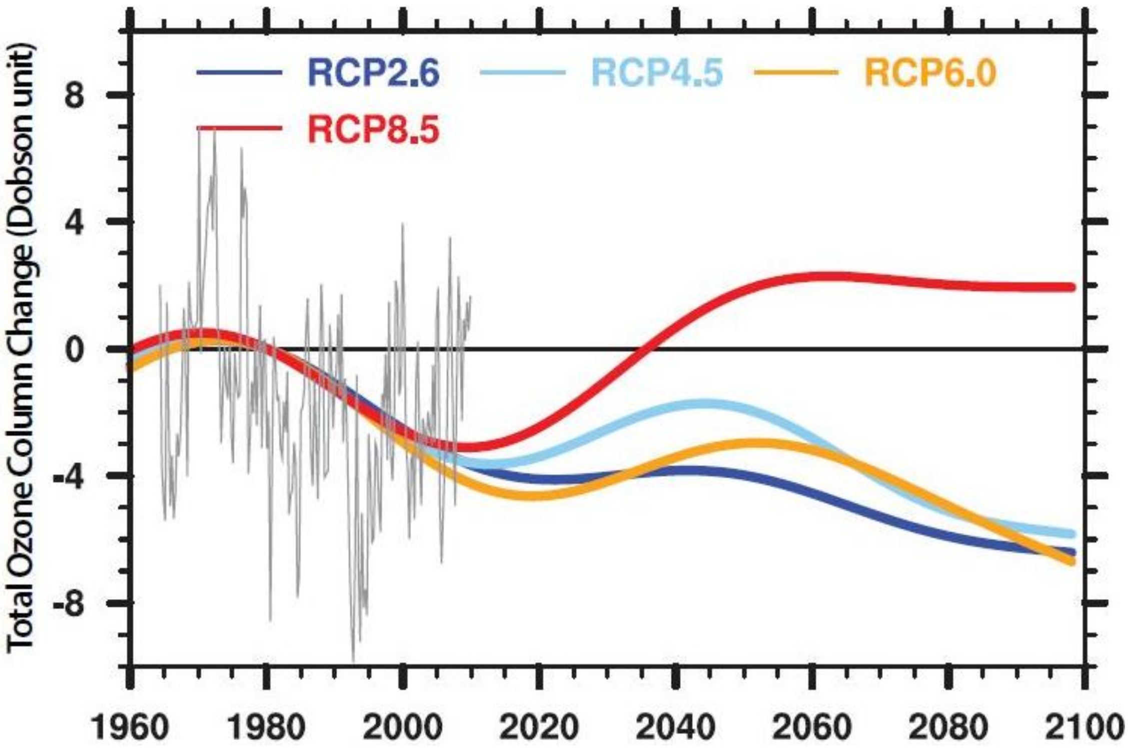

Figure 2: Total column ozone time-series averaged over the tropical latitude band 25°S-25°N for Coupled Model Intercomparison Project-Phase 5 (CMIP5) models for the four RCP scenarios (adjusted to a 1980 baseline). Also shown are seasonal mean total column ozone values from ground-based observations, relative to the 1964-1980 average. The RCP simulations are averaged over 5 models, except RCP8.5, which uses 6 models. The four RCP scenarios correspond to +2.6 (dark blue), +4.5 (light blue), +6.0 (orange), and +8.5 W m^{-2} (red) of global radiative forcing. The "high" 8.5 W m^{-2} (red) scenario has steadily increasing greenhouse gases during the 21st century (figure taken from WMO, 2014).

The future evolution of the polar ozone layer shows differences with regard to the Arctic and Antarctic stratosphere. The Antarctic ozone hole will continue to occur at least until mid-century. Occasional large Arctic ozone depletion, such as that in spring 2011, is well understood, and is also possible in coming decades. Recovery of polar ozone would occur earlier if there were no further emissions of controlled ODSs, and would be delayed by increases in stratospheric aerosol that could be caused by injection of sulfur by large volcanic eruptions or geoengineering.

There are clear indications that stratospheric changes, in particular changes related to ozone depletion, have an effect on surface weather and climate. It has been shown that the Antarctic ozone hole has caused significant changes in Southern Hemisphere surface climate, e.g. the summertime tropospheric circulation has been affected in the recent decades, with associated impacts on surface temperature and precipitation.

3.2 Comparison of Ozone_cci total columns with CCM simulations

Validation of new results derived from CCM simulations[1] for the past with ozone data derived from European space-borne-instruments are carried out. The performance of such ozone data sets are analysed and results of supporting modelling efforts with CCMs are confronted with Ozone-cci data products. The synergies of model data and observations are exploited to address scientific questions, e.g., assessment of ozone depletion/recovery in a changing climate, interannual variability and extremes and regional changes of the ozone distribution.

Ozone data products derived from long-term (multi-year) CCM simulations (e.g., 1980 to 2013) are provided. Among others using set ups of the CCM with specified dynamics (so-called “nudged mode” using a relaxation towards observed dynamic fields) to be able to compare with specific observations. The CCM includes a comprehensive description of stratospheric ozone chemistry (e.g. Jöckel et al., 2016).

Two simulations performed with version 2.51 of the European Centre for Medium-Range Weather Forecasts – Hamburg (ECHAM) / Modular Earth Submodel System (MESSy) Atmospheric Chemistry (EMAC) model have been confronted with the ESA Ozone_cci GOME-type Total Ozone Essential Climate Variable (GTO-ECV) data record (Coldewey-Egbers et al., 2015). A detailed description of the model system and its different set-ups can be found in Jöckel et al. (2016) and references therein. We investigate two hindcast simulations (1980-2013) with specified dynamics, i.e. meteorology nudged towards ERA-Interim reanalysis data (Dee et al., 2011). The nudging is applied for the prognostic variables divergence, vorticity, temperature, and surface pressure, in which the nudging strength varies with altitude. Sea surface temperatures and sea ice concentrations are taken from ERA-Interim reanalysis data, too. The so-called “RC1SD-base-07” simulation includes the nudging of the global

[1] The CCM simulations have been defined on the basis of the SPARC/IGAC Chemistry-Climate Model Initiative (CCMI), in particular to support the next WMO Scientific Assessment of Ozone Depletion, that is scheduled for 2018 (see http://www.geo.fu-berlin.de/met/ag/strat/publikationen/docs/Eyring-et-al_SPARC-Newsletter40.pdf).

mean temperature, whereas this is omitted in the second simulation “RC1SD-base-10”.

Jöckel et al. (2016) provided a first evaluation of the modeled ozone distributions by comparing with observations such as satellite measurements and ozone sonde data. They found that total ozone columns are overestimated for all latitude bands with the bias generally increasing from north to south. The simulation RC1SD-base-07 with temperature nudging agrees better with the observations than the corresponding simulation without nudging the global mean temperature.

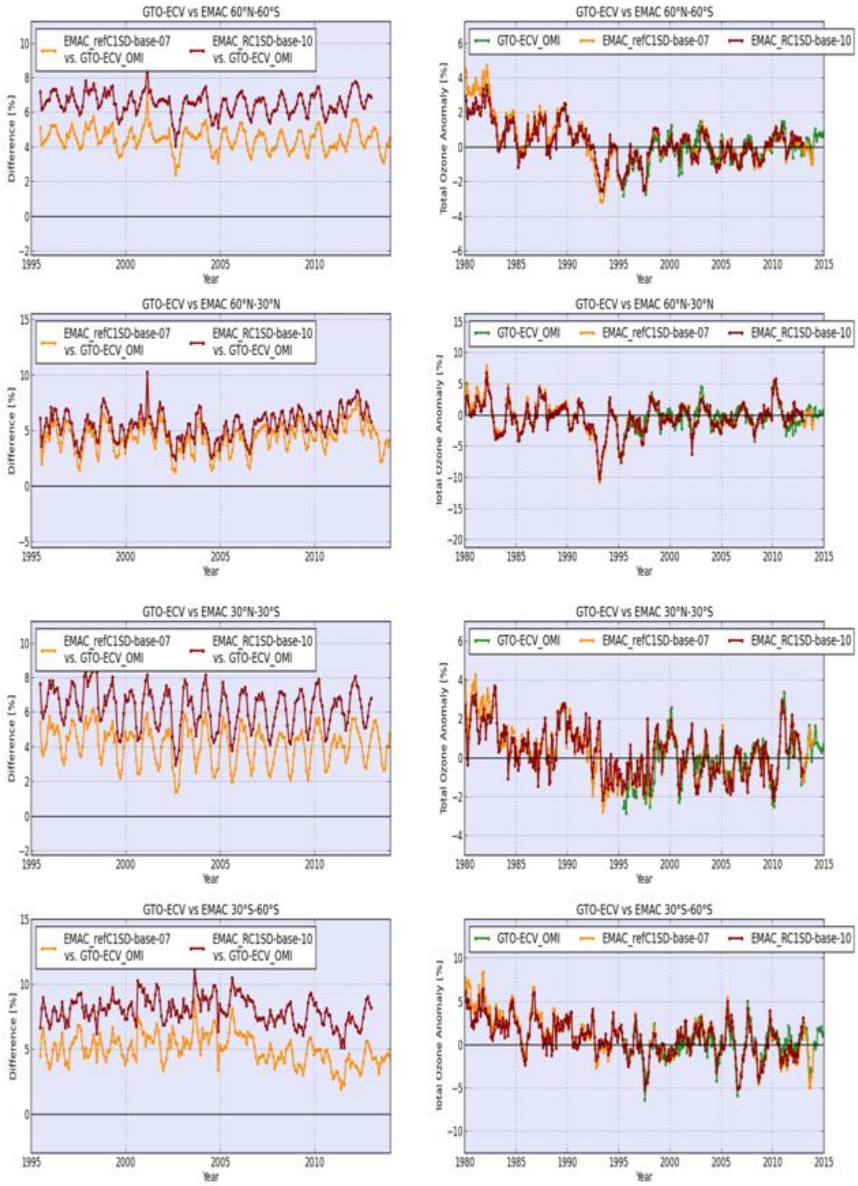

Figure 3: Left column: Difference [%] as a function of time from 1995 to 2013 between EMAC model simulations and GTO-ECV total ozone data. Right column: Total ozone anomalies [%] from 1980 to 2015. From top to bottom: Latitude belts 60°N-60°S, 60°N-30°S, 30°N-30°S, and 30°S-60°S. Red: RC1SD-base-10 simulation, yellow: RC1SD-base-07 simulation and green: GTO-ECV satellite data.

Figure 3 shows the monthly mean differences between model simulations and GTO-ECV data (left) and ozone anomalies for simulations and GTO-ECV (right) as a function of time for different latitude bands: 60°N-60°S, 60°N-30°N, 30°N-30°S, and 30°S-60°S, from top to bottom. Anomalies have been calculated with respect to the multi-year average from 1998 to 2012.

Total ozone is overestimated for both simulations. The bias is larger in the Southern Hemisphere than in the Northern Hemisphere. Nudging the global mean temperature (RC1SD-base-07, yellow curves) reduces the bias between model and observation, in particular in the tropics and the middle latitudes of the Southern Hemisphere. The reduction in the Northern Hemisphere is smaller, because the bias is reduced only in the troposphere, whereas in the stratosphere it is enlarged (Jöckel et al., 2016).

Ozone anomalies (**Figure 3**, right column) show an excellent agreement between simulations (both nudging versions, yellow and red curves) and observations (green curves). During the overlap period, interannual variability is very well captured by the model system, and extreme values are well reproduced in most cases.

Figure 4 shows the same as **Figure 3**, but for March values in the northern high latitudes (85°N-60°N, top row) and for October values in the southern high latitudes (60°S-85°S, bottom panels). As for the other latitude bands (**Figure 3**) the model has a positive bias for total ozone columns in both polar regions (left column). The bias is significantly reduced when the nudging includes the global mean temperature (RC1SD-base-07, yellow curve). Furthermore, the model is able to capture ozone anomalies even in high latitudes (right column) and in extreme cases such as the record low ozone values in the Arctic in March 1997 and 2011 and in October 2002 when the Antarctic vortex was disturbed and split up into two parts.

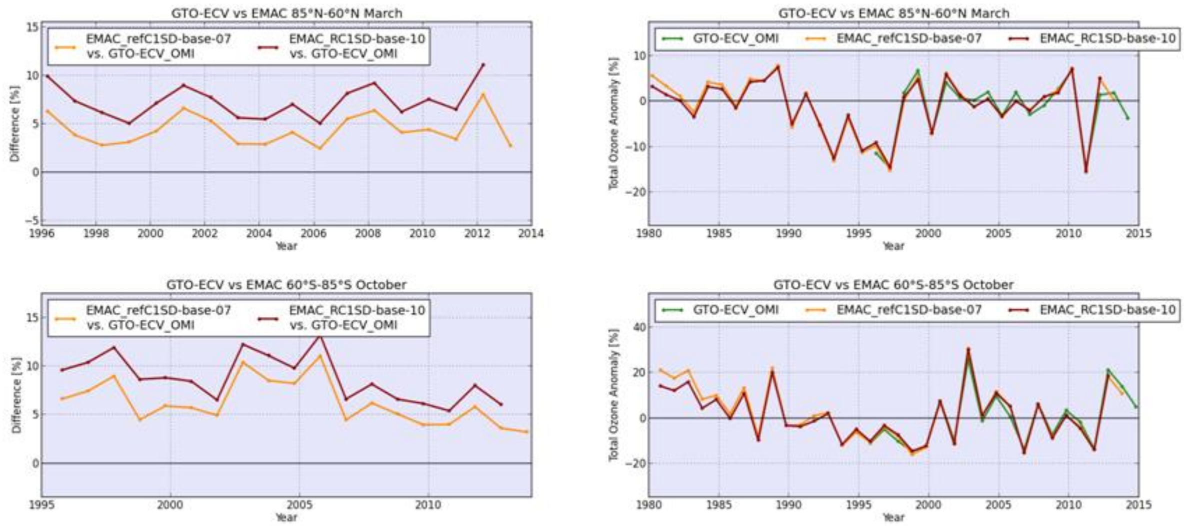

Figure 4: Top row: Difference [%] from 1995-2013 between EMAC model simulation and GTO-ECV total ozone column (left) and ozone anomalies [%] from 1980-2015 for EMAC and GTO-ECV for March, 85°N-60°N. Bottom panels: same as top panels, but for October, 60°S-85°S.

The combination of CCM data based on simulations with specified dynamics allows determining the recent evolution of the ozone layer in a consistent manner. Since the ozone anomalies calculated from the CCM are in excellent agreement with the respective Ozone_cci data product, reliable signs for the temporal development of the ozone layer in specific regions can be identified. For instance, in **Figures 3 and 4** obvious reduction of the total ozone amount is detected, but with different amplitudes: In the northern mid-latitudes there is no statistically significant trend over the last 35 years (Figure 3, right column, second row), whereas the southern mid-latitudes show a clear reduction of the ozone content by about 5% until the year 1997 (Figure 3, right column, forth row). In the tropics (Figure 3, right column, third row) the ozone reduction before 1995 is in the order of 2-3%. The anomalies show a clear signature of the 11-year solar cycle, as discussed in detail in the WMO ozone report of 2006 (WMO, 2007). During spring time, both polar regions indicate a strong trend of ozone depletion, i.e. about 15% in the Arctic stratosphere and up to 35 % in the Antarctic stratosphere, which are stopped around 1997 (Figure 4, right column). So far, no latitudinal region of the stratosphere is showing an obvious beginning of ozone recovery.

3.3 Comparison of ozone profiles

To estimate the quality of CCM results it is necessary to evaluate not only the total ozone column but also the vertical structure of ozone. In a first step here we are using the ozone (ESA) data product derived from the ENVISAT-MIPAS instrument.

The ENVISAT mission with on-board the MIPAS instrument lasted ten years, from the 1st of March 2002 until the 8th of April 2012. Data are available after the commissioning phase from 1st March until July 2002. The Level 2 products consist of a number of geophysical parameters derived from the measured atmospheric limb emission spectra and some instrument auxiliary information, including e.g. the pointing information (for details see: https://earth.esa.int/documents/700255/2635669/RMF_0141+MIP_NL_2P_issue1.pdf/59beb833-5ad4-4301-8422-f41001da36d4). The current status of the MIPAS consolidated Level 2 (L2) data set version 7.03-W is available at: https://earth.esa.int/web/sppa/mission-performance/esa-missions/envisat/mipas/products-availability/level-2. In the following we are using volume mixing ratio (VMR) vertical profile data of ozone derived from MIPAS L2 v7.03 (hereafter called simply L2v7). As stated in the above mentioned pdf-document (on page 21) L2v7 overestimates ozone relative to co-located ozonesonde and lidar measurements, with a magnitude that depends mildly on latitude and pressure. The positive bias is about 5% in the middle and upper stratosphere, and 10-15% in the lower stratosphere.

First, we have checked the mean ozone distribution based on the complete MIPAS-data set from July 2002 and April 2012. In **Figures 5 and 6** the altitude and latitude (zonal mean) dependences is shown, indicating a good agreement between the

MIPAS measurements and the EMAC simulation results with respect to the vertical and zonal structure. Some obvious differences are turned out looking at the differences between the ozone data derived from MIPAS and the model results. **Figure 7** (lower parts) indicate that around 100 hPa the MIPAS data may be uncertain due to the detection limit there. In the lower stratosphere the EMAC data are showing slightly higher ozone mixing ratios (about 5-10%). In the middle and upper stratosphere and lower mesosphere MIPAS ozone values are clearly higher than the model data (up to about 20%). For example, the stratospheric ozone maximum in the tropics is underestimated by the model simulations, i.e. about -0.8 ppmv (less than 10%). These first assessments are pointing out that this CCM is absolutely able to reproduce the observed ozone distribution in the middle atmosphere. Longer time series of the vertical structure of ozone are required to estimate the long-term behaviour of the different height regions which are, among others, depending on climate change (see also Section 3.4).

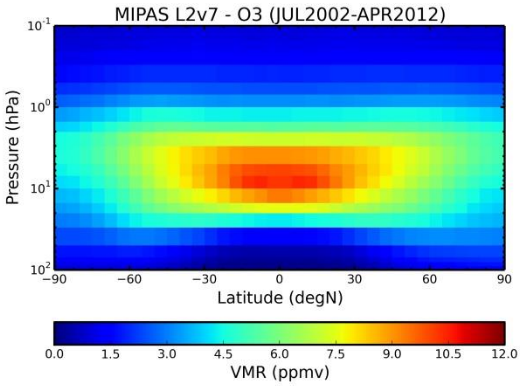

Figure 5*:* Mean ozone distribution (volume mixing ratio, VMR) between 100 hPa and 0.1 hPa for the time period between July 2002 and April 2012 derived from the ENVISAT-MIPAS instrument (worked out by Massimo Valeri, University of Bologna, Italy).

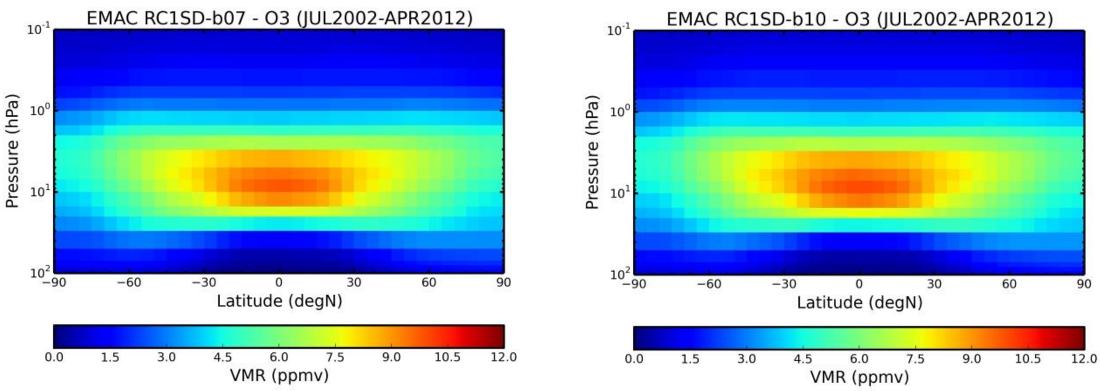

Figure 6*:* Mean ozone distribution (mixing ratios) between 100 hPa and 0.1 hPa for the time period between July 2002 and April 2012 derived from the EMAC-RC1SD simulations, left version base-07 (b07), right version base-10 (b10). (Worked out by Massimo Valeri, University of Bologna, Italy.)

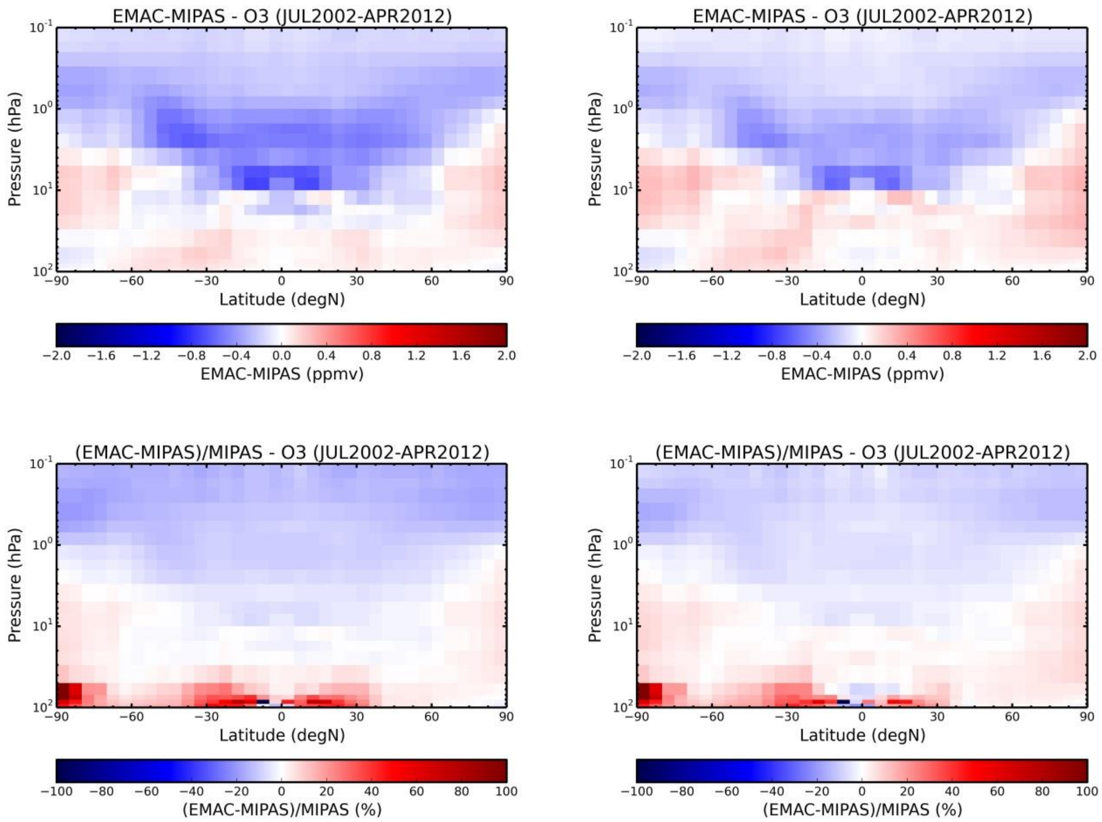

***Figure 7**:* (top) Absolut and (bottom) relative ozone differences between MIPAS and EMAC simulations (left: differences between MIPAS and EMAC RC1SD-b07 and right: differences between MIPAS and EMAC RC1SD-b10).

3.4 Assessment of CCM results and future projections

Figure 8 shows a previous example of the temporal evolution of total ozone deviations regarding a mean ozone value (1995-2009) for the near global mean (i.e. global mean values neglecting polar regions). Looking into the past it is obvious that the CCM (here the DLR CCM E39CA, i.e. the predecessor of EMAC) was able to reproduce seasonal and interannual fluctuations in a sufficient manner, although the amplitudes of ozone anomalies are slightly underestimated (Loyola et al., 2009; Dameris and Loyola, 2011). Model data and data derived from satellite observations clearly show the signature of the 11-year solar cycle. The absolute minimum ozone values observed in years 1993-95, which are caused by the eruption of the volcano Pinatubo, are not adequately reproduced by the CCM. The simulated increase in stratospheric ozone amount after year 2010 is a direct consequence of the prescribed decrease of stratospheric chlorine content. The speed at which the ozone layer will rebuild in future depends on a range of other factors, however. Rising atmospheric concentrations of radiatively active gases (such as CO_2, CH_4 and N_2O) do not just cause the conditions in the troposphere to change (i.e. the greenhouse effect warms the troposphere), but also in the stratosphere which cools down with increasing CO_2 concentrations. The regeneration of the ozone layer thus takes place under atmospheric conditions different to those prevailing during the ozone depletion processes of recent decades. Due to climate change, it is highly unlikely that the ozone layer will return to exactly the way it was before the time of increased concentrations of ozone depleting substances (ODSs). Due to further increasing greenhouse gas concentrations, global atmospheric temperatures will continue to change over the coming decades: It is expected that the troposphere will continue to warm up and that the stratosphere will cool down further due to radiation effects.

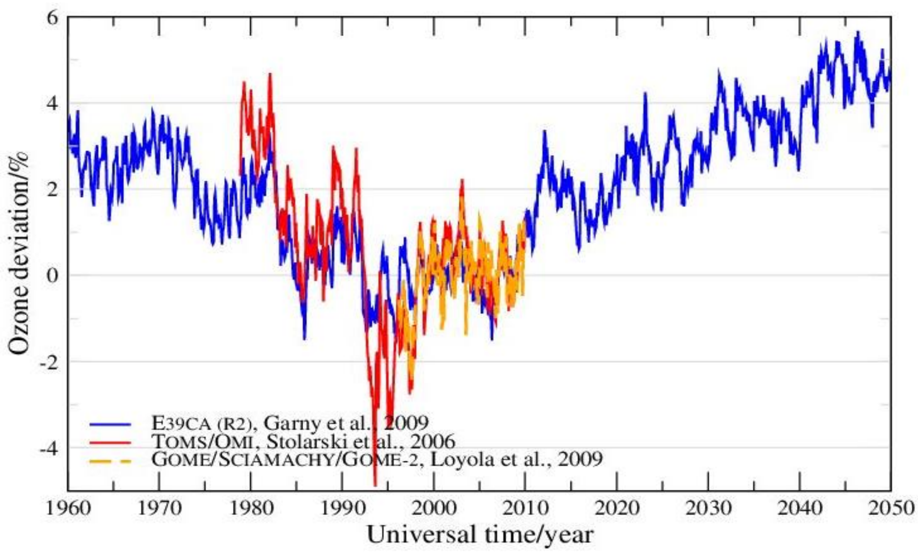

***Figure 8**:* Total ozone anomalies over 60°N to 60°S. The mean annual cycle for 1995 to 2004 is subtracted from satellite measurements (orange and red) and in blue results of the CCM E39CA model simulation R2 from 1960 to 2050 (update of Loyola et al., 2009).

Future prognostics with CCMs also clearly indicate that ozone regeneration will be faster in some areas than in others, where it's quite possible that the recovery of the ozone layer will be delayed. The results of CCM simulations also indicate that the recovery of the ozone layer will vary from region to region and does not represent a simple reversal of the depletion observed over recent years. Examples are presented in **Figure 9**, showing the evolution of the stratospheric ozone layer in the Northern and Southern polar regions (Dameris and Loyola, 2011). In contrast to **Figure 8**, only the data for respective spring months are shown when ozone depletion maximizes. First of all, the CCM reproduces nicely the different evolution of the ozone layer in the Northern and Southern Hemisphere in the past showing a more pronounced thinning of the ozone layer in the Southern Hemisphere due to the formation of the ozone hole. Interannual fluctuations are well captured by the CCM in the Northern Hemisphere while they are underestimated in the Southern Hemisphere. Here, for example, the model does not create dynamical situations leading to weak polar vortices in late winter and early spring and therefore higher ozone values as particularly observed in 1988 and 2002. Obviously, the recreation speed of the ozone layer is different in the Northern and in the Southern Hemisphere: In the Northern Hemisphere ozone values found in the 1960ies and 1970ies are reached again around 2030 and further increase afterwards. In the Southern Hemisphere the 2050-values are still below the values found in the 1960ies.

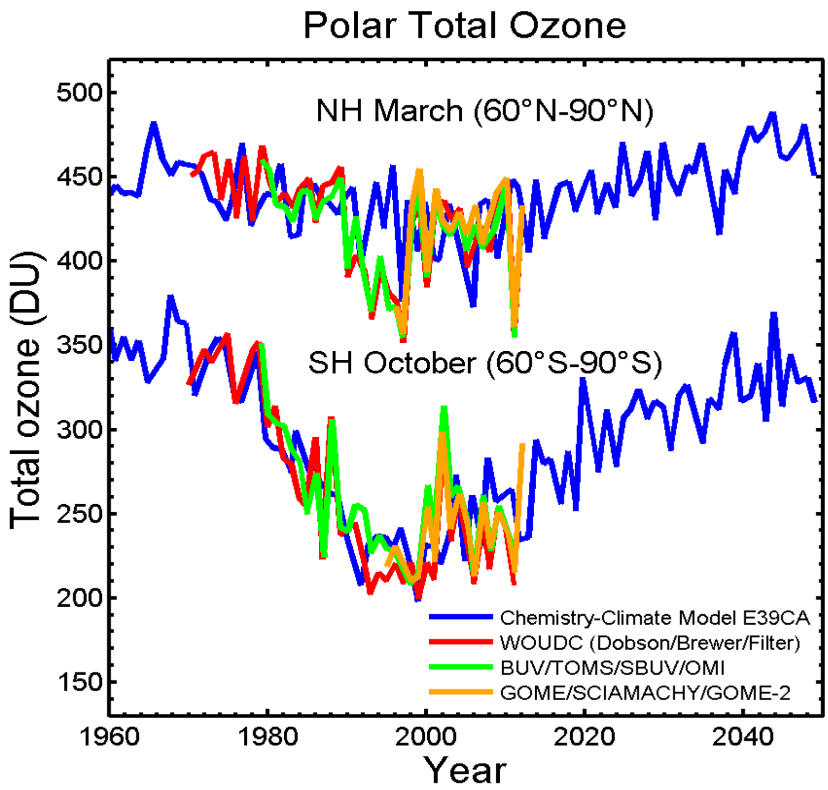

Figure 9: As Figure 8, but now total ozone values for the polar regions (top: Northern Hemisphere for March; bottom: Southern Hemisphere for October). Deviations are given with regard to the mean value of the period 1995-2009 (in %) for the region between 60° and 90°. Notice the different scales on the y-axis.

In the last years the SPARC/IGAC Chemistry-Climate Model Initiative (CCMI) has been established as successor of the SPARC CCMVal activity. Among others it has been initiated to support the upcoming “WMO Scientific Assessment of Ozone Depletion” which is planned to be released in late 2018. New model simulations with updated (further developed) CCMs are proposed. For instance, three different sets of reference simulations have been suggested by CCMI, namely free-running hindcast simulations from 1960 to 2010 (REF-C1), hindcast simulations with specified dynamics (SD) from 1980 to 2010 (REF-C1SD), and combined free-running hindcast and projection simulations from 1960 to 2100 (REF-C2). The hindcast simulations with specified dynamics have been branched off from restart files (1 January 1979) of the corresponding free-running hindcast simulations and “nudged” by Newtonian relaxation towards ERA-Interim reanalysis data, which are available with a 6-hourly time resolution from the year 1979 onwards. In this connection the CCM EMAC has carried out these reference simulations (some results of the RC1SD simulations have been presented already in Sections 3.2 and 3.3). A comparison of these model data derived from the reference simulations are used to confront them with updated ESA Ozone_cci GOME-type Total Ozone Essential Climate Variable, which is now completed with OMI data (GTO-ECV_OMI). In the following some preliminary results (not published so far!) are presented. They mostly confirm our recent findings which were published some years ago. An improved future assessment of the ozone layer with EMAC until 2100 (REF-RC2) is presented, allowing to distinguish in detail between the different geographical regions.

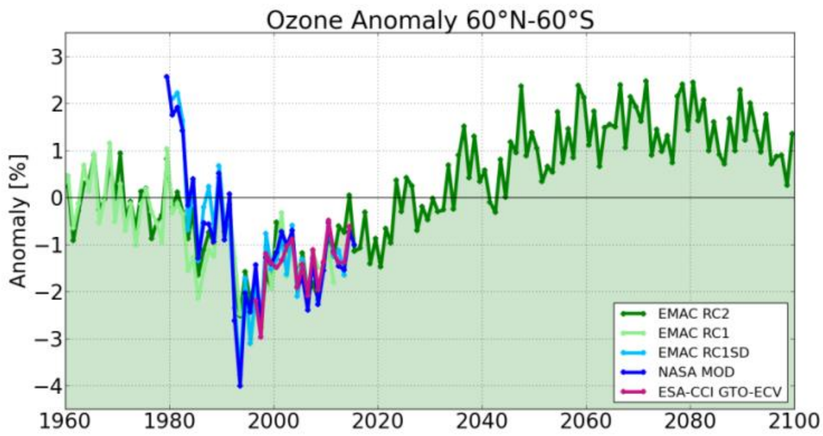

Figure 10*:* Temporal evolution of the near global mean total ozone column anomaly (60°N-60°S). Anomaly values are related to the mean from 1960 to 1980. In addition to the three EMAC reference simulations and ESA-CCI data products, a data product prepared by NASA (1979 to 2015) is shown.

Figure 10 illustrates the good agreement between the model results and the NASA and ESA data set derived from observations. This is the foundation for a robust prediction of the recovery of the ozone layer. Based on this model assessment it is obvious that a full recovery of the near-global mean total ozone column can be expected around 2035. This date is earlier than expected with respect to the decline of the stratospheric chlorine content due to the regulations of ozone depleting substances in the Montreal protocol. The major reason for this behaviour is the impact of climate change (stratospheric cooling and modifications of the circulation). The “super-recovery” of the ozone layer after about 2045 is also the results of stratospheric changes caused by higher greenhouse gas concentrations.

Figure 11 shows the different behaviour in Arctic and Antarctic region. Here the results are given for the spring season (March and September, respectively) indicating strongest ozone depletion particularly in the 1990 and 2000s. The largest negative anomaly is identified in the South Polar Region, i.e. the ozone hole phenomenon. Back to normal ozone content is predicted after about 2025 in the North Polar Region, whereas the ozone hole will be closed around 2060. It turned out that the Antarctic lower stratosphere is not obviously affected by climate change with respect to the ozone depleting chemical reactions. A further cooling of this region is of no significant importance for the amount of ozone destruction because it is already very cold there and a complete activation of ozone depleting substances is currently observed.

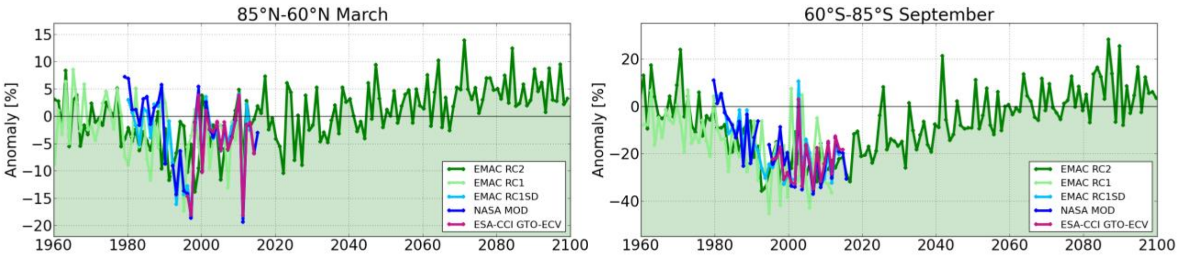

Figure 11: Temporal evolution of the total ozone column anomalies in the North (left) and South polar region (right) during the spring months March and September. Anomaly values are related to the mean from 1960 to 1980.

Based on the observations over the Antarctic region in September, a first sign of a beginning ozone recovery is detected (Solomon et al., 2016). The EMAC results show a consistent reaction.

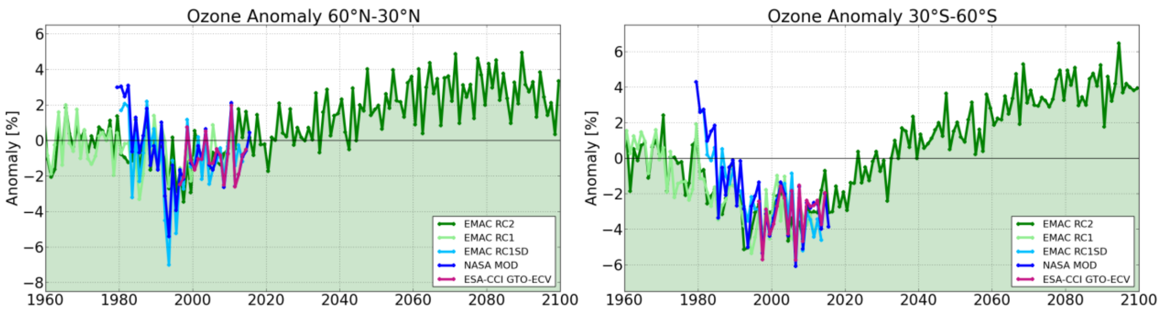

Figure 12: Similar to Figure 10, but now for the mid-latitude regions in the Northern (left) and Southern hemisphere (right).

At Northern mid-latitudes the EMAC REF-C2 simulation indicates a full recovery in these days, but one has to consider the large interannual variability in this region. The model results for the mid-latitudinal region in the Southern hemisphere show a return to undisturbed total ozone values around 2035. Both geographical regions imply a super-recovery of the ozone column in the second half of this century.

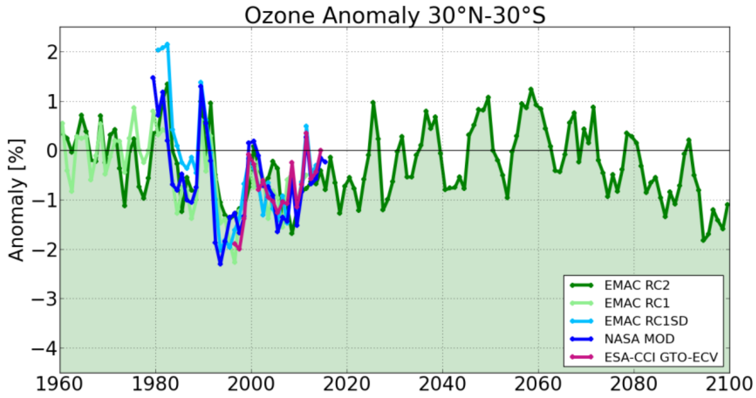

Figure 13: Similar to Figure 10, but now for the tropical region.

As pointed out in Section 3.1 (see Figure 2) there may be the possibility for a future reduction of the tropical total ozone column with implication for the UV-B content near the surface. The EMAC REF-C2 simulation indicates the same future behaviour. In the following results of an investigation of the possible future evolution of the tropical ozone layer is presented.

3.5 Special investigation of tropical ozone in future

In particular, future projections of tropical total column ozone (TCO) are challenging, as its evolution is affected not only by the expected decline of ozone depleting substances but also by the uncertain increase of greenhouse gas (GHG) emissions. To assess the range of tropical TCO projections, CCM simulations forced by three different GHG scenarios (Representative Concentration Pathway (RCP) 4.5, RCP6.0, and RCP8.5) were analysed. It was found that tropical TCO will be lower by the end of the 21st century compared to the 1960ies in all scenarios with the lowest TCO value in the medium RCP6.0 scenario in the 2090ies (**Figure 14**). Uncertainties of the projected TCO changes arise from the magnitude of stratospheric column decrease and tropospheric ozone increase which both strongly vary between the scenarios. In the three scenario simulations the stratospheric column decrease is not compensated by the increase in tropospheric ozone. The concomitant increase in harmful ultraviolet irradiance reaches up to 15% in specific regions in the RCP6.0 scenario. For more details see Meul et al. (2016).

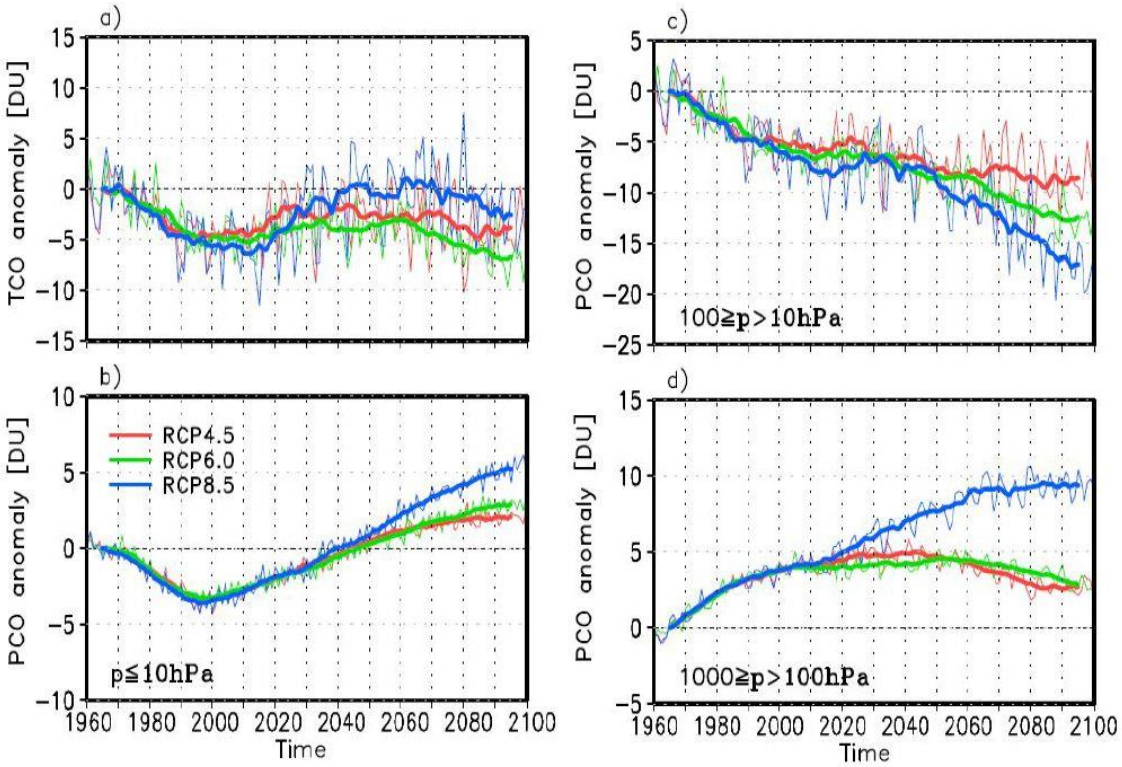

Figure 14: (a) Time series of annual mean tropical mean (20°S-20°N) total ozone column (TCO) anomaly to the 1960-1970 mean for the RCP4.5 (red), RCP6.0 (green), and RCP8.5 (blue) simulations, (b–d) same as (a) but for the partial ozone column (PCO) for the (b) upper stratosphere (pressure ≤ 10 hPa), (c) middle stratosphere (100 hPa ≥ pressure > 10 hPa), and (d) troposphere (1000 hPa ≥ pressure > 100 hPa). Thick solid lines indicate the smoothed time series (figure taken from Meul et al., 2016).

3.6 A new health check of the ozone layer at global and regional scales

The first version of the ESA Ozone_cci Gome-type Total Ozone Essential Climate Variable (GTO-ECV) data record (Coldewey-Egbers et al., 2015) has been used to calculate spatially resolved ozone trend and variability patterns based on the 18-year period from June 1995 to June 2013 (Coldewey-Egbers et al., 2014). This comprehensive global long-term data set enables us to disentangle the various sources of ozone variability and its drivers by multivariate linear regression. The regression model quantifies the relationship between ozone and several explanatory variables describing natural and/or anthropogenic forcing. We adopted the form according to Vyushin et al. (2007) and included – in addition to the seasonal cycle and a linear trend term - the quasi-biennial oscillation (QBO) signal (represented by both 30hPa and 50hPa equatorial zonally averaged winds), the 10.7cm radio flux accounting for the solar cycle impact, and the Multivariate El Niño-Southern Oscillation Index (MEI).

The annual mean linear trend coefficients are calculated for the region 60°N to 60°S and are shown in **Figure 15**, left panel. Grey crosses denote regions where the trends are not statistically significant. Estimated trends are positive (yellow and red shading) in major parts of the globe. Small areas indicating nonsignificant negative trends are found in the northern middle latitudes and in the southern Indian Ocean around 30°E-90°E. Largest positive trends of about 1.5-2% per decade are found in the Northern Hemisphere in the European and North Atlantic region, but they are statistically significant in limited small areas only. In southern middle latitudes significant trends of about 1.5% per decade are found around southern South America, Australia, and New Zealand. Thus, the expected onset of ozone recovery in the middle latitudes is still only on the edge of detection.

However, the GTO-ECV data record shows significant positive trends around 1% per decade in large parts of the tropics and subtropics. In order to explain the physical mechanisms that control interannual variability and thus small trends in the tropics, we discuss now the link between the El Niño-Southern Oscillation (ENSO) phenomenon and total ozone as well as lower stratospheric temperature and tropopause pressure.

The correlation between MEI and total ozone is negative for almost the entire tropical zone except the eastern Indian Ocean and Southeast Asia, which means that ozone values are higher than the mean during La Niña cold phases and lower during El Niño warm phases. Five to 15 DU of ozone variability can be explained by this phenomenon in those regions. The longitudinal structure in the tropics can be explained with a shift in the convection pattern from east to west during warm El Niño events. The same correlation pattern is found for the lower stratospheric temperature at 100 hPa. Negative correlation between MEI and temperature means that temperature is increasing during ENSO cold events (when temperature in the lower tropical troposphere is decreasing), and temperature is decreasing during ENSO warm events (when temperature in the lower tropical troposphere is increasing). This anticorrelation between troposphere and stratosphere is related with respect to enhanced tropical upwelling and a strengthened Brewer-Dobson circulation during El Niño events (Calvo et al., 2010). Furthermore, we calculated the linear trend term for tropopause pressure (pressure at 395 K potential temperatures). The trend pattern shows some agreement with the ozone trend over the Pacific, southern South America, and the North Atlantic region. Positive pressure trends indicate that a descending tropopause is associated with an expanding stratosphere and hence increasing ozone levels. In the tropics tropopause pressure decreases (ascending tropopause) during ENSO warm events - leading to reduced stratospheric ozone amounts - and tropopause pressure increases (descending tropopause) during ENSO cold events leading to enhanced stratospheric ozone amounts.

With regard to the detected ENSO-related correlations the observed regional trends in the tropics for ozone, temperature, and pressure can now be explained having a look at the MEI time series itself for the period 1995 to 2013. We conclude that a strong ENSO warm event 1997/1998 at the beginning of the fit period and a strong ENSO cold event 2010/2011 at the end of the fit period, and hence the apparent negative trend in ENSO toward cold events, induce the derived changes in the atmospheric parameters in this region.

The right panel of **Figure 15** shows the year in which we can expect to detect a total ozone trend of a given magnitude (according to Weatherhead et al., 1998, their Eq.(3)). We use the variance and autocorrelation determined from the GTO-ECV record, and we use model projections for the first half of this century to obtain a zonal distribution of expected ozone trends, which are smallest in the tropics (~0.5% per decade) and increase toward higher latitudes. Values in middle latitudes of the Southern Hemisphere (1–2% per decade) are expected to be slightly larger than in the Northern Hemisphere (0.7–1.7% per decade). The plot indicates that detection of changes in the tropics will not be possible before 2030, because the expected trend itself is small and autocorrelation is not negligible. On the other hand, variability is low in this region. Toward higher latitudes the number of years decreases. Early trend detection will be possible from ~2015 onward in some regions in the Southern Hemisphere (20°S poleward), whereas in the Northern Hemisphere stronger interannual and intraannual variabilities lead to longer periods needed to observe a recovery of ozone (trend detection possible from 2020 onward).

As can be readily seen from the results the length of the current GTO-ECV data records covering 18 years is still at the lower end for reliable recovery detection as natural variability still dominates the evolution of total ozone in middle latitudes since the mid-1990s. Therefore, trend estimates presented in **Figure 15** (right) are not significant in major parts of the extra-tropics.

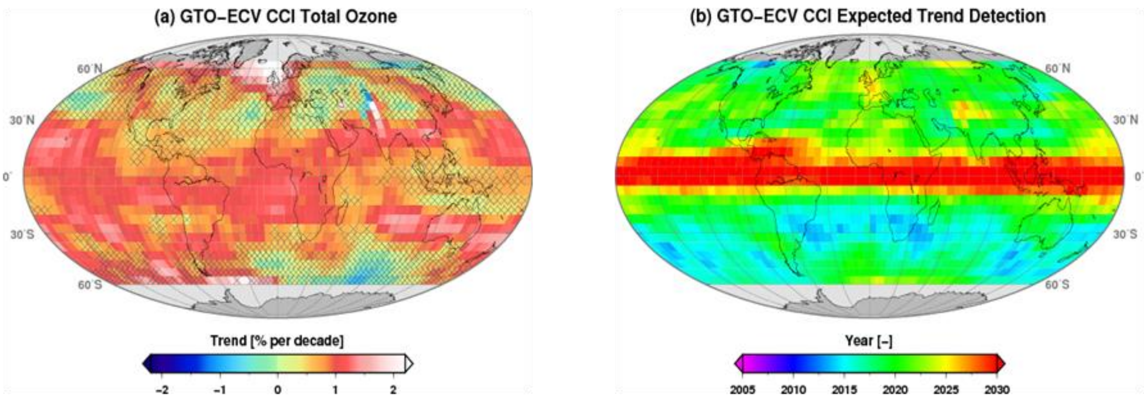

***Figure 15*:** Left: total ozone trend [%/decade] and right: year of expected trend detection.

Thus, our results clearly indicate a need for continuous monitoring of ozone and an extension of the current data records using future missions in order to (1) detect the expected success of the Montreal Protocol and (2) achieve a better understanding of the interaction and feedback mechanisms between ozone and climate change.

3.7 The QBO signal in model data and observations

Attributing variability is a key element of a reliable trend analysis. One example of a dominant mode of variability is the quasi-biennial oscillation (QBO) in tropical zonal mean zonal wind. Recurring westerly and easterly phases of the dominant zonal wind directions are associated with characteristic horizontal and vertical ozone distributions. A spectral band-pass filter is a convenient way to extract the QBO associated changes in ozone and to compare the patterns between model implementations and observational data. A QBO signal exists in column data and in profile data of ozone. The complementary use of column and profile data will be discussed.

Starting with column data we use results derived from the CCM EMAC simulations (Jöckel et al., 2016). A number of model integrations simulated the climate and composition of the recent past using free running and *nudged* configurations of EMAC (see Section 3.4). **Figure 16** shows band-pass filtered ozone and ozone variability on longer time scales in each panel. The panel on the upper left of **Figure 16** shows results for ERA-Interim column ozone. Note that for the nudging of the EMAC model (lower left panel in **Figure 16**) ERA-Interim meteorological data has been used. Thus the expectation should be, that if the assimilation for ozone works well in ERA-Interim and the ozone in the REF-C1SD integration is well represented we should find good agreement (which we do). In the free running model (REF-C1) the circulation constraint is weaker and thus the amplitude of ozone anomalies seems to be smaller (lower right panel in **Figure 16**). However the purely observational data set (upper right panel in **Figure 16**) is showing a similar behaviour (note the optical caveat that the observational data has a smaller latitudinal extent). A detailed investigation using anomaly correlations has been conducted and will be published in the near future (Kerzenmacher et al., in preparation).

Figure 17 shows latitude-pressure cross-sections of ozone volume mixing ratio composites (see definition in the figure caption). There is a clear vertical structure in the tropical ozone caused by the QBO (as indicated by the two maxima/minima at the equator) and the QBO related ozone changes extend far beyond the narrow latitudinal range that is dominated by the zonal mean zonal wind reversal. Considering the sampling issues of the satellite product there is good agreement between the REF-C1SD simulation and the SCIAMACHY observations.

A side product of the band-pass filtered data is a delineation of variability on longer time scales, including the ENSO signal. A recent paper (Kunze et al., 2016) discussed the interplay of the Monsoon and ENSO modulations on UTLS composition. The Monsoon (here: the Indian summer monsoon) is an important modulator of composition on the annual time scale, however it shows also interannual variability and some co-variability with the ENSO (see also Coldewey-Egbers et al., 2014 for details on ENSO ozone variability). Further studies are required to disentangle the variability on longer time scales and to interpret the spectrum of “slow” variability better (as illustrated in **Figure 16** in the lower part of the individual panels).

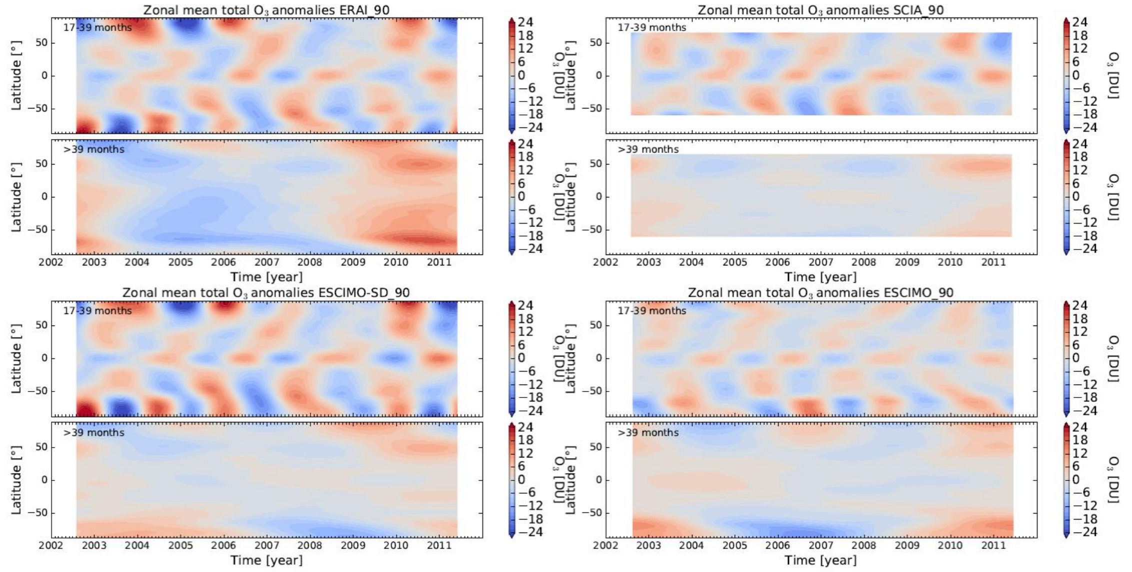

Figure 16: Filtered column ozone data for ERA-Interim (upper left), the SCIAMACHY ozone CCI data set (upper right), REF-C1SD simulation (lower left), and REF-C1 free running simulation (lower right). In each category there a two panels. The upper panel shows the QBO related variability the lower panel the longer time scales. (The residuals on short time scales are not shown.)

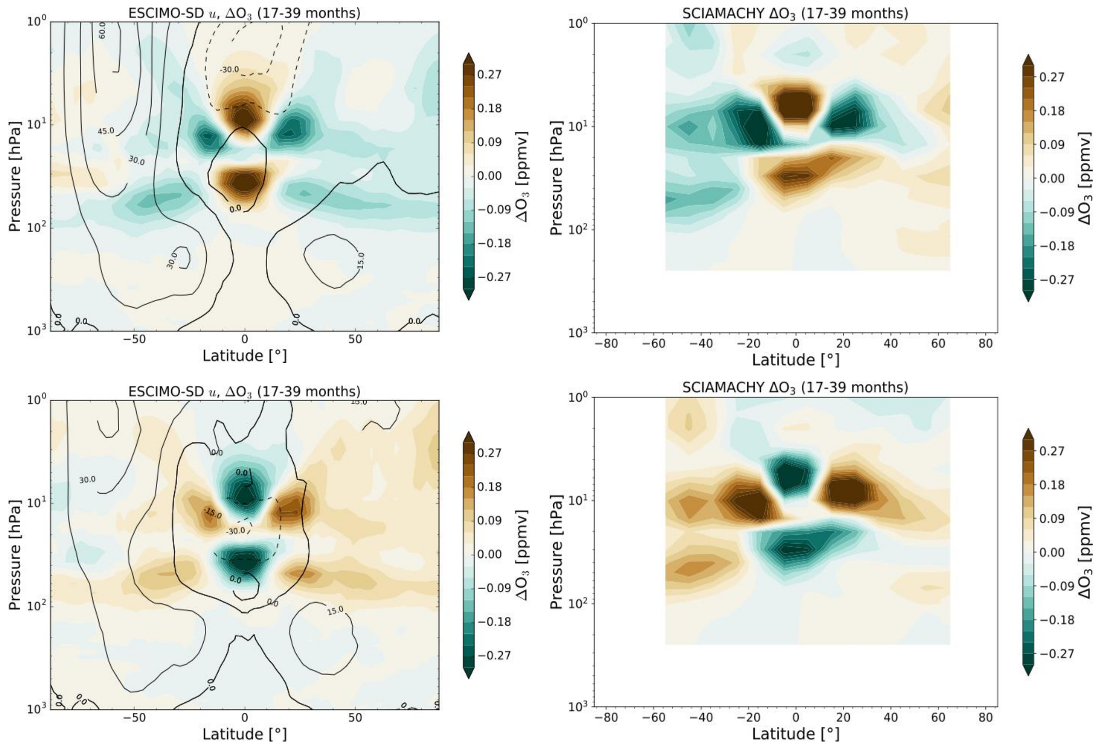

Figure 17: Latitude-pressure cross-sections of ozone volume mixing ratio composite differences for the times when the filtered column ozone data (Figure 16) has a maximum (top row) and when it has a minimum (bottom row) for the REF-C1SD simulation (left column) and the satellite observations from SCIAMACHY (right column).

3.8 Ozone variability in EC Earth-TM5 coupled climate simulations

A new model version (V3.2) of the Earth System Model EC Earth (Hazeleger et al., 2012) is currently under development, in preparation for the next round of model simulations in support of the next cycle of the IPCC assessment reports (AR6 / CMIP6). The historical forcing data and scenarios are planned to be provided to the climate modelling community, and planned to be implemented in EC Earth, during the course of 2016.

By the end of the project the first model simulations including coupling with ozone will be available through EC-EARTH seasonal simulations. Focus for the CRG study with EC Earth in Ozone_cci will be a study on the importance of interactive vs. prescribed ozone. The ozone profile spatial and temporal variability of these simulations in the UT/LS will be confronted to the variability in the newly produced Ozone_cci climate data records.

The new EC Earth model version in development (EC Earth V3.2; IFS cy36r4 T255L91; 0.7 degree spatial resolution, 91 layers model top at 0.01 hPa; NEMO ORCA1L75; ~1 degree spatial resolution 75 layers, LIM3 sea ice) contains many model improvements compared to V2. One key extension crucial for ozone-climate interactions is the model top upward extension to include the stratosphere and mesosphere up to 0.01 hPa. Also important is the amount of vertical layers, which has been increased from 62 to 91 levels. The new sub-km vertical resolution in the UT/LS is considered a major improvement for process studies on ozone profile - climate interactions.

EC Earth is coupled to the TM5 chemistry-transport model which is currently ran at 3x2 degrees spatial resolution and 34 layers. Two-way coupling of ozone between EC Earth and TM5 has been implemented, i.e. the ozone which is being transported and is chemically reacting and deposited in TM5, is used in IFS in the radiation schemes, while the meteorological wind and temperature fields from IFS are used to drive the transport in TM5.

The CMIP6 prescribed 3-D ozone distribution for the period 1850-2014 that has been released in 2016 for use in preparation of the climate simulations for the next IPCC report. The CMIP6 ozone was implemented both in IFS for non-coupled climate runs with EC Earth and in TM5 for the coupled chemistry-climate simulations. The CMIP6 ozone profile distribution has been compared with the cci-based total column ozone observations (MSR-2 multi-decadal record) and shows overall consistency.

Figure 18 shows a latitude-height comparison between the CMIP6 zonal-mean distribution for 2010 (DJF) and the MSR-2 observations for the same months and distributed vertically to the standard Fortuin and Kelder (1998) climatological vertical profile as used in TM5. More comparisons between CMIP6 ozone and other ozone_cci climate records are still to be made.

The key difference between the non-coupled EC Earth simulations using IFS only and the simulations with IFS coupled to TM5 is the dynamic ozone transport in the tropopause region in TM5. While the 3-D ozone distribution is prescribed in IFS and its radiation routines the simulations coupled with TM5 will use the 3-D ozone distribution from TM5 in the radiation routines and thus ozone changes may affect the UT/LS circulation. In TM5 ozone is not prescribed though nudged to the CMIP6 ozone fields and only (well) above the tropopause. In the tropics (30°S-30°N) stratospheric ozone is nudged for pressures < 45 hPa, whereas in the extra-tropics ozone is nudged for pressures < 90 hPa to account for differences in the height of the tropopause. The relaxation times applied are 2.5 and 4 days for the tropics and extra-tropics, respectively. Consequently, the magnitude of stratosphere-troposphere exchange (STE) in TM5 depends on the strength of the overturning circulation determined by the climate model which will depend on the climate forcing and subsequent climate change. The change in STE will affect the tropospheric ozone budget and chemistry of the upper troposphere. Because stratospheric chemistry is lacking in TM5 there is not a full coupling of the general circulation to mid-upper stratospheric ozone changes in these simulations and thus with EC-Earth/TM5 focus is given on UT/LS ozone-climate couplings.

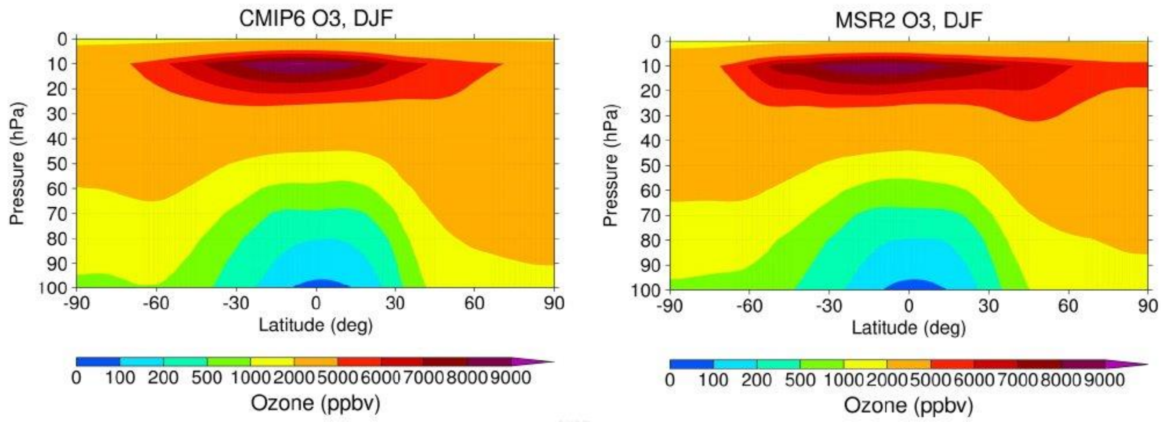

Figure 18: Comparison of latitude-height cross section analysis for ozone volume mixing ratio between the CMIP6 zonal-mean distribution for 2010 (DJF) and the MSR-2 observations for the same northern winter months.

One key question for ozone-climate interactions is the importance of ozone short-term variability in the UT/LS. There are some indications in the scientific literature that suggest a potential large impact of ozone variability, e.g. through studying the impact of zonal asymmetries in ozone (McCormack et al., 2011; Albers et al., 2012). By comparison of seasonal northern hemisphere winter simulations with interactive ozone to simulations with prescribed (zonal-mean) CMIP5/CMIP6 forcing the importance of ozone variability for climate and atmospheric circulation in the new version of EC Earth will be diagnosed. The realism of the ozone profile variability in the interactive simulations will be evaluated using the Phase-2 Ozone_cci ozone profile extended climate data records.

4. Conclusions

Apart from the work performed within the Ozone_cci project, additional assessments are carried out by the CCI - Climate Modelling User Group (CMUG). In particular, several Ozone_cci products were individually tested for assimilation in the ECMWF data assimilation system, using a configuration similar to the one that will be employed for the coming ERA5 production (replacement of ERA-Interim). Among others, they found that the assimilation of these products could improve the meridional ozone gradients, and, by exploiting the synergy with other ozone products simultaneously assimilated, also improve the tropospheric ozone concentrations. A full account of the CMUG results to date can be found in the recently published CMUG Quality Assessment Report (version 0.5, http://ensembles-eu.metoffice.com/cmug/CMUG_D3.1_QAR_v0.5.pdf).

To further establish the leading role of European science, European research institutes and technological companies (business) should expand the excellent starting position in areas of European research and technology. Moreover ESA-CCI fosters the dialogue and cooperation between climate observation and the modelling community. The interdependence of ECVs is another emerging topic for the near future. Are observed trends and changes consistent? Can one ECV be used to improve the observation of another?

Other important questions which should be answered in near future are how do we concretely use in practice the new prolonged data sets of “Ozone_cci” and what do we learn from the data sets on the UT/LS and troposphere?

In future, ESA should be in an excellent position to evaluate the quality of its space-borne observations, to reap benefits from new data products, including uncertainty measures and consequently to further develop and improve coming missions. European research institutes and organizations should be able to propose new and successful future space-borne missions.

Acknowledgement

Thanks to Massimo Valeri, University of Bologna, Italy, for preparing and analyzing the MIPAS ozone data and determining the differences regarding the EMAC model simulations.

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