COMPARISON BETWEEN ERA-Interim AND ERA-40 IN THE TROPICAL TROPOPAUSE REGION

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1. INTRODUCTION

Reanalyses are fundamental tools in climate and variability studies. Their applicability runs through a wide range of fields: from the performance of empirical analyses to their use as initial condition or validation for general circulation models (GCM). In the last years the active role of the stratosphere in the climate system has been recognized, and the necessity to accurately study its climatological characteristics and variability has arisen. In the middle atmosphere reanalysis data are even more helpful due to the short number of observations. However, it is crucial to understand the limitations and biases in these databases, caused either by model errors, by the assimilation techniques or coming directly from observations.

With the philosophy of evaluating the current understanding and uncertainties in the stratosphere, the SPARC Project (Stratospheric Processes And their Role on Climate) brought together eleven middle-atmosphere climatologies and made detailed comparisons (Randel et al., 2004a). One of the conclusions of this intercomparison was that the best database in reproducing tropical processes in the middle-atmosphere is ERA-40 reanalysis, the last one by ECMWF at that moment.

More recently a new reanalysis, named ERA-Interim, has been developed at the ECMWF (Simmons et al., 2006). This reanalysis presents several improvements in key aspects affecting the stratosphere. A brief description of these advances is given in section 2.

In the present work we compare ERA-40 with ERA-Interim in the tropical tropopause layer (TTL), key region which determines to a large extent the chemical, radiative and dynamical properties of the whole stratosphere (Fueglistaler et al., 2009a).

The TTL constitutes a current issue in climate and atmospheric sciences studies. The interest of the TTL arises not only because it represents the interface between two different dynamical regimes, but also because the tropospheric air enters the stratosphere mostly across this region. The upward mass flux in the tropical tropopause, named tropical upwelling, is caused by mass continuity as a result of stratospheric residual circulation (meridional wave-forced circulation characterized by ascents in the tropics, meridional poleward transport and descents at high latitudes). This upward flux yields adiabatic cooling in the TTL, contributing to lift tropopause in tropical region and thus increasing the difference in tropopause height between tropics and extratropics.

Currently there is a controversy on the mechanisms driving tropical upwelling. It has been proved that wave drag is necessarily involved in this process (Plumb, 2002), given that the penetration of Hadley circulation into the stratosphere, previously thought to be responsible of the annual cycle in tropical upwelling, has a significant contribution only in the upper stratosphere (Semeniuk and Shepherd, 2001). The discussion is focused now on the type of waves originating tropical upwelling. Kerr-Munslow and Norton (2006) argue that equatorial Rossby wave dissipation, local to the tropics, is mostly driving annual cycle in tropical upwelling. Bohem and Lee (2003) highlight the importance of tropical convection in generating Rossby waves that will in turn force tropical upwelling. Randel et al. (2008) conclude that both tropical and extratropical eddies, dissipating in the subtropics, are required to explain upwelling seasonality, and further suggest that gravity wave drag can lead to widen the stratospheric upwelling region. Fueglistaler et al. (2009a) point out the current discussion on the relative importance of wave activity and deep convection in determining the unique properties of the TTL.

There have been identified trends in tropical upwelling related to anthropogenic increase of green house gasses (Butchart et al., 2006; Calvo et al., 2009). Also tropopause height shows trends due to anthropogenic forcing (Santer et al., 2004).

It is important to recall the role of the TTL as a “gate to the stratosphere” (Fueglistaler et al., 2009a) which tracers need to cross, determining the boundary condition for the chemical composition of the whole stratosphere. Particularly important are the chemical species with tropospheric sources involved in ozone destruction processes. The efficiency of tracer entrance into the stratosphere is controlled by their concentration in the TTL, their lifetime in this region and the probability of being absorbed by ice crystals with a sufficient weight to precipitate out of the TTL (Fueglistaler et al., 2009a). The stratospheric ozone concentration is also directly affected by tropical upwelling. The annual cycle in ozone content in the TTL region has been related to the upwelling cycle (Randel et al., 2007).

Stratospheric chemistry is also strongly dependent on the water vapor concentration in the air masses penetrating from the troposphere. Most of the water vapor freezes in the TTL before reaching the stratosphere, and the concentration of water vapor in the air mass drops by two orders of magnitude (dehydration). Thus, the propagation of water vapor into the stratosphere is controlled by TTL temperature, and in fact the annual cycles of these variables are in phase. Water vapor transport across the TTL has been widely studied in recent works (e.g. Randel et al., 2004b; Randel et al., 2006). A negative trend has been detected in water vapor starting in 2001 (Randel et al., 2006), and it has been linked to observations revealing upwelling increase and ozone decrease in this region.

Ozone and water vapor are particularly interesting tracers in studying the TTL, because both show strong concentration gradients across the tropopause due to the location of their sources and sinks; also their lifetimes in the TTL are long enough to be affected by transport. In the present work both tracers have been analyzed. Particularly, we have studied their distribution in the TTL, and also we have focused on moisture transport.

2. DATA

The data from ERA-40 and ERA-Interim used in this work were extracted from the ECMWF web page http://data.ecmwf.int/data/. The comparative study has been performed with monthly means of daily means from the common period (1989-2001).

ERA-40 is a second generation ECMWF reanalysis, covering the period 1957-2002, widely used in climate studies. It has a T159 spectral horizontal resolution, and 60 vertical levels in a hybrid sigma-pressure coordinate system. Data assimilation is performed through a 3D-Var system (Uppala et al., 2005).

ERA-Interim is the new ECMWF reanalysis. This database starts in 1989 and is brought up to date on a monthly basis. Its production was initiated in 2006 to provide a bridge between ERA-40 and a future ECMWF extended reanalysis. The period covered by ERA-Interim coincides with the so-called data-rich period or satellite period.

An extensive description of the main differences in data assimilation techniques, bias correction and modelling between ERA-40 and ERA-Interim is found in Simmons et al. (2006). Particularly relevant is the introduction of the 4D-Var assimilation method, which performs a statistical interpolation in space and time variables. Also the new scheme of variational bias correction applied in ERA-Interim shows a better performance than previous bias handling. Horizontal resolution was increased to T255, while the number of vertical levels was kept at the same 60 levels of ERA-40. New humidity analysis and improved model physics have a positive effect on tropical precipitation (Uppala et al., 2008).

As a result of the changes performed in the mentioned key aspects, the new reanalysis presents several improvements respect to ERA-40. Focusing on the advances concerning the stratosphere, we must mention the residual circulation and the hydrological cycle (Simmons et al., 2006). In a recent study Fueglistaler et al. (2009b) identify improvements in age of air and heating rates in ERA-Interim compared to the older reanalysis. Age of air in ERA-40 is found to be notably smaller than observed. By calculating and comparing the assimilation increments required by each reanalysis to reach radiative balance, the authors conclude that ERA-Interim presents more realistic heating rates.

3. RESULTS

In agreement with previous studies, we have observed a more intense residual circulation in ERA-40 compared to ERA-Interim. Figure 1 shows the annual cycle of tropical upwelling at 100hPa for both ECMWF reanalyses. We can clearly see that ERA-Interim has a weaker upward mass flux in the TTL when averaging over tropical latitudes. If we look at the latitudinal structure of upwelling (Figure 2), we notice further differences between the reanalyses. Approximately from May to October the upwelling in ERA-Interim is confined at northern latitudes, while in ERA-40 we have upward velocities between 20ºS and 20ºN approximately during the whole year.

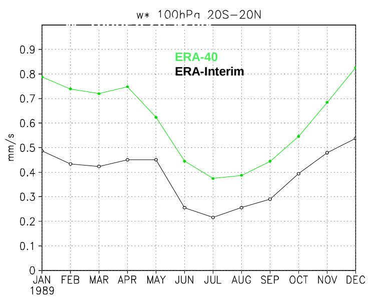

Figure 1. Annual cycle of the vertical component of the *Transformed Eulerian Mean* (TEM) residual circulation (in mm/s) at 100 hPa averaged over 20ºS-20ºN from ERA-Interim (black line) and ERA-40 (green line).

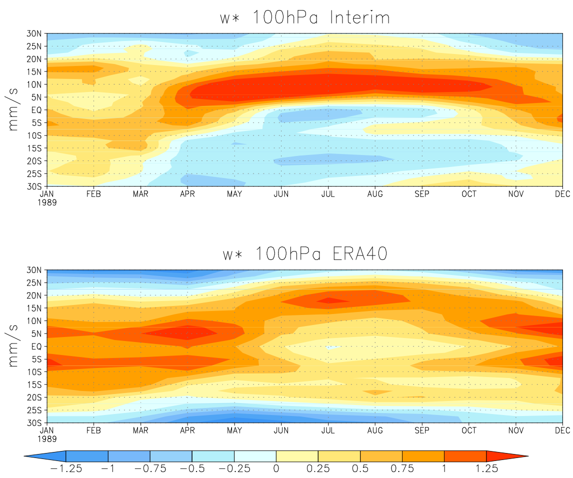

Figure 2. Latitude-month diagram of the vertical component of the TEM residual circulation (in mm/s) at 100 hPa from ERA-Interim (top) and ERA-40 (bottom).

An effect of this enhanced tropical upwelling is found in the water vapor transport across the TTL. Following Randel et al. (2004b), we have used the so-called *freeze drying effect* (i.e. the dehydratation of air masses when during an ascent they come across the cold tropopause temperatures) to study water vapor transport through the TTL. In particular, we have performed linear correlations between tropical tropopause temperatures and specific humidity. The former was calculated as the zonal mean temperature at 100hPa averaged over 20ºS-20ºN. The specific humidity was lagged up to 12 months in order to visualize water vapor transport (Figure 3). Focusing on vertical transport we can see the effect of stronger upwelling in ERA-40: the air mass ascends faster in this database than in ERA-Interim. Relevant discrepancies are observed also in latitudinal water vapor transport. Comparing Figure 3 with that shown in the mentioned work by Randel et al. (2004b), obtained from observational data, we conclude that ERA-Interim represents water vapor transport in the stratosphere far more realistically than ERA-40.

The lag-0 correlations in Figure 3 (top panels) show different spatial structure of the region where tropospheric air masses entry into the stratosphere. Particularly, this region seems to have higher vertical extension and narrower horizontal length in ERA-40 compared to ERA-Interim.

The physical process by which upwelling influences the TTL structure can be explained as follows (Birner and Collins, 2009). Upwelling in the tropics induces adiabatic cooling near the tropopause, producing a negative forcing on the static stability budget. This forcing tends to maintain the lapse rate at upper levels, lifting the tropopause.

We have performed further analyses to check if the characteristics deduced from Figure 3 are reflecting the TTL structure. We found evidences that support this hypothesis: ERA-40 shows a deeper TTL with less latitudinal extension than ERA-Interim. To examine the TTL structure we made two analyses.

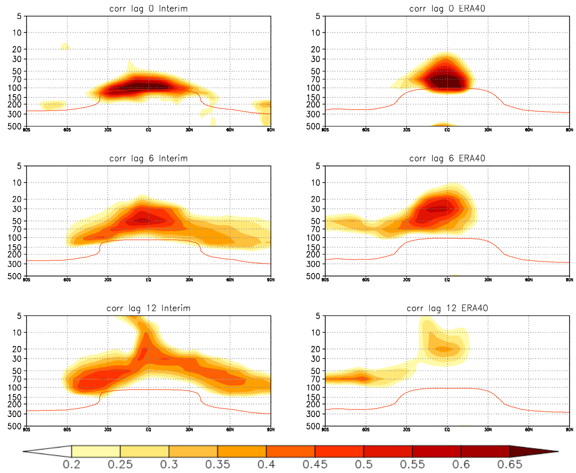

Figure 3. Statistically significant correlations (at 99% confidence level) between tropical tropopause temperature and specific humidity for ERA-Interim (left) and ERA-40 (right) Specific humidity has been lagged 0, 6 and 12 months. The red line represents the thermal tropopause, calculated as the -2K/km lapse rate level.

First we calculated the static stability parameter (in terms of the Brunt-Väissälä buoyancy frequency) and its vertical gradient (not shown). The maximum in vertical static stratification gradient is considered to be a good representation of the thermal tropopause (Birner and Collins, 2009). The results show a higher thermal tropical tropopause in ERA-40 (reaching 100 hPa) compared with ERA-Interim. Also we spot a somewhat larger latitudinal extension in the ERA-Interim tropical tropopause. As these analyses are based on averages of monthly means, this effect could be a result of more frequent double tropopause events in ERA-Interim.

The second diagnostic we have performed to enlighten the TTL structure is the O_3 versus H_2O diagram, in order to analyze the transition layer from a chemical point of view. As we mentioned in the Introduction, these tracers present a strong vertical gradient in their mixing ratio across the tropopause. Changes in their concentration profiles are determined to a great extent by tropopause height and in turn their distribution influences the TTL structure (Pan et al., 2007). Due to small cross-tropopause mixing and the slow upwelling this diagram presents an “L-shape”, where the left-upper part coincides with stratospheric chemical characteristics (low water vapor and high ozone concentrations), and the right-lower part with tropospheric ones (Palazzi et al., 2009). The TTL in tracer-tracer space is represented by the left-lower region.

Comparing both reanalyses (Figure 4) we conclude that, regarding chemical composition, the TTL penetrates deeper into the stratosphere than ERA-Interim. In fact, in ERA-40 the TTL-like behavior arrives up to 70 hPa, while in ERA-Interim this level is purely stratospheric.

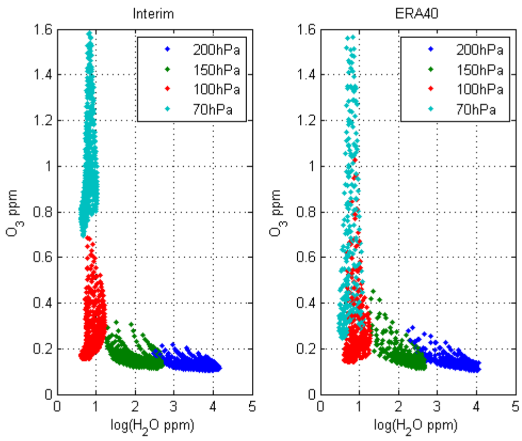

Figure 4. Ozone versus water vapor for levels near the tropical tropopause in ERA-Interim (left) and ERA-40 (right). Zonal mean of monthly mean data for the period 1989-2001 averaged between 20° S and 20° N. (mg/kg) (Only common levels are shown).

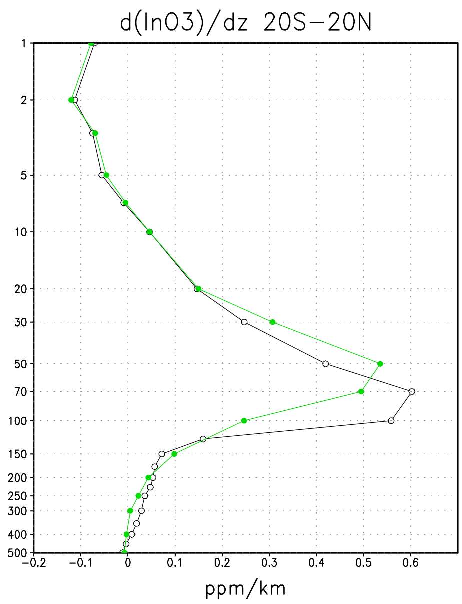

Figure 5. Vertical distribution of $dlnO_3/dz$ from ERA-40 (green line) and ERA-Interim (black line). Zonal mean annual mean averaged over 20ºS-20ºN (ppm/km).

We have further analyzed the effect of upwelling on ozone distribution in the tropical stratosphere. Figure 5 shows an important discrepancy between reanalyses regarding this issue. The maximum gradient in ozone concentration in ERA-40 is found around 50 hPa, while in ERA-Interim the major increase of ozone occurs in lower levels. The change in ozone concentration across 100 hPa is much stronger in ERA-Interim than was in ERA-40. The intense upwelling in ERA-40 seems to be pushing ozone-poor tropospheric air deeper into the stratosphere. Comparing with observational data in Randel et al. (2007) we conclude that the new ECMWF reanalysis provides a much improved ozone vertical distribution representation.

SUMMARY AND DISCUSSION

We have performed a comparison of the reproduction of the tropical tropopause layer, a key region for stratospheric circulation, between the widely used ERA-40 and the new generation ECMWF reanalysis, ERA-Interim. We summarize the main discrepancies identified by this study:

- The tropical upwelling is more realistic in ERA-Interim, being overestimated in ERA-40.
- Humidity transport in the stratosphere is considerably more realistic in ERA-Interim than in ERA-40.
- Ozone vertical distribution in the stratosphere has been largely improved in ERA-Interim respect to ERA-40 in the tropical region.
- The TTL penetrates higher in the stratosphere in ERA-40 than in ERA-Interim.

In section 2 we have described the main changes in ECMWF reanalysis system that may have contributed to the improvements detected in ERA-Interim respect to ERA-40. Still, there are several possible sources of errors affecting particularly the TTL region. For instance, deep convection remains a challenge in modeling, and its impact in the TTL region is currently not quantified (Fueglistaler et al., 2009a). Parametrization of non-resolved wave activity is a critical task in GCM development, strongly affecting stratospheric residual circulation. Likely the increase in model resolution has a positive effect on tropical upwelling representation because more waves will be resolved and less parametrizations will be required.

The improvements observed in the new reanalysis highlight the importance of carefully understanding the biases and uncertainties of the databases used in climate studies. The analyses on the TTL have revealed some unrealistic processes in ERA-40 that could drive to wrong conclusions if no caution is taken. Nevertheless, an encouraging message is inferred: progress in assimilation techniques and modeling is demonstrating to be of great help to improve the representation of the atmospheric circulation.

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