1.9A STRATOSPHERE TO TROPOSPHERE EXCHANGE: THE ROLE OF CONVECTIVE TRANSPORT AND THE SENSITIVITY TO MODEL RESOLUTION

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1 INTRODUCTION

The limitations of some commonly used model-based methods of diagnosing of extratropical cross-tropopause transport in tropopause folding events are revealed by performing forecasts using the Met Office Unified Model including an idealised passive tracer.

The transfer of chemical species, both natural and anthropogenic, between the stratosphere and troposphere is of particular importance for the prediction of global climate change. The local stratosphere to troposphere exchange rate in the extratropics is dependent on small scale near-tropopause processes. Irreversible mixing as a result of tropopause folding is thought to be the major process through which stratosphere-troposphere exchange occurs in the extratropics and is perhaps the major source of transport from the stratosphere into the troposphere (Andrews *et al.*, 1987) . These issues are elaborated upon in the review paper on stratosphere-troposphere exchange by Holton *et al.* (1995).

Model based estimates of cross-tropopause exchange during tropopause folding events and cut-off lows vary considerably. Kowol-Santen *et al.* (2000) found that the net exchange varied significantly amongst the five case studies they considered. However, it differed by less than 10% for the two commonly used methods they considered, a trajectory based analysis and an analysis performed using the equation of continuity based formula of Wei (1987) with potential vorticity (PV) as the vertical coordinate. A limitation of these two methods is that they fail to take into account the transport and mixing of tracer by parameterized processes such as convection and turbulent mixing. Trajectories are calculated using the resolved three-dimensional wind field and the continuity based method only considers the transport which occurs through the nonconservation of PV. Thus although exchange will be diagnosed due to the feedback of the parameterization schemes on the large scale (through the modification of PV and the associated effect on the resolved winds), neither method is capable of additionally diagnosing the transport occuring directly in the parameterized processes. Estimates of stratosphere-troposphere exchange in tropopause folds may also be sensitive to model resolution, especially if the rich structure observed in such folds is not well resolved. For example, Vaughan *et al.* (1994) found radiosondes showed their analysed fold to be about twice as long as its representation in model fields (with horizontal resolution of 1.5° and 12 vertical levels).

The aims of this study are

- to determine the effect and magnitude of transport and mixing by parameterized convection and turbulent mixing in cross-tropopause transport and
- to assess the sensitivity of model derived estimates of cross-tropopause transport to model spatial resolution and the artificial diffusion required to maintain model stability.

To address these aims a passive tracer has been incorporated into the Met Office Unified Model and two day forecasts, starting from the global analysis at 0 UTC 9 February 2000, have been performed over a large limited area domain which covers most of the North Atlantic region and part of western Europe.

2 METHODOLOGY

An idealised, online, passive tracer has been incorporated into version 4.5 of the Met Office Unified model (Cullen, 1993) following the method of Donnell *et al.* (2001). The tracer mixing ratio is initialised to 1 kg kg^{-1} above the dynamically defined tropopause, taken as the 2 PVU (1 PVU = 10^{-6} K m^2 kg^{-1}s^{-1}) surface, and to 0 kg kg^{-1} below this. There are no sources or sinks of tracer but tracer may enter and leave the domain though the lateral boundary conditions. At inflow boundaries the mixing ratio is set to 1 kg kg^{-1} above the 2 PVU surface (diagnosed at each timestep).

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Tracer can be transported in the model by three processes: horizontal and vertical advection by the resolved winds (including resolved large scale convection) and transport and mixing by both the convective and turbulent mixing parameterization schemes. The relative importance of the three different processes has been determined by performing each forecast with four different tracers. The first tracer is transported by horizontal and vertical advection only, the second tracer is transported by advection and turbulent mixing, the third tracer is transported by advection and convection and the final tracer (so-called 'full physics' tracer) is transported by all three processes. The effect of model resolution and dynamical diffusion on stratosphere to troposphere exchange was determined by performing a set of six forecasts in which these were varied. The dynamical diffusion is not applied to the tracer which is advected using a positive definite conservative scheme.

The measure of cross-tropopause transport used in this study is the net deep stratosphere to troposphere exchange. Deep transport is defined as having occurred if tracer has crossed a PV defined tropopause zone, from 2 PVU to 1 PVU and entered the so-called lower troposphere region (which may contain isolated high PV regions e.g., due to convection).

3 RESULTS AND DISCUSSION

Four distinct synoptic weather features with associated upper-level PV signatures evolve during the two day period studied and these can be identified at 0 UTC 10 February (figure 1). These are a mature low pressure system (A), a rapidly developing frontal wave (B), an intense upper level trough (C, located from 300 mb geopotential height field (not shown here)), and a developing low pressure system (D). As expected, the passive tracer is primarily transported across the tropopause in the tropopause folds as shown by the height integrated lower tropospheric tracer amount at this time. (Figure 2).

The domain integrated, lower tropospheric tracer amount is shown as a function of time in figure 3. The lower tropospheric tracer amount at a given time is equivalent to the net deep stratosphere to troposphere tracer transport which has occurred since the start of the simulation (in the absence of advection of lower tropospheric tracer out of the domain). For the initial conditions used, this tracer transport is equivalent to mass transport. The full physics tracer transport is $\sim 1.5 \times 10^{15}$ kg over the two day integration. This is consistent with previous estimates of mass exchange in tropopause folding events. Transport of tracer by both the parameterized turbulent mixing and convection increase the domain integrated cross-tropopause transport. At the time of maximum lower tropospheric tracer (32 hours into the forecast), turbulent mixing increases the domain integrated lower tropospheric tracer amount by about 6% relative to that for a tracer which is only advected; convective transport increases it by about 27%.

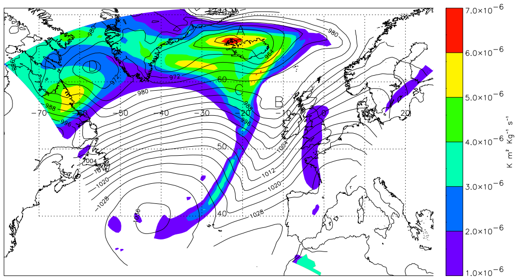

Figure 1: Control forecast fields of 295 K PV (shaded) and mean sea level pressure (contoured) for 0 UTC 10 February 2000. Labels A, B, C, and D explained in text.

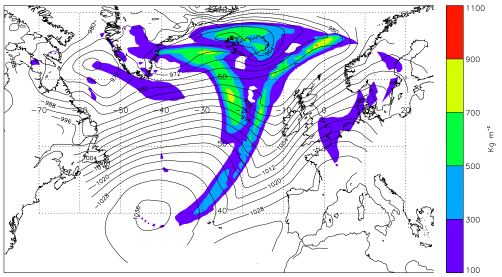

Figure 2: Control forecast fields of full physics height integrated lower tropospheric tracer amount (shaded) and mean sea level pressure (contoured) for 0 UTC 10 February 2000

Analysis of the tracer distribution and convective mass fluxes and entrainment rates show that the observed effects of convective transport are consistent with those expected from the updraft parameterization scheme: dilution of tracer in the regions of updraft detrainment and enhancement of tracer below the tropopause where compensating subsidence is assumed to be occurring.

The amount of transport was found to decrease with increasing horizontal resolution for a given diffusion coefficient, increase with decreasing the diffusion coefficient, and markedly decrease with increas-

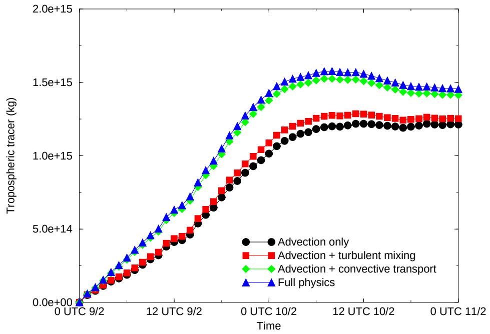

Figure 3: Lower tropospheric tracer amounts as a function of time for the four tracers in the control forecast.

ing midtropospheric vertical resolution (figure 4). This sensitivity to vertical resolution can be attributed to to a weakening of convection at higher resolution in the model used.

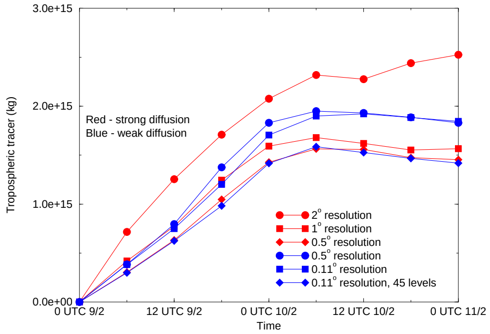

Figure 4: Lower tropospheric tracer amounts as a function of time for forecasts with varying horizontal and vertical resolution and diffusion coefficient. All forecasts use 38 vertical levels unless otherwise stated. Diffusion coefficients chosen based on typical values for the global and mesoscale model versions: Strong diffusion, 2.0$\times 10^7$ m^{4}s^{-1}; weak diffusion, 1.9$\times 10^6$ m^{4}s^{-1}

4 CONCLUSIONS

Evidence has been presented showing that commonly used potential vorticity or trajectory based methods of estimating extratropical cross-tropopause transport neglect a transport mechanism which can be significant, namely the transport and mixing which occurs in the parameterized convection and turbulent mixing. In this case study, the inclusion of transport by parameterized convection leads to an increase in domain averaged transport of around 27%. The importance of these processes depends on the synoptic system under consideration and local effects can greatly exceed the domain average. Increased net stratosphere to lower troposphere exchange was found to occur on decreasing the horizontal and midtropospheric vertical resolution and on decreasing the dynamical diffusion coefficient (for otherwise identical model simulations).

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