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Regional modelling of tracer transport by tropical convection – Part 2: Sensitivity to model resolutions

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Abstract

The general objective of this series of two papers is to evaluate long duration limited-area simulations with idealised tracers as a tool to assess the tracer transport in chemistry-transport models (CTMs). In this second paper we analyse the results of three simulations using different horizontal and vertical resolutions against meteorological observations and their impact on idealized tracer transport. The reference simulation (REF) uses a 60 km horizontal resolution and 300 m vertically in the upper troposphere/lower stratosphere (UTLS). A 20 km horizontal resolution simulation (HR) is run as well as a simulation (CVR) with 850 m vertical resolution in the UTLS. The simulations are run for one month during the SCOUT-O3 field campaign. The Falcon and Geophysica aircraft data and the TRMM rainrate estimates have been used to evaluate the simulations. They show that the HR configuration gives generally a better agreement with the measurements than the REF simulation, the CVR simulation giving generally the worst results. The vertical distribution of the tropospheric tracers for the simulations has a similar shape with a 15 km altitude maximum of 0.4 ppbv for REF, 1.2 for HR and 0.04 for CVR. This is related to the dynamics produced by the three simulations that leads to larger values of the upward velocities on average for HR and lower for CVR compared to REF. The HR provides more frequent overshoots over the cold point dynamical barrier than REF and CVR. For the stratospheric tracers the differences between the three simulations are small. The diurnal cycle of the fluxes of all tracers in the TTL (Tropical Tropopause Layer) exhibits a maximum linked to the maximum of convective activity that is particularly well marked in the HR simulation. The largest integrated fluxes are found for tropospheric tracers in HR.

1 Introduction

Tropical convection is a very important atmospheric feature acting firstly on the global water and radiative budgets. It also has a significant effect on the spatial distribution of the trace gases through convective transport. The horizontal extension for tropical convection ranges from a few kilometres for individual clouds to several hundreds of kilometres for convective clusters or organized convective systems. In global atmospheric weather or chemistry models the horizontal resolution is generally not fine enough (typically one to a few degrees) to take into account explicitly the convection process leading to the use of a convective parameterization. These parameterizations are designed to represent the effect of sub-grid scale convection on its environment. Although many parameterizations have been proposed in the literature in the past (e.g. Arakawa and Schubert, 1974; Tiedke, 1989; Kain and Fritch, 1990; Grell, 1993; Zhang and McFarlane, 1995) it remains an important source of uncertainty in current global models. Apart from the large variability linked to the different parameterization formulations proposed (adjustment methods, mass-flux methods based on plume ensemble or on bulk formulations), the results of any convective parameterization are known to be sensitive to the model horizontal and vertical resolutions leading to generally enhanced convective fluxes for finer horizontal resolutions (e.g. Brankovic and Gregory, 2001) and a modification of the detrainment level with vertical resolution (Pope et al., 2001; Roeckner et al., 2006).

The transport of tracers by convection is taken into account in global Chemistry Transport Models (CTMs) through the fluxes provided by a convective parameterization. In the tropics, convection is of particular importance in CTMs since it is known to lift rapidly a significant part of the surface emissions from the lower troposphere into the Tropical Tropopause Layer (TTL) (e.g. Wang et al., 1995; Pickering et al., 1996; Marécal et al., 2006). The TTL is defined as the transitional layer between pure tropospheric and pure stratospheric conditions. Its boundaries, as proposed recently by Fueglistaler et al. (2008), are the levels of main convective outflow at the zero radiative level under all sky conditions (~150 hPa, 355 K) and the top of the most energetic and intense cumulonimbus can reach (~70 hPa, 425 K). The zero radiative heating level is located within the TTL around 15.5 km (360 K). Above this level, the trace gases are slowly lifted into the lower stratosphere where they can act on the ozone budget at the global scale. The errors on the fluxes provided by the convective parameterizations lead to uncertainties on the tracer transport and consequently on the spatial distribution of the chemical species in the TTL. Therefore, the evaluation of the transport of tracers by tropical convection in global CTMs is a required step towards foreseen improvements. The approach we propose for assessing the convective tracer transport in CTMs is to use long-duration (15 days to one month) regional (typically 6000 km×4000 km) simulations with a limited-area atmospheric model including tracer transport having intermediate horizontal/vertical resolutions (20–60 km/850 m) between typical CTM resolutions (1°–5°/1–2 km) and cloud resolving model (CRM) resolutions (∼1 km/100–200 m). This regional approach allows for case study comparisons with local measurements from field campaigns or CRM simulations as well as statistical comparisons with CTM results.

The objective of this series of two papers is to evaluate long-duration regional simulations with a limited-area model as a tool to produce realistic tracer transport by tropical convection that could then be used for the assessment of CTMs. Part 1 is devoted to the study of the sensitivity of the regional modelling approach to the subgrid scale deep convection parameterization chosen and the present paper (Part 2) studies the sensitivity to the model vertical and horizontal resolutions since they are the two main sources of uncertainties on the convective tracer transport. The model used is the mesoscale model CATT-BRAMS (Freitas et al., 2007) that is specially designed for tropical studies.

In Part 1, we compared six simulations using the mass-flux framework proposed by Grell and Dévényi (2002) for subgrid scale deep convection. The five first simulations use five different closure assumptions and the sixth experiment is an ensemble based on these five closures. The model was run for one month in the Maritime Continent area during the pre-monsoon season. Meteorological results do not show large variations between the six simulations except for the rainrates that are better simulated by the Ensemble parameterization and two other closures. These three experiments also provide significantly more tracer transport in the TTL and likely simulate rare overshoots.

In the present paper, we focus on the effect of spatial resolution on the transport of the same idealized tracers used in Part 1. The issue of the impact of model resolutions on atmospheric simulation results has often been discussed for global models (e.g., Sperber et al., 1994; Phillips et al., 1995; Pope et al., 2001) as well as for mesoscale models (e.g. Lane and Knievel, 2005; Smith et al., 2007). Fewer studies have explored the impact of model resolution on tracer transport (Gray, 2003; Deng et al., 2004; Wild and Prather, 2006; Rind et al., 2007; Aghedo et al., 2008). Wild and Prather (2006) found a continuous improvement of tropospheric ozone compared to NASA TRACE-B campaign data when varying the horizontal resolution from coarser to finer (T21 down to T106) in a CTM. They also showed that the export of short-lived precursors such as NO_x by convection is overestimated at coarse resolution. Rind et al. (2007) found using the GISS global circulation model that the vertical resolution has a significant effect on tracer transport. This effect is enhanced when both finer horizontal and vertical resolutions are used. Agheda et al. (2008) also showed that the tracer transport in the ECHAM5 global circulation model is mostly dependent on the vertical resolution with a faster transport associated with finer resolutions. Using the mesoscale MM5-SCIPUFF model Deng et al. (2004) found an improvement of the statistical skill for interregional tracer transport compared to field experiment data using finer horizontal (down to 12 km) and vertical resolutions but a detrimental effect with further reduction of the horizontal resolution. Gray (2003) conducted a detailed study on a case of extratropical cross-tropopause transport in a tropopause folding event. Their simulations with the UKMO Unified model showed that the transport from stratosphere to troposphere by parameterized processes was dominated by convection transport. They also found a high sensitivity of the model results to horizontal and vertical resolution. All these studies clearly show that the choice of horizontal and vertical resolutions in models is an important issue for tracer transport. Compared to previous studies, the present work addresses the issue of tracer transport by tropical convection in a mesoscale model in the framework of CCM/CTM/mesoscale model comparisons. In particular, the occurrence of overshooting convection will be discussed.

In the present paper, the model set-up for the different simulations is given in Sect. 2. Section 3 is devoted to the analysis of the comparison of model results to local measurements. The statistical analysis over the one month simulation period is discussed in Sect. 4. Section 5 concludes this study.

2 Model set-up

We run several simulations with the CATT-BRAMS model (Freitas et al., 2007) using a set of different spatial resolutions (Table 1). The general model description is given in the first paper (Part 1) and not detailed here. The simulations include one grid covering a 7200 km by 5000 km domain ranging from 100° E to 160° E and from 20° N to 20° S. The simulation lasts 30 days from the 15th November 2005 to the 15th December 2005. During this period, evidence of overshooting convection has been identified (Corti et al., 2008). All radiative calculations were done with the Harrington (1997) scheme. We use the one-moment bulk microphysics parameterization which includes cloud water, rain, pristine ice, snow, aggregates, graupel and hail (Walko et al., 1995). Shallow convection and deep convection are parameterized as described in Grell and Devenyi (2002) using the Ensemble closure (see Part 1 for details). This closure shows better meteorological results than other available closures.

The reference simulation (designed afterward as REF) was done with a 60 km horizontal grid spacing. The model topography and geography of the domain is illustrated in Fig. 1 in Part 1. It includes 56 vertical levels, with a high resolution (300 meters depth) between 14.5 km and 19 km altitude, in order to accurately model the TTL region. It is identical to the simulation called EN in Part 1. A high resolution simulation (high resolution: HR) was run using the same vertical levels as the reference simulation but using a 20 km horizontal grid spacing. A simulation with a 60 km horizontal resolution but with a coarse vertical grid spacing (coarse vertical resolution: CVR) was also run including 43 vertical levels similar to the reference run except that a resolution of 850 m is used between 14.5 and 19 km. The transport of tracers is activated in all the simulations. We chose the same set of four idealized tracers as in Part 1 to characterize the fluxes between the troposphere and the stratosphere (see Table 2).

3 Analysis of cases studies

In this section we analyse the results from the different simulations with respect to campaign measurements for two case studies in order to evaluate the model for the chosen configurations. During the simulation period several DLR-Falcon and Geophysica (M55) flights were done around Darwin (Australia) in the framework of the SCOUT-O3 field campaign (Vaughan et al., 2008; Brunner et al., 2008). Most of the flights were done around the Hector convective events regularly occurring over the Tiwi Islands but some of them were extended flights planned for the study of the surrounding regions: survey flights on the 23rd and the 29th November 2005, remote sensing flight on the 5th December 2005. We chose two cases sampled by both Falcon and Geophysica aircrafts during coordinated flights, on the 23rd and the 25th November. For these days, the aircraft performed extended tracks well into the simulation domain.

3.1 Case of the 23rd November 2005

On the 23rd, the Geophysica and the Falcon flew over the Timor Sea to probe the TTL in details. The flight paths are displayed in Fig. 14 in Brunner et al. (2008). Both aircraft flew along north-east oriented legs perpendicular to the mean flow expected to be north-westerly in the TTL. Flying back and forth along the same line twice, the Geophysica sampled around the cold point tropopause at four different levels, one significantly below the cold point level at ∼15.6 km (leg 1), two close to the cold point tropopause at ∼17.5 km (leg 3) and ∼16.4 km (leg 4), and one level well above at ∼18.3 km (leg 2).

Figures 1 and 2 show the airborne measurements for temperature, horizontal wind speed and direction, and specific humidity, collected respectively by the Geophysica and the Falcon instruments for the flight of the 23rd November 2005 and the corresponding results for the three simulations (REF, HR and CVR). The model results are interpolated at the location and time of the measurements using an hourly time resolution for the model outputs. Whatever simulation set-up used, the model provides too warm temperatures around the cold point tropopause and too cold temperatures in the troposphere up to 14 km. There is only a slight dependence of the model results to the vertical or horizontal resolutions (Figs. 1a and 2a) with maximum differences of about 1 K.

The horizontal wind speed and wind direction simulated by the three run along the aircraft trajectories are generally in good agreement with both the Geophysica (Fig. 1b and 1) and the Falcon (Fig. 2b and c) measurements although they tend to underestimate the wind speed compared to Geophysica measurements. The model values are significantly closer to the Geophysica measurements when using a finer vertical or a finer horizontal resolution. The HR run gives the best values, with differences up to $2\,\mathrm{m\,s^{-1}}$ compared to the CVR run. The HR and REF simulations also give a better agreement for the wind direction with the Falcon data than the CVR. The HR simulation provides the best results with differences up to 15° with the CVR run. The CVR simulation only provides better results for the comparison with the Falcon wind speed for legs 2 and 3.

For specific humidity the Geophysica and Falcon measurements (Figs. 1d and 2d) are generally well modeled in the three simulations with a slight model overestimation for all Geophysica legs performed above the cold point tropopause. There are improvements between the modeled specific humidity values provided by the HR simulations and to a lesser extent by the REF simulation compared to CVR. The two strong peaks observed by both Geophysica and Falcon (e.g. around 16 000 s and 18 000 s in the Geophysica flight), and identified as signature of deep convection events in Part 1, are not captured by the model even using the HR 20 km horizontal resolution. These peaks are very well located in space (~few km) and time and a very high vertical and horizontal resolution has to be used to simulate them.

3.2 Case of the 25rd November 2005

On the 25th November 2005, the Falcon and Geophysica aircraft flights were partly dedicated to the probe of cirrus clouds over the Arafura Sea (North-west of Darwin) and partly to the Hector event (from 06:30 UT). The flight paths are displayed in Fig. 12 in Brunner et al. (2008). The Geophysica flew to the north of the Tiwi Islands where it characterized the tropopause region in east-west direction at two levels below (∼370 K) and above (∼390 K) the cold point tropopause. The Falcon made a transect leg along the same line but in opposite direction. Then the aircraft flew in different directions to connect cloudy and clear parts of the domain.

Modeled temperatures (Figs. 3a end 4a) show an underestimation of the temperature of about 3°C along the Falcon aircraft trajectory in the troposphere and an overestimation along the Geophysica trajectory (∼3°C), when flying above the cold point tropopause (legs 2 to 4). These results are consistent with those of the flight of the 23rd November 2005. The differences between the three simulations are less than 1°C and much lower than the differences between the model and the measurements.

Figures 3b, c and 4b, c show respectively the horizontal wind speed and wind direction for Geophysica and Falcon flights. The modeled values for the three simulations are close to the measurements, and the variability in wind speed and wind direction around the cold point tropopause is well captured by the model. Similarly to the flight of the 23rd November 2005, the wind speed is underestimated by about 3 m s^{-1} on average with maximum bias of 4 m s^{-1} at the end of leg 1 for the Falcon aircraft. The spatial resolution has a very low impact at the height of the Falcon measurements, the three runs giving no significant differences. However, increasing the vertical and horizontal resolutions gives better results for the wind speed and the wind direction when compared to the Geophysica measurements.

Compared to the Falcon measurements of specific humidity (Fig. 4c) the REF, HR and CVR simulations give fairly good results, with almost no difference between each other. Along the Geophysica aircraft trajectory, the specific humidity is overestimated by about 0.001 g/kg by the model for all simulations when flying around the cold point tropopause, and underestimated during the leg 5, when flying above TTL. The three simulations give close results. During the legs 2 and 3, at 18.5 km above sea level, the REF and HR simulations give significantly better results than CVR indicating dependence to the vertical resolution. This corresponds to convection events well modeled by HR and REF, and not seen by CVR.

3.3 Conclusion of the analysis of case studies

The model shows a generally good consistency with the aircraft observations for the two case studies. The differences between the three simulations are generally significant but smaller than the differences with the aircraft data. The HR simulation gives better results than the REF and CVR simulations. This shows that there is a positive impact of using both a fine vertical resolution and a fine horizontal resolution. The HR simulation provides more variability than the other two simulations thanks to its 20 km horizontal resolution although less than in the observations.

4 Statistical analysis

In the perspective of a comparison with the tracer transport in CTMs it is necessary to characterize the model behaviour on a statistical basis using the whole one month results. Firstly the meteorological fields for the three simulations are discussed against measurements (TRMM products and a series of radiosoundings) and secondly the idealized tracer distribution is analysed.

4.1 Model comparison with TRMM surface rainrates

We compared the surface accumulated rainfall rates obtained with the REF, HR and CVR to those estimated by TRMM. The dataset used is 3-hourly and 0.25°×0.25°

resolution and was produced by the 3B42 algorithm (Huffman et al., 2007, http://trmm.gsfc.nasa.gov). Note that the same dataset was used in Part 1 of this series of papers to evaluate the sensitivity to convection parameterizations. Figure 5a shows the daily mean surface rain rates (in mm day^{-1}) estimated by TRMM during the one-month simulation period with four areas experiencing high precipitation rates (above 10 mm day^{-1}): New Guinea, Eastern coast of Malaysia, Indonesian Islands and Eastern coast of Philippines. The daily mean surface rainrates provided by the three simulations are shown in Fig. 5b to 5d. The spatial distribution of the rainrates is generally consistent with the TRMM-based values. However, there are significant differences between the three runs. The REF simulation correctly locates high precipitation areas and the associated values, but tends to underestimate low precipitation values. This difference, as discussed in Part 1, can be partly attributed to a large uncertainty on light precipitation in 3B42 TRMM product that possibly leads to an overestimation of surface precipitation, but also to an uncertainty in light precipitation in the model. When refining the horizontal resolution (HR simulation), the model is able to better reproduce the intensity and spatial distribution of the estimated rainrates compared with the TRMM-based observations. In particular, low to medium rainrates are better represented, especially over the north of Australia. Values around 5 mm day^{-1} near Darwin and Tiwi Islands are correctly modelled, while they are largely underestimated by the REF simulation.

The results provided by the simulation with a coarser vertical resolution (CVR) show large differences with the REF and HR simulations and with the TRMM-based observations. Areas of high precipitation rates are correctly located but underestimated by about 5 mm day^{-1}. Medium and low precipitation rainrates are largely underestimated especially over sea in the North of Australia. No averaged values below 1 mm day^{-1} are simulated.

This indicates that both the vertical and horizontal resolutions have an important impact on the representation of convective and stratiform precipitations. Coarse horizontal and vertical resolutions are able to correctly locate highly convective areas but underestimate convection intensity and occurrence. Increasing the vertical resolution allows for a better representation of the deep convection intensity but still underestimates the low precipitation rainrates. Only a high resolution in the vertical and in the horizontal gives good results for both high and low rainrates.

4.2 Model comparison with Manus radiosoundings

The model results have been compared with a series of 12-hourly radisoundings launched from Manus Island (North of New-Guinea, 147° E; 2° S) in the frame of the ARM program (Atmospheric Radiation Measurement, http://www.arm.gov/) during the simulation period. Table 3 gives the means bias and mean standard deviation of bias between the radiosoundings and the three simulations for temperature, wind speed and direction and specific humidity. To calculate these statistics the radiosounding data were averaged over the model vertical levels. The specific humidity has been preferred to the relative humidity because the errors on the relative humidity include not only the uncertainties on the specific humidity but also on temperature. Moreover since the specific humidity decreases with altitude, the specific humidity statistics given in Table 3 are less weighted by the upper tropospheric levels that are known to be dry biased in the radiosoundings (http://www.arm.gov/publications/tech_reports/handbooks/sonde_handbook.pdf).

The comparison between the HR and REF simulations shows that the HR simulation provides significantly lower biases and standard deviations than REF for all meteorological fields. This clearly indicates that the fine horizontal resolution used in the HR improves the model simulation of the meteorological fields at Manus which is located in an area of high convective activity.

The interpretation of the results of CVR against REF or HR have to be done keeping in mind that the CVR statistics are done on a smaller number of levels since the CVR simulation uses less vertical levels. This means that the mean profile calculated using the radiosounding data for CVR is smoother in the TTL than the mean radiosounding profile for HR and REF. Nevertheless, the REF simulation generally gives better statistical results than the CVR simulation indicating an improvement when using a fine vertical resolution in the TTL.

4.3 Mean tracer mixing ratio vertical profiles

Figure 6 shows the mean mixing ratio profiles averaged over the model domain and over the one month simulation period using 3-hourly outputs (REF, HR and CVR) for Tracer 1 (tropospheric tracer with a 6 h lifetime) and Tracer 2 (tropospheric tracer with an infinite lifetime). To test the impact of the use of three hourly outputs on mean tracer profiles, we also calculated the average using hourly model outputs. The mean profiles obtained using the 3 hourly and the hourly calculations are very close with differences much smaller than the differences between the three simulations (not shown here). This means that a 3-hourly sampling is representative statistically of the mean model behaviour. In Fig. 6 the mean cold point level (~17.3 km altitude), TTL bottom (~14 km) and TTL top (18.9 km) from the simulations have been displayed. The definition proposed recently by Fueglistaler et al. (2008) has been used to determine the TTL top and bottom from the simulation results.

In Fig. 6 the shape of the simulated profiles for both tracers is typical of convective areas, with large values in the low troposphere, decreasing in the mid-troposphere and increasing in the upper troposphere with a maximum value reached around 15 km altitude. Above, there is a rapid decrease reaching very low values at 20 km altitude. The three profiles also exhibit a relative maximum around 8 km altitude for Tracer 1. This is linked to the preferred altitudes for the convective outflows in the Grell and Dévényi (2002) convection parameterization. This local maximum is smoothed in the Tracer 2 mean profile by the large scale advection and diffusion.

The comparison between the REF and the HR simulations shows that the HR configuration provides larger amount of both tracers in the upper troposphere with a ratio of ~3.3 for Tracer 1 and ~2.7 for Tracer 2 around at 15 km altitude. Increasing the horizontal resolution provides stronger and/or more frequent convective events as illustrated by the surface rainrates (see Fig. 5) leading to an increase of the tracer transport from the lowest model levels into the TTL. The effect of the increase of the convective activity in the HR simulation is also visible on the highest levels which exhibit larger values above 15 km altitude for Tracer 1. Since this tracer has a very short lifetime, this indicates that the HR configuration provides more frequent and/or more efficient overshooting above the mean cold point level which is a dynamical barrier and also above the mean TTL top. This effect is more pronounced on Tracer 2 that undergoes diffusion and slow radiative uplift once it has reached the TTL.

The comparison between the REF and the CVR simulations for Tracer 1 and Tracer 2 (Fig. 6) shows that the CVR configuration provides much lower tracer transport in the TTL, both tracers being mainly vertically distributed from the surface to 9 km altitude in the CVR run. This simulation is not able to uplift efficiently tropospheric tracers. This indicates that the tracer transport in the convective parameterization is very sensitive to the vertical resolution in the TTL. For the same convective instability in the low levels in the REF and the CVR simulations, the CVR model determines a lower cloud top altitude leading to an important underestimation of the tracer transport in the TTL. In the CVR simulation, the model diffusion and advection that acts on Tracer 2 once lifted by convection is not able to modify the general shape of the vertical mean distribution.

Figure 7 shows the mean mixing ratio profiles for Tracer 3 and Tracer 4 (idealised stratospheric tracer with a 6 h and an infinite lifetime) averaged similarly to Tracers 1 and 2 in Fig. 6. As found in Part 1, the three simulations for both tracers provide a similar shape with values close to 1 down to the top of the TTL layer (∼19 km altitude), a sharp decrease of the tracer mixing ratio below down to 17 km followed by a smoother decrease down to 14–15 km where it reaches zero. The comparison with the initial mean profile indicates that the 6 h lifetime stratospheric tracer is partly mixed with the TTL air with more than 0.4 ppt found at the cold point level. This shows that the convection parameterization is able to transport significant amounts of stratospheric tracers below the dynamical barrier of the cold point level. Below the cold point tropopause, CVR provides a smoother profile because of its 850 m vertical resolution. Below 16.9 km altitude, the HR simulation provides larger mixing ratio values compared to REF possibly related to more frequent overshoots in HR, leading to more irreversible mixing of the stratospheric tracer in the TTL. For the infinite lifetime tracer, there is almost no more differences between REF and HR because of the mixing by diffusion. CVR using less vertical levels, the mixing is done over larger depths than in REF and HR, leading to a more mixed TTL. This is consistent with Brunner et al. (2005) who showed that sharp tracer gradients across the tropopause are usually not well represented in the models with an excessive mixing between tropospheric and stratospheric air.

4.4 Diurnal evolution of the mean vertical speed and tracer fluxes

To get a better understanding of these results we analyse the differences between the three simulations for the vertical wind speed and the tracer fluxes in the TTL. The vertical wind speed in the TTL is an important variable acting in the exchanges between the troposphere and the stratosphere. Species lifted up from ground level by deep convection will pass above the zero clear-sky radiative level and eventually above the cold point level depending of the vertical motions. Figure 8 shows the diurnal evolution of the monthly-mean vertical wind speed for the three simulations respectively at 14 km (TTL bottom) and 17.3 km (cold point level) using hourly model outputs. The TTL bottom is chosen because it is the limit from which the tracers can be transported in the stratosphere. The cold point level is chosen since it is a dynamical barrier that convection can sometimes cross allowing an irreversible transport of the tropospheric tracers to the lower stratosphere.

At the TTL bottom height (Figs 8a) the mean diurnal evolution of vertical wind speed can be divided in two parts. Between 00:00 UT and 12:00 UT, the vertical speed varies according to the convective activity, with a maximum around 08:00 UT. Since the mean values are calculated over a longitude range of 60°, this maximum is smoothed because convection maxima occur at the same local time, and therefore at different UT times. After 12:00 UT, the vertical wind speed is almost constant and positive. The three simulations exhibit differences in the mean vertical wind speed values but show the same diurnal evolution. Increasing the resolution in the vertical or in the horizontal gives higher speeds. This means that tropospheric air masses enter the TTL in all simulations but the amount is directly related to the resolution used.

The same shape for the diurnal vertical wind speed evolution is found at cold point level (Figs. 8b) but with some important differences in the intensity and sign. Between 00 UT and 12 UT the vertical speed is positive with a peak at 08:00 UT and its intensity is around 3 times lower than at 14 km. The dependence with the vertical and horizontal resolutions is still present with higher speeds when refining the resolution. On the second part of the day, the vertical wind speed becomes negative for all simulations, indicating subsidence of the air. Thus the air masses can pass above the cold point level when local convection is established and go down during local night. However, during the whole day, the mean vertical wind speed is positive for REF and HR simulation ($2.2\times10^{-4}\,\mathrm{m\,s^{-1}}$ and $5.7\times10^{-4}\,\mathrm{m\,s^{-1}}$ respectively), and negative for CVR ($-2.1\times10^{-5}\,\mathrm{m\,s^{-1}}$). The spatial resolution has an important impact on the TTL budget above the cold point level. A coarse resolution preferentially indicates on average a subsidence of air masses while it is the opposite with fine resolutions.

To quantify the tracer transport between the troposphere and the stratosphere, the mean fluxes for Tracers 1 and 2 are calculated at two altitudes in the TTL: at the TTL bottom level (14 km) and at the cold point level (17.3 km). Results are represented in Fig. 9. The same fluxes for Tracers 3 and 4 are shown in Fig. 10. The tracer flux through the TTL depends on the vertical wind speed discussed above but also on the tracer mixing ratio.

At 14 km altitude, the tropospheric tracer fluxes are positive consistently with the vertical wind speed. For the three simulations, the maximum fluxes for both tropospheric tracers are found around 07 UT close to the maximum of vertical wind speed indicating that deep convection activity is driving the tracer transport in the upper troposphere. The tropospheric tracer amount entering the TTL depends on the spatial resolution. HR provides the greatest fluxes for both tropospheric tracers. The fluxes simulated with REF run are ~3 times lower and CVR ones are very low. This shows that the tracer fluxes depend not only on the vertical wind speed simulated but also on the vertical distribution of the tracers provided by the convection parameterization. Using a coarse vertical resolution reduces on average the altitude of the convection outflow down to heights usually below the TTL bottom. Tracer 2 fluxes are larger than Tracer 1 fluxes. This can be attributed to the fact that the 6h lifetime tracer is partly depleted before reaching the TTL bottom and to the enhancement of the infinite lifetime tracer amount by large scale upward motions of the Hadley cell. The integrated values over the whole day are positive for all three simulations and both tracers (see Table 4), but significantly larger for HR and very low for CVR. This confirms that the model provide upward transport on average at the TTL bottom.

At the cold point level, the shape of the diurnal evolution of the fluxes is different. We still observe a maximum at 07 UT but a negative minimum is also simulated in the afternoon linked to average downward motions. CVR always simulates very low fluxes meaning that a very small amount of tracers go through the cold point level. For REF and HR runs, the tracer fluxes are well correlated with the convection activity in the model. Before 10UT, the tropospheric tracers are passing across the cold point from troposphere to stratosphere. After 10:00 UT, the opposite flux is found with fluxes oriented from stratosphere to troposphere. The integrated values over the whole day for both tracers are positive for HR and REF indicating a slow rate of tracer transport from troposphere to stratosphere. HR values are two orders of magnitude larger than REF confirming that HR transports significantly more tropospheric tracer at the cold point level. For CVR, the integrated values are of the same order of magnitude as REF. However, these fluxes are extremely low compared to the lower tropospheric values and therefore not significant.

For the stratospheric tracer fluxes (Fig. 10) the three simulations also show a diurnal cycle with maximum occurring around 07:00 UT. Between ~03:00 UT and ~11:00 UT, fluxes are positives while they are negative elsewhere, but still very low. Integrated values over the day for both stratospheric tracers are negative but almost equal to zero. This indicates that transport of stratospheric tracer is small and is not sensitive to the model resolution.

5 Conclusions

Tropical convection is known to be a major source of uncertainty in transport processes of chemical species. In the frame of the European SCOUT-O3 project, a CTM/CCM/mesoscale model inter-comparison exercise of idealised tracer simulations is conducted. One of the main objectives of this inter-comparison is the evaluation of the tracer transport by tropical convection. Compared to CTMs, the mesoscale models use on-line dynamic fields and finer vertical and horizontal resolutions. They also try to bridge the typical small convective scale with the global model scale. In this context the objective of this series of two papers was to evaluate long-duration regional simulations with the mesoscale model CATT-BRAMS with idealized tracers as a tool to produce realistic tracer transport by tropical convection. On the first part, we analysed the impact of different deep convection parametrizations. In the present paper, we studied the impact of the vertical and horizontal resolution on this transport. For this purpose three simulations over a 60° longitude×40° latitude domain in the Maritime Continent were run (i) with a 60 km horizontal grid spacing and a 300 m vertical grid spacing in the TTL, (ii) with a 20 km horizontal grid spacing and a 300 m vertical grid spacing in the TTL and (iii) with a 60 km horizontal grid spacing and a 850 m vertical grid spacing in the TTL, for one month during the period of the SCOUT-O3 aircraft campaign.

Since it is not possible to compare the idealised tracers with measurements, we used an indirect evaluation of the tracer transport through the assessment of the meteorological fields over case studies and statistical comparisons. The detailed comparison with two coordinated flights of the Geophysica and Falcon aircrafts performed during the SCOUT-Darwin campaign shows that the three simulations provide good agreement with the measurements for temperature, horizontal wind speed/direction and specific humidity. However, the high resolution (HR) simulation is better correlated to the data and provides an enhancement of the model spatial variability. This result is consistent with the statistical comparison of the simulation results with the series of radiosoundings launched from Manus Island during the simulation period. The comparison with the TRMM surface rainrate estimates shows that the three simulations reproduce well rainrates in deep convective areas but degrading the horizontal or vertical resolutions leads to an underestimation of light stratiform precipitation. Only the HR run is able to correctly simulate both deep convective and light stratiform precipitation.

The impact of both the horizontal and vertical resolutions is large on the transport of tropospheric tracers within the TTL. The HR (resp. CVR) simulation provides significant larger (resp. weaker) tracer amounts and fluxes at the TTL bottom linked to larger (resp. weaker) vertical velocities. Refining the vertical resolution in the TTL from 850 m to 300 m allows convection to reach higher altitudes in the upper troposphere leading to a large increase of the tracer transport into the TTL. The use of a fine horizontal resolution together with a fine vertical resolution provides more frequent convection events with higher vertical velocities giving much more tracer transport into the TTL and at the cold point level. Contrarily to REF and CVR, the HR simulation predicts occasional significant overshooting above the dynamical barrier at the cold point level.

There are no important differences between the three simulations for stratospheric tracers on average. However, HR provides larger mixing ratios below 16.9 km altitude than REF. This also indicates significant irreversible transport in the TTL by overshooting convection in the HR simulation.

The results of this study clearly show the positive impact on the meteorological fields of using fine vertical and horizontal resolutions and the large effect on the tracer transport. Although this study makes use of a limited area model it gives some useful information on the tracer transport in models in global. In particular it indicates that the altitudes reached by the tropospheric tracers are linked to the model vertical grid spacing that is usually coarse in CTMs.

The present study was restricted to the Maritime continent and an extension to other tropical convective areas and periods is planned: West Africa in summer 2006 using AMMA data and South America for February and March 2005 using TROCCINOX

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(TROpical Convection, CIrrus and Nitrogen OXides experiment) data. This study will be the scope of a forthcoming paper.

To go a step further, real tracers could be used to make a direct evaluation of the tracer transport. This can only be achieved if the tracer emissions are properly determined. One possibility would be to use the detailed emission inventories over West Africa from the AMMA (African Monsoon Multidisciplinary Analyses) project.

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Table 1. Description of the characteristics of the different simulations.

Simulation	Horizontal resolution	Number of vertical layers (depth in UTLS)
REF	60 km×60 km	56 (300 m)
HR	20 km×20 km	56 (300 m)
CVR	60 km×60 km	43 (850 m)

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Table 2. Characteristics of the idealized tracers used in the simulations.

Tracer	Lifetime	Initial conditions	Emissions
1	6 h	0	10^{-9} kg m^{-2} s^{-1} over land
2	infinite	0	10^{-9} kg m^{-2} s^{-1} over land
3	Infinite if $\theta>380$ K 6 h $\theta<380$ K	1 ppt if $\theta>380$ K 0 ppt if $\theta<380$ K	No emissions
4	infinite	1 ppt if $\theta>380$ K 0 ppt if $\theta<380$ K	No emissions

Table 3. Mean bias and standard deviation of bias between Manus radiosoundings and the simulations.

		REF	HR	CVR
Temperature (°C)	Mean bias	−0.307	−0.200	−0.455
	Mean bias standard deviation	1.108	1.065	1.095
Horizontal wind speed (m s^{-1})	Mean bias	−1.322	−1.122	−1.523
	Mean bias standard deviation	3.185	3.134	2.916
Wind direction (°)	Mean bias	7.724	4.261	4.581
	Mean bias standard deviation	62.78	60.81	54.70
Specific humidity (g/kg)	Mean bias	−0.088	−0.085	−0.114
	Mean bias standard deviation	0.541	0.524	0.535

Table 4. Mean tracer fluxes integrated over the simulation domain and during the whole simulation period using hourly model outputs.

		REF	HR	CVR
Tracer flux at 14 km (10^{-9} kg m^2 s)	Tracer 1	0.0036	0.0147	0.0002
	Tracer 2	0.0645	0.1911	0.0134

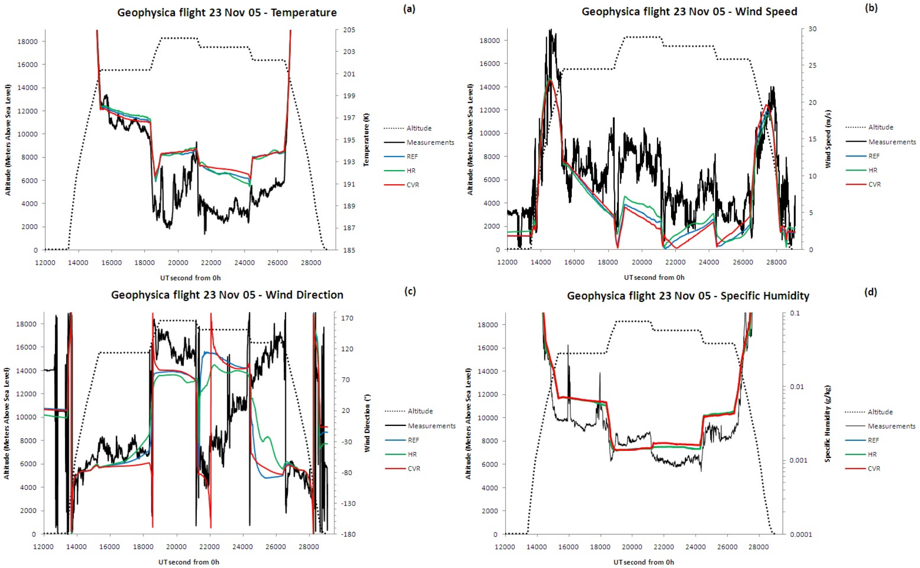

Fig. 1. Comparison between the Geophysica meteorological data and the three model simulations for the 23rd November 2005. **(a)** Temperature (K), **(b)** horizontal wind speed ($\mathrm{m\,s^{-1}}$), **(c)** wind direction (°) and **(d)** specific humidity ($\mathrm{g\,kg^{-1}}$). The black lines are for the aircraft measurements and the colored lines for the model results. The dashed line is the model altitude in m.

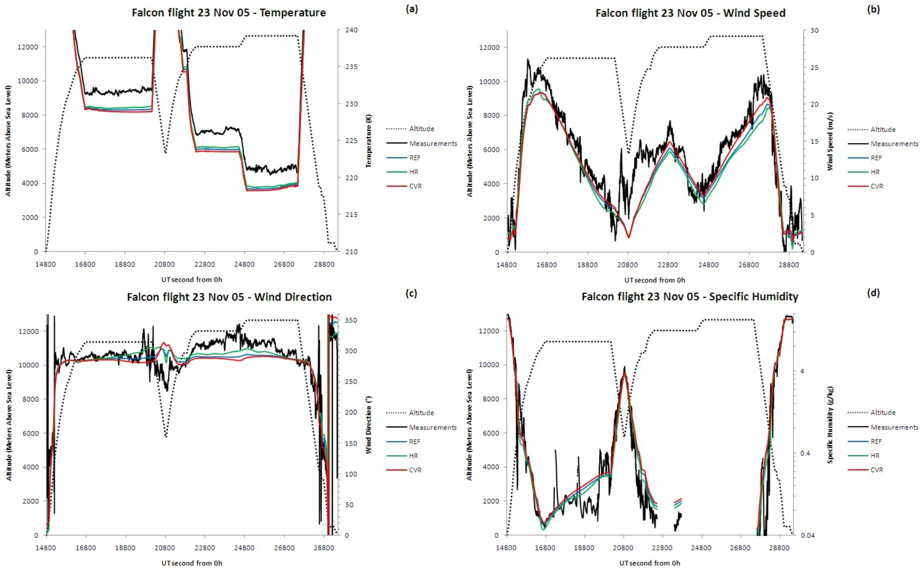

Fig. 2. Same as Fig. 1 but for the Falcon data of the 23rd November 2005.

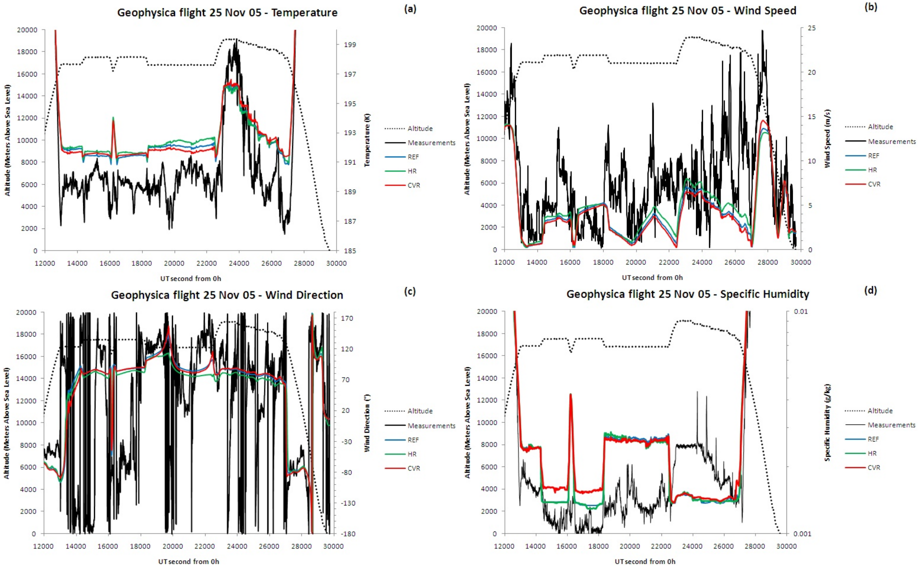

Fig. 3. Same as Fig. 1 for the Geophysica data of the 25th November 2005.

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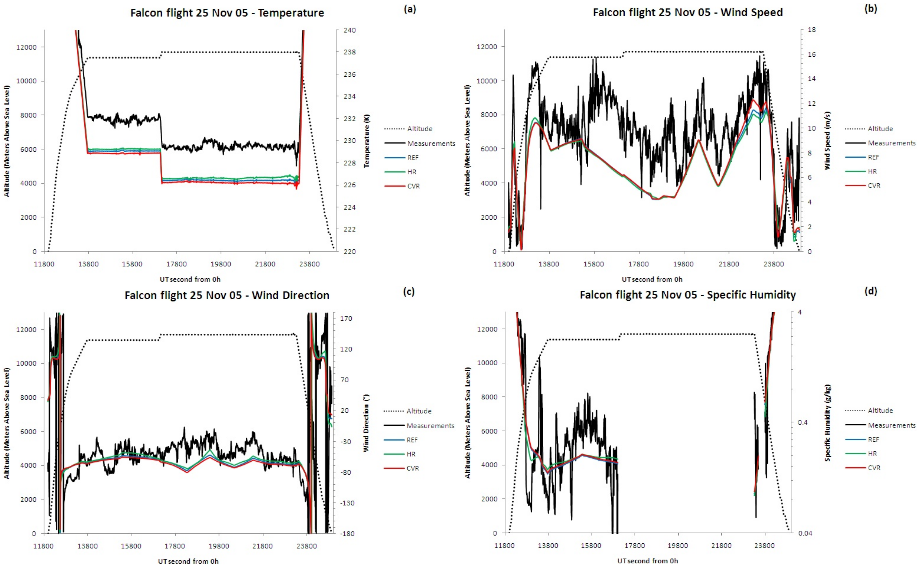

Fig. 4. Daily mean surface rainrate in mm day^{-1} from 15 November 2005 to 15 December 2005 for **(a)** TRMM and **(b)** the model REF simulation, **(c)** CVR simulation and **(d)** HR simulation.

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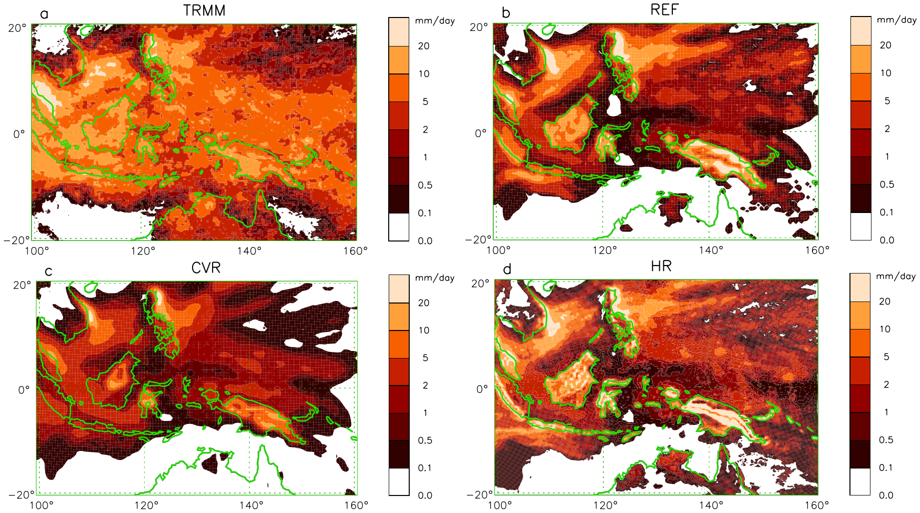

Fig. 5. Same as Fig. 1 for the Falcon data of the 25th November 2005.

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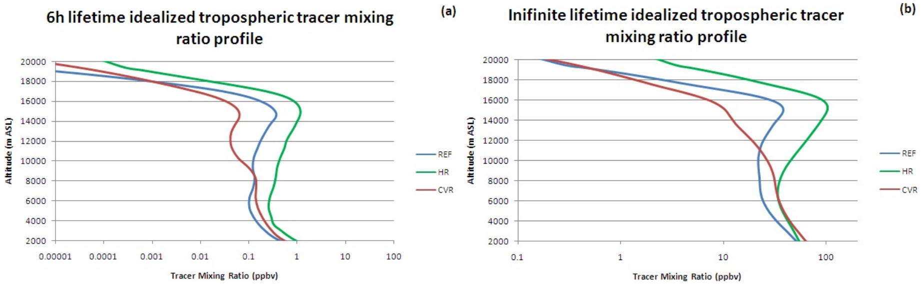


Fig. 6. Volumic tracer mixing ratio profiles averaged over the model domain and over the one month simulation period using 3-hourly model outputs for **(a)** Tracer 1 and **(b)** Tracer 2.

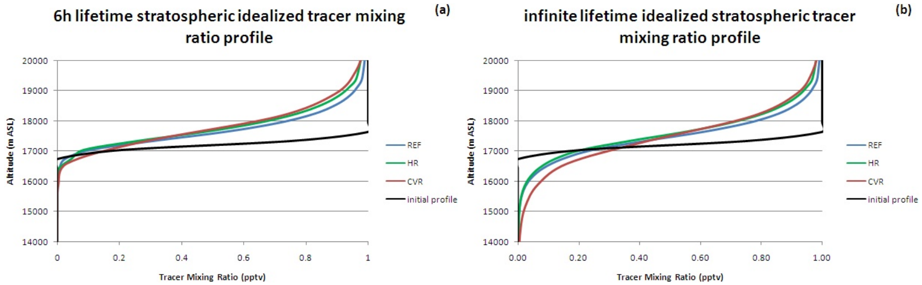


Fig. 7. Same as Fig. 6 but for Tracer 3 and 4 (stratospheric tracers). The dark line is the mean vertical profile at the initial time of the simulation.

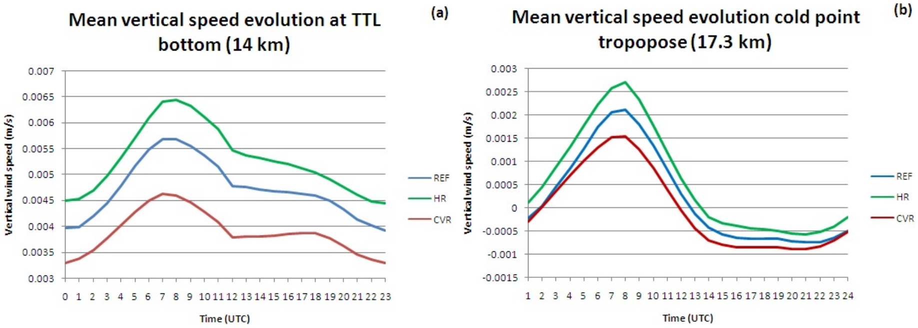
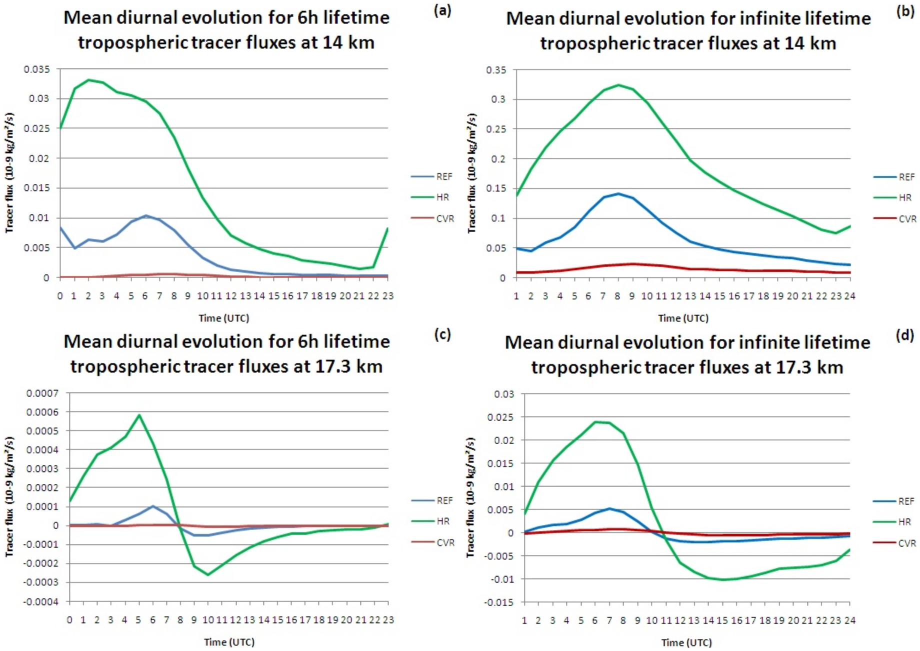


Fig. 8. Diurnal evolution of the vertical wind speed averaged over the model domain at **(a)** 14 km and **(b)** 17.3 km altitude.


(a) Mean diurnal evolution for 6h lifetime tropospheric tracer fluxes at 14 km

(b) Mean diurnal evolution for infinite lifetime tropospheric tracer fluxes at 14 km

(c) Mean diurnal evolution for 6h lifetime tropospheric tracer fluxes at 17.3 km

(d) Mean diurnal evolution for infinite lifetime tropospheric tracer fluxes at 17.3 km

Fig. 9. Diurnal evolution of the mean vertical Tracer 1 and 2 fluxes over the model domain at 14 km and 17.3 km altitude.

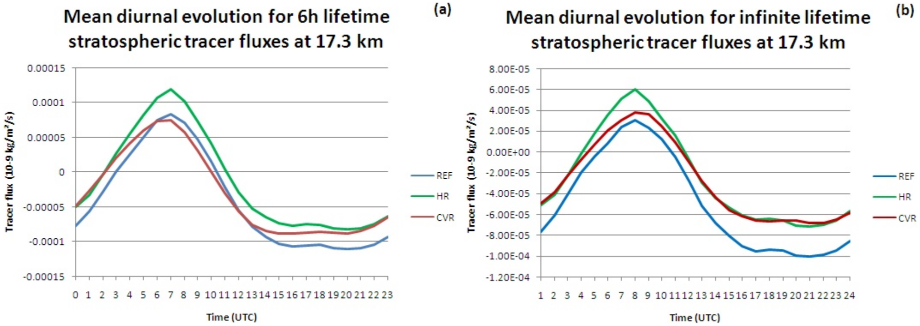


Fig. 10. Same as Fig. 9 but for Tracer 3 and 4 (stratospheric tracers).