Reply to the referee comments (comments in black / reply in **blue** / changed text passages in **red**):

Referee #1:

Review on "Aircraft routing with minimal cost impact: the REACT4C climate cost function modelling approach (v1.0)" by V. Grewe et al.

The paper presents a modelling approach for aircraft routing to minimize their climate impact. The approach is based on different modelling tools: a model to design air traffic routes, an emission model and a chemistry-climate model. The output of the model chain comprises the climate impact of air traffic routes taking into account CO_2 and non-CO_2 effects (NOx, O_3, CH_4, H_2O, contrails).

General comments:

Although I think that the basic idea behind this modelling approach, that is minimizing the climate impact of air traffic, is an important contribution to the climate change discussion and the development of mitigation strategies, and, therefore, deserves publication, I really have trouble to assess whether the described approach is valid or not. While the design of the flight path and the calculation of the emissions along that flight path seem to be straight forward, the calculation of the climate cost functions remains a mystery to me. This part of the model chain involves so many different grids, sub-grids, regions, trajectories, modules, assumptions etc., and the actual interaction is not clear at all. Together with the use of precalculated input (RF) this seems to be piecemeal. For example, the fit of the relation between instantaneous and adjusted radiative forcing of ozone changes in Fig. 11 based on two different studies without any overlap. This makes it impossible to identify potential shortcomings and uncertainties of the present study.

Reply:

We acknowledge the positive remark on the basic idea behind our modelling approach. We are grateful for the ideas on how to better present this modelling approach. Indeed, we have included a large number of processes, necessary for the calculation of the climate-cost functions and their use in the routing calculation. It ranges from transport, microphysics, chemistry, radiation and the impact on climate (near surface temperature) as well as fuel consumption and emissions of CO_2, H_2O, and NO_x. It is indeed a massive modelling effort, which relies on tradeoffs between accuracy and computing time and which is has been conducted in this complexity for the first time as far as we know. It is hence only indirectly comparable to other studies. We do not claim that the adopted approach is unique, and indeed one can only "learn by doing" when interconnecting so many modelling components. We hope that our work will act as a platform for future work (by others and ourselves) in terms of considering the different elements of the design of such a system.

We have tried to present overviews in sketches (Figure 1 and 2) to guide along the model description and a Figure on the grid of the climate cost function. However, it seems that this was not enough. Therefore we revise the presentation following the referee's suggestions and

- **replace Figure 4 by the referee's suggestion by a more informative figure (see below)**

- **included a table, which summarises the individual modelling parts and assumptions (see below)**
- **included a Section between the model description and verification, which summarises the approach and gives an overview on the verification**
- **Give a consistent definition of the grids and trajectories:**
    - **EMAC grid**
    - **Time-region grid**
    - **Climate cost function grid (equal to EMAC grid)**
    - **SAAM grid**

And

- **Aircraft trajectory vs. air parcel trajectory**

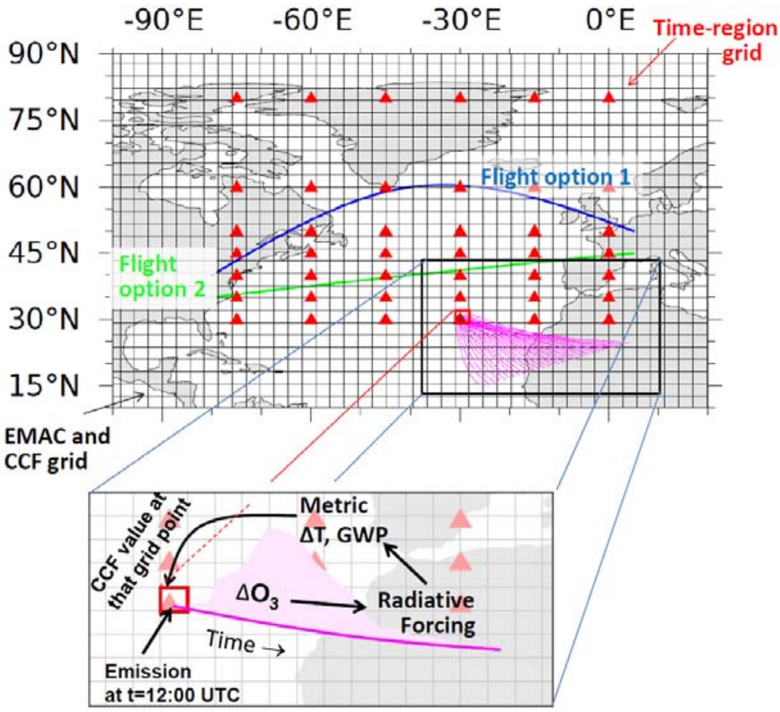

Table 1. Overview on the climate-cost function calculation, assumptions and verification.

	Description	Assumptions	Verifications
Grid representations			
EMAC grid	2.8125° latitude × 2.8125° longitude	Base model resolution sufficient	e.g. Jöckel et al. (2006, 2010)
Time-region grid	504 data points for one day (Tab. 2)	Main structures can be resolved with lower resolution as long as the main processes are calculated with a higher resolution	Sensitivity study in Sec. 3.2.3
Trajectories	50 air parcel trajectories per EMAC grid cell in which the time-region grid point is located	Number of air parcels large enough to cover chaotic behaviour of the atmosphere	Convergence tests in Sec. 3.2.2
Climate cost function grid	Interpolation of the time-region grid to the EMAC grid	Interpolation valid	see "Time-region grid"
Emissions			
NO, H_2O, flown distance	Pre-defined values are used (Tab. 3 and 4)	Saturation effects for NO_x chemistry, contrail-cirrus, and water vapour are less important than the 3D structure of the response to the emission	This verification will be performed in a follow-up publication, since it includes an analysis of the implication on air traffic emissions, which is beyond the scope of this work (see also shaded box in Fig. 1).
Chemistry			
Tagging	Calculation of contribution of the time-region emission to the atmospheric composition independently from each other (no feedback to background chemistry)	Linearisation of the specific reaction rates for small perturbatios (eq. 9) is valid	Comparison to other modelling studies in Sec. 4.1
Microphysics			
Contrails	Contrail-cirrus are described by contrail coverage and ice water content; Results are masked with the potential contrail coverage in the EMAC resolution.	Effects are sufficiently described without explicit simulation of e.g. ice number concentration	Comparison to observational data and modelling studies in sec. 4.2
Radiative forcing			
Contrails	Calculated with the EMAC radiation	no specific assumption	Benchmark test and comparison to other modelling studies in Sec. 4.2
Ozone	Calculated with the EMAC radiation	no specific assumption	Comparison to other modelling studies in Sec. 4.1
Methane	Calculated with IPCC formula	no specific assumption	Comparison to other modelling studies in Sec. 4.1
Water vapour	Parameterised as described in Sec. 3.4	A prescribed emissions leads to a linear relation between change in mass and RF	Based on the results from Grewe and Stenke (2008) and comparison to other studies in Sec. 4.1
Metrics			
GWP100, GWP20, ATR20	Standard formulas; Focus on the question "What is the long- and shortterm climate impact, if the rerouting strategy will be applied every day?"	The combination of the metric and emission scenario answers the posed question	Sanity check given in Sec. 4.3 and Tab. 8; Relation of impacts are given in Fig. 14; All metrics will be used in forthcoming papers to investigate this uncertainty

Included Section:

3.6 Summary on climate cost function calculation

We have set-up a modelling approach linking potential emissions at locally and temporarily confined regions to their climate impact, measured with climate metrics. This procedure follows previous approaches (e.g., IPCC, 1999; Grewe et al., 2007; Grewe and Stenke, 2008; Lee et al., 2010), however, differs in some details, taking into account new findings. Tab. 1 shows the main features of this modelling chain. We used different grids (see also Fig. 3), starting from the grid of the base model EMAC, in which we included 504 selected time-region grid points, which cover the North-Atlantic region. From the area immediately around each of the time-region grid points, we started 50 air parcel trajectories each and allocated the resulting climate impact to this grid point. An interpolation to the original EMAC grid provides the final climate cost function grid. The impact of the interpolations and definition of the time-region grid is tested in Sec. 3.2 (see also Tab. 1).

Physical and chemical processes are calculated on the air parcel trajectories, with extracting process information from the detailed EMAC model. The temporal evolution of chemical species, their lifetimes and relations between e.g. ozone and methane radiative forcing are analysed and compared to other studies in more detail in Sec. 4.1 and 4.2. The climate impact metrics are derived by standard formulas (see e.g., Fuglestvedt et al., 2010) and a sanity check given in Sec. 4.3. An overall evaluation of the metrics are given in Sec. 4.3 by intercomparing the P-AGWP20 metrics derived from this work with results obtained with the climate-chemistry response model AirClim (Grewe and Stenke, 2008; Grewe and Dahlmann, 2012).

We find it a little bit hard to exactly understand where the reviewer had problems to understand the modelling approach. We think that a part of the problems is due to the break-up into a model description and a subsequent results paper, which is planned for Atmos. Environm., where the results are discussed in more detail and uncertainties / sensitivity studies are performed. We have added one Figure from that paper into a new Section 4.4 which shows the contributions from the whole trans-Atlantic fleet at that day to the climate metric P-AGWP20. This is a closure experiment, which was also requested by the second reviewer:

To obtain an overall assessment of the metric results (here P-AGWP20), we take the trans-Atlantic air traffic emissions, calculated with the SAAM model for the minimum economic cost, and compare these results with an AirClim simulation based on the same emission data. AirClim is a fast climate-chemistry response model (Grewe and Stenke, 2008; Grewe and Dahlmann, 2012), which takes into account annual mean emissions and their regional different effects (basically latitudes and altitudes), based on a number of pre-calculated cases with complex chemistry-climate modelling. Note that in REACT4C the climate response is taken the specific weather situation into account, whereas in the case of the AirClim simulation, the emissions are assumed to occur every day at the same place, i.e. identical for all weather situations throughout a year. The results (Fig. 14) show almost identical values for all emission components, except for contrail-cirrus, which is reasonable, since the day-to-day variability of the contrail effects are highly variable and a one-day simulation cannot be expected to be representative for the whole year. However, the comparison shows that the overall results are comparable in magnitude.

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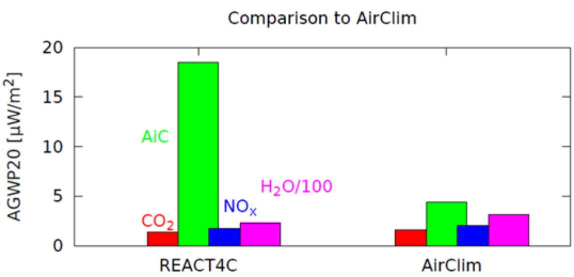

Fig. 14. Comparison of the pulse absolute global warming potential (P-AGWP20) in [$\mu W/m^2$] for emissions of CO_2 (red), contrail-cirrus (green), NO_x (blue), and H_2O (magenta). Note that the H_2O values are multiplied by 100 for presentational purpose. The emissions from the minimum economic cost 1-day trans-Atlantic air traffic, which are calculated with SAAM are multiplied with the climate cost functions (REACT4C, left) and taken as annual mean emissions for the climate-chemistry response model AirClim (right).

Concerning Figure 11 and 12: Yes, the reviewer is right it would be nice to have an overlap area. Both studies were performed with the same modelling system and they agree that lower tropospheric ozone has a ratio of the adjusted RF to the instantaneous RF, which is close to one. Figure 12 and the discussion in the text gives an explanation for the behaviour of the ratio around the tropopause. However, we do not believe that the precise details of the way we convert instantaneous and adjusted forcing is critical to the method or to its description and we now move that discussion into an appendix, where it can be consulted by those who are sufficiently interested. Therefore, we believe that we can use the data to derive an estimate for the adjusted RF.

The paper is a bit lengthy and would benefit from a shortening, e.g. Sect. 3.1 could be shortened or skipped. I included a little sketch at the end of the review, showing my understanding of different grids/trajectories and how they interact. Maybe that helps to understand where my confusion comes from. I am convinced that the authors can do much better in explaining their approach. Therefore, I would give the paper a second chance after major revisions.

Reply:

Yes, indeed the paper is lengthy. The aim of GMD is clearly to document model development in detail. This is a quite complex model development and hence includes a lot of descriptions, equations, reactions, Figures and Tables and in addition some overview sketches and tables to show how the individual model parts are linked together. In our opinion a shortening would imply a loss of information in most cases and we feel there is a real tension between being comprehensive enough for readers to understand the modelling chain and being succinct.

However, we omitted Figure 5, which showed the decoupling; indeed the description in the text is sufficient and we moved a large part of the RF calculation to the appendix, so that the Sections are more balanced.

Specific comments:

- P 4347, l 2: "... substantial contribution to ..."
- P 4347, l 20-23: Does this statement refer to NOx emissions in particular or to aircraft emissions in general?

Reply

We think that this is likely to be true for all non-CO_2 species emitted by aviation". We re-phrase the sentence to be clearer.

- P 4347, l 24: REACT4C – either explain the meaning of the acronym or add a reference to the appendix

Reply

Explanation added in brackets.

- P 4349, l 8: Which properties do you mean? Properties of contrails?

Reply

Changed to 'contrail properties'

- Sect. 2.1: In which horizontal/vertical resolution is EMAC run?

Reply

The resolution is T42L41, i.e. roughly 2.8 by 2.8 degrees and 41 layers with the uppermost centred at 5 hPa. Text added to Sec. 2.1.

> - Sect. 2.2.1: Does SAAM include worldwide city pairs or only the North Atlantic flight corridor?

Reply:

SAAM can include all world regions. For this application we focus on the North-Atlantic and we only simulate and optimise the North-Atlantic flights, which are roughly 400 in each direction. Text added in Sec. 2.2.1

> - P 4351, l 8: I assume that "a set of full 4-D trajectories" means 84 routings as described in Sect. 2.2.3.

Reply:

This is a misunderstanding. We just meant one aircraft trajectory in space and time (4D) for one flight option. Sentence adapted.

> - P 4351, l 14-16: Isn't it necessary to consider load balancing for all optimisation models to get realistic air traffic routes and, therefore, realistic information about the climate impact of different flight routes?

Reply:

The work load of controller is normally not regarded in the calculation of air traffic emission data. An exception is the AERO2K (and a few others) emission data, which are based on real flight trajectories, based on radar data. This sentence just should emphasise that SAAM was used in optimisation problems before, but for applications other than climate impact minimisation. Text re-written:

~~Other optimisation models, for instance focusing on controlled sectors load balancing, were developed in SAAM~~ Climate impact minimisation has not been performed before with SAAM, but other optimisation problems were considered, for instance a balancing of the air traffic controller's work load (Champougny et al., 2001).

> - P 4352, l 4-6: Route generation – when you are talking about alternative routes, how is the reference trajectory defined? Shortest way?

Reply

Minimum costs, which basically reflects minimum fuel use and hence a wind optimal route. Text adapted.

> - P 4352, l 9: What do you mean by "larger"? Which grid size is used for the present approach?

Reply

The used grid is Grid 0 in Fig 3. Text adapted.

- P 4352, l 17: What is the spatial and temporal resolution of the 4-D trajectories?

Reply

The length of the flight segments is variable, but always less than 5 nm (=9.26 km).

- P 4353, Eqn. 2 and l 8: Do I understand this correctly – the number of conflicts is ≥ 0 (which makes sense), but the entries of the conflict matrix are ≤ 0?

Reply:

Yes that is the normal way an optimisation problem is posed. Normally, only ranges are defined. In this case the only solution is that the number of conflicts is zero. The canonical form of linear programming can be found in http://en.wikipedia.org/wiki/Linear_programming :

$$\begin{array}{ll} \text{maximize} & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & A\mathbf{x} \le \mathbf{b} \\ \text{and} & \mathbf{x} \ge \mathbf{0} \end{array}$$

- P 4354, l 1: How many flight legs "m" are considered?

Reply

The parameter m is variable from flight to flight, but in the order of 10^3. Now mentioned in the text.

- Sect. 3.1: Here is one of my major problems, the approach of the predefined time-regions is not clear to me. Are the time-regions to be interpreted as a kind of sub-grid of the GCM grid? Is AIRTRAC a box model that is applied for the time regions? I assume that the Lagrangian trajectories are not identical to the 4-D flight trajectories calculated by SAAM. If so, clearly distinguish between both types of trajectories by using different terminology.

Reply

Good point. We now distinguish between aircraft trajectory and air parcel trajectory. We define a location and a time when we emit (see Figure above). This information is available for the EMAC model via a namelist (TREXP submodel) and trajectories are started in the surrounding of the time-region-grid point. There is no other use of the time-region grid in the EMAC model runs. AIRTRAC is an EMAC submodel, which consists of two parts (like most of the EMAC submodels), an interface (submodel interface layer), which provides all necessary information for the AIRTRAC core, and the core (submodel core layer), where the processes are calculated as a box model for every trajectory.

We included a better Figure and a table, describing the grid terminology and usage (see above) and revised the text to clearly distinguish between EMAC grid, time-region grid, air parcel trajectory, and climate cost function grid.

- P 4354, l 24: Figure 4 shows Figure 6 and vice versa.

Reply

No idea how that could have happened. – sorry -

- Sect. 3.2.1: How do the predefined time-regions correspond to the SAAM flight routes? What are the reasons for choosing those longitudes, latitudes and pressure levels?

Reply

The time-regions cover the area of the flight tracks between the entries into the North Atlantic track system and flight levels 240 to 400. Text adapted in the introduction.

- P 4356, l 19: Those 50 trajectories are Lagrangian trajectories, right?

Reply:

Yes, text adapted see above.

- P 4357, l 3: 24 emission points??? How are the defined?

Reply

We regard a subset of time-region grid points, those which are located in the given domain (l3 ff). We re-phrased it to make it clear.

- P 4357, l 20-23: Why is the standard deviation for ozone smaller than for NOx?

Reply:
Indeed that is an interesting question. We analysed a lot of trajectories and found that there are frequently two regimes. In one case the trajectories are transported upwards and northwards, when they start east of a low pressure system (no surprise of course as this is expected). Hence they remain a long time in the northern lowermost stratosphere, where they do not experience washout and do not produce large amounts of ozone. Hence we have large NOx masses but low ozone masses. The other regime is west of the low pressure system, where the air parcels are transported downwards and to the tropics. The consequence is a short lifetime of NO_x with a very effective ozone production. Result is low NO_x amounts but large ozone amounts. We know that ozone chemistry is non-linear and this is a nice example, which leads to a lower ozone variability compared to the NO_x variability. This mechanism will be explored in more detail in a forthcoming paper, which deals more with the understanding of these processes and the climate cost functions.

- P 4359, l 17: Which species are combined to families?

Reply:

Actually, it is only one family for nitrogen oxides, which are not NO, NO_2 and HNO_3. Text adapted.

- P 4360, Eqn. 10: What means "$D_{O3,1}$" and "$D_{O3,2}$"? D (=depletion) = L (=loss)? In Eqn. 8 loss is written as "L".

Reply

Yes, D means depletion and L means loss, which is the same. We change "depletion" into "loss".

- P 4360, l 14: "Production of OH:" needs a new line
- Eqn. R3: $O(^1D)$
- Eqn. 44: What is "ρ"?
- P 4369, l 15: which
- P 4370, l 16: "... and the difference..."
- P 4371, l 14: Why is August used as reference months?

Reply

Changed. Rho is the air density. August was chosen since it shows the maximum values. Any month can be chosen, however, the parameters would be different.

- P 4376, l 14: What is shown in Fig. 14? One flight route?

Reply:

For every time-region grid point (504) the mean (over 50 air parcel trajectories) evolution of the species are shown. On could think about an aircraft flying at that time in that region and emitting, but it is just a locally confined emission and not a flight route. With the clearer definition of the time-regions (see above) this should be clearer now.

- Fig. 3: How is the grouping of the cells done?

Reply:

The grouping is done based on EUROCONTROL expert knowledge.

- Fig. 5: This figure is not very meaningful. Since this paper includes a lot of figures, I would skip this one here.
- Fig. 6 (currently Fig. 4) is also not very helpful. I think it is enough to list the locations of the different time –regions the table.
- Fig. 7: Why don't you simply use % as units?
- Fig. 9: RFinst and RFadj: Colour coding and figure caption do not match.
- Fig. 14, caption: "... by an emission..."

Reply:

Figure 5 is deleted.

Figure 4 is updated by the referee's suggestions.

Figure 7: right that would be the same.

Figure 9: Adapted.