We are grateful to the referee #1 for the very helpful and encouraging comments on the original version of our manuscript. We took all comments into account and rewrote the manuscript accordingly. Here are our replies:

- **General comment:** This paper documents the AirTraf version 2 submodel of the EMAC chemistry-climate model, developed to enable simulation of global air traffic in a climate model in order to investigate optimized routing strategies for the aviation sector. A set of one day simulations are run, showing that the model gives plausible output and the results are discussed in the context of previous literature. While the topic of abatement strategies for reducing aviation's climate impact is both important and current, and this modeling framework is a useful tool in this regard, the paper is not of a sufficient quality for publication in its current form. In general, the main messages can be polished and highlighted better. The introduction is long and unstructured, and it's difficult to extract the essence of what's new in this work (and why it's important). This does not really get much clearer in the methods where most of AirTraf 2 seems to follow AirTraf1 and is mostly described in Yamashita et al. 2016. While the discussion section is quite good, the results is only one page out of a 14-page paper, which is not quite convincing. The paper also needs substantial additional work to improve the writing and language. There are number strange formulations, short sentences and imprecise use of terminology that make the paper difficult to follow at times. Some examples are given below, but a general language check/copyediting is recommended.

Reply: We thank the referee #1 for the useful comments. We have addressed all the comments and structured our reply according to the reviewer's general comments into

a) Highlight improvements
b) Shortening and improved structure of the introduction
c) Methods: clarifying the improvements of AirTraf 2.0 over AirTraf 1.0
d) Extension of the results section
e) Language improvements
f) Modification of short sentences
g) Explanation of terminologies
h) Formula improvements
i) Modification of references.

We believe that this revision represents a polishing of the whole paper.

a) Highlight improvements:

To highlight the main messages of this paper, we rewrote the abstract and the conclusions. We also modified the introduction to improve the structure, and to show what's new in this work and why AirTraf 2.0 is important. Details are described in the "b) Shortening and improved structure of the introduction" below.

[Abstract]

Aviation contributes to climate change and the ~~C~~**c**limate impact of aviation is expected to increase further. **Adaptions of** ~~A~~**a**ircraft routings **in order to reduce the climate impact** are an important **climate change mitigation** measure ~~for climate impact reductions~~. ~~To find an effective aircraft routing strategy for reducing the impact, the first version of the submodel AirTraf has been developed; this submodel can simulate global air traffic in the ECHAM/MESSy Atmospheric Chemistry (EMAC) model.~~ **The air traffic simulator AirTraf, as a submodel of the ECHAM/MESSy Atmospheric Chemistry (EMAC) model, enables the evaluation of such measures. For the first version of the submodel AirTraf, we concentrated on the general set-up of the model, including departure and arrival, performance and emissions, and technical aspects such as the parallelization of the aircraft trajectory calculation with only a limited set of optimization possibilities (time and distance).** ~~This paper describes the updated submodel AirTraf 2.0. Seven new aircraft routing options are introduced, including contrail avoidance, minimum economic costs, and minimum climate impact.~~ **Here, in the second version of AirTraf, we focus on enlarging the objective functions by seven new options to enable assessing operational improvements in many more aspects including economic costs, contrail occurrence and climate impact. We verify that the AirTraf set-up, e.g. in terms of number and choice of design variables for the genetic algorithm, allows finding solutions even with highly structured fields such as contrail occurrence. This is shown by** ~~E~~**e**xample simulations of the new routing options ~~are presented by using~~**, including** around 100 north-Atlantic flights of an Airbus A330 aircraft for a typical winter day. The results clearly show that **AirTraf 2.0 can find** the **different** famil~~y~~**ies** of optimum flight trajectories (three-dimensional) ~~varies according to the~~ **for specific routing options; those trajectories minimize the corresponding objective functions successfully.** ~~The comparison of the results for various routing options reveals characteristics of the routing with respect to air traffic performances.~~ The minimum cost option ~~obtains a trade-off solution~~ **lies** between the minimum time and the minimum fuel ~~solutions~~ **options. Thus, aircraft operating costs are minimized by taking the best compromise between flight time and fuel use.** The aircraft routings for contrail avoidance and minimum climate impact reduce the potential climate impact, which is estimated by using algorithmic Climate Change Functions, whereas these two routings increase **the** ~~flight~~ **aircraft** operating costs. A trade-off between the aircraft operating costs and the climate impact is confirmed. The simulation results are compared with literature data and the consistency of the submodel AirTraf 2.0 is verified.

[Conclusions]
We revised the conclusions to highlight the outcomes in a better way, e.g., on page 14 lines 25-32, "AirTraf 2.0 simulates the one-day air traffic successfully for **the newly developed routing option concerning different optimization objectives, e.g., contrail avoidance, cash operating cost, and climate impact (represented by average temperature response over 20 years), and finds the different families of optimum flight trajectories, which minimize the corresponding objective functions**. The characteristics of the**se** routing options ~~were analyzed on the basis of the nine performance measures.~~ **include that** ~~A~~**a**ircraft ~~wa~~**i**s flown as the minimum economic cost with both, the SOC and the COC options. These options are comparably effective for economic cost indices. The AirTraf 2.0 differentiates the minimum time, the minimum fuel, and the minimum COC ~~solutions~~ **options**~~;~~**.** ~~that is,~~ ~~t~~**T**he COC option ~~obtains a trade-off solution~~ **lies** between the minimum time and the minimum fuel ~~solutions~~ **options**~~.~~**, and thus minimizes COC by taking the best compromise between the flight time and the fuel use into account.** The NO_x option minimizes NO_x emission; this option differs from the fuel and the COC options. The contrail and the climate options decrease **the** climate impact (indicated by $ATR20_{total}$), which causes extra operating costs. A trade-off between the cost and the climate impact **certainly** exists."

b) Shortening and improved structure of the introduction:
To shorten the introduction and to improve its structure, we modified the text and structured the introduction into

- Background: the climate impact of aviation
- Introduction of a climate-optimized routing
- Previous studies: benefits of the climate-optimized routing
- Ultimate aims and introduction of the AirTraf model
- Objective of this study
- Significant aspects of AirTraf 2.0
- Contents of the paper.

The concrete modifications are as follows:
− We deleted some redundant sentences from the introduction (please see the replies to the referee comments (4), (8) and (15)).
− We deleted one paragraph from the introduction (please see the reply to the referee comment (18)).
− We rewrote the text: on page 4 line 3, "Here, we ~~focus on~~ **mention the importance of** the variety of the routing options."

In addition, we modified the text to make clear what's new in this work and why AirTraf 2.0 is important, and to emphasize its advantage, compared to other models as follows:
− We added the text to the introduction (please see the reply to the referee comment (28)).
− We rewrote the text: on page 3 lines 27-29, "This paper presents a technical description of **the new version of the submodel** AirTraf **2.0** ~~(version 2.0)~~. The simple aircraft routing options of great circle (minimum flight distance) and flight time (minimum time) were developed in **the previous version of** AirTraf 1.0 (Yamashita et al., 2016). ~~Here~~ **In AirTraf 2.0**, seven new aircraft routing options have been introduced.…"
− We added the word "2.0" to emphasize the new development in AirTraf 2.0: on page 4 line 3, "Various

routing options have been made available in AirTraf **2.0**, because.…”

c) Methods: clarifying the improvements of AirTraf 2.0 over AirTraf 1.0:

As the referee noted, AirTraf 2.0 builds on the previous version of AirTraf 1.0. AirTraf is a comprehensive model to enable air traffic simulations on-line in the chemistry-climate model EMAC. In AirTraf 1.0 (Yamashita et al., 2016), we developed the basic modules, including the main structure of trajectory calculations and the optimizer module for flight trajectory optimization. We had also introduced two simple routing options (the great circle and the time-optimal options) to verify, whether the whole system and the optimization module work correctly.

For our ultimate aims described on page 3 line 19, we have expanded the model framework substantially to include seven new routing options with respect to different optimization objectives. We highlight the key changes (i.e. what is new in AirTraf 2.0) in Fig. 1 (on page 22 in the caption, “updates from AirTraf 1.0 are highlighted by red texts and arrows”) and in Tables 1 and 2 (on pages 25-26 in the caption, “The column ‘New in V2.0’ denotes parameters/properties newly introduced in AirTraf 2.0”). We believe that they are useful for readers to recognize the new changes. To show the new changes more clearly, we added the text as follows:

− On page 5 line 2, “The present version is based on the model components of AirTraf 1.0~~.~~**, and** ~~T~~**t**hus, this section outlines them **(updates from AirTraf 1.0 are highlighted in Fig. 1)**.”

− On page 5 line 7, “Table 1 lists the relevant data of an A330-301 aircraft and constant parameters used in AirTraf 2.0 **(the new parameters are listed in Table 1)**.”

− On page 5 line 28, “The first step finds an optimum flight trajectory for a selected routing option by using the aircraft routing module (Fig. 1, light green)**, in which the seven new routing options are introduced in AirTraf 2.0**.”

− On page 6 line 2, “In AirTraf 2.0, 15 new properties are calculated~~.~~**, as highlighted in Table 2**.”

− On page 6 line 5, “… at the departure time of the flight. **The methodologies of the fuel-emissions calculation module developed in AirTraf 1.0 are expanded in AirTraf 2.0.** Details of the fuel-emissions-~~cost-climate~~ calculation module ~~(Fig. 1, light orange)~~ and its reliability have been reported.…”

− On page 6 line 13, “… are gathered along the flight segments (Table 2)**; the global fields of $\mathbf{PCC_{dist}}$ and ATR20s are newly calculated by AirTraf 2.0**.”

− On page 7 line 15, “**In AirTraf 2.0,** ~~S~~**s**even new objective functions were developed.…”

d) Extension of the results section:

We analyzed simulation results in more detail and additionally rewrote the text for Sect. 3.2 and 3.3. Please see the reply to the referee comment (24).

e) Language improvements:

To improve the writing and language, we rechecked and modified the text, redundant words and sentences, articles, and consistency of wording in the manuscript. The referee comments (1), (2) and (4) also pointed out this issue, and thus we replied to them in the corresponding sections. We list here other modifications:

− On page 3 line 6, “~~In general,~~ **The** benefits of ~~flying climate-optimized trajectories~~ **the climate-optimized routing** were investigated.…”

− On page 3 line 8, “… pulse AGTP values for three ~~different~~ time horizons.…”

− On page 3 line 10, “… for the medium-term climate goal~~, i.e., the time horizon~~ of 50 years.…”

− On page 3 line 34, “… are referred to simply as, e.g. the ~~'~~**“**fuel option~~'~~**”**).”

− On page 10 line 14, “… whereas the~~se~~ trajectories **of the westbound flights** are shifted northward ~~for the westbound flights~~.”

− On page 10 line 26, “… decrease the respective objects (target measures) ~~to~~ **which should** be minimized.…”

− On page 10 line 29, “… Table 4 lists a summary of ~~typical~~ **nine** performance measures of.…”

− On page 11 line 26, “… which offers additional aircraft routing options for defining overall target functions for ~~aircraft~~ **the flight** trajectory optimization.”

− On page 11 line 29, “The quantitative values of the changes in **the** performance measures vary.…”

− On page 24 in the caption of Fig. 3, “… climate impact indicated by ATR20total ~~for one-day~~ **during the**

day (from December 1, 2015 00:00:00 to December 2, 2015 00:00:00 UTC).”

f) Modification of short sentences:
We rewrote the three short sentences as follows:
− On page 4 line 5, “The time option is useful for delay recovery. **Because** ~~D~~**d**elays cause costs to airlines~~.~~**,** ~~Thus,~~ pilots are often forced to temporarily use the time option during a flight to maintain flight schedules.…”
− On page 4 line 11, “AirTraf enables analyzing those subjects.” We modified the sentence in reply to the referee comment (28).
− On page 5 line 3, “Thus, this section outlines them.” We modified the sentence in reply to the “Methods: clarifying the improvements of AirTraf 2.0 over AirTraf 1.0” described above.

g) Explanation of terminologies:
Some terminologies related to the genetic algorithm optimization are used in the present manuscript. We added the explanations to the words and rewrote the text:
− On page 6 line 29, “… and creates an initial **“**population**,”**~~,~~ which ~~consists of~~ **represents** a random set of solutions**.** ~~(population approach;~~ ~~t~~**T**he population size is set by n_p **and ARMOGA starts its search with the solutions**~~)~~. An evaluation function *f* **(called an objective function)** is defined, depending on a selected routing option.…”
− On page 7 line 4, “… the stochastic universal sampling selection (Baker, 1985) was used for the selection operator **to pick two solutions (parent solutions) from the population**; the Blend crossover operator (BLX-alpha; Eshelman, 1993) was applied to the ~~population~~ **parent solutions** to create new solutions (child solutions) ~~by picking two solutions (parent solutions) from the population~~; the revised polynomial mutation operator (Deb and Agrawal, 1999) was used to add a disturbance to the child solutions. When ~~the evolution~~ **those** process**es** ~~is~~ **are** iterated for a number of generations (**the term “generation” represents one iteration of ARMOGA;** this is set by n_g).…”
− We changed the word “RI” into “RF” (please see the reply to the referee comment (6)).

h) Formula improvements:
We added the definitions (equations) of the five ATR20s to the revised manuscript. Please see the reply to the referee comment (21). In addition, we added explanations on Eq. (A5), which is the algorithmic Climate Change Functions of contrails ($\mathrm{aCCF}_{\mathrm{contrail}}$) to the Appendix. Please see the reply to the referee comment (22).

i) Modification of references:
We modified the wrong references as follows:
− On page 3 line 31, “…Yin et al., 2018~~a~~**b**.…”
− On page 8 line 9, “Yin et al. (2018a) ~~and Yin et al. (manuscript in preparation, 2019)~~.…”
− On page 9 line 17, “…Yin et al., 2018~~a~~**b**.…”
− On page 15 line 13, “… published by Van Manen (2017)**, Yin et al. (2018b),** and Van Manen and Grewe (2019); the aCCF of contrails is described by ~~Yin et al. (2018a) and~~ Yin et al. (manuscript in preparation, 2019).”

- **Selected specific comments:**
  (1) Title: suggest removing “Various”. Makes it seem vague.

  Reply: Thank you very much. We removed the word “Various” from the title, and rewrote the title as “**Newly developed** aircraft routing options for air traffic simulation in the chemistry-climate model EMAC 2.53: AirTraf 2.0”.

- (2) Abstract: Line 1: Add “the” before “climate impact of aviation.…”

  Reply: We added the word “the” to the revised manuscript: on page 1 line 1 in Abstract, “… **the** ~~C~~**c**limate impact of aviation.…”

- (3) Abstract: Line 6-9: unclear, I don’t really understand what the important result here is.

  Reply: We rewrote the text to highlight the messages: on page 1 lines 6-9, “The results clearly show that **AirTraf 2.0 can find** the **different** famil~~y~~**ies** of optimum flight trajectories (three-dimensional) ~~varies according to the~~ **for specific routing options; those trajectories minimize the corresponding objective functions successfully.** ~~The comparison of the results for various routing options reveals characteristics of the routing with respect to air traffic performances.~~ The minimum cost option ~~obtains a trade-off solution~~ **lies** between the minimum time and the minimum fuel ~~solutions~~ **options. Thus, aircraft operating costs are minimized by taking the best compromise between flight time and fuel use.**”

- (4) Pg1: Line 16: The sentence starting with “the aviation sector is not” is redundant as you’ve just said that aviation contributes only 5% total climate impact.

  Reply: Thank you very much. We removed the sentence: on page 1 line 16, “~~The aviation is not the largest contributor to climate impact at the moment (e.g., the road transport contributes 11 % to the anthropogenic climate impact; Skeie et al., 2009).~~ However, the aviation’s contribution.…” Related to this, we added the word “only” to the revised manuscript: on page 1 line 15, “Nowadays the global aviation contributes **only** about 5 % to the anthropogenic climate impact.…”

- (5) Pg1: Line 23: a more up-to-date reference would be the Brasseur et al. 2016 paper in BAMS.

  Reply: Thank you very much. We referred to the paper in the revised manuscript: on page 1 line 23, “…(Wuebbles et al., 2007; Lee et al., 2009; **Brasseur et al., 2016**)”. This paper is listed in the present References.

- (6) Pg2: Line 1: I don’t understand the rationale behind introducing the terminology radiative impact (RI) instead of keeping well-established radiative forcing (RF). This is confusing and adds nothing to the paper. Please explain or change.

  Reply: Thank you very much. We believe that the term “radiative impact” is the more general term, and the two sentences, starting from page 1 line 23 “These effects change ... a radiative impact (RI). The RI potentially ... through temperature changes” describe the general mechanism of climate change. Thus, the term “radiative impact” would be appropriate. On the other hand, Lee et al. (2009) and other literature use the term “RF” to report those figures (in mW/m^{-2}). By following the referee comment, the best modification would be to remove the abbreviation “RI” in the two sentences, and to use the word “radiative forcing (RF)” in other sentences. Finally, we rewrote the text: from page 1 line 23 to page 2 line 4, “… cause ~~a~~ radiative impact ~~(RI)~~. The ~~RI~~ **radiative impact** potentially drives the climate system into a new state of equilibrium through temperature changes. Lee et al. (2009) stated that the CO$_2$ emission has the main impact and that the estimated ~~RI~~ **radiative forcing (RF)** of aviation CO$_2$ in 2005 was 28.0 mWm^{-2} (15.2−40.8 mWm^{-2}, 90 % likelihood range). The non-CO$_2$ emissions and the induced clouds also have a large effect on ~~RIs~~ **RFs**; for example, the estimated ~~RIs~~ **RFs** in 2005.…”

- (7) Pg2: Line 5: there are number of more recent studies showing higher contrail-cirrus forcing, reflecting more recent emission inventories. One example is the 2016 paper by Bock and Burkhardt in JGR-A. Such work should be reflected.

  Reply: Thank you very much. We referred to the three recent papers here and rewrote the sentence: on page 2 line 4, “… the estimated ~~RIs~~ **RFs** in 2005 for total NO$_x$ and for persistent linear contrails were 12.6 mWm^{-2} (3.8−15.7 mWm^{-2}, 90 % likelihood range) and 11.8 mWm^{-2} (5.4−25.6 mWm^{-2}, 90 % likelihood range), respectively (Lee et al., 2009). **In particular, the radiative impact of contrails remains uncertain and recent studies report higher RF. Burkhardt and Kärcher (2011) estimated the contrail cirrus RF of 37.5 mWm^{-2} for the year 2002; Schumann et al. (2015) reported the RF of 63 mWm^{-2} for the year 2006; and**

Bock and Burkhardt estimated the RF of 56 mWm^{-2} for the year 2006."

Related to this, we added the three papers to the References:
− On page 17 line 8, "**Bock, L., and Burkhardt, L.: Reassessing properties and radiative forcing of contrail cirrus using a climate model, Journal of Geophysical Research: Atmospheres, 121, 16, 9717−9736, https://doi.org/10.1002/2016JD025112, 2016.**"
− On page 17 line 13, "**Burkhardt, U., and Kärcher, B.: Global radiative forcing from contrail cirrus, Nature Clim Change, 1, 54–58, https://doi.org/10.1038/nclimate1068, 2011.**"
− On page 20 line 34, "**Schumann, U., Penner, J. E., Chen, Y., Zhou, C., and Graf, K.: Dehydration effects from contrails in a coupled contrail–climate model, Atmos. Chem. Phys., 15, 11179–11199, https://doi.org/10.5194/acp-15-11179-2015, 2015.**"

- (8) Pg2: Line 6: "Here the difference between time scales (…)": suggest removing, no point in telling the reader what you will tell them next.

  Reply: We removed the sentence and rewrote the text "As for time scales of their impacts" in context: on page 2 line 6, "~~Here, the difference between time scales of their impacts is noted.~~ **As for time scales of their impacts**.…"

- (9) Pg2 Line 6: "The emitted CO_2 (…)" – this is not precise; the emitted CO_2 does not have century-long timescale, the perturbation does.

  Reply: We rewrote the sentence: on page 2 line 6, "~~The emitted CO2 has a long residence time (a century) and becomes uniformly mixed in the whole atmosphere,~~ **the emitted CO_2 becomes uniformly mixed in the whole atmosphere and its perturbation remains for millennia.**" This modification is related to our reply to the minor comment (2) of the referee #2.

- (10) Pg2: Line 7: "the impact is proportional to (…)": this may be true for emission, and perhaps even for RF, but when approximating fuel with temperature impact or other climate change seems doubtful.

  Reply: As the referee pointed out, the sentence is not precise. Actually, this sentence does not give any necessary information. Thus, we removed the sentence: on page 2 line 7, "… ~~, i.e., its impact is proportional to fuel use~~."

- (11) Pg2: Line 10: the recent work by Lund et al. 2017 ESD include all components and show how this translates into temperature impacts. Could be a useful references.

  Reply: Thank you very much. We referred to the paper in the revised manuscript: on page 2 line 10, "… Mannstein et al., 2005; Gauss et al., 2006; Grewe and Stenke, 2008; Frömming et al., 2012; Brasseur et al., 2016; **Lund et al., 2017**)."

  Related to this, we added this paper to the References: on page 19 line 26, "**Lund, M. T., Aamaas, B., Berntsen, T., Bock, L., Burkhardt, U., Fuglestvedt, J. S., and Shine, K. P.: Emission metrics for quantifying regional climate impacts of aviation, Earth Syst. Dynam., 8, 547–563, https://doi.org/10.5194/esd-8-547-2017, 2017.**"

- (12) Pg2: Line 17: Why is climate-optimized routing limited to the present-day fleet?

  Reply: The climate-optimized routing is **not** limited to the present-day fleet. What we want to say here is that the climate-optimized routing is **immediately** applicable to the fleet, which airlines currently operate. Although technological measures (e.g. efficient engines, new aircraft) can significantly reduce the aviation climate impact, it takes a long time for airlines to introduce such new technological measures. To make clear the meaning of the sentence, we rewrote the text: on page 2 line 17, "The climate-optimized routing is

immediately applicable to present airline fleets, whereas other, more technical measures require several years before implementation.”

- (13) Pg2: Line 22: because of the long residence time of CO_2, its impact is the same regardless of location of emission. Please be more precise.

  Reply: Thank you very much. We rewrote the sentence more precisely: on page 2 line 21, “… Frömming et al. (2013) and Grewe et al. (2014b) developed Climate Cost Functions (CCFs) for the climate-optimized routing. ~~The CCFs can identify climate sensitive regions with respect to aviation’s CO2 and non-CO2 effects (H2O, ozone, methane, primary mode ozone, and contrails) and estimate corresponding climate impacts. Here, ozone changes arizen from changes of methane are called primary mode ozone (Dahlmann et al., 2016).~~ **They calculated global-average RFs resulting from local unit emissions (CO_2, NO_x, H_2O and contrails) over the north-Atlantic for typical weather patterns by using the ECHAM5/MESSy Atmospheric Chemistry model EMAC (Jöckel et al 2010, 2016). Those RFs were used to calculate the global and temporal average near-surface temperature response over 20 years, which describe the climate impacts (i.e. future temperature changes) caused by those emissions on a per unit basis. The resulting data set is called the Climate Cost Functions (CCFs). The CCFs describe the climate impact which is induced by aviation’s CO_2 and non-CO_2 effects (H_2O, ozone, methane, ozone originating from methane changes, and contrails including the spread into contrail-cirrus); and the CCFs of those effects except CO_2 are a function of geographic location, altitude and time. Because of the long residence time of CO_2, its impact is the same regardless of location, altitude and time of emission. The obtained CCFs can be used as a measure of the climate impact of aviation and form the basis for the climate-optimized routing.**”

  Related to this, we rewrote the following text, because the modified sentences described above refer to the word “EMAC” for the first time in the revised manuscript: on page 3 line 22, “… developed as one of the submodels of ~~the ECHAM/MESSy Atmospheric Chemistry (EMAC) model~~ **EMAC**.…”

- (14) Pg2: Line 22: Please add a more detailed definition of CCS as the reader needs this later on.

  Reply: Thank you very much. We added the details of the Climate Cost Functions (CCFs) to the revised manuscript. Please see the reply to the comment (13).

- (15) Pg2: Line 24: Another strange sentence to suddenly introduce here instead of adding above when listing aviation non-CO_2 effects.

  Reply: We deleted this sentence: on page 2 line 24, “~~Here, ozone changes arizen from changes of methane are called primary mode ozone (Dahlmann et al., 2016)~~”. In addition, we added this description to the list of non-CO_2 effects: on page 2 line 23, “… and non-CO_2 effects (H_2O, ozone, methane, **ozone originating from methane changes**, and contrails.…” Please see the reply to the comment (13).

- (16) Pg2: Line 29: what about trade-offs between e.g., contrail avoidance and increased fuel use?

  Reply: As the referee pointed out, the trade-off between contrail avoidance and increased fuel use is also an important subject. Actually, this is the reason why we develop many routing options in AirTraf 2.0; one can analyze the trade-off by using AirTraf 2.0. This point is described in the paragraph (on page 4 lines 3-13). On the other hand, the paragraph (on page 2 lines 20-33) focuses on the “climate-optimized routing,” and thus we did not mention trade-offs between other routing strategies there.

  To emphasize the importance of analyzing other trade-offs, we rewrote the text: on page 4 line 9, “Moreover, conflicting scenarios (trade-offs) between different routing strategies have been studied; for example, **avoiding contrail formation generally increases fuel use and CO_2 emissions.** Irvine et al. (2014) assessed ~~a~~ **the** trade-off between ~~climate impact of contrails~~ **contrail avoidance** and ~~extra~~ **increased** CO_2 emission (∼ ~~extra~~ **increased** fuel use) for a single flight.”

- (17) Pg3: Line 2: Presumably this is global-mean temperature response? Please specify.

  Reply: The referee is right. This represents the global-mean temperature response. Unfortunately, this part is deleted by following the referee comment (18). Please see the reply to the comment (18) below.

- (18) Pg3: Line 5: what about the other way around, does a cost-optimized route increase climate impact?

  Reply: In this paragraph (on page 2 line 34 - on page 3 line 5), Lührs et al. (2016) clearly show a trade-off between climate impact and economic cost. Thus, as the referee pointed out, one can say that the cost-optimized route increases climate impact with a decrease in cost, compared to the climate-optimized route.

  On the other hand, we deleted this paragraph to shorten the introduction by following the referee's general comment. This paragraph introduces the study of Lührs et al. (2016) which clearly shows the trade-off between climate impact and economic costs; however, the previous paragraph (on page 2 lines 20-33) has already introduced two studies to show the same trade-off on the basis of the same climate metrics CCFs. Thus, this paragraph would be redundant. On page 2 line 34, "~~Lührs et al. (2016) performed a flight trajectory optimization for nine sample trans-Atlantic routes for a specific weather pattern in winter by the Trajectory Optimization Module (TOM). The trajectories were optimized for economic cost (expressed by the cash operating cost (COC; Liebeck et al., 1995; see Sect. 2.5.6), which is commonly used as a criterion for airline economics) and for climate impact (measured as average temperature response estimated by integrating the CCFs). The results showed that the climate-optimal route differed from the cost-optimal route. The climate-optimum trajectory (3D-optimized trajectory in lateral and vertical) decreased the climate impact by about 45 % over that of the economical route, whereas it increased COC by 2 %. Thus, the climate impact drastically decreased with a small increase of economic cost.~~"

  Related to this, we moved the reference "Lührs et al. (2016)" from the current position (on page 2 line 34) to another position: on page 2 line 21, "… 2013; Søvde et al., 2014**; Lührs et al., 2016**)…." In addition, we rewrote the text, because the deleted paragraph refers to the word "COC" for the first time in the present manuscript: on page 3 line 29, "… simple operating cost (SOC), **cash operating cost** (COC), and climate impact.…"

- (19) Pg3: Line 6: do you mean using different emission metrics, of which AGTP is one? And which other metrics do you find in the literature? Here you only describe one approach. (from here on I do not list language issues, but note that there are a number of them also in the next pages...)

  Reply: Yes. We believe that it is important to show that the benefit of the climate-optimized routing is confirmed on the basis of different climate assessment metrics (AGTP is one of them). On page 3 line 6, Ng et al. (2014) clarified the benefit by using the three AGTP values for the short (25 years), medium (50 years) and long-term (100 years) climate goals. As we only described the results for the medium-term climate goal in the present manuscript, we added the text below to the revised manuscript.

  As the referee pointed out, there are other climate metrics. For example, Grewe et al. (2014a) compared the trade-off between economic costs and climate impact from one-day trans-Atlantic air traffic simulations with respect to three climate metrics. The results indicated that all metrics show a similar trade-off between economic costs and climate impact. We believe that this information would be useful for readers, and thus we added this information to the revised manuscript.

  Finally, we rewrote the text: on page 3 line 14, "… between climate impact and economic cost~~.~~**; this trade-off was also found for the short-term (25 years) and long-term (100 years) climate goals. Grewe et al. (2014a) compared the trade-off between economic costs and climate impact from the one-day trans-Atlantic air traffic simulations described above with respect to three climate metrics: the average temperature response with future increasing emissions (F-ATR20) and the absolute global warming**

potential with pulse emissions at a 20 year time horizon (P-AGWP20) for short-term climate impacts, and P-AGWP100 (time horizon of 100 years) for long-term climate impacts. The trade-offs obtained with the three metrics were very similar.”

Concerning language issues, we rechecked the manuscript and added some modifications to the revised manuscript. We list them in the reply to the referee’s general comment.

- (20) Pg8: Section 2.5.4: The treatment of contrail-cirrus is quite essential for routing strategies and I would like to see some more details of how this is done and what the limitations are (e.g., natural cloud suppression, life cycle etc.) here, not just a reference to earlier work.

  Reply: Thank you very much. We rewrote the paragraph to describe more details of how this routing option is made and its limitations: on page 8 line 9, “Yin et al. (2018a) ~~and Yin et al. (manuscript in preparation, 2019)~~ developed the routing option ~~for contrail avoidance~~ **to avoid contrail formations by using the submodel CONTRAIL (version 1.0; Frömming et al., 2014), which calculates the potential persistent contrail cirrus coverage Potcov (Ponater et al., 2002; Burkhardt et al., 2008; Burkhardt and Kärcher, 2009; Grewe et al. 2014b) within an EMAC grid box.** ~~This option avoids regions where persistent contrail formation is expected.~~ **The Potcov represents the fraction of the grid box, which can be maximally covered by contrails under the simulated atmospheric condition. The threshold for contrail formation is determined from a parameterization scheme based on the thermodynamic theory of contrails, i.e., the Schmidt-Appleman theory (Schmidt, 1941; Appleman, 1953; Schumann, 1996). In the CONTRAIL submodel, Potcov indicates the difference between the maximum possible coverage of both, contrails and cirrus, and the coverage of natural cirrus alone; values of Potcov along the waypoints are taken from the nearest grid box (Table 2). With that, we define a contrail distance (**$\mathbf{PCC_{dist}}$**) in km(contrail) as Potcov multiplied by the flight distance in km. The corresponding routing option minimizes the total contrail distance of a flight and thus** ~~T~~**t**he objective function ~~represents a total contrail distance km(contrail) of a flight~~ **is formulated as**:.…”

  In addition, we rewrote the text: on page 8 lines 14-19 in the same paragraph, “~~$PCC_{dist,i}$ is calculated by using the potential contrail coverage Potcov (Ponater et al., 2002; Burkhardt et al., 2008; Burkhardt and Kärcher, 2009; details of Potcov have been reported by Frömming et al., 2014). The Potcov represents fractional areas in which contrails can maximally occur under a given atmospheric condition. The Potcov is calculated by the submodel CONTRAIL (version 1.0; Frömming et al., 2014), using a parameterization scheme based on the thermodynamic theory of contrails, i.e., the Schmidt-Appleman theory (Schmidt, 1941; Appleman, 1953; Schumann, 1996)~~ **Note that the objective function is formulated in the simple form to consider only the contrail distance. Thus, further physical processes such as contrail spreading, changes in contrail coverage area, contrail lifetime, and the contrail radiative forcing are not included**.”

- (21) Pg9: Line 20: ATR20 needs a definition. Is it calculated based on input of RF? What is assumed for contrail-cirrus properties?

  Reply: Thank you very much. We replied the three referee comments, respectively.

  [“ATR20 needs a definition.”]
  Table 2 (on page 26) included the definitions (equations) of the five ATR20s; however, as the referee noted, those definitions are important information for readers to understand the climate impact routing option. Thus, we moved those equations from Table 2 to Sect. 2.5.7 and rewrote the text as follows:

  − On page 26 in Table 2 (the second group divided by rows), “~~$ATR20_{O3,i} = aCCF_{O3,i} \times NO_{x,i} \times 10^{-3}$~~ **See Eq. (8)**; ~~$ATR20_{CH4,i} = aCCF_{CH4,i} \times NO_{x,i} \times 10^{-3}$~~ **See Eq. (9)**; ~~$ATR20_{H2O,i} = aCCF_{H2O,i} \times FUEL_i$~~ **See Eq. (10)**; ~~$ATR20_{CO2,i} = aCCF_{CO2} \times FUEL_i$~~ **See Eq. (11)**; ~~$ATR20_{contrail,i} = aCCF_{contrail,i} \times PCC_{dist,i}$~~ **See Eq. (12)**; ~~See Eq. (8)~~ **See Eq. (13)**.”

  − On page 9 line 20, “… ATR20s of ozone, methane, water vapour, CO_2, and contrails are estimated on a per unit basis **by** ~~(the definition of the aCCFs are given in the Appendix and examples are shown in Fig. S1 in the Supplementary material).~~

$$\mathbf{ATR20_{O3,\mathit{i}} = aCCF_{O3,\mathit{i}}\ NO_{\mathit{x,i}} \times 10^{-3}\ (8)}$$
$$\mathbf{ATR20_{CH4,\mathit{i}} = aCCF_{CH4,\mathit{i}}\ NO_{\mathit{x,i}} \times 10^{-3}\ (9)}$$
$$\mathbf{ATR20_{H2O,\mathit{i}} = aCCF_{H2O,\mathit{i}}\ FUEL_{\mathit{i}}\ (10)}$$
$$\mathbf{ATR20_{CO2,\mathit{i}} = aCCF_{CO2}\ FUEL_{\mathit{i}}\ (11)}$$
$$\mathbf{ATR20_{contrail,\mathit{i}} = aCCF_{contrail,\mathit{i}}\ PCC_{dist,\mathit{i}}\ (12)}$$

where the respective aCCF values of ozone, methane, water vapour, CO_2, and contrails are given as flight properties at the i^{th} waypoint. These five ATR20s are.…"

− On page 9 line 24, "$ATR20_{total,i}$ = …, ~~(8)~~**(13)**."
− On page 9 line 25, "f = …, ~~(9)~~**(14)**."

["Is it calculated based on input of RF?"]
In AirTraf 2.0, ATR20s are calculated for the climate-optimized routing by using the algorithmic Climate Change Functions (aCCFs) of ozone, methane, water vapour, CO_2, and contrails (shown in the Appendix), for which RF is not used as an input parameter. However, the aCCFs are approximation functions based on regression analyses for the CCFs data set (this point is described on page 9 line 18). As we reply to the referee comment (13), the CCFs data set was obtained from detailed EMAC model simulations including RF calculations (for contrails, the calculated RF data set was obtained in a different way; details are described in the "What is assumed for contrail-cirrus properties?" below); the CCFs data set describes the climate impact which is induced by ozone (plus ozone originating from methane changes), methane, H_2O, CO_2, and contrails. Thus, the aCCFs approximately express the climate impact (ATR20) by taking radiative impacts into account.

["What is assumed for contrail-cirrus properties?"]
The ATR20 of contrails is calculated by using the approximation function of $aCCF_{contrail}$ in AirTraf 2.0; the $aCCF_{contrail}$ was created from contrail RF calculations based on the ERA-Interim reanalysis data and contrail trajectory data. To reply to this referee comment, let us explain the derivation of $aCCF_{contrail}$ briefly. First, the contrail RF data set was calculated following these steps:

(a) Lagrangian trajectories (air parcels) were computed by using the ERA-Interim reanalysis data (the methodology is described by Irvine et al., 2014); the trajectories were initialized over the north Atlantic (1 degree horizontal spacing) at three vertical levels (300, 250 and 200 hPa) in winters of 1994, 1995 and 2003. The contrail lifetime was calculated by analyzing each of the trajectories to see how long the conditions persisted for: relative humidity with respect to ice above 98 % and a temperature below 235 K.

(b) Contrail properties were calculated along the trajectories by following Schumann et al. (2017), where an effective radius for contrail cirrus ice particle was set to 23 microns described by Schumann et al. (2011). The contrail optical depth was calculated by a simple formula for the extinction coefficient (Unterstrasser and Gierens, 2010), where the initial contrail depth was set to 200 m (Grewe et al., 2014).

(c) The long-wave and short-wave RFs were calculated from the trajectory data by using the parametric equations described by Schumann et al. (2012). The area covered by each contrail was assumed constant along the trajectory. By taking values from Grewe et al. (2014), we used a contrail width of 200 m, and a contrail length of the square root of the grid box area (1 degree by 1 degree grid). The net RF was calculated for each contrail and was converted to a global-mean value by following Grewe et al. (2014). The contrail RF data set was obtained, in which the lifetime of contrails ranges from 3 to 48 hours.

The $aCCF_{contrail}$ was derived based on regression analyses for the RF data set. The methodology was based on that used by van Manen and Grewe (2019) to derive the other aCCFs for ozone, methane and water vapour. For the regression analyses, a constraint on deriving $aCCF_{contrail}$ was that only meteorological information available at the time of flight can be used. In addition, we restricted the calculation to conventional meteorological data, so that $aCCF_{contrail}$ was simple to implement. This means, for example, no information on the contrail lifetime could be used, because this is not something which can be estimated a priori from meteorological data. Since a lifetime was required to be input to the net RF calculations, we chose a contrail lifetime of six hours for all contrails, because 92 % of contrails have a lifetime up to six hours in the data set. Night-time and day-time contrails were analyzed separately. The night-time contrails referred to contrails with their entire (six hours) lifetime occurring at night; the day-time contrails referred to contrails which existed only during daylight hours and those which had part of their lifetime during the day. The obtained aCCF$_{\text{contrail}}$ (Eq. (A5) on page 15 in the Appendix) was converted from RF to ATR20 by multiplying a factor of 0.114 (provided by Katrin Dahlmann, DLR).

The derived aCCF$_{\text{contrail}}$ has been assessed by plotting the original net RF with the RF calculated by using aCCF$_{\text{contrail}}$. In addition, the performance of aCCF$_{\text{contrail}}$ has been assessed against the rest of the contrails with lifetimes of 3 to 48 hours in the data set. The Spearman's rank correlation coefficient and the ability to correctly predict the sign of the forcing were examined. For day-time contrails with lifetimes of 6 hours, for example, the coefficient was R = 0.86, and the ability (in percentage) was 88 %; for those with lifetimes of 12 hours, R = 0.83 and 78 % were obtained. These results provide the confidence in the use of aCCF$_{\text{contrail}}$ in the aircraft routing decision.

Here, we would like to make clear that the literature, which is given on page 9 lines 17-18, describes how to develop aCCFs from the CCFs data set, and their limitations in detail. The aCCFs are calculated online in EMAC by another submodel named ACCF in MESSy (version 2.54), and thus the AirTraf submodel uses the ACCF submodel for the climate routing option. In addition, the detailed description of the CCFs data set was added to the revised manuscript by following the referee comment (13).

Finally, we rewrote the text to show the relation between the CCFs data and the aCCFs more clearly: on page 9 line 18, "The aCCFs are approximation functions based on regression analyses for the ~~simulated~~ CCFs data **set, which was obtained from detailed EMAC model simulations including radiative impacts** (see Sect. 1); **the CCFs data set for contrails was exceptionally obtained from contrail RF calculations based on the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim) data (Dee et al. 2011) and contrail trajectory data (Yin et al. (manuscript in preparation, 2019); the definition of the aCCFs ~~are~~ is provided in the Appendix and examples are shown in Fig. S1 in the Supplementary material**). ~~t~~**T**he aCCFs represent…."

Related to this, we added this paper to the References:
− On page 17 line 32, "**Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J-J., Park, B-K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J-N., Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system., Q. J. R. Meteorol. Soc., 137, 553–597, https://doi.org/10.1002/qj.828, 2011.**"

References:

Grewe, V., Frömming, C., Matthes, S., Brinkop, S., Ponater, M., Dietmüller, S., Jöckel, P., Garny, H., Tsati, E., Dahlmann, K., et al.: Aircraft routing with minimal climate impact: the REACT4C climate cost function modelling approach (V1.0), Geoscientific Model Development, 7, 175–201, https://doi.org/10.5194/gmd-7-175-2014, 2014.

Irvine, E. A., Hoskins, B. J., Shine, K. P.: A Lagrangian analysis of ice-supersaturated air over the North Atlantic, J. Geophys. Res., 119, 1, 90–100, https://doi.org/10.1002/2013JD020251, 2014.

Schumann, U., Baumann, R., Baumgardner, D., Bedka, S. T., Duda, D. P., Freudenthaler, V., Gayet, J.-F., Heymsfield, A. J., Minnis, P., Quante, M., Raschke, E., Schlager, H., Vázquez-Navarro, M., Voigt, C., and Wang, Z.: Properties of individual contrails: a compilation of observations and some comparisons, Atmos.

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Schumann, U., Mayer, B., Graf, K., and Mannstein, H.: A Parametric Radiative Forcing Model for Contrail Cirrus, Journal of Applied Meteorology and Climatology, 51, 6, https://doi.org/10.1175/JAMC-D-11-0242.1, 1391–1406, 2012.

Schumann, U., Mayer, B., Gierens, K., Unterstrasser, S., Jessberger, P., Petzold, A., Voigt, C., and Gayet, J-F.: Effective Radius of Ice Particles in Cirrus and Contrails, Journal of the Atmospheric Sciences, 68, 2, 300–321, https://doi.org/10.1175/2010JAS3562.1, 2011.

Unterstrasser, S. and Gierens, K.: Numerical simulations of contrail-to-cirrus transition – Part 1: An extensive parametric study, Atmos. Chem. Phys., 10, 2017–2036, https://doi.org/10.5194/acp-10-2017-2010, 2010.

Van Manen, J. and Grewe, V.: Algorithmic climate change functions for the use in eco-efficient flight planning, Transportation Research Part D: Transport and Environment, 67, 388–405, https://doi.org/10.1016/j.trd.2018.12.016, 2019.

- (22) Pg9: Line 26: But ATR20 is an average over 20 years? How can values be negative when the overall contrail-cirrus effect is a warming? Perhaps related to the above comment…

Reply: Yes. ATR20 represents an average over 20 years. In AirTraf 2.0, the ATR20 of contrails is calculated by using the approximation function of aCCF$_{\text{contrail}}$. The aCCF$_{\text{contrail}}$ consists of two formulas for the day-time and night-time contrails, as shown in Eq. (A5) on page 15 in the Appendix. The aCCF$_{\text{contrail}}$ for the day-time contrails can take positive and negative values, depending on the outgoing long-wave radiation (OLR) (the threshold is –193.18 Wm^{-2}), whereas the aCCF$_{\text{contrail}}$ for the night-time contrails takes positive values.

In the revised manuscript, we rewrote the text to make clear the points described above:
− On page 9 line 26, "… ATR20$_{\text{contrail},i}$ can take positive and negative values, because ~~of~~ **the aCCF$_{\mathbf{contrail}}$ consists of two formulas for** the day-time and night-time contrail effects **(see Eqs. (12) and (A5) in the Appendix).**"
− On page 16 line 6 in the Appendix, "… calculated by AirClim. **The aCCF$_{\mathbf{contrail}}$ for the night-time contrails takes positive values; if the temperature is less than 201 K, aCCF$_{\mathbf{contrail}}$ for the night-time contrails is set to zero. The aCCF$_{\mathbf{contrail}}$ for the day-time contrails can take positive and negative values, depending on the OLR (the threshold is –193.18 Wm^{-2}).**" The rewriting highlighted by blue texts comes from our reply to the major comment (2) (starting with "Firstly, Eq. (A5) assumes") of the referee #2.

This referee comment is related to the referee comment (21). We describe how ATR20$_{\text{contrail}}$ is calculated in the AirTraf submodel, and how aCCF$_{\text{contrail}}$ was created in the reply to the referee comment (21).

- (23) Pg10: Line 3: how sensitive are results and conclusions to the running of only one day? E.g., dependence on meteorological conditions that day?

Reply: We acknowledge that the simulation results depend on the atmospheric conditions of the target day. If we perform an AirTraf simulation with the same flight plan for another day, we obtain different optimized trajectories and performance measures. Thus, we clarified this point: on page 11 line 22, "Note that this performance is a narrow result obtained using AirTraf 2.0 under the specific conditions (e.g., the simulations were carried out with the 103 north-Atlantic flights on December 1, 2015…"; and on page 11 line 29, "The quantitative values of the changes in performance measures vary, depending on different methodologies, atmospheric conditions.…"

We believe that it is an important point to examine whether the findings described in the Conclusions (e.g. the trade-off between the cost and the climate impact) are common under any atmospheric conditions. Actually, this is our next study. Recently, Yamashita et al. (2020) examined this for representative weather types over the North Atlantic by using EMAC with AirTraf 2.0.

To emphasize the importance of the point, we added the text: on page 15 line 5, "The integration of AirTraf into EMAC allows one to optimize **flight trajectories** and to study ~~flight trajectories~~ **aircraft routings** under historical, present-day and future conditions of the climate system. **We acknowledge that the simulation results depend on the atmospheric conditions of the target day. Thus, it is important to examine whether the findings, e.g., the trade-off between the cost and the climate impact, are common under any atmospheric conditions. Recently, Yamashita et al. (2020) examined this for representative weather types over the North Atlantic by using EMAC with AirTraf 2.0.** Furthermore, the integrated aircraft routing options could be extended to conflicting scenarios. ~~Recently,~~ Yin et al. (2018a)…."

Related to this, we added the literature "Yamashita et al. (2020)" to the References: on page 21 line 25, "**Yamashita, H., Yin, F., Grewe, V., Jöckel, P., Matthes, S., Kern, B., Dahlmann, K., and Frömming, C.: Comparison of various aircraft routing strategies using the air traffic simulation model AirTraf 2.0, 3rd ECATS Conference, Gothenburg, Sweden, 1–4, 2020.**"

- (24) Pg10: Line 11: showing direct results is not a verification of simulations output.

  Reply: Thank you very much. As the referee pointed out, the sentence starting with "To verify" is inappropriate. Section 3 focuses on a demonstration of AirTraf 2.0, and we intend to show the simulation output as an example in Sect. 3.2. On the other hand, Sect. 4 verifies the consistency of the simulation results with literature data. For the appropriate wording, we changed the word "verify" into the "demonstrate": on page 10 line 11, "To ~~verify~~ **demonstrate** the simulation output…"; on page 14 line 24, "To ~~verify~~ **demonstrate** the submodel AirTraf 2.0, example simulations were carried out.…"

  This referee comment is related to the referee's general comment: "While the discussion section is quite good, the result is only one page out of a 14-page paper, which is not quite convincing." To provide convincing explanations for the simulation output, we analyzed the simulation results in more detail, added the two new figures "**Figure 3**" and "**Figure 5**", and additionally wrote the text as follows:

  [Section 3.2]
  − On page 10 line 18, "… flight altitudes (∼FL410, 12.5 km)~~,~~**. Figure 3 shows the mean fuel consumption (in kg(fuel)/min^{-1}) vs. mean flight altitude (in km) for individual flights for the three routing options.** Because fuel consumption decreases ~~due to~~ **as a result of** aerodynamic drag reduction **at high altitudes** (Fichter et al., 2005; Schumann et al., 2011; Yamashita et al., 2016)**, the COC optimum trajectories select the high flight altitudes, as shown in Fig. 3. We acknowledge that limitations of BADA 3 affect the selection of the flight altitudes (the same applies to the fuel, the NO_x, the H_2O and the SOC options; see Fig. S3 in the Supplementary material). According to Nuic et al. (2010), BADA 3 has a tendency to underestimate aircraft fuel consumption at high altitudes and Mach numbers, as the compressibility effect and wave drag are not modeled. These effects will cause differences in the selection of the flight altitudes.**" This rewriting comes from our reply to the major comment (3) of the referee #2.

  As we add the new figure, we changed the original figure number: on page 10 line 21, "Figure ~~3~~**4** shows …"; on page 10 line 25, "… it is apparent from Fig. ~~3~~**4** …"; and on page 24 in the caption, "Figure ~~3~~**4**."

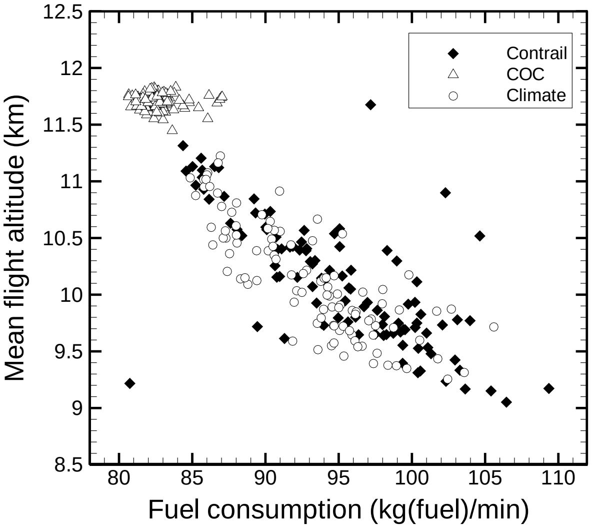

Figure 3. Mean fuel consumption vs. mean flight altitude for 103 individual flights obtained by the contrail formation, the COC and the climate impact routing options.

− On page 10 line 22, "We see **from Figs. 4b, 4e and 4h** that the contrail option certainly decreases the contrail ~~distance~~ **formation, which is mostly located over northwest Europe and over the east coast of the U.S.**~~;~~ **Comparison of Figs. 4a, 4d and 4g shows that** the COC option ~~shows~~ **produces** a narrower fuel distribution than that of the contrail and climate options~~;~~**.** ~~and~~ **In addition, Figs. 4c, 4f and 4i show that** the climate option ~~shows~~ **decreases the positive values of ATR20$_{\text{total}}$ (warming effects) over northwest Europe and over the east coast of the U.S., and produces regionally negative values (cooling effects) near Iceland and over eastern Canada, which result in** the net climate impact reduction ~~(the local negative values, i.e. cooling effects, are mainly caused by contrails)~~."

[Section 3.3]
− On page 11 line 4, "**The individual routing options are now discussed in turn.** We see from Table 4 that the great circle option has the minimum flight distance **of 660.3 × 10^3 km**, whereas this option increases **the** other measures. The time option shows the minimum flight time **of 739.4 h** with a **large** penalty on fuel use, NO$_x$ emission.…"

− On page 11 line 6, "… (further discussion in Sect. 4). **The fuel option shows the minimum fuel use of 3758.5 ton. Of the nine routing options,** ~~T~~**t**he fuel (and also the H$_2$O), the NO$_x$, the SOC, and the COC options obtain similar values on all the measures (see also Supplement Fig. S4)~~.~~**:** ~~Of the nine routing options,~~ these options show decreased fuel use, NO$_x$ and H$_2$O emissions.…"

− On page 11 line 9, "… is considered significant for airline operations and thus is discussed **in more detail** in Sect. 4. The contrail option shows the minimum contrail distance **of 26.3 × 10^3 km** and ~~decreases~~ **the second-lowest** ATR20$_{\text{total}}$ **of 3.45 × 10^{-7} K**, whereas the other measures ~~considerably~~ increase **considerably**. This option allows aircraft to widely detour the potential contrail regions (because no constraint function is used in Eqs. (1) and (5)**; see below for more discussion**). Thus, **the flight distance,** the flight time and the fuel use ~~drastically~~ increase **drastically**, which results in the increase of NO$_x$ and H$_2$O emissions, SOC, and COC. **In particular,** ~~T~~**t**he contrail option shows the highest ~~SOC and~~ COC **of 5.99 Mil.USD** of the nine routing options."

− On page 11 line 15, "The two options show similar values for all the measures and have the same minimum SOC **of 3.96 Mil.USD** and COC **of 5.35 Mil.USD**. ~~This is because the objective function of the two options is a function of flight time and fuel.~~ In fact, the obtained optimum trajectories for ~~the SOC and the COC~~ **those** options are approximately the same (see Figs. 2c, 2d and Supplement Figs. S3k and S3l). **This is because the objective function of the two options is a function of flight time and fuel, as defined in Eqs. (6) and (7). An interesting aspect of their performance measures is that both options do not correspond to the minimum flight time and fuel use (see further discussion in Sect. 4).**"

− On page 11 line 18, "The climate option achieves the minimum $\text{ATR20}_{\text{total}}$ **of 1.96×10^{-7} K** and ~~decreases~~ **shows** the **second-shortest** contrail distance **of 92.6×10^{3} km**, whereas ~~this option increases all~~ **the** other measures **increase**, particularly ~~SOC and COC increase sharply~~ **this option shows the second-highest COC of 5.87 Mil.USD**. The present results indicate that the contrail and the climate options considerably reduce the climate impact indicated by $\text{ATR20}_{\text{total}}$~~.~~**; however, these options increase COC.**"

− On page 11 line 24, "**Figure 5 shows the contrail distance (in $\times 10^{3}$ km) vs. $\text{ATR20}_{\text{contrail}}$ (in $\times 10^{-7}$ K) for individual flights for the contrail, the COC, and the climate options. We see that the contrail option decreases the contrail distance drastically and shows the positive values of $\text{ATR20}_{\text{contrail}}$ for almost all the flights. On the other hand, the climate option has the longer contrail distances than those of the contrail option (although the climate option achieves the second-shortest total contrail distance, as shown in Table 4) and shows the negative values of $\text{ATR20}_{\text{contrail}}$ for many flights. These results imply that the contrail option minimizes the overall contrail distance at all times, whereas the climate option actively forms cooling contrails during the day and avoids the formation of warming contrails during the day and night.**" <u>This rewriting comes from our reply to the major comment (4) of the referee #2.</u>

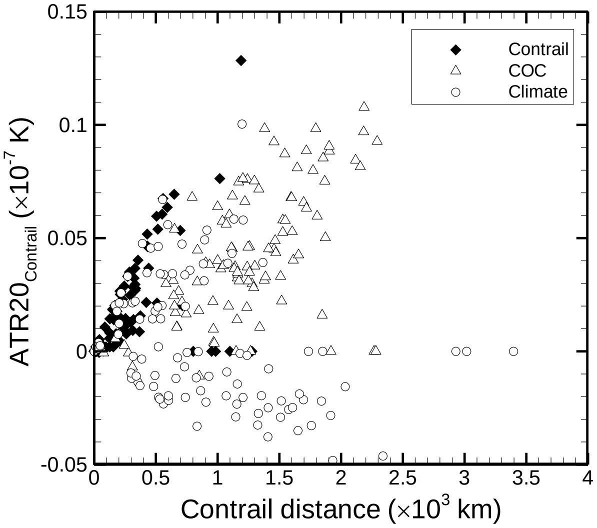

Figure 5. Contrail distance vs. $\text{ATR20}_{\text{contrail}}$ for 103 individual flights obtained by the contrail formation, the COC and the climate impact routing options.

- (25) Pg10: Line 21: over what time frame is the km coverage estimated? Integrated over the 1-day simulations?

  Reply: Yes. We integrated the contrail distance [km] of the total 103 flights over the target day. To clarify this point, we rewrote the text: on page 10 line 21, "~~Figure 3 shows t~~The global fields of fuel use, contrail distance, and climate impact indicated by $\text{ATR20}_{\text{total}}$ for the three options **are shown in Fig. 3, where distributions represent sum of all the flights during the day.**"

- (26) Pg11: Line 2-3: this is a very strange argument for correctness.

  Reply: We rewrote the text: on page 11 line 2, "These results confirm ~~the correctness of the new routing options~~ **that the new routing options work correctly in AirTraf 2.0**, since we solve a single-objective minimization problem defined by Eq. (1).…"

- (27) Pg14: Line 10-11: how well does the treatment of contrails work for longer time integrations (in particular decades as mentioned earlier)? Is the potcov based on present day conditions?

  Reply: This is an important point, and this referee comment is related to the referee comments (20), (21) and (22). The climate routing option uses $\mathrm{aCCF}_{\mathrm{contrail}}$. The $\mathrm{aCCF}_{\mathrm{contrail}}$ estimates the anticipated climate impact of contrails $\mathrm{ATR20}_{\mathrm{contrail}}$, which is caused by local contrail formation during the present day, on the basis of the present day conditions including potcov; the calculated impact of contrails is integrated over time. As we reply to the referee comments (20), (21) and (22), $\mathrm{aCCF}_{\mathrm{contail}}$ (as shown in Eq. (A5) on page 15 in the Appendix) represents the climate impact of contrails, taking into account physical processes of contrails over a longer time period (e.g. contrail lifetime, contrail radiative forcing, etc.). This is because $\mathrm{aCCF}_{\mathrm{contrail}}$ has been developed from the CCFs data sets obtained from contrail RF calculations based on the ERA-Interim reanalysis data and contrail trajectory data over a longer time period, in which such physical processes of contrails were included.

  We believe that the replies to the referee comments (20), (21) and (22) describe this point in detail; those descriptions were added to the revised manuscript (please see the replies to the referee comments (20), (21) and (22)).

- (28) Pg14: Line 5-10: this type of information would be useful in the introduction.

  Reply: Thank you very much. We moved the information from the current position (on page 14 lines 5-10) to the introduction, and then we rewrote the text as follows:

  − On page 14 lines 4-11, "As discussed above, the many previous studies ~~verify~~ **corroborate** the consistency of the AirTraf simulations. ~~Before concluding the discussion, two superior aspects of the AirTraf submodel are emphasized, compared to the simulation models used in the previous studies. First, AirTraf enables an intercomparison for various aircraft routing options all at once, because all the options are integrated. Normally, one or two specific routing options are available for a flight trajectory optimization in other models. Second, AirTraf performs air traffic simulations not under ISA conditions, not under a fixed atmospheric condition for a specific day, but under comprehensive atmospheric conditions which are calculated by the chemistry-climate model EMAC. AirTraf can simulate air traffic for long-term period in EMAC, which enables one to examine effects of aircraft routing strategies on climate impact on a long time scale.~~"

  − On page 4 line 11, "… for a single flight. AirTraf **2.0** enables analyzing those subjects **all at once, because all the options are integrated. Normally, one or two specific routing options are available for a flight trajectory optimization in other models. Another aspect to be emphasized compared to other models is that AirTraf performs air traffic simulations not under International Standard Atmospheric (ISA) conditions, not under a fixed atmospheric condition for a specific day, but under comprehensive atmospheric conditions which are calculated by EMAC; that is, AirTraf can simulate air traffic for long-term periods in EMAC, which enables one to examine effects of aircraft routing strategies on climate impact on a long time scale.** Last but not least, the aCCFs are new proxies.…"

  Related to this, we rewrote the following text, because the modified sentences described above refer to the word "ISA" for the first time in the revised manuscript: on page 12 line 8, "… respectively, under ~~International Standard Atmospheric (~~ISA~~)~~ conditions. A typical single-aisle aircraft.…"