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Effective Radiative Forcing – a New Approach to Assessing the Impact of Aviation on the Atmosphere

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***Abstract*—This article discusses new possibilities of assessing the impact of aviation on the atmosphere. The second part of this text describes a project realized at the Department of Air Transport at the Czech Technical University in Prague. The project is focused on investigating the effect of air transport on contrails.** *(Abstract)*

Keywords-contrails, effective radiative forcing, radiative forcing, IPCC (key words)

I. INTRODUCTION

The impact of commercial air transport on the atmosphere has been researched over a long time. Information on the effects of air transport on the atmosphere and environment can be found for example in (1). This material also provides an explanation of the estimate of radiative forcing (RF), which is used to estimate the impact of air transport on the atmosphere. It also mentions the fact that air transport most probably affects changes in the atmosphere also in other ways. Given the fact that those effects are related, it is necessary to determine their relationship. A new indicator, the effective radiative forcing (ERF), is used for this purpose. Differences between those two indicators are explained in the following chapter.

II. EFFECTIVE RADIATIVE FORCING

A. Definition of ERF

ERF, as used here, is based on the understanding of this indicator as described in (2). ERF indicator is an overall indicator representative of all effects of a particular activity in the atmosphere. The reason why the use of RF has been found partially unsuitable is that the direct effect of a flight can be expressed as a change in CO_2 quantity in the atmosphere. A change in CO_2 theoretically leads to an increase in temperature because an atmosphere abundant in greenhouse gases absorbs more infrared radiation from the Earth. Such potential increase in temperature proportional to the amount of greenhouse gases produced is RF. Previous scientific work has, therefore, usually assessed the overall impact of air transport on the atmosphere as the cumulative effect of individual RF contributors. However, this is not the most suitable method, considering that some factors are of multiplicative character. ERF partially solves this problem. ERF is an absolute measure of radiative effects of all responses triggered by aviation that are independent of surface temperature change. Thus, ERF is in principle the sum of all radiative forcing of cloud, contrails, atmospheric moisture and other possible effects caused by an airplane's flight. Because of that, ERF cannot be determined in real time but its amount can be estimated only once all induced effects have taken place.

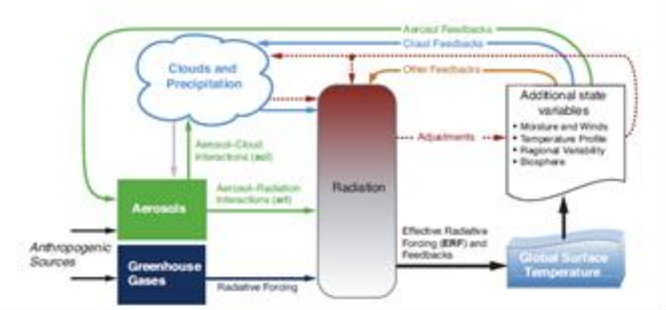

Figure 1 ERF (2)

B. ERF and cloudiness

Unfortunately, it is not possible to determine ERF directly. One possibility is to transform the incremental energy resulting from a particular effect into an increase in temperature. Another option is to simulate atmospheric changes through changes under constant sea temperature conditions. The effect of cloud is instrumental in both approaches. Satellite data allow an estimate of RF values in areas covered with cloud and clear sky areas. Therefore it is possible to estimate that cloud contributes to the changes with approximately -20 W/m^2. This means that cloudiness generally decreases global temperatures. However, the global effect should not be confused with the

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local effect, because cloud properties such as the ability to reflect radiation change with cloud composition, altitude or thickness. The actual effect of a particular cloud can significantly differ from the above mentioned value. This is where we come to the limits of current sensors located on satellites. Satellites first of all do not allow us to determine the composition and thickness of a particular cloud, and, also have limited resolution. Their resolution frequently prevents the detection of smaller cloud clusters, hence causing some bias, because the measured value of RF in the area, seemingly cloudless, is in fact the effect of a sky covered with smaller clouds of a size below the satellite's resolution. More details about this problem are discussed in (3). Generally, it is unfortunately not possible to determine specific properties of current clouds. Modelling of processes in aerosols and the effect of longwave and shortwave radiation is still biased by a large error. The most common and technically best achievable resolution of satellite data is 3.5km. Therefore the basic grid has an area of 12.25km^2, which makes it practically impossible to model contrails and induced clouds.

Most research in this field suggests that low cloud affects atmospheric cooling to a greater extent. On the other hand, very high cloud in the tropical zone, which commonly reaches up to more than 15km of altitude, may have an opposite effect and may lead to atmospheric warming. However, it is not clear if this effect is due to the lower pressure, temperature or cloud composition. Our research assumes that higher cloud has a more negative impact on the atmosphere. Nevertheless, this field is judged as yet poorly researched by IPCC.

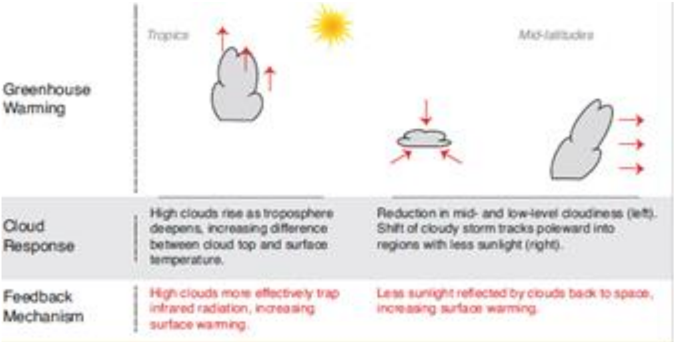

Figure 2 Cloud ERF impact based on altitude (2)

III. CONTRAILS AND INDUCED CLOUD

Contrails and the induced cloud resulting from those is most probably the greatest anthropogenic effect in the area of cloud formation. Considering the value published by IPCC, RF = 0.01W/m^2, it is probably lower than that previously claimed. The ERF of air transport will probably be higher. The impact of contrails can be assessed only with difficulties, given the lack of statistical data about the distribution of contrails, caused by the insufficient horizontal coverage of those and induced cloud for satellite observations and measurements. Research focused on global warming usually determines the Earth surface area covered with contrails by estimating annual averages of ice-supersaturated regions in the atmosphere from satellite data. Ice-supersaturated atmosphere is a prerequisite for persistent contrail formation. Subsequently, the annual total of contrail area theoretically formed by all commercial flights is determined. This area is then multiplied by the percentage of supersaturated atmosphere. The disadvantage of this method is not only the lack of local insight but also the fact that it is necessary to determine the mean time to disintegration of a contrail. Results are therefore heavily influenced by the estimate of this parameter. The main goal of our research at the Department of Air Transport is to determine the value of this parameter representative of atmospheric and meteorological conditions in the Czech Republic.

Further uncertainties in estimates of contrail ERF and the effect of air transport in general.

A. *Crystal size*

Contrails are not formed naturally. They are caused by a rapid temperature change, moisture and condensation nuclei added to the atmosphere by an aircraft in flight. As a result, contrails are composed of crystals of a smaller size compared to natural cloud at the same altitude. This results in more uncertainties in contrail ERF estimates because it seems probable that contrails are more sensitive to longwave radiation. Crystal size is discussed in more detail in (4).

B. *The effect of contrails on cloud*

Unfortunately, research based on satellite observations is restricted to surveying the top cloud layer or the overall character of cloud. Currently there is no satisfactory knowledge of the relationship between high altitude contrails and lower altitude cloud. There are some hypotheses about the formation of certain greenhouse layers caused by air transport, which further affect the formation and composition of cloud in lower levels.

C. *Induced cloud*

Contrail induced cloud is probably another contributive factor to the total ERF caused by air transport. Estimates of this effect differ to a great extent. The estimate based on the global view of the atmosphere without considering local particularities differs between 0.005-0.03W/m^2. However, this is related to the whole, global atmosphere. Differences in the height of troposphere are not included. Considering that the Czech Republic is located in such latitudes where flights are performed both above and below the tropopause throughout the year, it is probable that the local ERF differs from the global one. This issue constitutes another important part of our research.

D. *Aerosols in the atmosphere*

Another unknown factor is the effects of interaction of aerosols in aircraft exhaust and high tropospheric cloud. This impact is currently extremely difficult to estimate and it thus does not appear in any study related to aviation.

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	Evidence	Agreement	Confidence Level	Basis for Uncertainty Estimates (more certain / less certain)	Change in Understanding Since AR4
Contrails	Robust	Low	Medium	Contrails observations , large number of model estimates/Spread in model estimates of RF and uncertainties in contrail optical properties	Elevated owing to more studies
Contrail- induced cirrus	Medium	Low	Low	Observations of a few events of contrail induced cirrus/Extent of events uncertain and large spread in estimates of ERF	Elevated owing to additional studies increasing the evidence

Figure 3 Confidence level (2)

IV. Research at the Department of Air Transport

The Department of Air Transport launched research of the impact of aviation on the atmosphere in this year as part of the Student Grant Competition (SGS). The goal for the initial two years of the research is to acquire a more precise understanding of the differences in ERF indicators in aviation. Global values given as reference values in the IPCC report will be compared to values representative of the latitude of the Czech Republic. The aim is to research the probability of contrail formation, their mean time to disintegration and the probability of their transformation into induced cirrus cloud.

A camera station is used for this research, which continuously records cloud formation and above all contrails. In the next stage, a particular contrail will be identified and correlated with a particular flight using ADS-B receivers in order to determine the altitude of aircraft in the moment of contrail formation. Another part of the research will monitor the transformation of contrails into induced cirrus cloud, the time it takes for the contrail to disintegrate and an approximate estimate of the area covered by each contrail.

The camera system is located on a building of the Czech Technical University in Decin. It has been tested since September and it has been supplying data for statistical analysis since October.

A. *Statistics*

The initial data presented in this text were recorded during the first monitoring period from November to December 2014, which is a season that does not allow enough contrail observation due to the frequent cloud coverage. Despite that the data are valuable because only long term data evaluation can give an indication of how often contrails occur above low cloud layers and how often contrails and induced clouds form at high altitudes only. With respect to the above mentioned impact of situations when specific cloud types are formed and with respect to the probable interdependence of contrails and low altitude cloud, it is of utmost importance not only to record if contrails are formed, but also if they occur above other cloud layers and how they influence each other.

There were only eight days suitable for high altitude flights observation from the ground between November 8 and December 8.

Contrails with a time to disintegration of more than 30 seconds were observed only on three days, i.e. only 10% of the total time, which is 38% of time when observation was possible. This value will gain importance only in long term observation, above all in the context of the whole year. The longest observed life of a contrail during the monitored period was 9 minutes. This represents a length of 120km, considering a speed of 850km/h. Regarding the transformation of contrails into cirrus clouds, we have not determined yet a clear methodology of classifying partially disintegrated contrails and incompletely developed cirrus bands. This statistics is therefore not available yet. An observable transformation of a contrail into a fully developed cirrus cloud was recorded only once (between 12:30 and 13:30 on November 8, 2014).

The first interesting conclusion is that if contrails lasting more than 30 seconds form, the disintegration time is always longer than 5 minutes during the corresponding observation period (which is too short to make final conclusions). There have been no occurrences of contrails lasting between 30 seconds and 5 minutes recorded. If this interesting development is confirmed, it will be a significant scientific contribution of our research. Given the impossibility to compare this with other observations, it may either be due to certain correlation between weather enabling observation and ice-saturation of the atmosphere, or it could be a threshold function of contrail formation which has not been described yet.

Another interesting fact that has been observed is a phenomenon recorded during the test period on October 18, 2014, when contrail formation was observed only after several tens of seconds after the aircraft had flown through the area. The contrail started forming as cloud when the aircraft was already out of the scope of the camera. This phenomenon has not been described yet. However, it is probably related to sharply differentiated layers of atmosphere of different temperature. The contrail is in fact probably formed in a lower layer. The delay is caused by coagulation nuclei descending several seconds from the aircraft's cruising level to a layer of air of different physical properties.

V. Conclusion

The estimate of ERF of aviation on the atmosphere is biased by large uncertainties and unknown factors. The study of the Department of Air Transport is designed to decrease some uncertainties. The first month of observation has already provided some useful data. Among the most important ones are the 10% probability of contrail formation and a very interesting distribution of time to disintegration. We expect that the first conclusions will be ready for presentation after the first year because, as mentioned above, ERF is usually based on annual averages. The scientific contribution of this study will therefore be the definition of the local deviation for Central Europe compared to the global average both in terms of the probability of contrail formation and, owing to ADS-B identification, in terms of a better understanding of the vertical profile of contrails.

A change in the approach to the estimate of air transport impact on the atmosphere is clear not only in the absolute value of estimates but above all in the methodology of use of ERF instead of partial values. A total estimate of the impact of air transport of 0.14-0.04W/m2 is given in (5) and it is composed of eight items of which none is described in terms of the impact of its value on other factors. All those factors are covered by a single indicator, the ERF, which is the sum of all partial effects and their mutual interactions. However, it must be noted that it will probably take a long time before a realistic estimate of the order of ERF value of air transport is agreed upon and generally accepted. We hope that research conducted at the Department of Air Transport and co-funded by SGS SGS14/213/OHK2/3T/16 will provide a significant contribution.

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