

EUROCONTROL
Experimental Centre

**Frank Jelinek
Sandrine Carlier
Ian Crook
Kenneth Martin
James Smith
Minh Ngoc Vo**

**ATM Contrail Mitigation Options
Environmental Study**

EEC/SEE/2005/015



Prepared for EUROCONTROL Experimental Centre
under Contract no.C/1.060/CE/SS/02-TRSB156/03
by ISA Software Ltd – 38, rue des Gravilliers – 75003 PARIS

ISA Software Project team

Contributing Authors Sandrine Carlier
 Ian Crook
 Kenneth Martin
 James Smith
 Minh Ngoc Vo

Quality Review Ian Crook

Project Management Ian Crook

Contract Management Ian Crook

EUROCONTROL Experimental Centre

Project Manager Frank Jelinek – EUROCONTROL Experimental Centre SEE
 frank.jelinek@eurocontrol.int

For further information regarding this project please contact the EEC Project Manager

Document Revisions

<i>Revision 1.0</i>	<i>SC</i>	<i>13/05/2005</i>	<i>Draft Report – Initial (without results)</i>
<i>Revision 2.0</i>	<i>SC</i>	<i>13/10/2005</i>	<i>Draft Report – With results</i>
<i>Revision 2.1</i>	<i>IC</i>	<i>23/10/2005</i>	<i>Draft Report – Details concerning RAMS</i>
<i>Revision 3.0</i>	<i>SC</i>	<i>15/11/2005</i>	<i>Draft Report – EUROCONTROL Review</i>
<i>Revision 3.1</i>	<i>JS</i>	<i>16/11/2005</i>	<i>Draft Report – Output Sensibility Consolidation</i>
<i>Revision 3.2</i>	<i>RD,SC</i>	<i>18/11/2005</i>	<i>Technical Edition</i>

© European Organisation for the Safety of Air Navigation EUROCONTROL 2005

This document is published by EUROCONTROL in the interest of the exchange of information. It may be copied in whole or in part providing that the copyright notice and disclaimer are included.

The information contained in this document may not be modified without prior written permission from EUROCONTROL.

EUROCONTROL makes no warranty, either implied or express, for the information contained in this document, neither does it assume any legal liability or responsibility for the accuracy, completeness or usefulness of this information.

REPORT DOCUMENTATION PAGE

Reference: SEE Note No. EEC/SEE/2005/015		Security Classification: Unclassified				
Originator: Society, Environment, Economy Research Area		Originator (Corporate Author) Name/Location: EUROCONTROL Experimental Centre Centre de Bois des Bordes B.P.15 91222 BRETIGNY SUR ORGE CEDEX France Telephone: +33 1 69 88 75 00				
Sponsor: EUROCONTROL EATM		Sponsor (Contract Authority) Name/Location: EUROCONTROL Agency Rue de la Fusée, 96 B –1130 BRUXELLES Telephone: +32 2 729 90 11				
TITLE: ATM Contrail Mitigation Options - Environmental Study						
Authors : Frank JELINEK, Sandrine CARLIER, Ian CROOK, Kenneth MARTIN, James SMITH, Minh Ngoc VO	Date 10/05	Pages 84	Figures 25	Tables 14	Appendix 4	References 27
EATMP Task Specification -	Project		Task No. Sponsor -		Period 2005	
Distribution Statement: (a) Controlled by: EUROCONTROL Project Manager (b) Special Limitations: None (c) Copy to NTIS: YES / NO						
Descriptors (keywords): Global Emissions – AEM – TEA – Condensation Trail – Contrail – NO _x – CO – HC – CO ₂ – H ₂ O – SO _x – Contrail avoidance – RAMS – EEC – SEE – etc.						
Abstract: This study investigates the potential environmental impact of several ATM options to guide air traffic around, above and below airspace volumes of cold and moist air likely to produce contrails.						

Intentionally blank

EXECUTIVE SUMMARY

This study investigates the potential impact on air traffic of environmental management options aiming at guiding air traffic around, below or above airspace volumes of moist air where it is most likely to produce contrails.

Analysis has been carried out for ten typical days of 2004 traffic in the western European region. For each of these ten days, the meteorological situation was assessed to identify areas of moist and cold airspace volumes where contrails are the most likely to be formed.

Using RAMS Plus ATM simulator, and the zones identified using the GAES-Contrails model in conjunction with the MM5 Meteorological modelling tool, aircraft that would enter high contrails-risk airspace volumes are submitted to rerouting.

In the scope of the initial investigation into such an Environmental Air Traffic Management concept, three distinct avoidance scenarios were considered:

- Air traffic is guided *around* high contrails risk volumes,
- Air traffic is guided *above* high contrails risk volumes,
- Air traffic is guided *below* high contrails risk volumes.

Thus, for each of the 10 traffic days, four scenarios were simulated – the fourth being a standard baseline scenario where no Environmental management was involved.

For each scenario, fuel burn and emissions were calculated and the contrails coverage was gauged.

To best understand the potential for such a contrail mitigation scheme, we considered five "heavy contrail days" and five "light contrail days" to try to establish an upper and lower boundary to the contrail avoidance problem.

Several issues were encountered during the study, putting a damper on results from this study. In particular, the sheer size of the high contrails-risk airspace volumes to be avoided was so large on occasions that most of the avoidance algorithms were not applicable. On many occasions for the principal flight levels used in a typical days flight in Europe (FL310 – FL380) high-risk contrails zones became as large as the entire geographical airspace region. As a consequence contrails areas were for the most part difficult to avoid.

In the light of the study results, and of the problems encountered, it is considered that improvements to both the simulator's avoidance algorithm and the Contrails modelling tool used to identify high contrails-risk airspaces would generate more robust results.

Nevertheless, some general trends based on a small scale of data (limited sample of flights out of two simulation days) were obtained. In general, however, due to the size of the avoidance zones, and the fact that the majority of traffic either originates or terminates at European airports, of the three avoidance mechanisms investigated, only the *Below* option produced results that could be considered reasonable for such a mitigation scenario.

In most cases, the *Above* option could not be applied, as flights start or end *below* a given contrail avoidance zone.

The study's results suggest that extra fuel burn and emissions generated by the *Around* option, even during the "light contrail day", do not justify the implementing this option.

Although initial results are somewhat constrained by the technical problems encountered in the study, a limited set of aircraft could successfully avoid contrails zones and results for this subset of aircraft appeared promising.

Before any significant conclusions could be drawn, a further study would be required with improved modelling techniques to confirm, deny or modulate the previous statements. The current study has to be considered as an experiment aiming at determining necessary improvements in the data, tools and methodology to be achieved in the scope of a further study.

TABLE OF CONTENTS

1. Introduction	1
1.1 Context.....	1
1.2 Study process plan.....	2
2. Problem definition.....	3
3. Specification of study goals.....	4
3.1 Aviation Environmental Impacts from Carbon Dioxide (CO ₂)	4
3.2 Aviation Environmental Impacts from Nitrogen Oxides (NO _x)	5
3.3 Aviation Environmental Impacts from water vapour (H ₂ O)	5
4. Development of analysis instruments.....	8
4.1 RAMS Plus	8
4.2 Toolset for Emission Analysis (TEA).....	9
4.2.1 The Advanced Emission Model (AEM)	10
4.2.2 MM5.....	13
4.2.3 The CONTRAIL Model	14
5. Development of analysis plan.....	15
6. Input data collection	16
6.1 Modification of RAMS avoidance algorithm	16
6.2 Data source	16
6.3 Geographical footprint.....	17
6.4 Generation of contrails zones outlines.....	18
6.5 Preparation and execution of RAMS scenarios	19
6.6 Preparation of input files and execution of AEM3.....	19
6.7 Preparation and execution of CONTRAIL Model.....	20
6.8 Number of flights available for the study.....	20
7. Output data analysis and results.....	21
7.1 Main difficulties encountered during the study.....	21

7.1.1	CPR data	21
7.1.2	Huge contrail zones.....	21
7.1.3	Contrail zone avoidance algorithm	23
7.2	Environmental assessment – Impact on emissions.....	24
7.2.1	Overall results.....	24
7.2.2	Restriction of the data set to "correctly manoeuvring" flights	25
7.2.3	Breakdown by aircraft type.....	26
7.2.4	Breakdown by departure and arrival airport location.....	26
7.2.5	Conclusion on impact of emissions.....	28
7.3	Impact of H ₂ O emission on contrail formation.....	29
7.3.1	Contrail formation	29
7.3.2	Baseline Scenario: the CONTRAILS Project	30
7.3.3	Baseline Scenario CONTRAIL Model Output	32
7.3.4	Around / Above / Below Scenarios.....	35
7.3.5	Sample Contrail Model Maps	36
7.4	Trade-Off.....	38
8.	Output sensibility analysis	39
8.1	CO ₂ , H ₂ O, SO _x estimation with AEM3.....	39
8.2	NO _x , HC, CO estimation with AEM3	39
8.2.1	NASA study	40
8.2.2	NO _x average emission indices from ANCAT and NASA inventories	42
8.2.3	Conclusion on NO _x , CO and HC estimation	43
8.3	MM5 Output sensibility analysis.....	44
8.4	CONTRAIL Model sensibility analysis	51
8.5	Creation of contrail polygon zones.....	52
9.	Conclusions.....	53
Annex 1.	Boeing method 2 – EUROCONTROL Modified	55
1	The original Boeing Method 2 (BM2)	55
1.1	Methodology.....	56

1.2 Bibliography.....	57
2 EUROCONTROL modified Boeing Method 2 (EEC-BM2).....	58
Annex 2. High-risk contrail zones by flight level	59
Annex 3. CONTRAIL Calculation Procedure	63
Annex 4. Meteorological Situation	65
1 Surface Analysis.....	65
1.1 September 17, 2004: Meteorological Analysis.....	65
1.2 October 18, 2004: Meteorological Analysis	66
2 Additional Meteorological Charts	67
2.1 Surface Precipitation Rate (mm/hr).....	67
References	68

LIST OF TABLES

TABLE 1: COEFFICIENTS FOR EMISSIONS CALCULATION – CO ₂ , H ₂ O, SO ₂	12
TABLE 2: COEFFICIENTS FOR EMISSIONS CALCULATION – VOC, TOG	12
TABLE 3: NUMBER OF FLIGHTS AVAILABLE AND DELETED FOR THE STUDY	20
TABLE 4: DISTRIBUTION OF TRAFFIC OVER FLIGHT LEVEL BANDS	23
TABLE 5: AVOIDANCE SCENARIOS VS. BASELINE COMPARISON – ABSOLUTE FIGURES	24
TABLE 6: AVOIDANCE SCENARIOS VS. BASELINE COMPARISON – %	24
TABLE 7: AVOIDANCE SCENARIOS VS. BASELINE COMPARISON – ABSOLUTE FIGURES	25
TABLE 8: AVOIDANCE SCENARIOS VS. BASELINE COMPARISON – %	25
TABLE 9: AVOIDANCE SCENARIOS VS. BASELINE COMPARISON – BREAK DOWN PER AIRPORT LOCATION	27
TABLE 10: CONTRAIL PERCENTAGES FOR EACH SCENARIO.....	35
TABLE 11: VARIATION IN PUBLISHED COEFFICIENTS FOR FUEL PROPORTIONAL EMISSIONS (%)	39
TABLE 12: PUBLISHED AVERAGE EINOX (G/KG FUEL) OF REFERENCE PROJECTS [REF 20.]	42
TABLE 13: AVERAGE EINOX (NO _x /FUEL) IN G/KG FUEL.....	43
TABLE 14: ESTIMATION OF CONTRAIL MODEL ERROR LIMIT	51

LIST OF FIGURES

FIGURE 1: PROCESS PHASES FOR THE ATM CONTRAIL MITIGATION OPTIONS STUDY	2
FIGURE 2: NOAA-12AVHRR SATELLITE PHOTOGRAPH; CENTRAL EUROPE; MAY 4, 1995, PROC. BY DLR.....	6
FIGURE 3: INCREASED RF BY AVIATION-CAUSED CONTRAILS AND CIRRUS CLOUDS ([REF 14.])	7
FIGURE 4: EXAMPLE OF TRAFFIC AND AIRSPACE IN RAMS	8
FIGURE 5: OVERVIEW OF EUROCONTROL'S TOOLSET FOR EMISSION ANALYSIS (TEA).....	9
FIGURE 6: THE AEM3 CALCULATION CYCLE.....	13
FIGURE 7: MAIN STEPS OF THE STUDY'S PROCESS	15
FIGURE 8: CPR DATA AND STUDY GEOGRAPHICAL FOOTPRINT.....	17
FIGURE 9: THERMODYNAMICS OF CONTRAIL FORMATION.....	29
FIGURE 10: TYPICAL DAILY EXTENT OF EUROCONTROL'S CORRELATED POSITION REPORTS (CPR) RADAR DATA.....	31
FIGURE 11: RELATIVE HUMIDITY (LEFT) AND TEMPERATURE (RIGHT) AT FL 300: 12:00 MARCH 18, 2004....	33
FIGURE 12: MODELLED CONTRAILS (LEFT) AND OBSERVED CONTRAILS (RIGHT) AT 10:46 MARCH 18, 2004	34
FIGURE 13: RELATIVE HUMIDITY (LEFT) AND TEMPERATURE (RIGHT) AT FL 300: 12:00 MARCH 09, 2004....	34
FIGURE 14: MODELLED CONTRAILS (LEFT) AND OBSERVED CONTRAILS (RIGHT) AT 13:56 MARCH 09, 2004	35
FIGURE 15: SEPTEMBER 17: SCENARIO "BASELINE" (TOP LEFT), "AROUND" (TOP RIGHT), "ABOVE" (BOTTOM LEFT), "BELOW" (BOTTOM RIGHT)	36
FIGURE 16: OCTOBER 18: SCENARIO "BASELINE" (TOP LEFT), "AROUND" (TOP RIGHT), "ABOVE" (BOTTOM LEFT), "BELOW" (BOTTOM RIGHT)	37
FIGURE 17: EMISSIONS COMPARISON OF 757-200 FOR 400 NM AND 3000 NM MISSION	40
FIGURE 18: EMISSIONS COMPARISON OF OVERALL TRAFFIC – AVERAGE OF 4 SCENARIOS	41
FIGURE 19: MEAN ABSOLUTE TEMPERATURE ERROR: OBSERVATIONS VERSUS MODELLED [REF 27.]	45
FIGURE 20: MEAN ABSOLUTE RELATIVE HUMIDITY ERROR: OBSERVATIONS VERSUS MODELLED [REF 27.]	46
FIGURE 21: MEAN ABSOLUTE WIND SPEED ERROR: OBSERVATIONS VERSUS MODELLED [REF 27.]	47
FIGURE 22: MEAN ABSOLUTE WIND DIRECTION ERROR: OBSERVATIONS VERSUS MODELLED [REF 27.] ...	48
FIGURE 23: MEAN ABSOLUTE SEA-LEVEL PRESSURE: ERROR OBSERVATIONS VERSUS MODELLED [REF 27.].....	49
FIGURE 24: MEAN ABSOLUTE PRECIPITATION ERROR: OBSERVATIONS VERSUS MODELLED [REF 27.].....	50
FIGURE 19: HI-RISK CONTRAIL ZONES BY FLIGHT LEVEL – 17/09/04 [T= 00:00 TO 06:00].....	59
FIGURE 20: HI-RISK CONTRAIL ZONES BY FLIGHT LEVEL – 17/09/04 [T= 06:00 TO 12:00].....	60

FIGURE 21: HI-RISK CONTRAIL ZONES BY FLIGHT LEVEL – 17/09/04 [T= 12:00 TO 18:00]..... 61

FIGURE 22: HI-RISK CONTRAIL ZONES BY FLIGHT LEVEL – 17/09/04 [T= 18:00 TO 24:00]..... 62

FIGURE 23: METEOROLOGICAL ANALYSIS: SEPTEMBER 17, 2004..... 65

FIGURE 24: METEOROLOGICAL ANALYSIS: OCTOBER 18, 2004..... 66

FIGURE 25: SURFACE PRECIPITATION RATE (MM/HR)..... 67

ABBREVIATIONS

AEM.....	Advanced Emission Model
AEM3.....	Advanced Emission Model, 3rd version
ANCAT	Abatement of Nuisances Caused by Air Transport
ATC	Air Traffic Control
ATM.....	Air Traffic Management
CFMU	Central Flow Management Unit
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
Contrail	Condensation trail
CPR.....	Correlated Position Reports
DLR	German Aerospace Centre
EEC	EUROCONTROL Experimental Center
EEC-BM2	The EUROCONTROL modified Boeing Method 2
EI	Emission Index
EPA	Environmental Protection Agency
ESA	European Space Agency
FL	Flight Level
FNL.....	Global Final Analyses
GDAS	Global Data Assimilation System
GIFAS.....	Groupeement des Industries Françaises Aéronautiques et Spatiales
GIS	Geographical Information System
GTS.....	Global Telecommunications System
H ₂ O.....	Water
HC	Hydrocarbon
ICAO.....	International Civil Aviation Organisation
IPCC.....	Intergovernmental Panel on Climate Change
KNMI	Royal Netherlands Meteorological Institute
Lat	Latitude
Long	Longitude
LTO	Landing- and Take-Off cycle
Max.....	Maximum
Min.....	Minimum

MM5	Numerical weather model
MS	Microsoft
MTOW	Maximum Take-Off Weight
NASA.....	National Aeronautics and Space Administration
NCAR	National Centre for Atmospheric Research
NESDIS	National Environmental Satellite, Data, and Information Service
NM.....	Nautical Mile
NO _x	Oxides of Nitrogen
RF.....	Radiative Forcing
SEE	Society, Environment, Economy
SO _x	Oxides of Sulphur
TEA	Toolset for Emission Analysis
TOG.....	Total Organic Gases
VOC.....	Volatile Organic Compounds

Intentionally Blank

1. INTRODUCTION

1.1 Context

This study is motivated by the interest to better understand possible means for aircraft industry to contribute to the goals defined for all industry sectors by the Kyoto conference. The Kyoto protocol requires global emission output to be reduced until 2008/2012 by 5.2 %, where an even higher target of 8 % reduction has been fixed for EUROPE [Ref 3.].

Within the transport sector, aviation is not currently the highest polluter, however, the growth rate in the aviation sector remains significantly higher than other forms of transport. In this context, the air transport stakeholders have the responsibility to redouble their efforts in order to try to reach the goals set by the Kyoto's protocol. Major efforts in the airframe and aircraft engine manufacturing industry have lead to significant reductions in fuel burn and emissions per passenger-kilometre over the last 40 years. Although this process of technical improvements is still ongoing, the progress that has been through technological advances has been rapidly absorbed by the continuous air traffic increase. For this reason, other stakeholders in the aviation transport sector must increase their efforts to improve the situation.

An important issue affecting the environmental performance of air transport is the emission of H₂O out of aircraft's engines in the air at altitude. The emission of water vapour from the hot exhaust in areas of very cold moist air can lead to the formation of condensation trails (contrails) or vapour trails visible behind the aircraft at altitude. These contrails may lead to increase cirrus cloud production which may, in turn, contribute to global climate change. As a consequence, air traffic avoiding moist and cold areas should translate into less contrails formed.

Based on this statement, this study proposes to simulate moist and cold areas avoidance to assess the impact on fuel burn and emissions and estimate the resulting contrails coverage.

Moist and cold areas can be identified based on a meteorological assessment of the actual atmospheric conditions. Once high contrails-risk airspace volumes are located, intelligent avoidance algorithms are available from models. Different avoidance strategies can thus be simulated in order to bring out the best trade-off.

1.2 Study process plan

The methodology shown below was applied to this study. This report is presented following the same steps.

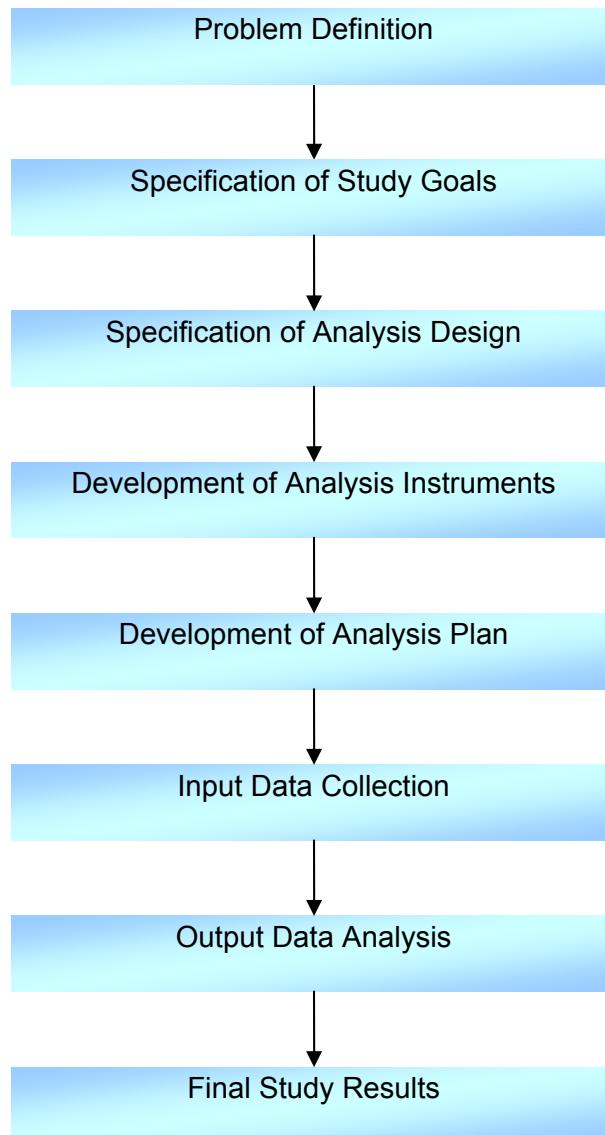


Figure 1: Process phases for the ATM Contrail mitigation options study

2. PROBLEM DEFINITION

As detailed in section 3.3, researches conducted mainly by NASA and DLR ([Ref 13.] and [Ref 14.]) in 2003 give every indication that the impact of H₂O on environment, and especially the following apparition of contrails, is much higher than estimated by IPCC ([Ref 2.]). The contribution of H₂O emission to radiative forcing (see Figure 3) might be one of the most penalizing to the environment. Indeed, the emission of H₂O in the air, on top of being a greenhouse gas, contributes to the apparition of contrails which are likely to affect, eventually, weather (see section 7.3.1).

The emission of water vapour is proportional to fuel burn. As a consequence, efforts put on fuel burn reduction by engines and aircraft manufacturer contribute directly to a diminution of H₂O emissions. This would potentially result in a lessening of radiative forcing of H₂O and should diminish the effects of contrail-induced cirrus cloud production.

With this aim in view, the current study locates airspaces where contrails are likely to be produced. These airspaces are determined using meteorological information, including ambient temperature, pressure and relative humidity and emission/exhaust temperature characteristics of modern commercial aircraft. Using RAMS Plus simulator, traffic data is rerouted to avoid high contrails-risk airspace volumes in different ways (rerouting around, above or below airspace volumes).

The amount of fuel burn and emissions resulting from these modified scenarios are then compared to assess the impact/benefit of rerouting on environment. In parallel, new contrails maps are produced for each scenario to address the validity of rerouting.

High contrails-risk airspace volumes avoidance may increase fuel burn and emissions by making routes longer and/or not using optimal flight level. A trade-off between increase of fuel burn / emission and apparition of contrails might be necessary to evaluate the accuracy of high contrails-risk airspace volumes' avoidance concept. Before being feasible, such a trade-off requires more research from scientific community about the actual radiative forcing of H₂O.

Given that this research is still in its infancy, this study does not attempt to make decisions on whether the concept of high contrails-risk airspaces' avoidance is currently feasible, or how such a policy could be implemented. Instead, it offers a mechanism to quantify the impact of environmental management, through a Contrail avoidance policy using aircraft rerouting, on both the operational efficiency of the core European airspace region and the environment trade-offs in terms of extra emissions and fuel burn compared to a reduction of contrails.

3. SPECIFICATION OF STUDY GOALS

The primary goal of this study is to assess how the implementation of a contrails avoidance policy would impact the ATM system, and to evaluate the additional environmental costs of extra fuel burn or less efficient flight level usage might be offset by the production of fewer contrails.

Thus in applying a contrails' mitigation policy we wish to evaluate how many contrails could possibly be avoided by avoiding the high-risk areas. However, to balance the gains, we also need to specifically investigate the potential environmental impact on fuel burn and emissions (due to avoidance), in particular in terms of CO₂, NO_x and H₂O, since those three emissions are seen to be the main factors in the chemical processes leading to radiative forcing (green house effect) and a reduced ozone layer. The investigation of CO and HC emissions (and therefore VOC and TOG which are linked to HC emissions) is also addressed, even if mostly emitted at low altitudes.

Increased emissions of H₂O would be a high-ranking factor in this study since it may affect the contrail and cirrus clouds coverage.

High contrails-risk airspace volumes to be avoided are particularly huge, going beyond RAMS avoidance algorithm capabilities (see details in section 7.1). The emission analysis hence does not pretend to much accuracy, and results should be seen as trend indications.

The paragraphs below present an overview of the main emissions covered by the study.

3.1 Aviation Environmental Impacts from Carbon Dioxide (CO₂)

CO₂ is a stable component in atmospheric chemistry. CO₂ is naturally occurring and is mixed homogeneously throughout the atmosphere. CO₂ affects the atmosphere directly and depending on the concentrations of molecules it affects the ability of the earth to absorb outgoing radiation emitted by the earth's surface and lower atmosphere. In terms of global warming this is of great concern as CO₂ can reside in the atmosphere for hundreds of years.

The CO₂ emitted by aircraft is mixed with CO₂ from other sources. As jet aircraft have only been in service over the last 50 years, CO₂ concentrations from aircraft alone are difficult to assess. Nevertheless the aviation sector is estimated to produce 2 – 3 % of overall man-made CO₂ emissions [Ref 2.]. For an analysis of its impact on the atmosphere, precise knowledge of the geographical position and altitude of the emission source is of low importance, and atmospheric CO₂ cannot be associated with local emitters. CO₂ emissions have to be reviewed in a global context.

3.2 Aviation Environmental Impacts from Nitrogen Oxides (NO_x)

NO_x is a common term used to refer mostly to two species of oxides of nitrogen collectively reported as NO₂ –equivalent: nitrous dioxide (NO₂) and nitrous oxide (NO), a greenhouse gas which accumulates in the atmosphere with other greenhouse gases leading to a rise in the earth's temperature over time. NO₂ is a strong oxidizing agent that reacts in the air to form corrosive nitric acid, as well as toxic organic nitrates. It also plays a major role in the atmospheric reactions that produce ground-level ozone or photochemical smog.

NO_x has two contradictory effects on ozone. In high altitudes of the stratosphere NO_x emissions contribute to the reduction of ozone, while in typical Cruise altitudes (8-13 km) NO_x emissions cause an ozone increase.

NO_x can react with other substances in the air to form acids which are deposited as rain, fog, snow (wet deposition) or dry particles (dry deposition). It can be carried by wind for hundreds of kilometres causing trans-boundary air pollution impacts such as acid rain damage to material, buildings and historical monuments, and the acidification and eutrophication of lakes and streams.

Apart from lightning, aircraft are responsible for all NO_x emissions at 8-15 km altitudes. The contribution of aviation to global NO_x emissions is currently estimated to be only 1.8 % [Ref 6.]. However, several studies predict, for the North Atlantic track system, an increase of NO_x from aircraft emissions of 10 – 100 % [Ref 7.], [Ref 8.], [Ref 9.].

3.3 Aviation Environmental Impacts from water vapour (H₂O)

Water vapour is a greenhouse gas and is formed as a by-product of the combustion of kerosene. At high altitude water vapour condenses to form thin cloud trails (contrails) in the sky.

Depending on meteorological conditions (such as air temperature and prevailing wind) these contrails can persist visibly for many hours often spreading out to join with other mature contrails, which may then influence the formation of cirrus clouds. Moreover, water vapour can reside in the troposphere for up to nine days before being eliminated in the form of precipitation. In the stratosphere it can last weeks or months, adding to the potential radiative forcing effect and man-made climate change over this period.

Following the 9/11 terrorist attacks in the US, almost all aircraft were grounded for 24-48 hours. Over the following days diurnal temperatures were between 1 and 2 degrees C higher than normal ([Ref 11.]). This may be explained because contrails were not produced in that period and so did not contribute to cirrus cloud formation. This allowed sunlight to enter the earth's atmosphere unimpeded, raising daytime temperature, and, as the returning radiation was not trapped by the cloud, lowering night-time temperature.

Approximately 10-20 % of all jet aircraft flights occur in air masses that are humid enough to cause contrails. With air traffic growing and contrails becoming more prevalent, the natural variation will further decline and some scientists speculate that this could disrupt regional ecosystems.

Figure 2 illustrates this with a 'snap-shot' of the situation over Northern Europe.

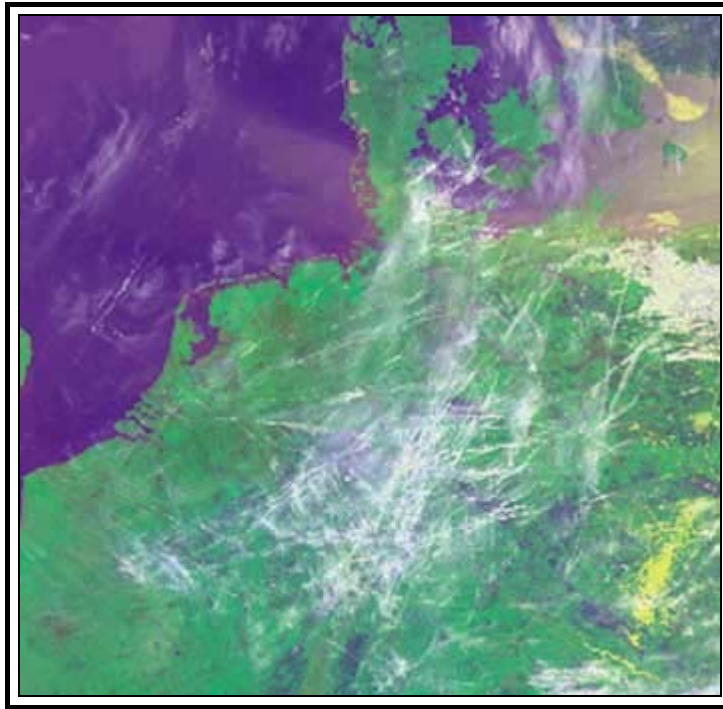


Figure 2: NOAA-12AVHRR Satellite photograph; Central Europe; May 4, 1995, proc. by DLR

Currently the contrail cover remains weak. The annual average contrail coverage is about 0.1 % of the earth's surface while the natural cirrus clouds global mean coverage reaches about 20 %. However over regions with intense air traffic, the local contrail cover can reach up to 5 % of the sky [Ref 5.]. According to the IPCC (Intergovernmental Panel on Climate Change) reference scenario documented in 1999, the global contrail cover is projected to grow to 0.5 % by 2050 ([Ref 2.]).

Most recent research of mainly NASA ([Ref 13.]) and DLR ([Ref 14.]) during 2003 indicates that the environmental impact in terms of radiative forcing resulting from contrails and contrail-caused cirrus clouds might be significantly higher than initially estimated by IPCC and might even be more important than the overall impact of the sum of all other greenhouse gases emphasised in the past.

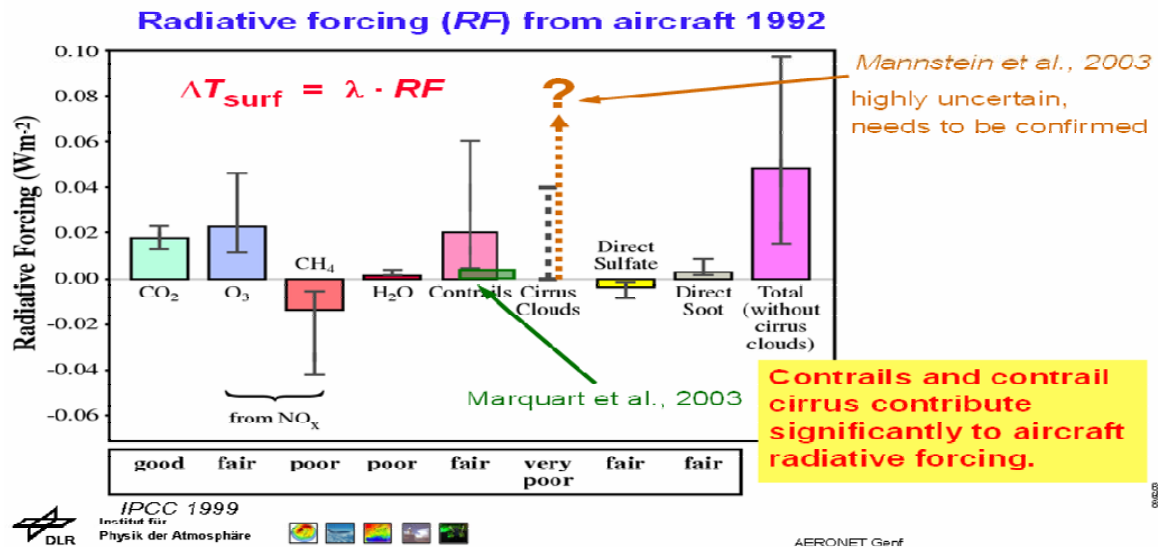


Figure 3: Increased RF by aviation-caused Contrails and Cirrus Clouds ([Ref 14.]

Since the scientific case is not yet sufficiently proven with the required statistical reliability, aviation cannot yet adopt measures that might later prove to be ineffective or, worse, counter-productive.

To test the scientific case the EUROCONTROL Experimental Centre (EEC) is working with and supports the European Space Agency's two-year project CONTRAILS ([Ref 15.] & [Ref 4.]). Part of the project is also to validate the EEC's contrail prediction model. Such a model would be required if contrail-related research results in the societal need to re-organise traffic flows to avoid the cold, damp air masses in which contrails form. Final results of ESA's CONTRAILS project are expected for End 2005.

For additional information, the influence of different emissions on health is detailed in Appendix A of [Ref 12.].

4. DEVELOPMENT OF ANALYSIS INSTRUMENTS

Based on CPR information, flight profiles were simulated using RAMS Plus fast-time simulator. Emissions and fuel burn were then calculated by AEM3.

Flight profiles were superposed over geographical data using the ARCVIEW GIS package. Further analysis has been performed using standard spreadsheet and database software as MS Excel and MS Access.

4.1 RAMS Plus

Each scenario of each date of movement data was simulated with the RAMS Plus fast time simulation tool based on CPR information. RAMS Plus is a fast-time discrete-event simulation tool which provides functionalities for the assessment and analysis of airspace structures, Air Traffic Control systems and future ATM concepts. The model is a task based software tool which records the impact of a given traffic demand on the ATC organisation simulated, and provides various types of results such as sector traffic loads, sector working times and controller workloads.

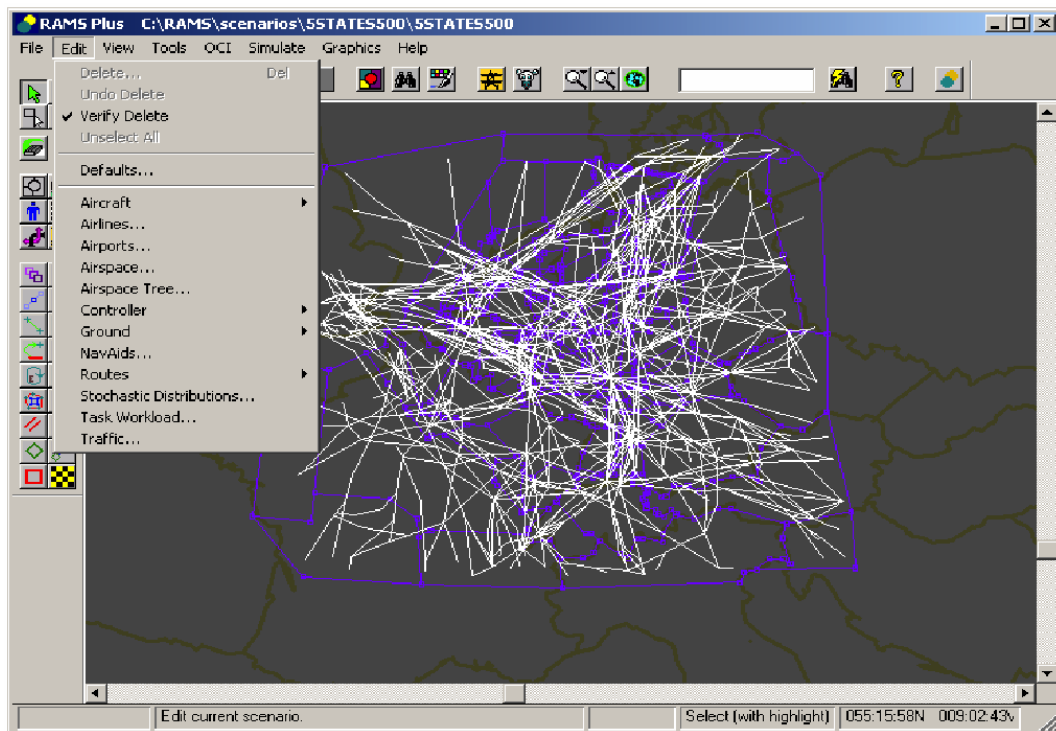


Figure 4: Example of traffic and airspace in RAMS

RAMS Plus is designed to study a broad range of ATM concepts, from airspace design & capacity, workload & safety concerns, to airport movements, capacity, and delay. Its features include 4D flight trajectory calculation (using great circle), 3D sectorisation, 4D spatial conflict detection, multiple separation strategies, rule based conflict resolution, TMA (SIDS/STARS, hold stacks, approach vectoring, etc), dynamic task assessment, airport movements (gate allocation, shortest path taxiing, runway acceleration/deceleration, etc).

RAMS Plus is geographically independent, and takes as input flight schedule information and sectorisation, and outputs a comprehensive set of flight history, conflict information, workload assessment, flight delays, etc.

RAMS Plus includes an horizontal avoidance algorithm rerouting the traffic around specific restriction areas. Nevertheless this algorithm did not offer any vertical avoidance possibility at the beginning of the projects. Such a vertical avoidance algorithm was hence developed and included into RAMS for the need of the study (see section 7.1.3).

4.2 Toolset for Emission Analysis (TEA)

TEA is a set of three inter-connected models, namely: AEM3, a EUROCONTROL system for estimating aviation emissions and fuel burn; MM5, a numerical weather model that provides forecast and analysis data for other EUROCONTROL models; and CONTRAIL, a EUROCONTROL tool for determining the probability and amount of contrail formation from aircraft (Figure 5).

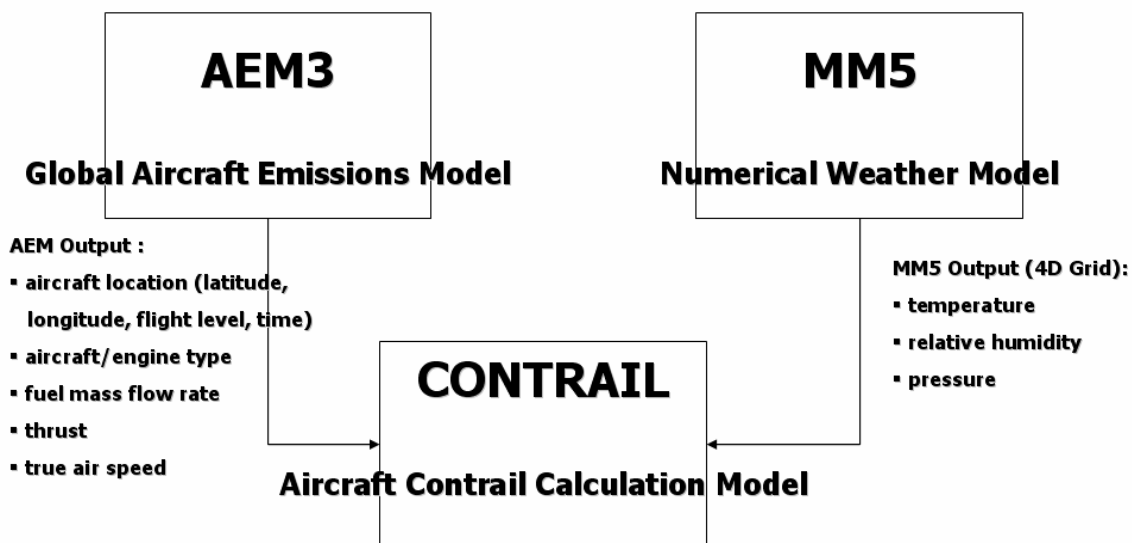


Figure 5: Overview Of EUROCONTROL's Toolset For Emission Analysis (TEA)

4.2.1 The Advanced Emission Model (AEM)

The current study used the AEM3 Advanced Emission Model 3 to estimate today's (i.e. 2004) aviation fuel burn and atmospheric emissions. The AEM3 model and the underlying calculation methodology are described in this section.

The Advanced Emission Model version 3 (AEM3) is used to estimate aviation emissions and fuel burn for a given set of traffic movements in an analysis region.

AEM3 is a stand-alone system able to analyse flight profile data, on a flight-by-flight base, for air traffic scenarios of almost any scope. It uses 4D-flight profile information to calculate fuel burn and, in addition, emissions produced (CO₂, H₂O, SO_x, NO_x, CO, HC, VOC, TOG).

The model is based on the use of several underlying databases, including a set of default databases that hold information related to aircraft, aircraft engines, fuel burn rates and emission indices. These default databases rely on external data providers, assuring the quality of the information provided. The user of the system is responsible to assure that the relation between those default databases is representative for the specific study purpose. This default system information is combined with dynamic input data, represented by the air traffic flight profiles.

Flight tracks were superposed over geographical data using the ArcView GIS package. Further analysis has been performed using standard spreadsheet and database software such as MS Excel and MS Access.

4.2.1.1 AEM3 Fuel burn calculation

4.2.1.1.1 Calculations for operation below 3000ft

Below 3000 ft, the fuel burn calculation is based on the Landing and Take-Off Cycle (LTO) defined by the ICAO Engine Certification specifications. ICAO LTO covers four engine operation modes, which are used to model the following six phases of aircraft operations in AEM3:

- Taxi-Out,
- Take-Off,
- Climb-Out,
- Approach,
- Landing,
- Taxi-In.

Landing is considered as an Approach phase (and thus uses Approach fuel flow and emission indices) which lasts for the same duration as the Take-Off phase.

The *ICAO Engine Exhaust Emissions Data Bank* [Ref 16.] includes emission indices and fuel flow for a very large number of aircraft engines. AEM3 links each aircraft appearing in the input traffic sample to one of the engines in the *ICAO Engine Exhaust Emissions Data Bank*.

The standard LTO cycle can be added to all input flight profiles, even when real data for those operations is available. The application of the ICAO LTO cycle is common practice in aviation emission estimation and assures complete information for all profiles during those phases of flight.

4.2.1.1.2 Calculations for operation above 3000ft

Above 3000 ft, fuel burn calculation is based on the "Base of Aircraft Data" (BADA). This database provides altitude and attitude dependent performance and fuel burn data for more than 150 aircraft types. The version 3.5 used with AEM3 for this study, covers nearly 90 % of the aircraft types that make up the European air traffic. BADA is developed and maintained by the EUROCONTROL Experimental Centre.

AEM3 links each aircraft performing one of the input flight profiles to the BADA fuel burn data. Where no data for a specific aircraft type is available, representative aircraft types are used to create the most realistic indirect link; e.g. the A319 is the reference aircraft for the A319 and A318, etc.

4.2.1.2 *AEM3 Emissions calculation*

4.2.1.2.1 Calculations for operation below 3000ft

Below 3000 ft, the emission calculation is based on the *ICAO Engine Exhaust Emissions Data Bank* [Ref 16.].

4.2.1.2.2 Calculations for operation above 3000ft

Above 3000 ft, the emission calculation is also based on the *ICAO Engine Exhaust Emissions Data Bank*, but emission factors and fuel flow are adapted to the atmospheric conditions at altitude using a method initially developed by The Boeing Company (The Boeing Method 2 – BM2) and subsequently modified by the EUROCONTROL Experimental Centre Business Unit for Environmental Studies (EEC-BM2) (see Annex 1 "Boeing method 2 – EUROCONTROL Modified"). In this way, emissions for the pollutants NO_x, HC and CO can be estimated for the entire flight operation.

The emissions for the pollutants H₂O and CO₂ are direct results of the oxidation process of carbon and the hydrogen contained in the fuel with the oxygen contained in the atmosphere. SO_x emissions depend directly on the sulphur content of the fuel used. All three are directly proportionally to the fuel burn, and can thus be calculated directly from fuel burn estimates.

An understanding of fuel composition is vital for determining the proportional coefficients between fuel burn and emissions. The constants used in AEM3 during this study are presented below.

Pollutant	Coefficient
CO ₂	3.149 kg / kg fuel
H ₂ O	1.230 kg / kg fuel
SO ₂	0.00084 kg / kg fuel

Table 1: Coefficients for emissions calculation – CO₂, H₂O, SO₂

These are average values obtained from an intensive literature review [Ref 17.] at the EUROCONTROL Experimental Centre Business Unit Environmental Studies.

Volatile Organic Compounds (VOC) and Total Organic Gases (TOG) emissions are estimated using a method developed by the U.S. Environmental Protection Agency (U.S. EPA). These are estimated in proportion to the HC emissions. Many individual organic gas emissions (e.g. benzene) are directly estimated from VOC and TOG value. The constants used in AEM3 during this study are presented below.

Pollutant	Coefficient
VOC = HC × 1.0947 VOC/HC correction factor	
acetaldehyde	VOC × 0.0519 acetaldehyde / VOC correction factor
acrolein	VOC × 0.0253 acrolein / VOC correction factor
POM as 16-PAH	VOC × 1.166E-4 16-PAH / VOC correction factor
POM as 7-PAH	VOC × 1.049E-6 7-PAH / VOC correction factor
styrene	VOC × 0.0044 styrene / VOC correction factor
TOG = VOC × 1.1167 TOG/VOC conversion factor	
1,3-butadiene	TOG × 0.0180 1,3-butadiene fraction
benzene	TOG × 0.0194 benzene fraction
ethylbenzene	TOG × 0.0017 ethylbenzene fraction
formaldehyde	TOG × 0.1501 formaldehyde fraction
propionaldehyde	TOG × 0.0095 propionaldehyde fraction
toluene	TOG × 0.0052 toluene fraction
xylene	TOG × 0.0048 xylene fraction

Table 2: Coefficients for emissions calculation – VOC, TOG

4.2.1.3 *AEM3 fuel burn and emissions calculations : Summary*

The following graphic indicates in a simplified way the different approaches applied in AEM3 to obtain the most realistic fuel burn and emission estimations for all phases of each flight profile.

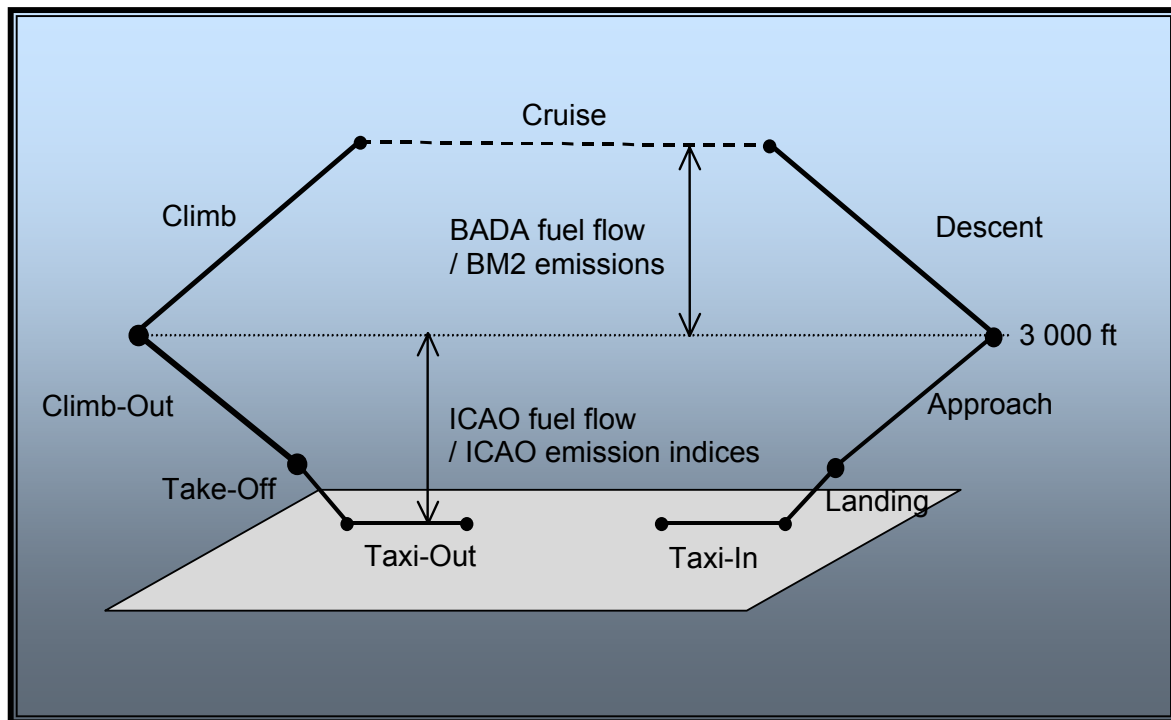


Figure 6: The AEM3 calculation cycle

4.2.1.4 *The AEM3 4D – Analysis Window*

The most widely separated geographical coordinates (min and max altitude, longitude, latitude), and the time limits given by the traffic and flight files, automatically define the 4D analysis window inside which fuel burn and emissions from aircraft operation are calculated. Nevertheless, AEM3 also provides the possibility to overwrite those values and to manually define the 3D airspace block and the start / end times a user wishes the system to use. Moreover, to overcome the potential limitations of such a rectangular analysis window, AEM3 allows the user to "cut" its output data into a geographical area defined by an irregular polygon.

4.2.2 **MM5**

The meteorological model MM5 is a 'state-of-the-art' system developed by the National Centre for Atmospheric Research (NCAR) and Pennsylvania State University. MM5 provides the surface and upper air meteorological data needed for local and global emission studies and contrail estimations, namely: pressure; geopotential height; temperature; horizontal and vertical winds speed; and humidity. MM5 has been used for a broad spectrum of theoretical

and real-time studies, including applications of both predictive simulation and four-dimensional data assimilation to monsoons, hurricanes, and cyclones. MM5 has been used by a wide range of agencies for studies involving convective systems, fronts, land-sea breezes, mountain-valley circulations, and urban heat islands.

MM5 is the latest in a series of weather models that developed from a mesoscale model used at Pennsylvania State University in the early 1970's. Since that time, it has undergone many changes designed to broaden its usage. These include: (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale, (iii) multitasking capability on shared-and distributed-memory machines, (iv) a four-dimensional data-assimilation capability, and (v) more physics options. The model is supported by several auxiliary programs, which are referred to collectively as the MM5 modelling system.

4.2.3 The CONTRAIL Model

The CONTRAIL model developed by the EEC is used to calculate contrails from actual aircraft flight tracks. This program uses the output from AEM3 and meteorological data from MM5. The CONTRAIL model first outputs the flight tracks that produce contrails and that would be visible to a satellite passing overhead at specific times during the day.

The CONTRAIL model then uses the output from AEM3 combined with meteorological data from MM5 to evaluate contrail formation. The required data provided by AEM3 for the CONTRAIL model are the 4D aircraft location (latitude, longitude, flight level, and time), the aircraft/engine type, fuel mass flow rate, thrust, and true air speed). For CONTRAIL, MM5 provides air temperature, relative humidity and air pressure at the AEM3 4D aircraft locations. The stages that make up the calculation of contrails consist of the following steps:

MM5 Stage

- Collect gridded meteorological analyses and observations for each time period.
- Run the MM5 model using these data.
- Reformat the MM5 output to allow direct input to the Contrails model.

AEM3 Stage

- Collect the relevant Flight and Traffic data.
- Verify and validate these data.
- Run AEM3 using these data.
- Reformat and grid the AEM3 output be compatible with the MM5 data and to allow input to the Contrails model.

CONTRAIL Stage

- Run the CONTRAIL model using the data from the MM5 and AEM3 stages.
- Create output files identifying the flight legs that would be visible to a satellite which would pass overhead at set, predetermined times.
- Grid these contrail output files to allow direct comparison with the actual satellite images.

5. DEVELOPMENT OF ANALYSIS PLAN

This study investigates the potential environmental impact of several ATM options to guide air traffic around, below and above airspace volumes of moist air likely to produce contrails. For each traffic day in the study, one baseline plus three avoidance scenarios were simulated using RAMS plus simulator.

- *Baseline*: No contrail zone is avoided.
- *Around*: When possible, high contrails-risk airspace volumes are avoided following an horizontal avoidance algorithm. In other words, the original flight level is used but the lat/long trajectory is modified.
- *Above*: When possible, high contrails-risk airspace volumes are flown over. Lat/long trajectory does not change.
- *Below*: When possible, traffic is rerouted below high contrails-risk airspace volumes. Lat/long trajectory does not change.

The main steps followed by the study are listed below and detailed in the next section:

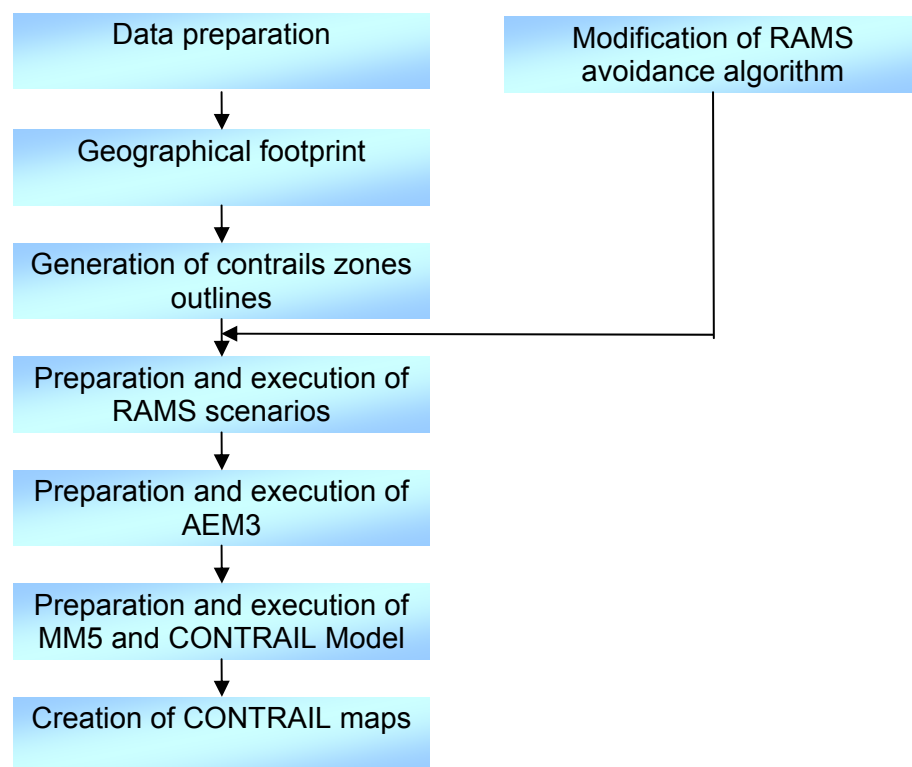


Figure 7: Main steps of the study's process

6. INPUT DATA COLLECTION

This section details the main process followed during the study to obtain exploitable starting point for the analysis.

6.1 Modification of RAMS avoidance algorithm

The aim of the project is to make flights avoid high contrails-risk airspace volumes. Such volumes are modelled in RAMS as avoidance zones, defined by geographical and temporal limits.

In the version of RAMS available at the beginning of the project, such avoidance zones inserted into RAMS could be avoided by aircraft being rerouted on a horizontal plan. This avoidance algorithm had to be modified to allow aircraft flying above or below a zone (see section 7.1.3).

6.2 Data source

60 traffic days of 2004 CPR data from an earlier emission project (CONTRAILS project, see section 7.3.2 and [Ref 4.]) were available for this study. However, as the use of such high-fidelity data in a simulator tool requires inordinate amounts of time (several days to simulate due to the millions of data points contained therein), the study focussed on the ten most interesting days showing atmospheric conditions with high and low contrails formation identified by Earth Observation Satellites.

In the context of a study focussing on the impact and trade-off with other pollutants of a "contrail-avoidance", choosing five "heavy contrail days" and five "light contrail days" each alternate month gives an upper and lower boundary to the contrail avoidance problem.

Therefore, low and high contrails-risk candidates are distributed as follows:

- 20th January (heavy contrail day)
- 26th February (light contrail day)
- 18th Mars (heavy contrail day)
- 22nd April (light contrail day)
- 28th May (heavy contrail day)
- 22nd June (light contrail day)
- 24th July (heavy contrail day)
- 1st August (light contrail day)
- 17th September (heavy contrail day)
- 18th October (light contrail day)

6.3 Geographical footprint

During the CONTRAILS project ([Ref 4.]), the initial CPR data set was reduced as follows:

- Longitude: 10W-20E
- Latitude: 40N-60N
- FL: >FL240 (altitude corresponding to contrail formation)

The current study does not address contrail formation only. Emissions produced at flight levels below FL240 have to be assessed. Therefore, it is necessary to use the complete set of CPR data and not only a reduced subset above FL240.

For consistency reasons the same region of interest as for the CONTRAILS project is chosen: 40N – 60N and 10W – 20E.

Figure 8 shows the study's geographical limits superimposed on a CPR traffic sample.

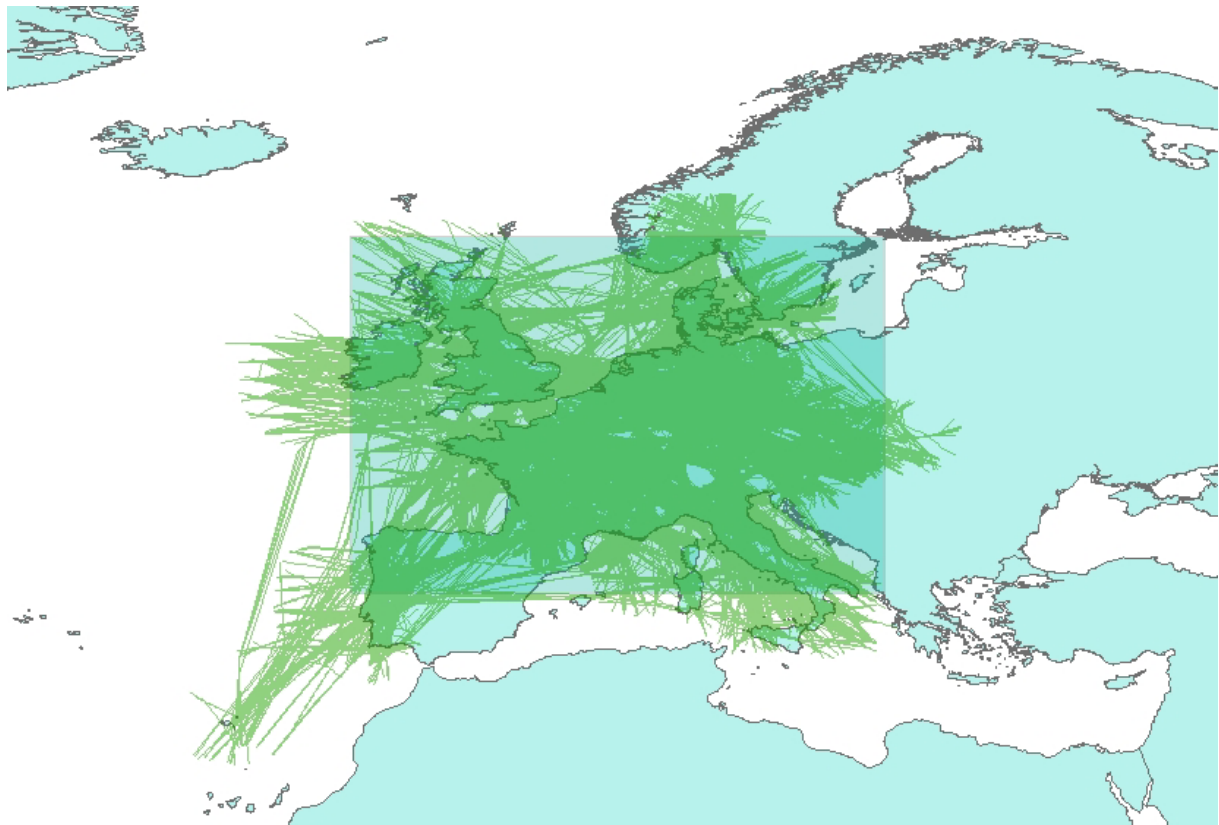


Figure 8: CPR data and study geographical footprint

6.4 Generation of contrails zones outlines

The information at disposal to determine contrail zones is the following: Contrails maps produced during CONTRAILS project ([Ref 4.]). This information is split into two types of data:

- Contrail model plots

These maps present a static situation corresponding to the density of contrail coverage for each satellite overpass. No information on formation/disappearance time of contrails volumes is available. Neither are available minimum and maximum flight levels of these volumes.

- Contrail model text file output format

A text file containing all the contrails, as flight legs, produced for each day. Nevertheless a GIS visualisation of this data does not allow to distinguish specific high contrails-risk airspace volumes.

In the previous work on contrails modelling, the algorithms used to produce contrails maps were based on flight legs that would have generated contrails. However, using this approach only indicates the areas of contrails where the aircraft actually flew and not the moist airspace blocks to avoid. There are fewer contrails on the late-night or early-morning maps, not because the likelihood of contrail formation is lower, but because most of the aircraft are on the ground – there "could have been" contrails if the aircraft were in the air. For this reason, it was necessary to come up with an alternative way of identifying areas of high contrail risk.

- Contrail Potential Routine

A new Contrail Potential routine was written to produce files of gridded "contrail potential" zones for the entire airspace. This routine was based upon the original contrail algorithm in the existing Contrail Model (which has been successfully validated against actual radar images) – it uses output from MM5 and the exhaust temperature and fuel/vapour emission of an "average" aircraft of the year 2004 as follows:

For each of the 10 days chosen for the Contrail Mitigation Study, to create the "zones of contrail potential" the new Contrail Potential routine was run using a "virtual" aircraft with an average engine fuel efficiency (0.3) at each grid cell of the following grid: grid points 0.25 degree x 0.25 degree (10E to 20W and 40N to 60N), every 1000 feet (FL 270 to FL 460), every hour. At each grid cell the Contrail Potential routine tested whether the correct atmospheric conditions existed (proper temperature, humidity, and pressure) for the formation of contrails given an average value for the engine fuel efficiency. The output data are values, whether "1" for contrail potential or "0" for no contrails at the grid points.

However, RAMS Plus does not use gridded data as provided by CONTRAILS project to define restricted zones, but irregular polygons. A sophisticated algorithm was thus produced to be able to create RAMS Plus format restricted zones from the gridded contrails data.

6.5 Preparation and execution of RAMS scenarios

For each sample day, a baseline and three avoidance scenarios were to be assessed:

- *Around* airspace
- *Above* airspace
- *Below* airspace

Although it was not originally designed for use with Radar data, RAMS Plus has been used on several occasions to ‘re-fly’ recorded track or radar data in order to carry out additional analysis (e.g. Controller workload assessment, Conflict density, traffic complexity assessment etc.).

Thus, for the purpose of this experiment, the original CPR data was used in RAMS to define the traffic for the baseline (i.e. traffic in RAMS was forced to re-fly along CPR flight profiles instead of basing flight profiles on aircraft performances only)¹. With the introduction of the high-risk contrails zones, the simulator was able to apply its internal ‘auto-avoidance’ mechanisms for each of the alternative scenarios.

Once the simulations had completed, the resulting output data (including the diversions to avoid restricted ‘high risk contrails’ zones for each of the 3 scenarios) had to be compared to the result for the corresponding baseline case to identify environmental benefits/impacts from such a mitigation policy.

6.6 Preparation of input files and execution of AEM3

Flight profiles were extracted from the RAMS Plus output. Files were modified to allow a quicker execution of AEM3. In particular, when RAMS created several points for the same flight, at the same position (i.e. several ATM actions at identical lat/long/FL/Time), only one flight point was kept for AEM execution. This modification has no impact on AEM3 results.

Landing- and Take-Off cycle (LTO) were not added during AEM3 execution since the study focuses on altitudes where contrails are produced, i.e. flight level above 240. LTO phases are identical in the scenarios to compare, making the comparison for these flight phases out of interest.

¹ Although it was not in the scope of this study, we would highly recommend that in any future simulations of this nature, where massive data samples of radar data (with many millions of radar points) are being used, filters are applied to the data to reduce the sample size (e.g. filtering points out when there has been no speed, level or direction change. (Note that each scenario took between 2 and 3 days to execute on a very high powered machine – i.e. around 100-120 days to execute all the sample days.)

6.7 Preparation and execution of CONTRAIL Model

Based on AEM3 outputs, the contrail model was executed 40 times (4 scenarios x 10 days). The methodology used is detailed in section 4.2.3.

6.8 Number of flights available for the study

A total of 198,539 flights over 10 traffic days were available. A number of flights were deleted during data preparation:

- 0.36% of the traffic sample was deleted because of unidentified airports.
- 0.28% of the traffic sample, operated by unidentified aircraft types, was ignored.
- 0.03% of the traffic sample was constituted by one single flight point, and thus not exploitable.
- Because of the geographical limits of the studied area, 2.80% of the traffic not entering the study's geographical area was ignored.

As a result, 191,640 flight profiles were available (see Table 3), corresponding to 96.5% of the initial traffic. The corresponding average traffic per day (19,164 flights) is considered as a statistically reliable data set.

Date	In the initial data set	Single flight event	Unknown aircraft	Unknown airport	Outside of study geographical area	Remaining number of flights for the study
20040120	17622	-6	-24	-48	-473	17071
20040226	18077	-5	-25	-64	-507	17476
20040318	18696	-12	-33	-61	-542	18048
20040422	19724	-2	-43	-57	-569	19053
20040528	22156	-6	-94	-64	-632	21360
20040622	20984	-5	-64	-70	-578	20267
20040724	19005	-11	-61	-112	-469	18352
20040801	19313	-6	-55	-87	-564	18601
20040917	22590	-7	-84	-92	-695	21712
20041018	20372	-6	-81	-52	-533	19700
Total	198539	-66	-564	-707	-5562	191640
Percentage of initial traffic	100%	-0.03%	-0.28%	-0.36%	-2.80%	96.53%

Table 3: Number of flights available and deleted for the study

7. OUTPUT DATA ANALYSIS AND RESULTS

7.1 Main difficulties encountered during the study

This study was particularly complex to handle since several problems appeared during the study's progress. The main problems are detailed below.

7.1.1 CPR data

CPR data used for this project hold on average one flight point per minute for traffic above all Europe. This generates a huge amount of data to handle all along the study process (1,040,000 to 1,370,000 flight points per single traffic day). Consequences are important on simulation times but also on computer memory to be installed on computers to achieve the simulations. Therefore an important time effort was necessary for RAMS, AEM and CONTRAIL Model simulations, while the added value of such detailed flight descriptions is not obvious.

Secondly, the use of actual traffic data lead to specific flight profiles. Indeed, some profiles were different from "ideal" flight profiles in order for example to avoid hazardous meteorological conditions. As a consequence, extra climbing/descending phases or slight detour may appear in the flight profiles used in this study. This aspect is not faded when RAMS re-flies the traffic.

Both problems could be avoided by using simulated or flight plan data instead of actual (CPR) data. Traffic sample would be more homogeneous in term of flight profiles.

7.1.2 Huge contrail zones

Annex 2 presents sample plots of contrail zones used during simulation of the 9th of September 2004. Plots are presented by flight level band between FL330 and FL400 (i.e. flight level where most of the contrails are formed), for each hour of the day.

This annexe, observed in parallel with study geographical footprint presented in Figure 8, clearly shows that huge high contrails-risk airspace volumes exist for the entire day between FL350 and FL400, and essentially results in a total 'no-fly' area in the most popular FL bands. Table 4 shows a break down of flight level usage in the baseline sample. (Flight level bands corresponding to the biggest contrail areas are in bold character).

Indeed a quarter of flying time of the whole traffic sample (17th of September) is spent above FL350. At least 3132 flights are impacted by the huge contrail zones preventing from correct avoidance.

FL band	Time spent in the FL band (min)		% of traffic		Number of flights using the FL band		% of traffic	
	20040917	20041018	20040917	20041018	20040917	20041018	20040917	20041018
0-10	9 945	5 882	0.7113%	0.4724%	1 921	1 122	1.5034%	0.9845%
10-20	15 443	12 396	1.1045%	0.9955%	2 981	2 446	2.3330%	2.1462%
20-30	23 443	18 796	1.6767%	1.5095%	4 259	3 544	3.3332%	3.1096%
30-40	24 376	22 032	1.7435%	1.7694%	4 344	4 005	3.3997%	3.5141%
40-50	17 496	18 176	1.2513%	1.4597%	3 178	3 280	2.4871%	2.8780%
50-60	14 966	13 961	1.0704%	1.1212%	2 633	2 469	2.0606%	2.1664%
60-70	17 001	13 838	1.2159%	1.1113%	2 713	2 316	2.1232%	2.0321%
70-80	19 530	15 623	1.3968%	1.2547%	2 913	2 546	2.2798%	2.2339%
80-90	22 436	17 857	1.6047%	1.4341%	3 191	2 770	2.4973%	2.4305%
90-100	21 522	18 015	1.5393%	1.4468%	3 045	2 774	2.3831%	2.4340%
100-110	24 652	19 600	1.7632%	1.5741%	3 345	2 936	2.6178%	2.5761%
110-120	25 390	22 507	1.8160%	1.8076%	3 741	3 380	2.9278%	2.9657%
120-130	23 236	19 433	1.6619%	1.5606%	3 486	2 993	2.7282%	2.6261%
130-140	22 465	20 354	1.6068%	1.6346%	3 471	3 210	2.7165%	2.8165%
140-150	23 481	21 448	1.6794%	1.7225%	3 582	3 243	2.8033%	2.8455%
150-160	24 506	22 342	1.7527%	1.7943%	3 617	3 386	2.8307%	2.9710%
160-170	26 376	23 675	1.8865%	1.9014%	3 582	3 118	2.8033%	2.7358%
170-180	27 170	24 409	1.9433%	1.9603%	3 423	3 159	2.6789%	2.7718%
180-190	31 406	28 231	2.2462%	2.2672%	3 499	3 229	2.7384%	2.8332%
190-200	28 592	26 309	2.0450%	2.1129%	3 325	3 076	2.6022%	2.6990%
200-210	25 555	23 070	1.8277%	1.8527%	3 178	2 745	2.4871%	2.4085%
210-220	23 751	21 923	1.6987%	1.7606%	3 025	2 714	2.3674%	2.3813%
220-230	24 832	23 203	1.7760%	1.8634%	3 216	2 852	2.5169%	2.5024%
230-240	29 695	25 447	2.1239%	2.0437%	3 556	3 017	2.7830%	2.6472%
240-250	29 733	29 852	2.1266%	2.3974%	3 550	3 304	2.7783%	2.8990%
250-260	26 046	22 097	1.8629%	1.7746%	3 315	2 888	2.5944%	2.5340%
260-270	29 033	26 345	2.0765%	2.1158%	3 416	3 005	2.6734%	2.6367%
270-280	37 186	33 131	2.6596%	2.6607%	3 617	3 202	2.8307%	2.8095%
280-290	39 487	36 618	2.8242%	2.9408%	3 598	3 243	2.8158%	2.8455%
290-300	29 775	27 602	2.1296%	2.2167%	3 255	2 970	2.5474%	2.6059%
300-310	35 699	33 830	2.5533%	2.7168%	3 144	2 823	2.4605%	2.4770%
310-320	40 472	35 951	2.8946%	2.8872%	3 204	2 931	2.5075%	2.5717%
320-330	58 728	51 434	4.2003%	4.1306%	3 437	3 032	2.6898%	2.6603%
330-340	69 543	56 704	4.9739%	4.5539%	3 524	3 154	2.7579%	2.7674%
340-350	87 419	75 147	6.2524%	6.0351%	3 596	3 004	2.8143%	2.6358%
350-360	85 509	71 724	6.1158%	5.7602%	3 132	2 715	2.4511%	2.3822%
360-370	94 966	84 386	6.7922%	6.7770%	2 779	2 533	2.1749%	2.2225%
370-380	80 553	67 356	5.7613%	5.4094%	2 277	2 054	1.7820%	1.8022%
380-390	56 321	59 704	4.0282%	4.7949%	1 404	1 454	1.0988%	1.2758%
390-400	26 811	30 632	1.9176%	2.4600%	743	779	0.5815%	0.6835%
400-410	14 548	14 120	1.0405%	1.1340%	323	306	0.2528%	0.2685%
410-420	6 193	6 615	0.4429%	0.5312%	149	145	0.1166%	0.1272%
420-430	462	443	0.0330%	0.0356%	23	22	0.0180%	0.0193%

430-440	1 728	1 903	0.1236%	0.1528%	43	38	0.0337%	0.0333%
440-450	27	62	0.0019%	0.0050%	4	6	0.0031%	0.0053%
450-460	513	959	0.0367%	0.0770%	12	18	0.0094%	0.0158%
460-470	5	6	0.0004%	0.0005%	1	1	0.0008%	0.0009%
470-480	145	17	0.0103%	0.0014%	2	2	0.0016%	0.0018%
480-490	0	0	0.0000%	0.0000%	0	0	0.0000%	0.0000%
490-500	0	1	0.0000%	0.0001%	0	2	0.0000%	0.0018%
500-510	1	3	0.0001%	0.0003%	1	1	0.0008%	0.0009%
510-520	0	2	0.0000%	0.0002%	0	2	0.0000%	0.0018%
520-530	1	0	0.0001%	0.0000%	1	0	0.0008%	0.0000%
530-540	2	0	0.0001%	0.0000%	1	0	0.0008%	0.0000%
540-550	0	2	0.0000%	0.0001%	0	1	0.0000%	0.0009%
550-560	0	1	0.0000%	0.0001%	0	1	0.0000%	0.0009%
560-570	0	0	0.0000%	0.0000%	0	0	0.0000%	0.0000%
570-580	1	0	0.0000%	0.0000%	1	0	0.0008%	0.0000%
580-590	0	3	0.0000%	0.0002%	0	2	0.0000%	0.0018%
590-600	1	0	0.0001%	0.0000%	1	0	0.0008%	0.0000%
600-610	0	0	0.0000%	0.0000%	0	1	0.0000%	0.0009%
610-620	0	0	0.0000%	0.0000%	0	0	0.0000%	0.0000%
620-630	0	0	0.0000%	0.0000%	0	1	0.0000%	0.0009%

Table 4: Distribution of traffic over flight level bands

7.1.3 Contrail zone avoidance algorithm

Due to the very large contrails zones, it was anticipated that a simple avoidance algorithm would not be adapted to deal with all flights from the data set. Nevertheless, it was decided to confirm this issue through several simulations (i.e. two traffic days).

In the scope of the simulation experiment, three approaches to contrails zone avoidance were proposed as an initial ATM action. As foreseen, once the simulations had been executed, it became very clear that the approach was too simplistic. Indeed, when considering the high contrails risk days, where zones are seen to be covering the entire European region between FL340 and FL400, it is very clear that avoidance using around or above is all but impossible.

When looking further into the concept of avoiding these zones, given that the majority of traffic in the region is either originating or terminating at a European airport – which is covered by the contrails zone, it is practically impossible to fly over such a zone (the airport is below it!) or around such a zone. Thus the only interesting option was to look at keeping traffic below the zone.

Furthermore, since the size of the zone would vary at each flight level (from the Contrails gridded data approach), several layered avoidance zones resulted, so the algorithm had to be further refined to continue to avoid zones at different flight levels until a clear profile could be found.

Given the variety of issues relating to the use of too simplistic avoidance algorithms, and the fact that for the majority of traffic, only one of the avoidance mechanisms could be applied (i.e. *below*), we restricted the environmental assessment to consider only two of the 10 traffic days – September 17 (high contrails) and October 18 (low contrails).

7.2 Environmental assessment – Impact on emissions

Overall totals for each day were computed for each scenario and compared to *baseline*. Results of the comparison are presented in the tables below and expressed in percentages obtained by the ration:

$$\frac{\text{Avoidance} - \text{Baseline}}{\text{Baseline}}$$

7.2.1 Overall results

Table 5 and Table 6 present overall results considering all the flights of the data set as defined in section 6.8.

Date	Number of flights	Δ Duration (s)	Δ Distance (km)	Δ Fuel burn (kg)	Δ NO _x (kg)	Δ CO (kg)	Δ HC (kg)	Δ H ₂ O (kg)	Δ CO ₂ (kg)	Δ SO _x (kg)
Around vs Baseline										
20040917	22429	1.70	0.18	2.35	0.07	0.00	0.00	2.89	7.39	0.00
20041018	20221	148.48	27.84	145.44	2.01	0.57	0.06	178.89	458.00	0.12
Above vs Baseline										
20040917	22429	12.33	0.47	1.94	-0.08	0.26	0.03	2.39	6.12	0.00
20041018	20221	10.29	0.29	4.20	0.00	0.14	0.02	5.17	13.22	0.00
Below vs Baseline										
20040917	22429	2.53	0.36	0.81	0.10	-0.04	0.00	0.99	2.54	0.00
20041018	20222	1.24	0.10	-3.42	0.02	0.06	0.00	-4.21	-10.78	0.00

Table 5: Avoidance scenarios vs. baseline comparison – absolute figures

Date	Number of flights	Δ Duration (%)	Δ Distance (%)	Δ Fuel burn, CO ₂ , H ₂ O, SO _x (%)	Δ NO _x (%)	Δ CO (%)	Δ HC (%)
Around vs Baseline							
20040917	22429	0.05%	0.03%	0.09%	0.24%	0.01%	-0.15%
20041018	20221	4.27%	4.17%	6.01%	7.16%	3.17%	3.41%
Above vs Baseline							
20040917	22429	0.35%	0.07%	0.08%	-0.27%	1.37%	1.44%
20041018	20221	0.30%	0.04%	0.17%	0.00%	0.79%	0.93%
Below vs Baseline							
20040917	22429	0.07%	0.05%	0.03%	0.36%	-0.20%	-0.21%
20041018	20222	0.04%	0.01%	-0.14%	0.07%	0.36%	0.26%

Table 6: Avoidance scenarios vs. baseline comparison – %

These tables are not representative of the real impact of high contrails-risk airspace volumes avoidance because most of the high number of flights missing at least one avoidance. The data set has to be filtered to provide more accurate results.

7.2.2 Restriction of the data set to "correctly manoeuvring" flights

Due to huge high contrails-risk airspace volumes, an overwhelming majority of the flights were not able to avoid all the contrails zones encountered. Only for several flight were all avoidance requested correctly performed for all the scenarios. For the analysis, the traffic sample is reduced to those flights only.

Table 7 and Table 8 below show results from the comparisons of *Around/Above/Below* scenario versus *Baseline*.

Date	Number of flights	Δ Duration (s)	Δ Distance (km)	Δ Fuel burn (kg)	Δ NO _x (kg)	Δ CO (kg)	Δ HC (kg)	Δ H ₂ O (kg)	Δ CO ₂ (kg)	Δ SO _x (kg)
Around vs Baseline										
20040917	32	72.47	-3.65	166.99	3.34	-0.91	-0.31	205.40	525.85	0.14
20041018	179	1408.34	256.23	1778.26	30.13	6.26	0.86	2187.25	5599.73	1.49
Above vs Baseline										
20040917	32	28.97	0.17	2.42	-0.22	1.13	0.14	2.97	7.61	0.00
20041018	179	44.50	0.25	23.94	0.29	1.11	0.14	29.45	75.39	0.02
Below vs Baseline										
20040917	32	7.84	0.93	-53.74	0.19	0.40	0.06	-66.10	-169.24	-0.05
20041018	179	5.73	0.03	-70.29	-0.21	1.12	0.13	-86.46	-221.35	-0.06

Table 7: Avoidance scenarios vs. baseline comparison – absolute figures

Date	Number of flights	Δ Duration (%)	Δ Distance (%)	Δ Fuel burn, CO ₂ , H ₂ O, SO _x (%)	Δ NO _x (%)	Δ CO (%)	Δ HC (%)
Around vs Baseline							
20040917	32	1.41%	-0.32%	3.23%	5.58%	-3.93%	-14.77%
20041018	179	26.50%	22.55%	32.40%	42.61%	27.98%	39.09%
Above vs Baseline							
20040917	32	0.56%	0.02%	0.05%	-0.37%	4.86%	6.46%
20041018	179	0.84%	0.02%	0.44%	0.42%	4.96%	6.28%
Below vs Baseline							
20040917	32	0.15%	0.08%	-1.04%	0.32%	1.73%	2.90%
20041018	179	0.11%	0.00%	-1.28%	-0.30%	5.01%	5.71%

Table 8: Avoidance scenarios vs. baseline comparison – %

The number of remaining flights is very low and not statistically reliable. Nevertheless, results let foresee some trends.

Regarding the precision of the results, no definitive conclusion can be derived from figures close to 0%. Nevertheless, results seems to indicate that flying above contrail zones would be slightly more penalizing for environment during a low contrail day. Less NO_x would even be emitted during the high contrails day but this statement needs to be confirmed by a more statistically reliable set of flights.

The same is true when flying below contrail zones. As expected, extra CO and HC are produced when flying below contrail zones.

A comparison of *Around* scenario versus *Baseline* gives more interesting results: much more fuel burn and emissions are observed when performing horizontal avoidance. This tendency is probably due to the significant extra distance to be flown to avoid contrail zones and extra time spent in Cruise mode, while other options mostly have an influence on the kind of emission (climbing/descending phases replacing cruising phases).

This information is striking for the low contrails sample. The analysis of extra traffic day would determine whether 17th of September was an exception or is representative of high contrail days.

It has to be underlined that the negative value obtained in 'Distance' column for *Around* option indicates that portion of flights are rerouted outside of the geographical zone. This means that the impact on fuel burn and emissions is higher than indicated in Table 7 and Table 8, since these tables only consider the situation inside the study geographical area.

7.2.3 Breakdown by aircraft type

A breakdown per aircraft type was performed. Nevertheless the results do not appear here since they didn't lead to any conclusion.

Indeed, no aircraft type distanced itself from the other by better avoidance possibilities. More determining is flight altitude. Aircraft using lower flight levels logically meet less huge contrail zones.

The aircraft type doesn't seems to have any visible effect on the contrail avoidance strategy.

7.2.4 Breakdown by departure and arrival airport location

A break down based on location of departure and arrival airport regarding the geographical area of the study was done. The idea was to test the hypothesis that the behaviour of flights toward scenarios depending on whether departure and arrival airports are inside or outside the study area is different.

Average percentages of difference between scenarios are presented in Table 9.

Departure airport	Arrival airport	Number of flights	Δ Duration (%)	Δ Distance (%)	Δ Fuel burn, CO ₂ , H ₂ O, SO _x (%)	Δ NO _x (%)	Δ CO (%)	Δ HC (%)
Around vs Baseline								
InZone	InZone	42	30.57%	20.94%	42.28%	56.14%	30.83%	39.62%
InZone	OutOfZone	114	13.45%	11.54%	21.04%	28.24%	8.00%	22.33%
OutOfZone	InZone	54	10.37%	11.85%	7.31%	7.95%	13.56%	9.33%
OutOfZone	OutOfZone	7	-2.55%	-5.87%	-6.30%	-0.42%	-22.63%	-43.56%
Above vs Baseline								
InZone	InZone	42	0.03%	-0.14%	0.90%	1.17%	0.40%	2.35%
InZone	OutOfZone	114	0.86%	0.04%	0.10%	-0.05%	7.48%	7.79%
OutOfZone	InZone	54	0.94%	0.09%	1.78%	2.57%	2.17%	3.08%
OutOfZone	OutOfZone	7	0.56%	0.00%	0.01%	-0.91%	5.22%	9.16%
Below vs Baseline								
InZone	InZone	42	0.09%	0.01%	0.54%	0.74%	-0.09%	-0.31%
InZone	OutOfZone	114	0.15%	0.07%	-1.68%	-0.46%	7.01%	7.69%
OutOfZone	InZone	54	0.09%	0.01%	-2.61%	-1.88%	1.46%	2.34%
OutOfZone	OutOfZone	7	0.17%	-0.03%	2.94%	4.46%	-4.45%	0.13%

Table 9: Avoidance scenarios vs. baseline comparison – break down per airport location

It comes out of Table 9 that, inside the studied zone, horizontal avoidance (i.e. *Around* scenario) leads to a gain for all the quantities addressed for flights crossing the geographical area.

On the opposite, flights taking-off and landing inside the study area produce a significant increase of all pollutants and fuel burn (42% increase on average for all pollutants plus fuel burn). This increase is even higher than the percentage of extra time and distance flown.

Flights taking-off or landing in the zone produce less extra fuel burn and emissions than the previous category, with take-off in study zone being a disadvantage.

This means that, due to horizontal high contrails-risk zones avoidance, aircraft have to make detours at low altitudes, when fuel consumption and NO_x are high (climbing phases) and CO and HC emissions are significant (descending phases).

Both *Above* and *Below* scenarios do not show the same tendency.

The *Above* scenario results in an increase in almost all emissions and fuel burn, wherever departure and arrival airports are located. No noteworthy trend comes out of results for this scenario.

As far as the *Below* option is concerned, aircraft landing in the study area produce less impact on environment due to contrails avoidance. If in addition taking-off out the study zone, the average percentage over all pollutants plus fuel burn is negative, which translates into a slight saving of fuel burn and emissions.

The most penalising airport combination concerns flights crossing the study zone. Nevertheless no significant difference regarding other percentages for this scenario allow to draw any conclusion.

7.2.5 Conclusion on impact of emissions

As a conclusion, no definitive trend in favour of one scenario comes out of this analysis. The impact of aircraft type is affected by individual flights trajectories regarding contrail zones while airports location influences mainly the *Around* option. Avoidance efficiency would have to be considered case by case, eventually with a combination of two or three options.

Nevertheless, generally speaking, the *Around* option seems to produce significantly more additional fuel burn and emissions than *Baseline* and other options. The *Above/Below* solutions seem to be the more favourable to environment.

An observation of high contrails-risk airspace volume plots (see Annex 2) leads to the following conclusion: contrail areas between FL350 and FL400 are so huge that they block avoidances.

- *Above* scenario would require aircraft to flight significantly higher, which is not realistic from an ATM point of view.
- *Around* scenario means very important detours to be made which is not worthwhile, at least for a high contrail day.
- *Below* scenario is the only realistic option since aircraft have "always" the possibility to reduce altitude to by-pass contrail airspace volumes.

As a result, *Below* option is the only viable one. Based on traffic samples and tools available for this study, the impact on environment is on the whole lower than for other avoidance options. The influence on contrail coverage may be determining in the assessment of this option.

7.3 Impact of H₂O emission on contrail formation

7.3.1 Contrail formation

Contrails are ice-crystal clouds that originate from aircraft exhaust emissions of particles and water. Contrails are commonly observed to have different life-times varying from the very short (typically a fast disappearing cloud the length of the aircraft) to the very long (when they may be persistent and eventually spread out to form a cirrus-like coverage) that is in its final form eventually indistinguishable from natural cirrus cloud.

Three main factors control contrail formation: water released from the combustion of fuel, ambient temperature, and relative humidity. The water released is a simple function of the amount of fuel burned at cruise altitudes. The specific design of a given engine may result in varying temperatures of the exhaust gases between engines and this will dictate whether a contrail is triggered or not for the same ambient temperature and humidity.

The formation of contrails arises from the increase in relative humidity that occurs during the mixing of the warm and moist exhaust gases from the aircraft engines with the colder and less humid ambient air. A contrail will form when saturation with respect to ice is reached or surpassed in the plume. The thermodynamic relation for contrail formation (Figure 9) requires knowledge of the air pressure, temperature, and relative humidity at a given flight level, as well as the fuel properties such as the emission index of H₂O, the combustion heat, and the overall aircraft propulsion efficiency. See Annex 2 of this report for the equations used by the Contrail Model and section 4.2 for details on MM5 and Contrail models.

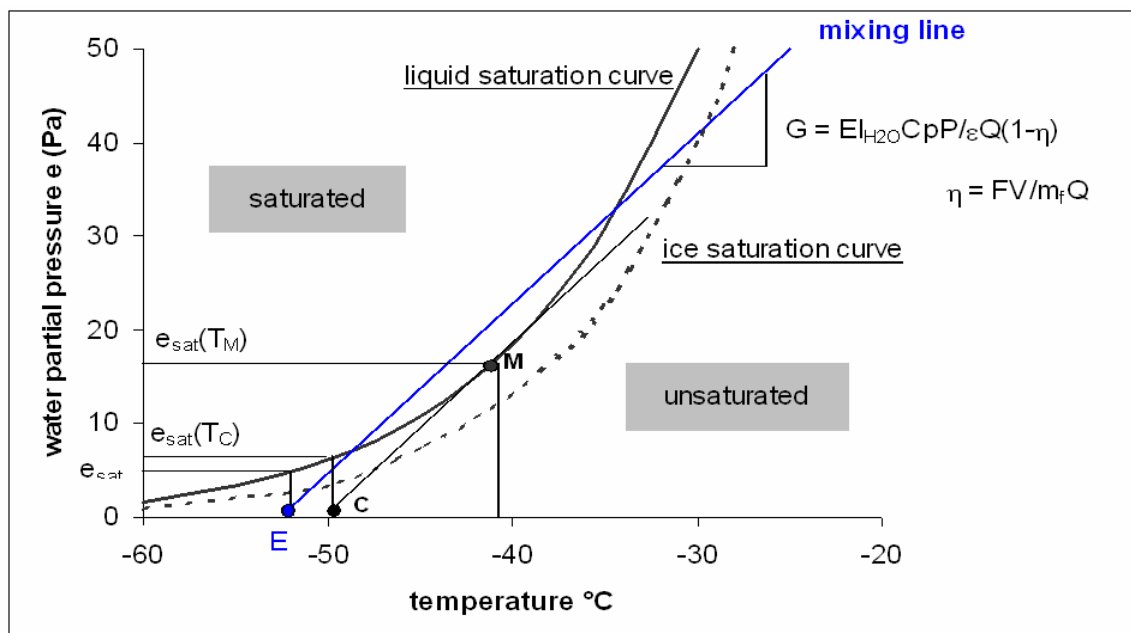


Figure 9: Thermodynamics Of Contrail Formation

7.3.2 Baseline Scenario: the CONTRAILS Project

The baseline scenario uses the output data from the CONTRAIL model which was used as part of a project, entitled “CONTRAILS: Aircraft Condensation Trails Monitoring Service”, between the European Space Agency (ESA), The EUROCONTROL Experimental Centre (EEC), the German Aerospace Centre (DLR), the Royal Netherlands Meteorological Institute (KNMI), and the Dundee Satellite Receiving Station (United Kingdom). The CONTRAILS project ([Ref 4.] & [Ref 15.]) seeks to support the continuous assessment of the environmental effects of increasing volumes of air traffic by monitoring the daily contrail and cirrus cloud coverage, for one year, over Europe and the North Atlantic. As part of this project, which focuses primarily on mapping observed contrails by satellite as well as on changes in cirrus cloud coverage, and on properties that can be related to changes in air traffic density, a complete and independent assessment of the EUROCONTROL CONTRAIL formation model shall be made by comparing model based contrail maps with the satellite derived contrail maps. The results described in this paper are based on the first stages of this assessment.

For this project, the EUROCONTROL Experimental Centre produced 60 days of contrail maps consisting of 6 days for each of January through October 2004 for each overpass of a weather satellite (NOAA 16 or NOAA 17, etc.) which can record the observation of contrails. The dates chosen for each month are the fixed dates, the 5th, the 14th, and the 23rd, plus 3 days chosen by DLR (one a “high” contrail day, i.e. a lot of observed contrails; a “low” contrail day, i.e. with very few observed contrails and a “medium” contrail day). The output is in NetCDF format with a grid size of 0.25° x 0.25° lat/lon grid. The geographical limits were 40°N-60°N latitude and 10°W-20°E longitude which allowed complete coverage by EUROCONTROL’s Correlated Position Reports (CPR) data.

7.3.2.1 Flight Data Used For AEM3

The flight data used as input for AEM3 in the CONTRAILS project were the EUROCONTROL Correlated Position Reports (CPR) provided by the Central Flow Management Unit (CFMU). These data contain the actual geographical position and altitude of each aircraft based upon based on radar tracks correlated with flight plan data and normally sent every minute. Figure 10 shows the typical daily geographical extent of EUROCONTROL’s CPR data for 2004.

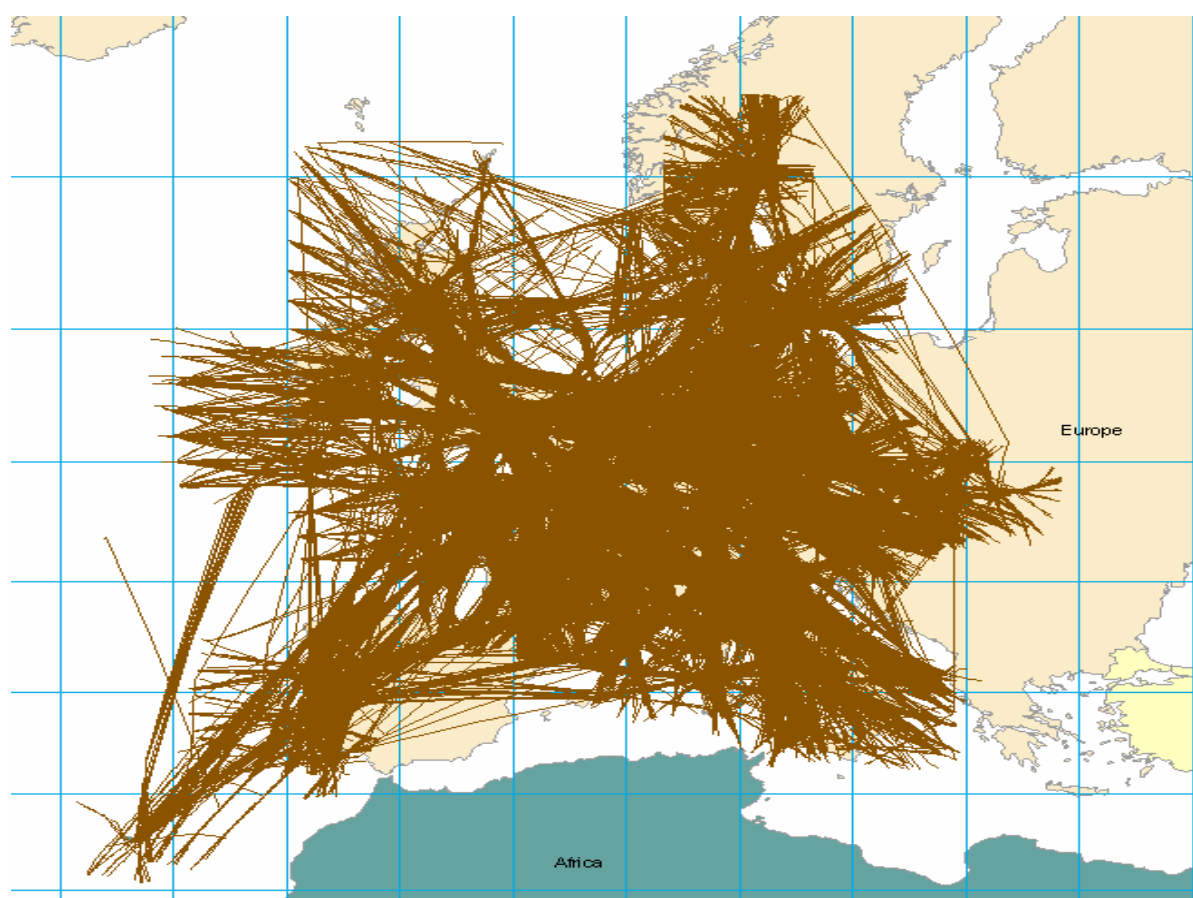


Figure 10: Typical Daily Extent Of EUROCONTROL's Correlated Position Reports (CPR) Radar Data.

7.3.2.2 Input Meteorological Data For MM5

The input meteorological data for MM5 for the CONTRAILS Project were the NCEP/DOE AMIP-II Reanalysis 2 gridded analysis data as well as the NCEP ADP Upper Air and Surface Observational Data.

7.3.2.2.1 NCEP/DOE AMIP-II Reanalysis 2

The NCEP/NCAR Reanalysis project uses a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present. There are over 80 different variables, (including geopotential height, temperature, relative humidity, U and V wind components, etc.) on 17 pressure levels (heights) on 2.5x2.5 degree grids, four times daily. The goal of Reanalysis-2 is to improve upon the NCEP/NCAR Reanalysis by fixing the errors and by updating the parameterizations of the physical processes.

7.3.2.2.2 NCEP ADP Upper Air Observational Data

NCEP ADP Global Upper Air Observation Subsets are a global synoptic set of 6 hourly upper air data reports. These were operationally collected by NCEP. They include radiosondes, pibals and aircraft reports received via the Global Telecommunications System (GTS) and satellite data from the National Environmental Satellite, Data, and Information Service (NESDIS). This data is the primary input to the Global Data Assimilation System (GDAS), which is used to make forecasts and the Global Final Analyses (FNL). It was also a major input for the NCEP/NCAR and ECMWF Reanalysis Projects. This data set includes upper air station data from land and ship-launched radiosondes. This involves, at 00Z and 12Z, about 650 - 1000 stations. It also includes satellite winds derived from cloud drift analysis and data from aircraft takeoff and landings with between 5000 and 10000 reports every 6 hours.

7.3.2.2.3 NCEP ADP Surface Observational Data

NCEP ADP Global Surface Observations are global synoptic set of 3 hourly surface data reports. These were operationally collected by NCEP. They include land and marine reports received via the Global Telecommunications System (GTS). This dataset is DSS' primary surface observation set. This data set includes these land surface station report types: SYNOP, METAR, AWOS and ASOS and also incorporates data from moving ships, fixed ships, MARS (moving and fixed) and buoy (moored and drifting).

7.3.3 Baseline Scenario CONTRAIL Model Output

Although the CONTRAILS project is still on-going, preliminary results are presented here in the form of two examples: one of a day with a lot of visible contrails over Central Europe and the other with very few contrails over the same area. This first example is of a day where many contrails were produced over central Europe.

7.3.3.1 Heavy Contrails Example: 18-03-2004

Contrails are produced in areas of high humidity and very low temperatures. The following Figure 11 shows the humidity and temperature plots (from Reanalysis 2) for 12Z 18-03-2004 at flight level 300.

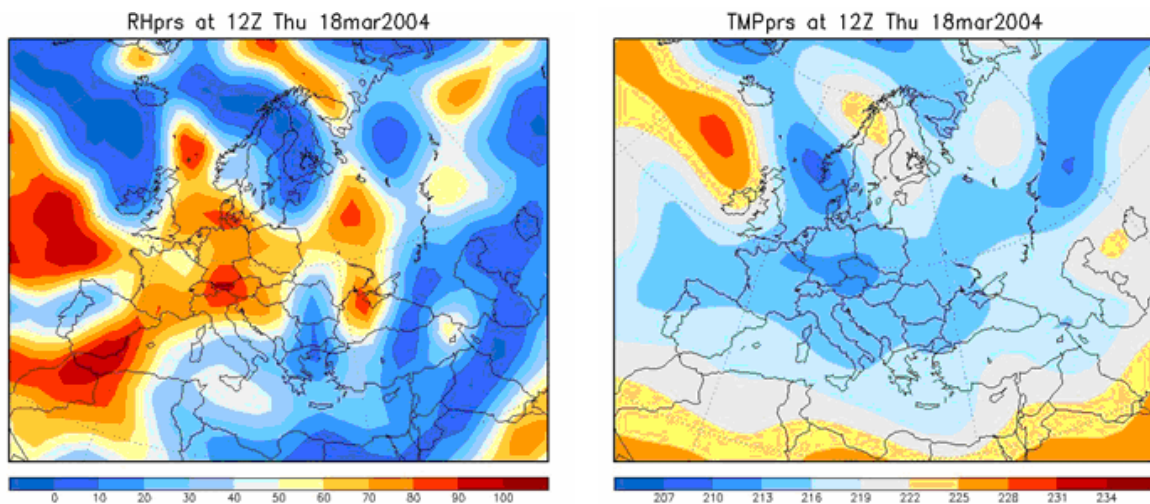


Figure 11: Relative Humidity (left) and Temperature (right) at FL 300: 12:00 March 18, 2004

The relative humidity plot (on the left) indicates areas of high humidity in red and the temperature plot (on the right) indicates areas of very cold air in blue. It can then be seen that the area above Central Europe is both very humid and very cold and this would then indicate that this area would be expected to produce contrails.

The following plots show the comparison of the CONTRAIL Model plot with the corresponding observed contrails from the satellite image over the same geographical area. The plot on the left shows where, on a map of Europe, contrails were modelled to be (using the Contrail Model). The plot on the right shows where, on a similar map and at the same scale, contrails were observed by satellite at the same time. Indeed, a very close correlation can be observed. The coloured boxes on the Contrail Model plots (left) are areas of "contrail density" (number of contrails per area) within a 0.25 degree latitude by 0.25 degree longitude grid cell.

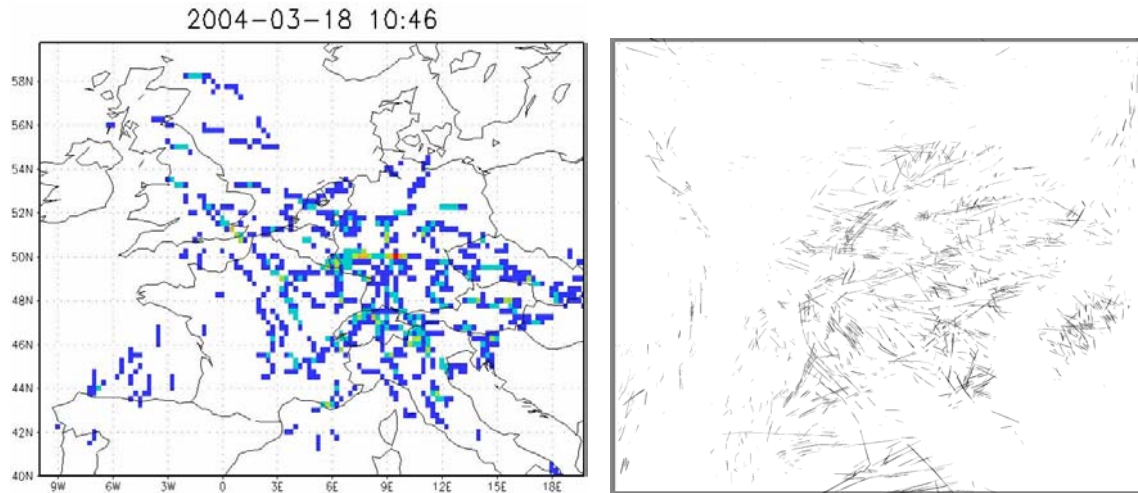


Figure 12: Modelled contrails (left) and observed contrails (right) at 10:46 March 18, 2004

7.3.3.2 Light Contrails Example: 09-03-2004

The second example is an example of a day where very few contrails were produced over central Europe. The humidity and temperature plots (from Reanalysis 2) for 12Z 09-03-2004 at flight level 00 are shown in Figure 13. It can be seen that the area over Central Europe is not very humid and not very cold which is the area where contrails are not expected. Rather, contrails would be expected over the ocean off the western coast of France.

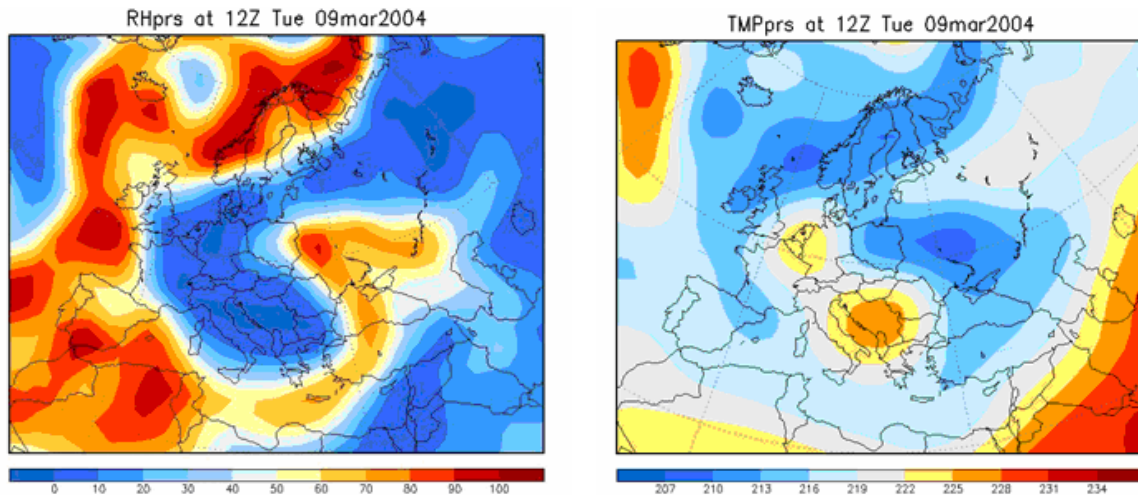


Figure 13: Relative Humidity (left) and Temperature (right) at FL 300: 12:00 March 09, 2004

As in the heavy contrails example, the following figures show the comparison of the Contrail Model plot with the corresponding observed contrails from the satellite image over the same geographical area. Again, a very close correlation can be observed.

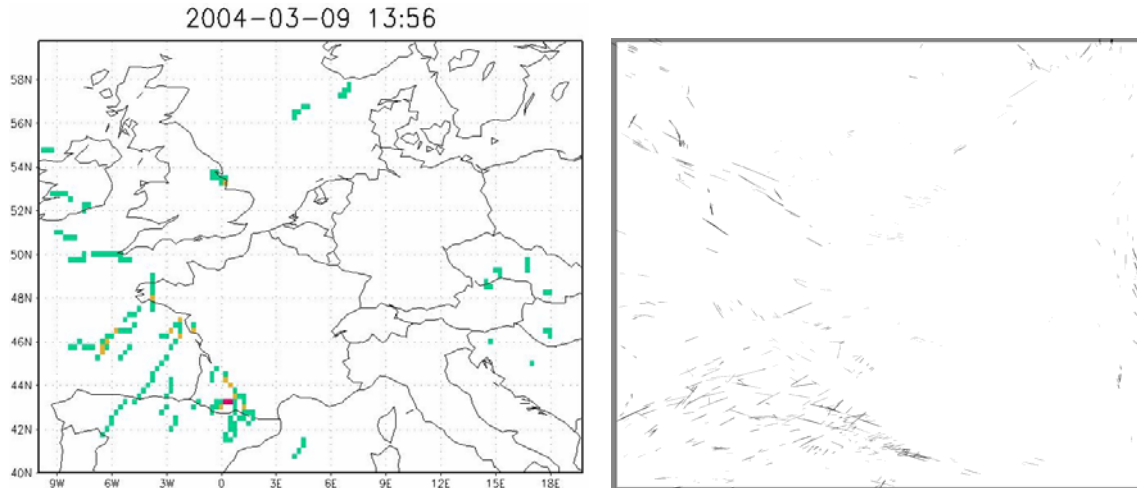


Figure 14: Modelled contrails (left) and observed contrails (right) at 13:56 March 09, 2004

7.3.4 Around / Above / Below Scenarios

The contrail model was run for 2 days, for each scenario, considering all the flights in the scenario. Also produced were contrail maps for the same satellite overpass times (a total of 135 maps) as the baseline scenario.

An estimation of contrail coverage for each scenario is shown below:

	Baseline				Around		
	Flight Legs >= FL240	Number of legs producing Contrails	% Contrail coverage		Flight Legs >= FL240	Number of legs producing Contrails	% Contrail coverage
20040917	158435	39572	24.98		157446	39077	24.82
20041018	144354	16611	11.51		143259	15321	10.69

	Above				Below		
	Flight Legs >= FL240	Number of legs producing Contrails	% Contrail coverage		Flight Legs >= FL240	Number of legs producing Contrails	% Contrail coverage
20040917	169481	46998	27.73		171401	41311	24.10
20041018	154075	19342	12.55		155996	17864	11.45

Table 10: Contrail percentages for each scenario

Percentage values indicate very little change for each scenario (briefly around 24% of the flight legs produced contrails on the high day (September 17) and around 10 % of the flight legs produced contrails on the low day (October 18)).

7.3.5 Sample Contrail Model Maps

The difference in contrail coverage for the four scenarios mentioned is demonstrated by a presentation of several of the maps produced by Contrail Model. The Contrail Model produced maps for each satellite overpass (135 in total). Presented here is one map per day for each scenario (the map closest to noon).

7.3.5.1 September 17:

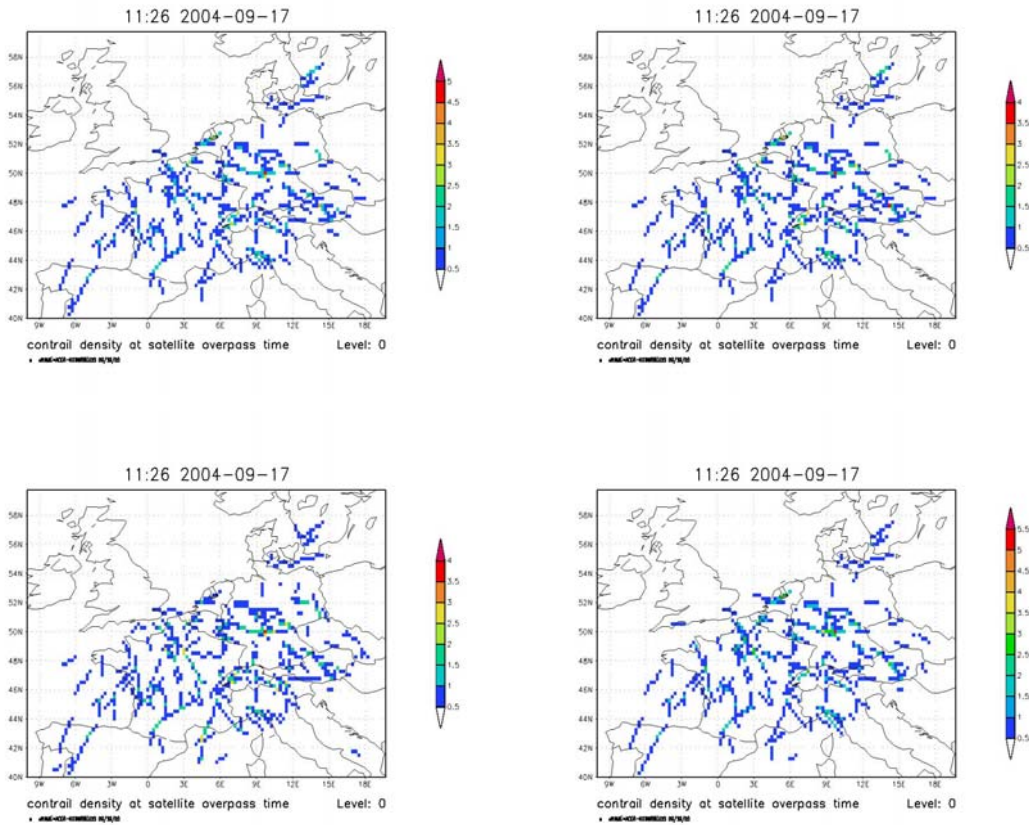


Figure 15: September 17: Scenario "Baseline" (Top Left), "Around" (Top Right), "Above" (Bottom Left), "Below" (Bottom Right)

7.3.5.2 October 18:

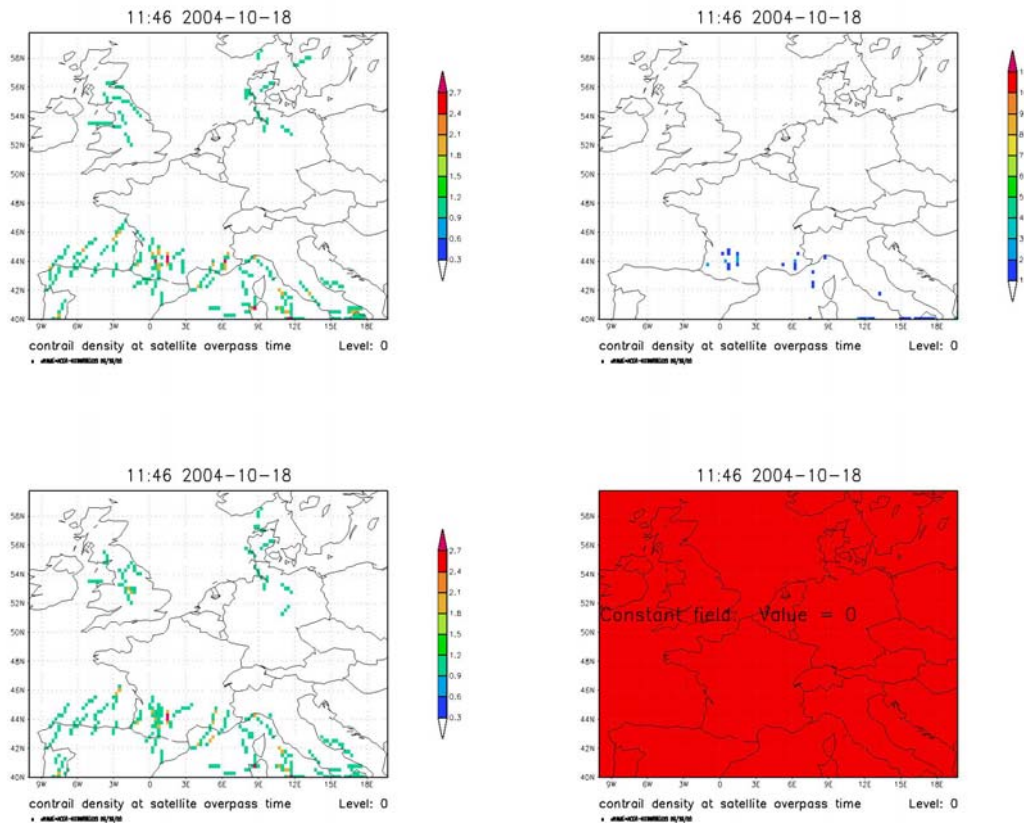


Figure 16: October 18: Scenario "Baseline" (Top Left), "Around" (Top Right), "Above" (Bottom Left), "Below" (Bottom Right)

Note that the plot felt in red indicate that all grids are equal to zero.

The maps indicate that there are far less visible contrails on the low day (October 18) for the *Below* and *Around* scenarios as compared to the *Baseline* scenario but similar contrail coverage to the *Baseline* scenario for the high day (September 17). This probably indicates that although the percentage of contrails is the same for *Baseline* and *Below/Around* scenarios, the contrails are probably much shorter lived in the *Below/Around* scenarios on the low day. Contrail lifetimes for the low day for the *Below* and *Around* scenarios must be probably only a few minutes in duration, which would cause them to disappear before the satellite overpass time (map time) and hence not be recorded on the map. Contrails of such short duration would be, environmentally speaking, innocuous.

7.4 Trade-Off

A comparison of each avoidance scenario with *baseline* gives an indication of the extra fuel burn and emissions to be supported to reduce contrails formation. The most efficient scenario in term of environmental impact was figured out through a comparison of avoidance scenarios two by two. The only viable scenario appeared to be *Below*. Percentage of difference when comparing *Below* versus *Baseline* do not indicate any significant increase of fuel burn or emissions.

In term of contrail coverage and based on all the flights in each traffic day (i.e. no subset of flight correctly avoiding contrail zones was created for the Contrails assessment), *Below* is the most economic scenario during the high contrails day. Even if less competitive as *Around* option during the low contrails day, contrail coverage obtained with *Below* option is lower than *Baseline*'s one. This initial aim is reached: the contrail coverage is reduced.

Hence on a contrail formation point of view, *Below* appears as well to be viable. A study on a larger set of flight avoiding correctly high contrails-risk zone would be necessary to confirm this result.

Nevertheless, as an environmental study, this document does not address all the items required to make a decision on the interest of *Below* option. Indeed, the establishment of *Below* avoidance option would lead to extra traffic below contrail zones. Possible consequences could be the following (not exhaustive list):

- Increase of traffic density,
- Increase of the number of conflicts and controller workload,
- Decrease of safety,
- Apparition of delays due to limited capacity of sectors.

An in depth complementary analysis of the impact of aircraft rerouting on safety, capacity and other ATM features is necessary to quantify drawbacks of contrail avoidance option and to confirm or infirm findings of this study.

In a real situation, aircraft would probably use a mix of the three avoidance scenarios considered in this study. The choice (*around*, *below*, *above*) would be made case by case, depending on many criteria such as weather, aircraft performances, fuel burn needed for the avoidance, etc. The resulting impact on environment would thus be an average between the results from the three avoidance scenarios.

Anyway, as the actual impact of contrails formation on environment is not precisely estimated by the scientific community today, no definitive conclusion can be made and no trade-off can be advised from the current study. This aspect should be detailed once the impact of contrails on the environment will be completely handled.

8. OUTPUT SENSIBILITY ANALYSIS

This chapter aims to indicate the level of confidence in the absolute figures obtained by AEM3 for this study. The results depend strongly on the quality of the input data, the quality of the underlying databases for engines, aircraft performance and fuel burn, and the realism of the applied methods to estimate the emission output in the AEM3 model. For a more detailed analysis of the level of confidence in AEM3, see "AEM3 Validation Report" [Ref 19.].

8.1 CO₂, H₂O, SO_x estimation with AEM3

The emissions for CO₂, H₂O and SO_x are directly proportional to the fuel burn. Any error level estimated for the fuel burn estimation will propagate, for that reason, for exactly the same level, into the results for those pollutants. The emission coefficients representing the degree of proportionality between fuel burn and the above pollutants were based on an in-depth literature review [Ref 17.]. There is only a slight variation for those coefficients in the different literature sources, and the values applied for this study have been qualified reasonable by a variety of domain experts.

Pollutant	Current Study	Max	Min	Max %	Min %
	(kg/kg fuel)			(%)	
CO ₂	3.149	3.22	3.1	2.25	-1.56
H ₂ O	1.23	1.25	1.17	1.63	-4.88
SO _x	0.00084	0.0012	0.000267	42.86	-68.21

Table 11: Variation in published coefficients for fuel proportional emissions (%)

The above table indicates the variation for the different coefficients in the different literature sources compared to the coefficients applied in this study. The variation indicates at the same time the level of error, which may apply to the results through the emission coefficients used for CO₂, H₂O, and SO_x estimations of this study.

8.2 NO_x, HC, CO estimation with AEM3

The estimation of the level of realism for the NO_x, HC and CO emissions calculated by AEM3 is based on information available from several other research projects, since real data for validation purpose is not available directly.

Note that VOC and TOG are assumed to be proportional to HC² and therefore suffer from the same level of error and sensibility as HC.

² VOC and TOG are based on e.g. average US EPA chemical specification factors for jet engine emissions, but they can vary between engines and for different fuel composition of kerosene.

8.2.1 NASA study

A NASA study [Ref 18.] provides an internal distribution between NO_x, CO and HC for a total mission (Taxi-Out to Taxi-In) of a B757-200, for standard mission ranges of 400 and 3000 nautical miles:

- NO_x 90 to 72.5%,
- CO 25 to less than 10%,
- HC 2.5 to less than 1%.

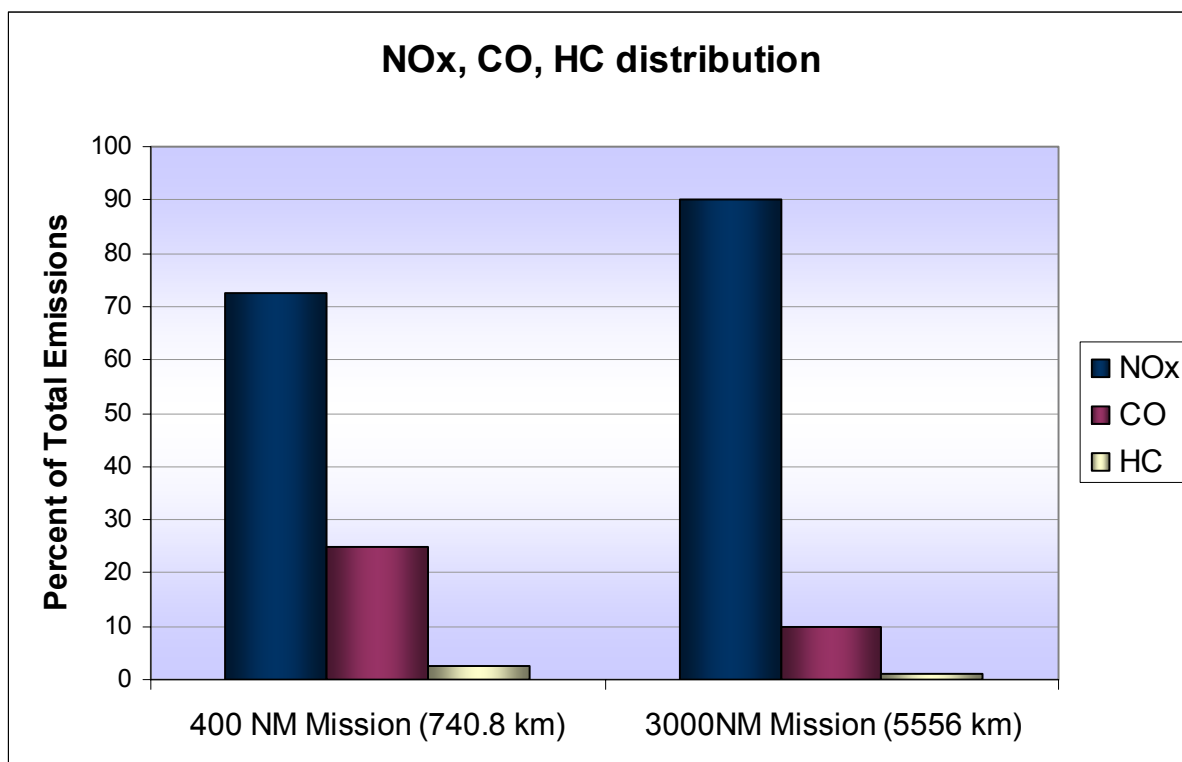


Figure 17: Emissions Comparison of 757-200 for 400 NM and 3000 NM Mission

By comparison, Figure 18 represents the distribution of average NO_x, CO and HC in the total emissions for the current study (2004's scenario), for an average distance flown in the geographical study's area lying between 680 and 700 km, depending on scenarios. Note that flight profiles are not complete in this study. Therefore the notion of mission range is cannot be used.

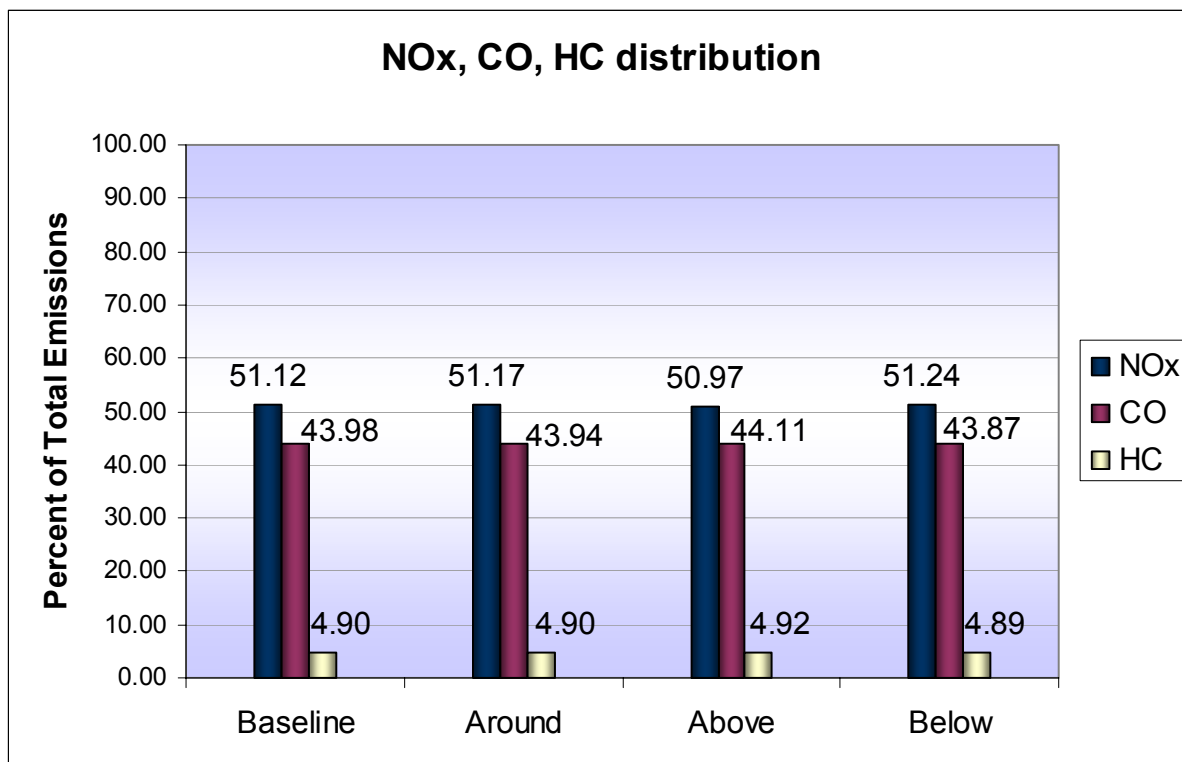


Figure 18: Emissions Comparison of overall traffic – Average of 4 scenarios

The distributions for the current study indicate a higher proportion of CO and HC than the reference information published by NASA. This phenomenon is mainly due to the fact that unlike NASA's traffic used for estimations, flights in the study are not necessarily complete (only 7.5% of complete flights). Moreover the average mission distance is shorter than NASA's missions, which amplifies the proportion of CO and HC: "Cruise" phase represents on average only 45.6% of a flight.

NO_x is mainly exhausted during climb and cruise phase (high engine trust setting) while CO and HC are characteristic from descent phase (low engine trust setting). In the data set under study, a portion of flight is missed at low level, especially take-off and climb-out phases where a lot of NO_x is emitted. In parallel, even if CO and HC exhausted during landing phase are ignored, the significant amount of CO and HC exhausted during landing phase, when aircraft begin the descent phase, are part of the study. The proportion of CO and HC taken into account in this study is thus relatively higher compared to the NO_x proportion, as reflected by Figure 18.

The influence of scenario on the results is no significant. Management of avoidance in particular for *Above* scenarios is responsible for the slightly decrease of NO_x and increase of CO and HC proportion: during rerouting, aircraft climb rapidly to fly over a contrail zone but descend slower after the avoidance to joint the initial flight level. Due to this longer descent phase, CO and HC proportion increase.

The "AEM3 validation report" [Ref 19.] confirmed that the distribution given by AEM3 for complete flights and nominal engine use is of high realism and very close to NASA's distribution.

8.2.2 NO_x average emission indices from ANCAT and NASA inventories

NASA and ANCAT researchers analysed the NO_x emissions estimation for larger traffic samples. They put the calculated amount of NO_x emissions in relation to the estimated amount of fuel burn by those traffic scenarios, to obtain an indication for average NO_x Emission Indices. This analysis led to the following estimations for average NO_x Emissions Indices (EINO_x) in g per kg fuel burn:

	ANCAT 1A	ANCAT 2	NASA	NASA
	1992	1992	1990	1992
Horizontal resolution (°)	2.8 × 2.8	1 × 1	1 × 1	1 × 1
Vertical resolution (km)	1	1	1	1
EINO _x (g/kg)	16.8	13.7	10.9	11.1

Table 12: Published average EINO_x (g/kg fuel) of reference projects [Ref 20.]

ANCAT 1A results were obtained using a thermodynamic NO_x emission model. This model was replaced during ANCAT 2 by the DLR NO_x estimation method. NASA results are based on Boeing Method 1 and Method 2.

A comparison by Rolls-Royce experts between the Boeing Method 2 and the DLR NO_x emission method indicates a difference of 3.6 %, with the DLR method giving the higher NO_x estimation.

The results published in the present report are obtained using AEM3, which applies a modified version of Boeing Method 2 (see Annex 1 "Boeing method 2 – EUROCONTROL Modified"). The modification compared to the original Boeing Method 2 covers a correction in the formula to correct for humidity at flight level.

A brief comparison during earlier studies, between DLR method, Boeing Method 2 and the EUROCONTROL modified Boeing Method 2 (EEC-BM2) indicates DLR method to deliver 4.28 % higher results than the Boeing Method 2 and 3.56 % higher results than the EEC-BM2.

Average EINO_x in g/kg fuel obtained in this study are presented in Table 13.

Scenario	Baseline	Around	Above	Below
20040917	10.40	10.40	10.38	10.42
20041018	10.29	10.32	10.28	10.30
Average	10.34	10.36	10.33	10.36

Table 13: Average EINO_x (NO_x/fuel) in g/kg fuel

As noticed in the previous section, scenarios don't have a significant impact on EINO_x. EINO_x follows exactly the percentage of NO_x obtained in the previous section if scenarios are compared. EINO_x is higher during high contrail day but this difference comes from the different traffic used and not from the contrail coverage.

The average EINO_x obtained in this study lies at 10.4 g/kg fuel burnt. These results are about 6.3 % lower than NASA results from 1992, and 24.1 % lower than ANCAT2 results.

Averaged EINO_x obtained for this study are close to NASA and ANCAT2 range of value. Nevertheless this value should read slightly higher if complete flight profiles were considered in the study. Moreover the average distance flown in the study is short (680 to 700km). The NASA and ANCAT values presented in Table 12 were obtained with a much more complete and varied data set.

8.2.3 Conclusion on NO_x, CO and HC estimation

In brief, the differences observed between reference (i.e. NASA and ANCAT) emission indices and NO_x, CO and HC quantities obtained in this study lie mainly in the shape of flight profiles. On average, flight phases in the dataset are distributed as follows:

- 26.5% of time spent in Climb phase
- 45.6% of time spent in Cruise phase
- 27.9% of time spent in Descent phase

On a flight scale, most of the NO_x is usually emitted during a long Cruise phase while emitted in a lesser extent during the proportionally short Climb phase. As opposed to this general trend, in this study, Climb phase is proportionally long regarding Cruise phase. 61% of NO_x is emitted during Climb phase while Cruise phase is responsible for 35.4% of the emission of NO_x. The total quantity of NO_x emitted during the flight is thus high, even if the proportion of NO_x regarding CO and HC is lower than observed by NASA (see 8.2.1). This is why the average EINO_x obtained in section 8.2.2 corresponds to the expectation.

In the same time 27.9% of flight time is spent in Descent phase. This is much higher than usually observed with longer flight profiles and explains the high proportion of CO and HC emission highlighted in section 8.2.1.

The estimation of NO_x, CO and HC emission with AEM is thus reliable.

8.3 MM5 Output sensibility analysis

The Penn State/NCAR Mesoscale Meteorological Model (MM5) is designed for high-resolution simulations or forecasts of mesoscale atmospheric circulation with four-dimensional data assimilation [Ref 21.]. This model has been used for real-time forecasting on small scales, process studies, sensitivity studies, and climate studies. The MM5 includes a finite difference formulation of the time-dependent Navier Stokes equations plus physics computations for the simulation of clouds, radiation, moist convection, etc. in a cubic three-dimensional region representing the atmosphere [Ref 22.].

Verification of MM5 model output is essential for diagnosing errors in model physics and ascertaining model biases and consistency and many hundreds studies have been performed over the 30 years since the development of MM5 [Ref 23.].

In recent studies (Tesche et al., 2001b [Ref 24.]; Emery et al., 2001 [Ref 25.]), an attempt has been made to formulate a set mesoscale model evaluation benchmarks based on the most recent MM5 performance evaluation literature. The purpose of these benchmarks is not to assign a passing or failing grade to a particular meteorological model application, but rather to put its results into a useful context. These benchmarks may be helpful to decision-makers in understanding how poor or good their results are relative to the range of other model applications.

Based upon the above considerations, the benchmarks suggested from these studies are as follows [Ref 26.]:

<i>Parameter</i>	<i>Measure</i>	<i>Benchmark</i>
<u>Wind Speed</u>	RMSE:	$\leq 2 \text{ m/s}$
	Bias:	$\leq \pm 0.5 \text{ m/s}$
	IOA:	≥ 0.6
<u>Wind Direction</u>	Gross Error:	$\leq 30 \text{ deg}$
	Bias:	$\leq \pm 10 \text{ deg}$
<u>Temperature</u>	Gross Error:	$\leq 2 \text{ K}$
	Bias:	$\leq \pm 0.5 \text{ K}$
	IOA:	≥ 0.8
<u>Humidity</u>	Gross Error:	$\leq 2 \text{ g/kg}$
	Bias:	$\leq \pm 1 \text{ g/kg}$
	IOA:	≥ 0.6

Another approach to verification of MM5 is being used by the Pacific North West (PNW) Realtime MM5 group at the University of Washington to verify MM5 model output directly with observations that have been quality controlled [Ref 27.].

At present, verification is done with surface observations data. These include:

Over 1000 surface observations over the northwestern United States.

Verification is performed for the following:

- Temperature,
- Relative Humidity,
- Wind Speed,
- Wind Direction,
- Sea Level Pressure (surface stations only),
- Rainfall (6-hour and 24-hour totals).

Differences are calculated by subtracting observed values from model-predicted values. The analysis of the Mean Absolute Error (MAE) of temperature for MM5 (and other models ETA and GFS) over the previous 2 years shows a MAE of 2.0-3.5 K.

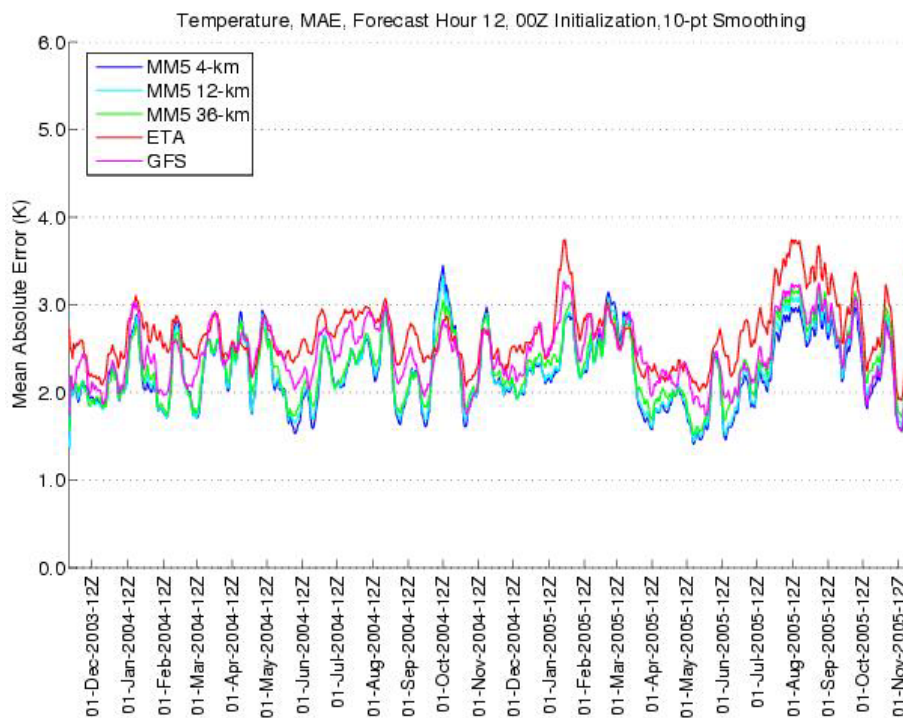


Figure 19: Mean Absolute Temperature Error: Observations versus Modelled [Ref 27.]

The analysis of the Mean Absolute Error (MAE) of Relative Humidity for MM5 (and other models ETA and GFS) over the previous 2 years shows a MAE of 10-20%.

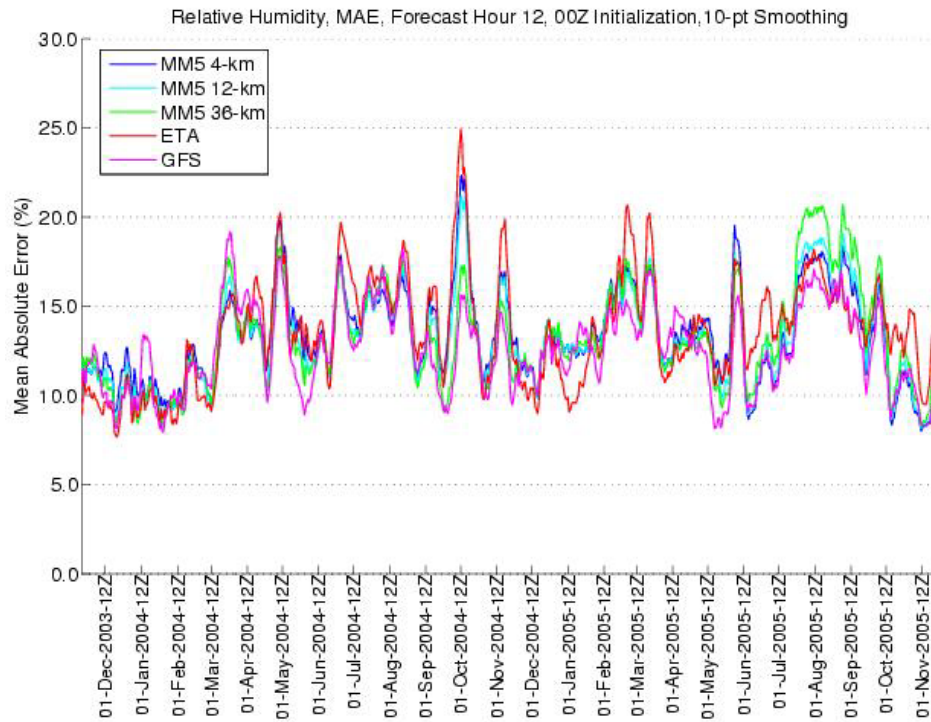


Figure 20: Mean Absolute Relative Humidity Error: Observations versus Modelled [Ref 27.]

The analysis of the Mean Absolute Error (MAE) of wind speed shows a MAE of 1.5–2.0 knots.

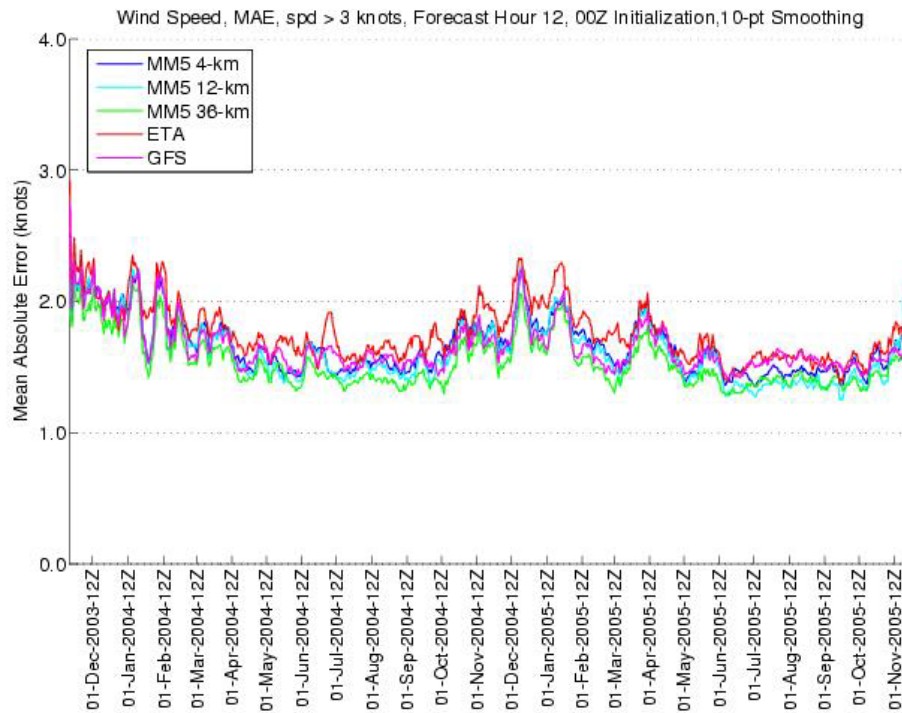


Figure 21: Mean Absolute Wind Speed Error: Observations versus Modelled [Ref 27.]

The analysis of the Mean Absolute Error (MAE) of wind direction (speed > 3knots) shows a MAE of 50-65 degrees.

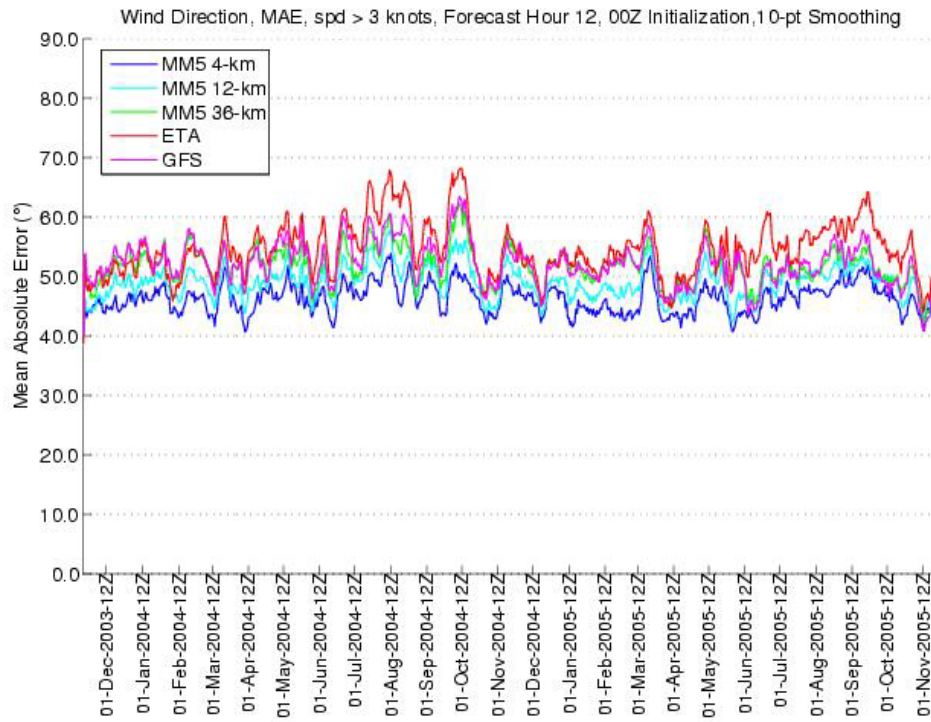


Figure 22: Mean Absolute Wind Direction Error: Observations versus Modelled [Ref 27.]

The analysis of the Mean Absolute Error (MAE) of sea-level pressure shows a MAE of 0.5–1.0 hPa (mb).

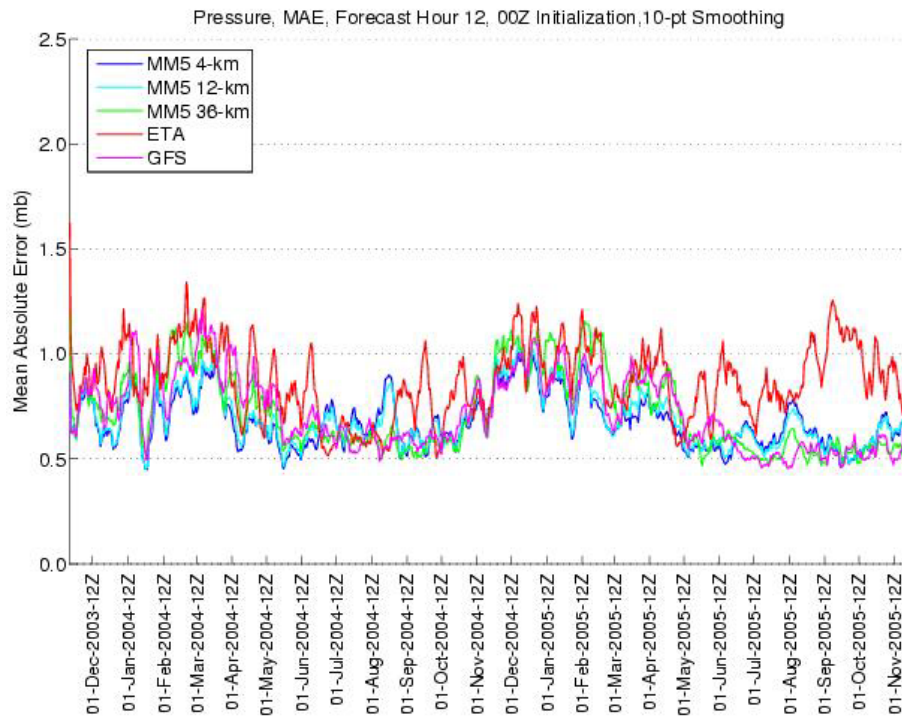


Figure 23: Mean Absolute Sea-Level Pressure: Error Observations versus Modelled [Ref 27.]

The analysis of the Mean Absolute Error (MAE) of precipitation shows a MAE of 0.01–0.04 inches.

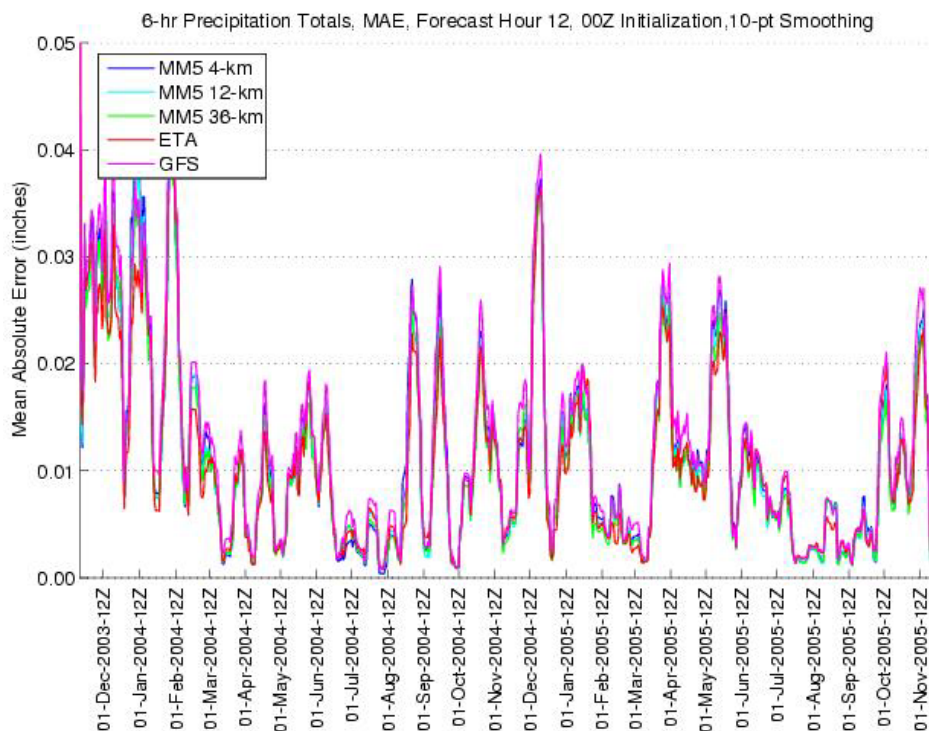


Figure 24: Mean Absolute Precipitation Error: Observations versus Modelled [Ref 27.]

8.4 CONTRAIL Model sensibility analysis

It should be noted that the error analysis above was for MM5 in “Forecast” mode. That is to say, MM5 was given initial observed data and then was run to generate a weather prediction. In the case of providing input meteorological data for the Contrail model, MM5 was run in “Hindcast” mode. In this case, because MM5 was used to re-create a weather scenario, real observed data was provided initially, as well as, during the MM5 run. The Mean Absolute Error (MAE) between observed and modelled data would be much smaller because in this case MM5 was being continually “corrected” with observations. If, however, we use the benchmark error guidelines for predictions from above we can estimate the upper level of the error of Contrail calculations.

Noting that contrails are formed in cold-moist air and using the benchmark guidelines, two error analysis scenarios have been created: an “Over-Estimate” and an “Under-Estimate” scenario. These two scenarios have been run by changing the input meteorological data to. The Over-Estimate scenario is one where the temperature has been lowered by 2K and the humidity increased by 2 g/kg (as per guidelines). The Under-Estimate scenario has the temperature has been increased by 2K and the humidity decreased by 2 g/kg. This should give the outer limit to the error estimate. The two scenarios run each run for the low contrail day (October 18, 2004) and the high contrail day (September 17, 2004).

The results indicate that if the estimated error on MM5 has been taken into account the error on the estimation of the visual contrail coverage is between +7.57 to - 0.16 % for the high contrail day and between +3.05 and -1.15% on the low contrail day. One should keep in mind that the systematic difference between observations and MM5 may not be as high owing to the fact that MM5 was run in “hindcast” mode. Also, this assumes that for the over-estimate scenario, for example, there has been a systematic over estimation of temperature and a systematic over estimation of humidity at the same time. Realistically the error in visible contrail coverage should be less then indicated.

	Baseline		Over Estimate	Under Estimate	Over Estimate	Under Estimate
	FlightLegs	Contrails	Contrails		% Difference	
20040917	158435	39572	51564	39317	7.57	-0.16
20041018	144354	16611	21013	14947	3.05	-1.15

Table 14: Estimation of Contrail Model Error Limit

8.5 Creation of contrail polygon zones

Any error in the creation of the contrail polygon zones would be a function of two factors:

- the error in the Contrail Model with regard to the creation of the gridded “contrail potential” data,
- the error in the contrail zone polygon algorithm itself.

The estimation of the contrail calculation error in the Contrail Model with regard to meteorological data has been discussed above. In addition there may be a small error in using an idealized aircraft for the estimation of the gridded zones. This is because, of necessity, in the creation of the gridded contrail potential data an average value of the engine efficiency must be used. However since there should be, statistically, as many aircraft with an engine efficiency below the average as above, this error should not be great.

Errors in the contrail polygon zone algorithm, using the contrail potential data, would depend upon the efficiency of the algorithm itself, and especially the ability of converting "contrail potential" grids out of Contrail Model into RAMS avoidance polygons. However grid's granularity is high ($0.25^{\circ} \times 0.25^{\circ} \times 1000\text{ft}$) regarding contrail zone polygons' expanse and a slight approximation on polygon's outline has no impact on the results.

Any future studies on the creation of contrail potential zones and avoidance polygons could possibly reduce the size of the zones by placing stricter constraints upon the identification of contrails. That is to say, for instance, “contrail potential” could be defined as only those contrails which would have a lifetime of greater than a baseline value, say, 1-2 hours. This would include only the most persistent of contrails. This approach, however, would need to be tailored to the intended aims of the study.

9. CONCLUSIONS

Several problems were encountered during the project, which have direct impacts on the reliability of the study's results. Among the problems were the following:

- **Data source:**
CPR data used for this project hold on average one flight point per minute for traffic above all Europe. This generates a huge amount of data to handle all along the study process. Therefore an important time effort was necessary for RAMS, AEM and CONTRAIL Model simulations (>100 days).
- **Contrails Zone definitions:**
The algorithm used to determine contrail zones resulted in huge contrails risk zones that regularly covered the entire airspace area. It would be worth reviewing literature and contrails research to see if the algorithm can be refined, perhaps by only identifying zones where contrails would form and would last longer than a significant time period (e.g. 5-minute) and therefore result in long-term radiative forcing.
- **Avoidance algorithm:**
As detailed in section 6.1, the version of RAMS available at the beginning of the project allowed horizontal avoidance but no vertical avoidance algorithm was implemented. Due to the complexity of avoidance algorithm, and in particular the mechanism to convert from gridded data to multiple layered 4D restricted zones, several unsuccessful versions of the algorithm were coded and debugged before a stable version of the avoidance algorithm was obtained and validated.
Furthermore, the process used to create avoidance routes automatically in the tool is quite time-consuming and resulted in the simulation times becoming even higher. Nevertheless, the avoidance '*below*' algorithm and the '*around*' seemed to produce positive results for low-contrails days. Apart from flights that '*overfly*' the entire region, avoidance '*above*' was rarely able to be used. An improved algorithm which combines the avoidance mechanisms according to the characteristics of the flight in question may result in more useful results.

Due to problems encountered, some of the data was not usable for any analysis. In particular huge contrail zones made results at high altitude un-useable for any environmental analysis. However this study was an initial work package, with limited time and effort which covers basic aspects only.

As a consequence, this study would need further effort based on a more solid approach with focus on how to choose source data, which criteria should be used to create contrail zones and how the avoidance algorithm should be improved.

Nevertheless, even if difficulties were encountered during the project, reliable results based on a small scale of data were produced, which seem promising enough to perhaps justify a further study with the improvements suggested earlier taken into account.

The principal conclusions from the data that was useful and for the three scenarios investigated show that:

The *Below* avoidance technique appeared to be the only reasonable one to use.

For low contrails day, the *Around* option could be justified but only if the extra time/distance to fly does not lead to a significant increase of fuel burn and emissions. In the samples we used for this study, this was not the case since the limits placed on the max avoidance distance increase where quite generous, however, further investigation may lead to a different conclusion.

Since most of the flights either originate or terminate at airports that are (more often than not) entirely covered by contrails avoidance zones, the *Above* option was rarely able to be applied. Similarly, for the same reasons, the *Around* option was also difficult to apply in many cases.

This study is thus to be considered as an experiment and demonstrates that ATM Contrails mitigation study worth being continued. Based on this project's results, it is recommended to:

- review contrail filtering algorithm. With a better filtering (for example, on contrail lifetime), avoidance area might turn out to be divided into several smaller avoidance areas and thus allow easier re-routing. Moreover if contrail zones can be more precisely defined (e.g. based on the times restrictions), the analysis of high altitudes would become possible.
- review RAMS avoidance algorithm. A detailed 'intelligent' avoidance algorithm has to be defined in the specifications of a further study. This algorithm should allow to make decisions on rerouting, whatever the contrail airspace configuration is. 'All' the avoidance situations a flight could have to face should be included in order to deal with complete data sets. For example, the avoidance scenario (*Around/Above/Below*) could be chosen flight segment by flight segment depending on the manageable solution. Such a combination may be more efficient than a strict *Around*, *Above* or *Below* avoidance scenario.
- try to improve data source. Simulated or flight plan data could be used instead of CPR data to enlarge the study geographical area and reduce simulation times.

In addition, ATC could be included in a future study by considering, for example, sector capacity and the number of conflicts generated by contrails avoidance. The economical impact could also be estimated in term of fuel cost to airline as well as cost of emissions to the environment. Such aspects would enrich the study and help in the identification of the best contrails avoidance strategy.

ANNEX 1. BOEING METHOD 2 – EUROCONTROL MODIFIED

This annexe describes the EUROCONTROL modified Boeing Method 2 (EEC-BM2)

1 The original Boeing Method 2 (BM2)

The International Civil Aviation Organisation (ICAO) has established standards and recommended practices (Annex 16 to the ICAO Conference, "Environmental Protection") for the testing of aircraft emissions on turbojet and turbofan engines. The world's jet engine manufacturers have been required to report to ICAO the results of required testing procedures, which pertain to aircraft emissions. ICAO regulations require reporting of emissions testing data on the following gaseous emissions: NO_x, HC, CO and smoke. In addition to this, ICAO requires that information be reported on the rate of fuel flow at various phases of flight. Hence, ICAO maintains a database of this where information is available to find out this information for each of the phases of flight as ICAO defines them:

Operating Mode	Throttle Setting (percent of maximum rated output)
Take-Off	100 %
Climb-Out	85 %
Approach	30 %
Taxi/ground idle	7 %

The Boeing Aircraft Company conducted an extensive study for NASA on emission inventories for scheduled civil aircraft worldwide (see Baugham et al., 1996). The Boeing 2 Method is an empirical procedure developed for this study, which computes in-flight aircraft emissions using, as a base, the measured fuel flow and the engine ICAO data sheets. Whereas the first Boeing method took into account ambient pressure, temperature and humidity, the second method was more complicated (and accurate). This new method allowed for ambient pressure, temperature and humidity as well as Mach number.

1.1 Methodology

The Boeing Method uses English units and not S.I. therefore the first step is to convert the Fuel Flow (W_f) from the ICAO data for a specific engine from kg/s to lbs/hr (multiply by 7936). The Emission Index (EI) values from ICAO are to be read as lbs/1000 lbs (same number as g/kg).

The ICAO fuel flow values are then to be modified by a correction for aircraft installation effects (W_f):

Take-Off	1.010
Climb-Out	1.013
Approach	1.020
Taxi/ground idle	1.100

STEP 1: Curve fitting the Data

The Emission Indices (NO_x , HC, CO) are to be plotted (log-log) against the corrected fuel flow (W_f).

STEP 2: Fuel Flow Factor

a) Calculate the values ϕ_{amb} (ambient pressure correction factor) and θ_{amb} (ambient temperature correction factor) where:

$$\phi_{\text{amb}} = \frac{P_{\text{amb}}}{14.696} \quad (P_{\text{amb}} = \text{ambient (inlet) pressure) and}$$

$$\theta_{\text{amb}} = \frac{T_{\text{amb}} + 273.15}{288.15} \quad (T_{\text{amb}} = \text{ambient (inlet) temperature})$$

b) The fuel flow values are further modified by the ambient values:

$$W_{\text{ff}} = \frac{W_f}{\phi_{\text{amb}}} \times \theta_{\text{amb}}^{3.8} \times e^{0.2 \times M^2}, \text{ where } M \text{ is the Mach number.}$$

c) Calculate the humidity correction factor H:

$H = -19.0 \times (\omega - 0.0063)$, ω = specific humidity,

$$\omega = \frac{0.62198 \times \Phi \times P_v}{P_{amb} - \Phi \times P_v}.$$

where Φ is relative humidity and P_v = saturation vapour pressure in psia. For a correction to this formula, please see the EUROCONTROL corrected Boeing 2 Method below.

$$P_v = (0.014504) \times 10^\beta$$

and,

$$\begin{aligned} \beta = & 7.90298 \times \left(1 - \frac{373.16}{T_{amb} + 273.16} \right) + 3.00571 + 5.02808 \times \log_{10} \left(\frac{373.16}{T_{amb} + 273.16} \right) \\ & + 1.3816 \times 10^{-7} \times \left(1 - 10^{11.344 \times \left(1 - \frac{T_{amb} + 273.16}{373.16} \right)} \right) + 8.1328 \times 10^{-3} \times \left(10^{3.49149 \times \left(1 - \frac{373.16}{T_{amb} + 273.16} \right)} - 1 \right) \end{aligned}$$

STEP 3: Compute EI

Calculate the emission indices of HC, CO and NO_x:

$$EI_{HC} = REI_{HC} \times \frac{\theta_{amb}^{3.3}}{\phi_{amb}^{1.02}}$$

$$EI_{CO} = REI_{CO} \times \frac{\theta_{amb}^{3.3}}{\phi_{amb}^{1.02}}$$

$$EI_{NOx} = REI_{NOx} \times e^H \times \sqrt{\frac{\phi_{amb}^{1.02}}{\theta_{amb}^{3.3}}}$$

Where the REI_{HC}, REI_{CO}, and REI_{NO_x} values are read off the graph (STEP 1) by substituting W_{ff} for W_f .

STEP 4: Total Emission

$$\text{Total (HC, CO, NO}_x\text{)} = \text{Number of Engines} \times \sum_i [(EI_{HC}, EI_{CO}, EI_{NOx})_i \times W_{fi} \times \text{time}_i \times 10^{-3}] \text{ in lbs}$$

1.2 Bibliography

[Ref 16.] & [Ref 18.]

2 EUROCONTROL modified Boeing Method 2 (EEC-BM2)

Eurocontrol has implemented an improved version of the Boeing Method2 as part of its AEM3 emission calculations used to obtain the results for the current study. The improvement covers a mistake within the published Boeing Method, specifically with regard to the humidity calculation (see above). The formula for the humidity correction factor should read:

$$\omega = \frac{0.62198 \times \Phi \times P_v}{P_{amb} - 0.37802 \times \Phi \times P_v}$$

The reason is that specific humidity, ω , is defined as the ratio of the mass of water vapour in a sample of moist air to the total mass of moist air, i.e.:

$$\omega = \frac{M_w}{M_w + M_d}$$

where M_w is the mass of water vapour and M_d is the mass of dry air.

Specific humidity can also be calculated from the actual vapour pressure (P_a) and ambient Pressure (P_{amb}) as:

$$\omega = \frac{e \times P_a}{P_{amb} - (1 - e) \times P_a}$$

The factor e is the ratio of the mole weight of water vapour to that of air ($18.016 / 28.966$ - both in g/mol) = 0.62198 (a dimensionless quantity).

Please note also that actual vapour pressure (P_a) is related to relative humidity (Φ) and the saturation vapour pressure (P_v) by the formula:

$$\Phi = \frac{P_a}{P_v}$$

Therefore the correct formula for specific humidity is

$$\omega = \frac{0.62198 \times \Phi \times P_v}{P_{amb} - 0.37802 \times \Phi \times P_v}$$

Note that the factor 0.37802 appearing is $1 - e = 1 - 0.62198 (= 0.37802)$ and must be included in the formula. This correction has been implemented as the Boeing Method 2 - EUROCONTROL modified.

ANNEX 2. HIGH-RISK CONTRAIL ZONES BY FLIGHT LEVEL

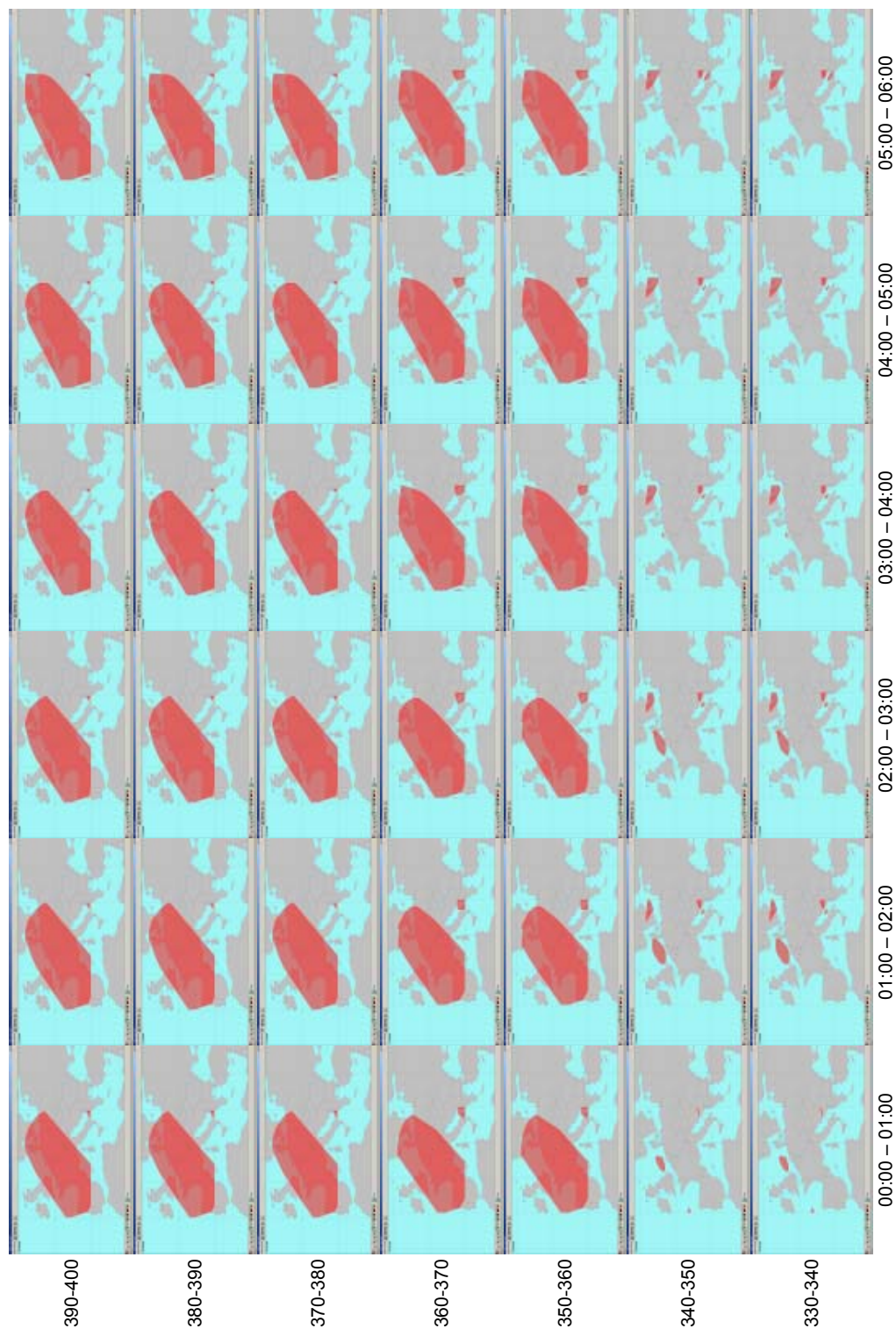


Figure 25: Hi-Risk Contrail Zones by Flight Level – 17/09/04 [t= 00:00 to 06:00]

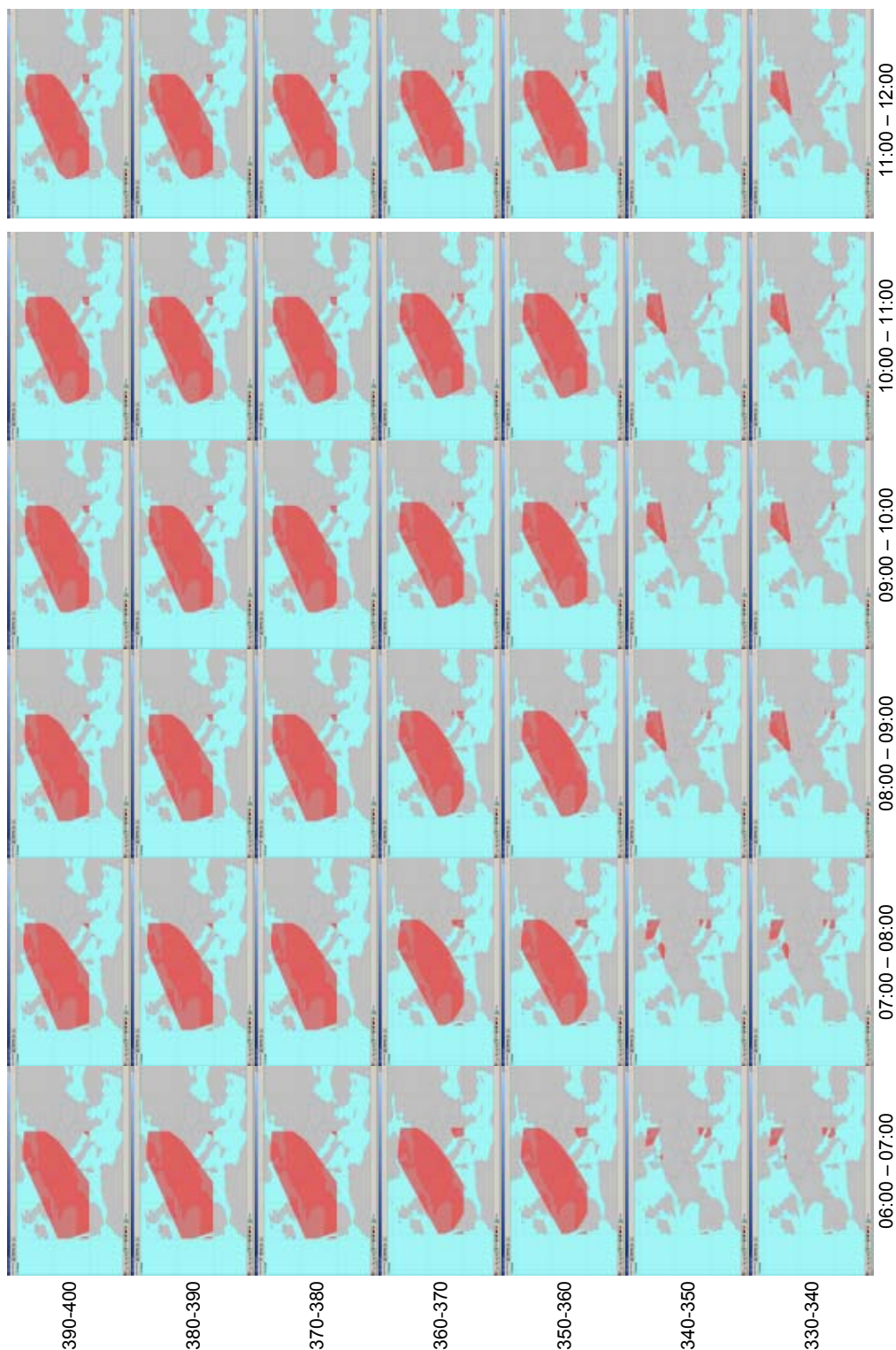


Figure 26: Hi-Risk Contrail Zones by Flight Level – 17/09/04 [t= 06:00 to 12:00]

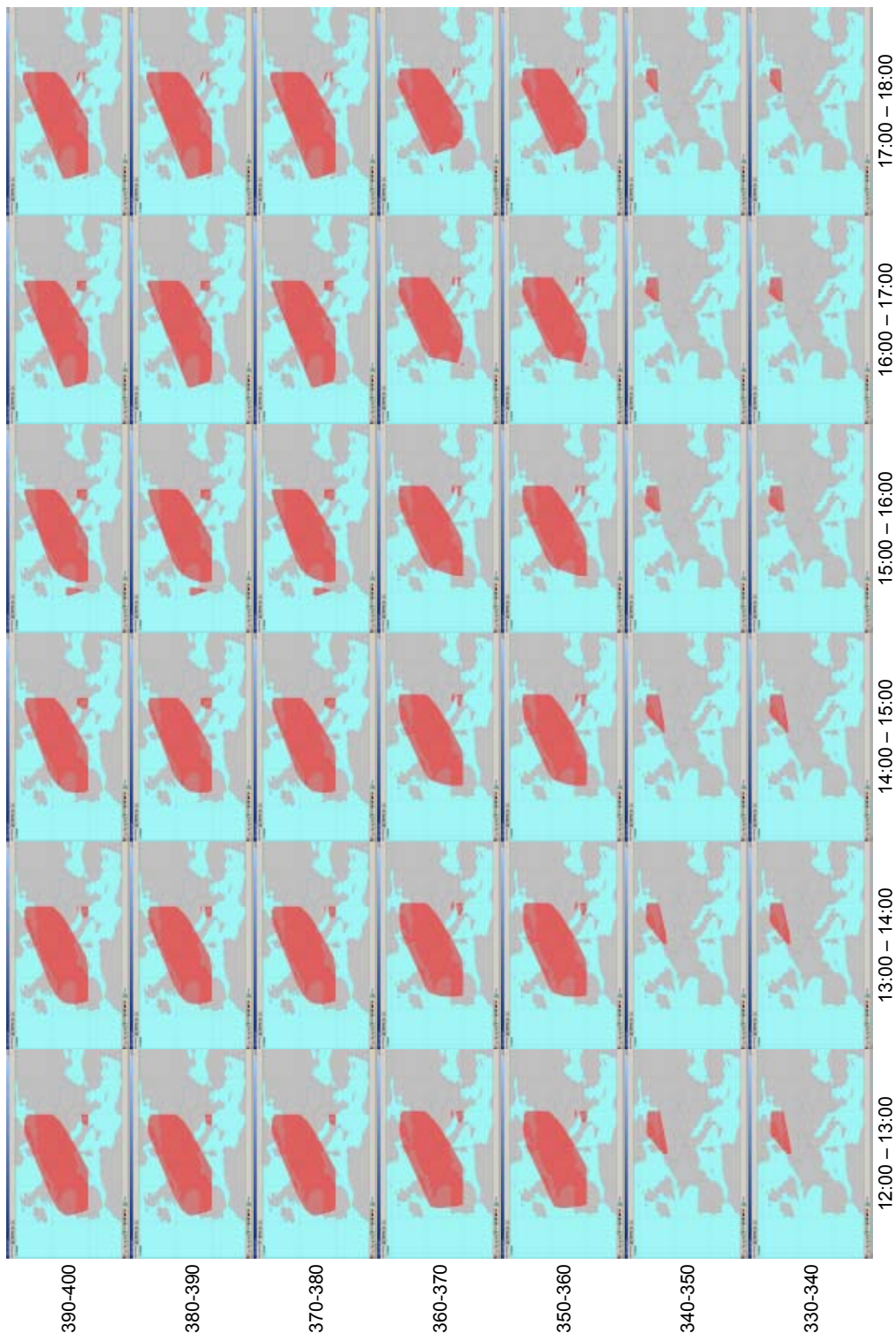


Figure 27: Hi-Risk Contrail Zones by Flight Level – 17/09/04 [t= 12:00 to 18:00]

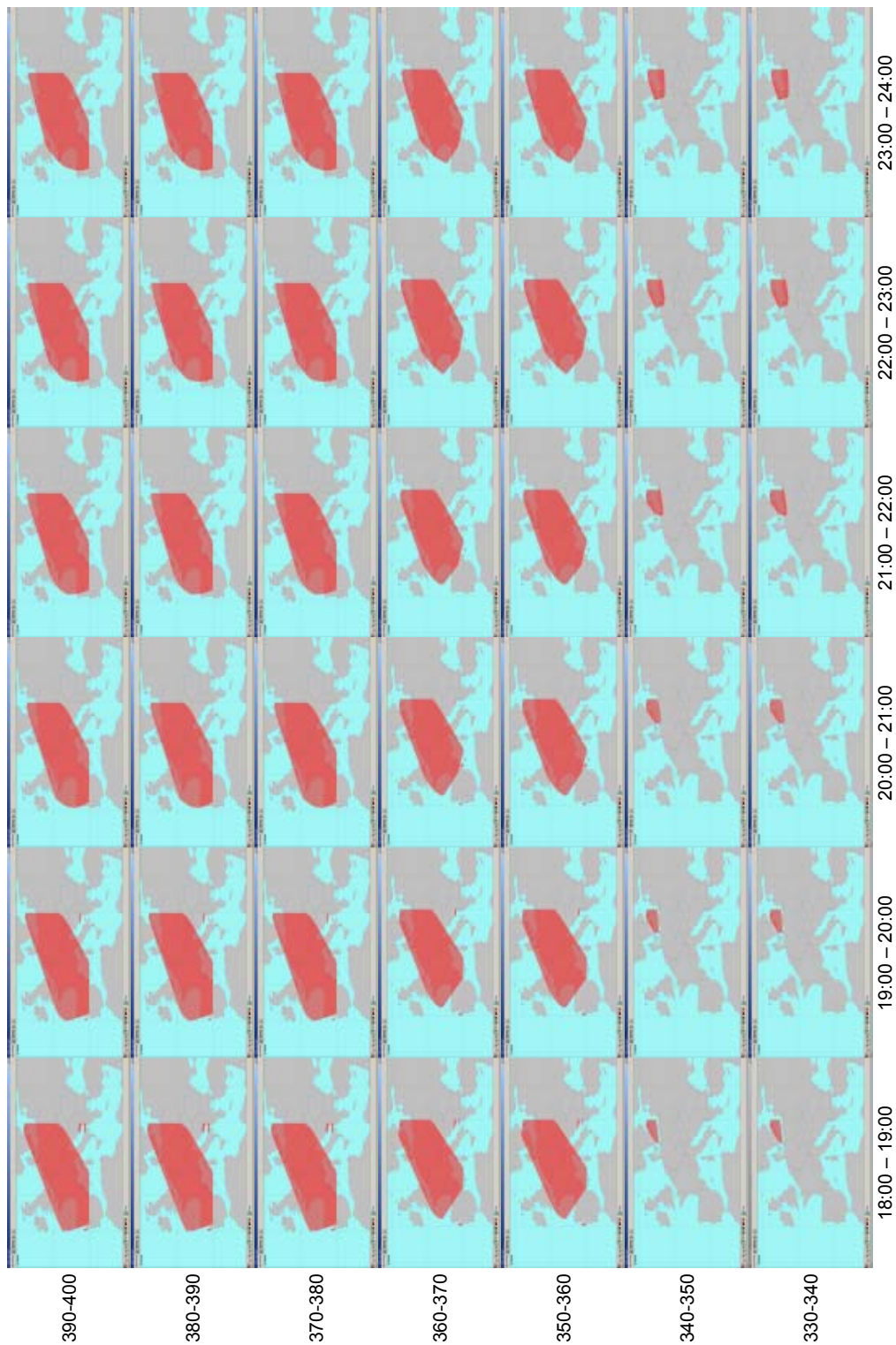


Figure 28: Hi-Risk Contrail Zones by Flight Level – 17/09/04 [t= 18:00 to 24:00]

ANNEX 3. CONTRAIL CALCULATION PROCEDURE

In order to calculate contrails in each grid cell, the CONTRAIL model performs the following calculations. These equations are based on the generally accepted “Schmidt-Appleman” criterion for contrail formation:

Engine Propulsion Efficiency:

$$\eta = FV/M_f Q$$

where:

F = engine thrust (N)

V = air speed (m/s)

M_f = mass fuel flow (Kg/s)

Q = combustion heat of fuel (taken as constant 43 MJ/kg)

Slope Of The Exhaust/Ambient Air Mixing Line:

$$G = EL_{H_2O} C_P P / \varepsilon Q (1 - \eta)$$

where:

EL_{H₂O} = Water emission index (water is a result of the oxidation process of carbon and hydrogen contained in the aviation fuel with the oxygen in the atmosphere) = 1.230 kg/kg fuel burn;

C_P = specific heat capacity of air at constant pressure = 1004 J/KgK

P = pressure (hPa)

ε = ratio of the gas constants of air and water vapor = 0.622

η = engine propulsion efficiency

Q = combustion heat of fuel (taken as constant 43 MJ/kg)

Saturation Vapor Pressure Over Water:

$$E_{satW}(T) = 6.112 \exp[6816(1/273.15 - 1/T) + 5.1309 \ln(273.15/T)] \text{ (hPa)}$$

with T = ambient temperature measured in K

Saturation Vapor Pressure Over Ice:

$$E_{satI}(T) = 6.112 \exp[4648(1/273.15 - 1/T) - 11.64 \ln(273.15/T) + 0.02265(273.15 - T)] \text{ (hPa)}$$

with T = ambient temperature measured in K

Ambient Vapor Pressure:

$$E = U_W E_{\text{sat}W} / 100 \text{ (hPa)}$$

where

U_W = ambient relative humidity over water

Ambient Relative Humidity Over Ice:

$$U_I = E/E_{\text{sat}I} * 100 \text{ (\%)}$$

Threshold Temperature For Saturated Air:

$$T_M = -46.46 + 9.43 \ln(G-0.053) + 0.720(\ln(G-0.053))^2 \text{ (C)}$$

using the slope of the exhaust / ambient air mixing line G

Threshold Temperature For Dry Air:

$$T_C = T_M - (E_{\text{sat}} W(T_M)/G) \text{ (C)}$$

this is also known as critical temperature

Exhaust/Ambient Air Mixing Line Intercept Temperature:

$$T_E = T - (E/G) \text{ (C)}$$

where

U = ambient relative humidity and T = ambient temperature in C

Contrails form when $T_E < T_C$. However, persistent contrails form when $T_E < T_C$ and $E > E_{\text{sat}I}$ (i.e. in very moist cold air).

ANNEX 4. METEOROLOGICAL SITUATION

This brief report will outline the meteorological situation for the 2 days in 2004: September 17 and October 18. Information is presented for general weather conditions and the relative humidity and temperature at flight level FL 300. September 17 was a “high” contrail day and October 18 was a “low” contrail day.

1 Surface Analysis

1.1 September 17, 2004: Meteorological Analysis

A very intense low pressure system south of Iceland brought very strong westerly winds to all of Britain. With this system two fronts passed in succession through Britain, first a warm front and then a cold front each bringing moderate to heavy rain. A low centred over Sardinia brought very heavy cold-front induced rains to central Italy. A low over northern Finland brought strong north-westerly winds and rain to north-western Russia. A low over eastern Turkey brought rain to this region. A large area of high pressure centred over central Germany brought clear skies and light winds to most areas of Europe.

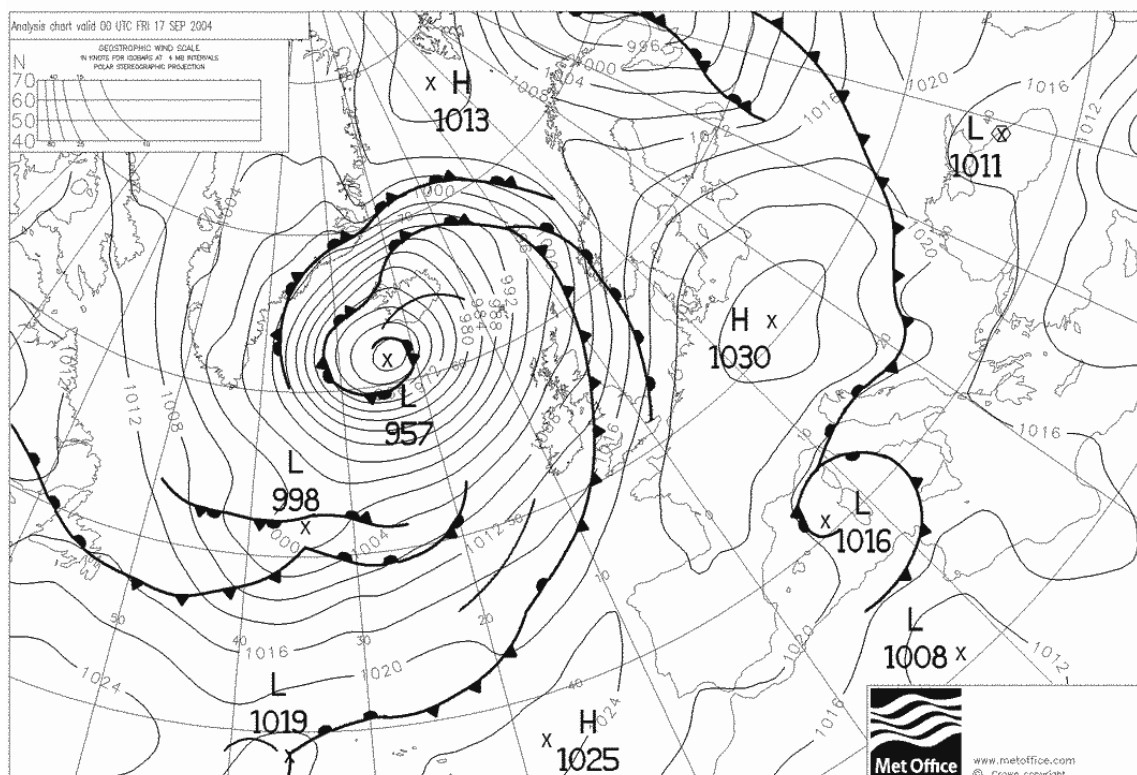


Figure 29: Meteorological Analysis: September 17, 2004

1.2 October 18, 2004: Meteorological Analysis

A deep low pressure system located over the Atlantic off the south-west portion of the Iberian Peninsula with an associated warm front, brought heavy rain and strong southerly winds to Portugal and southern Spain. A low located south of Iceland brought moderate to heavy rain and strong northerly winds to Iceland and moderate rain and less strong northerly winds to northern Scotland. A low pressure system located over southeast Sweden which brought strong westerly winds to northern Europe including Germany and Poland. With this system an associated cold front passed through bringing rain which was heavy at times. Another low pressure system located over the central portions of western Russia brought strong westerly and north-westerly winds and moderate to heavy rain to most of the northern sections of European Russia with an associated cold front. Highs located over the western and eastern areas of the Mediterranean and over the Adriatic brought clear skies and light winds to calm conditions to southern Europe.

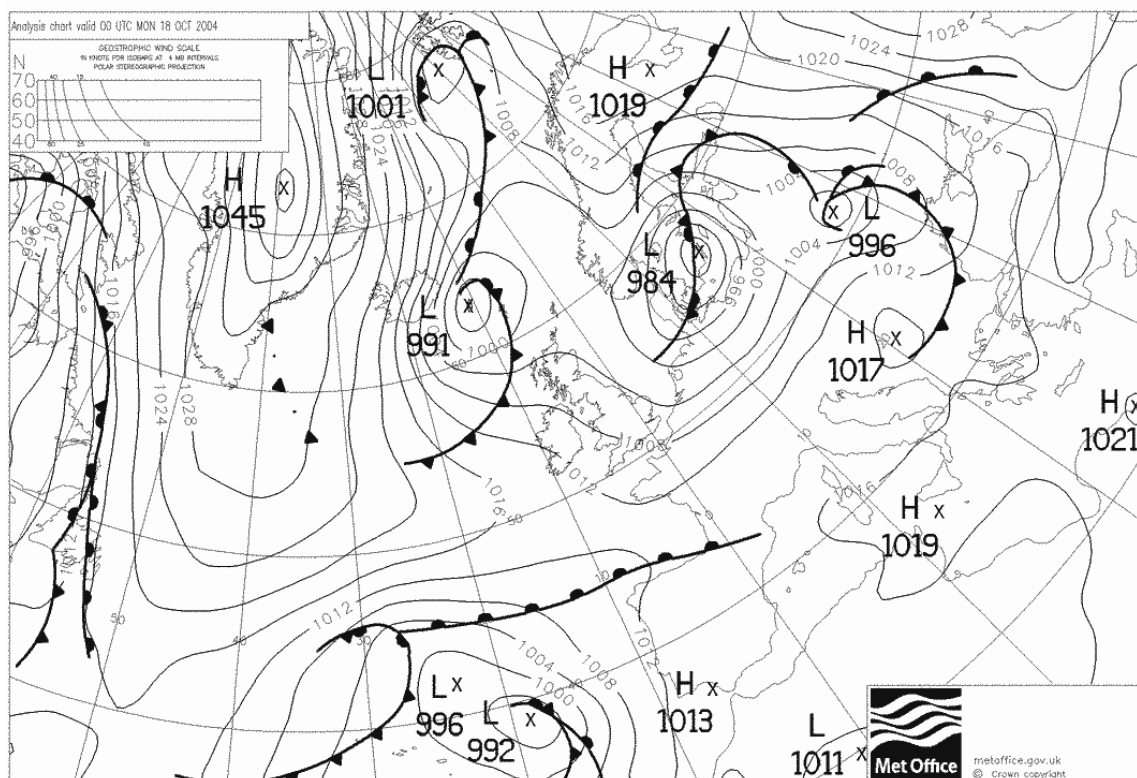


Figure 30: Meteorological Analysis: October 18, 2004

2 Additional Meteorological Charts

2.1 Surface Precipitation Rate (mm/hr)

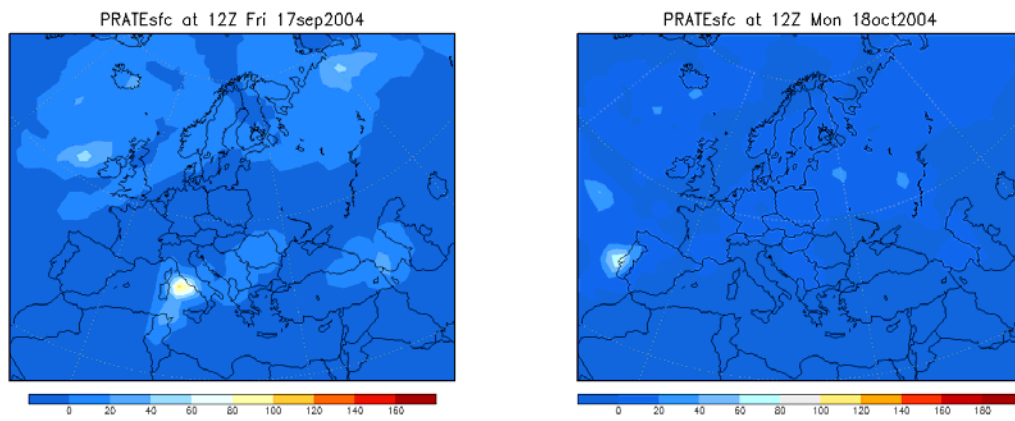


Figure 31: Surface precipitation rate (mm/hr)

REFERENCES

- [Ref 1.] FAA, 2004, Aviation and Emissions – A Primer, Federal Aviation Administration, <http://www.aee.faa.gov/emissions/>
- [Ref 2.] "Aviation and the Global Atmosphere", Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, 1999
- [Ref 3.] "Document de synthèse GIFAS GROUPE ENVIRONNEMENT" – J.M. JACQUET – Snecma Moteur – YY N° 358-01 /JMJ – April 2000
- [Ref 4.] "ESA-EEC/SEE Contrail Maps – Description of Product" – EUROCONTROL Experimental Centre / Isa Software – Smith, Jelinek, 2004
- [Ref 5.] Klaus Gierens and Susanne Marquat, Regions that are conditioned for Contrail Formation, DLR, 2001.
- [Ref 6.] Lee, D.S., I. Koehler, E.Grobler, F.Rohrer, R. Sausen, L.Gallardo-Klenner, J.g.J. Olivier, F.J. Dentener, A.F. Bouwam: Estimations of global NO_x emissions and their uncertainties" Atmos.Env.,31, 1735-1749, 1997.
- [Ref 7.] WMO, 1995 WMO (World Meteorological Organisation): "Scientific assessment of ozone depletion: 1994", global ozone research and monitoring project, Report No.34, WMO, Geneva, 1995.
- [Ref 8.] Koehler and. al, 1997: Koehler, I., R.Sausen, R.Reinberger: "Contributions of aircraft emissions to the atmospheric NO_x content" Atmos. Env., 31, 1801-1818, 1997
- [Ref 9.] Brasseur and. al., 1998: Brasseur, G.P., R.A. Cox, D. Hauglustaine, I.Isaksen, J. Lelieveld, D.H. Lister, R.Sausen, U. Schumann, A. Wahner, P. Wiesen: "European scientific assessment of the atmospheric effects of aircraft emissions", Atmos. Env., 32, 1998
- [Ref 10.]Travis, DJ, Carleton, AM and RG Lauritsen (2002) Contrails reduce daily temperature range. Nature 418:601.
- [Ref 11.]Minnis, P., *et al.* 2002. Spreading of isolated contrails during the 2001 air traffic shutdown. American Meteorological Society 10th Conference on Aviation, Range, and Aerospace Meteorology. May 13. Portland, Ore
- [Ref 12.]Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft; United States Environmental Protection Agency; EPA420-R-99-013; April 1999
- [Ref 13.]NASA Langley Cloud and Radiation Research - Minnis Group; <http://www-pm.larc.nasa.gov/>
- [Ref 14.]Environmental issues in flight – Global scale environmental impact of aviation; Sausen, R. AERONET II / X-NOISE II Joint Workshop on ENVIRONMENTAL INTERDEPENDENCIES IN AIR TRANSPORT; IATA, Geneva, 10-11 Feb 2003
- [Ref 15.]<http://www.pa.op.dlr.de/contrails/>
- [Ref 16.]ICAO Engine Exhaust Emissions Data Bank; ICAO; Doc 9646-AN/943 ; First Edition – 1995 ; Internet Issue 1(3/10/1998) ; Internet Issue2(8/2/99).

[Ref 17.]Emission Indices – State of the Art; Literature Review; EUROCONTROL Experimental Centre; BU Environmental Studies; A.Celikel ; 1999 ; unpublished internal paper.

[Ref 18.]Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis; April 1996; NASA LRC; Contractor Report 4700; Steven L. Baughcum, Terrance G. Tritz, Stephen C. Henderson, David C. Picket

[Ref 19.]"The Advanced Emission Model (AEM3) Version 1.5 – Validation Report", EUROCONTROL Experimental Centre; Society, Environment and Economics Business Area; Jelinek; Carlier; Smith; EEC/SEE/005/2003

[Ref 20.]"Impact de la flotte aérienne sur l'environnement atmosphérique et le climat", Rapport no.40, Décembre 1997, Institut de France, Académie des sciences – Académie Nationale de l'air et de l'espace

[Ref 21.]R. A. Anthes, E. Y. Hsie and Y. H. Kuo, *Description of the Penn State/NCAR mesoscale model version 4 (MM4)*. Tech. Report NCAR/TN-282+STR, National Center for Atmosphere Research, Boulder, Colorado, 1987.

[Ref 22.]D. O. Grell, J. Dudhia and D. R. Stauffer, *A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)* Tech. Report NCAR/TN-398+STR, National Center for Atmosphere Research, Boulder, Colorado, 1994.

[Ref 23.]<http://www.mmm.ucar.edu/mm5/Publications/mm5-papers.html>

[Ref 24.] Tesche, T. W., D. E. McNally, C. A. Emery, and E. Tai, 2001b. "Evaluation of the MM5 Model Over the Midwestern U.S. for Three 8-Hr Oxidant Episodes", prepared for the Kansas City Ozone Technical Work Group, prepared by Alpine Geophysics, LLC, Ft. Wright, KY and ENVIRON International Corp., Novato, CA.

[Ref 25.] Emery, C., E. Tai, and G. Yarwood, 2001. "Enhanced Meteorological Modeling and Performance Evaluation for Two Texas Ozone Episodes", report to the Texas Natural Resources Conservation Commission, prepared by ENVIRON, International Corp, Novato, CA

[Ref 26.]Tesche, McNally, Tremback, Operational Evaluation Of The MM5 Meteorological Model Over The Continental United States: Protocol For Annual And Episodic Evaluation, 2002.

[Ref 27.]<http://www.atmos.washington.edu/mm5rt/>

For more information about the
EEC Society, Environment and Economy Research Area
please contact:

Ted Elliff
SEE Research Area Manager,
EUROCONTROL Experimental Centre
BP15, Centre de Bois des Bordes
91222 BRETIGNY SUR ORGE CEDEX
France

Tel: +33 1 69 88 73 36
Fax: +33 1 69 88 78 90
E-Mail: ted.elliff@eurocontrol.int

. . .