Supplement to

Air traffic and contrail changes during COVID-19 over Europe: A model study

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1 Introduction

The input required for contrail simulations with CoCiP is listed in Table S 1. Besides the waypoint coordinates, it includes the aircraft mass, fuel flow rate, engine overall efficiency, true airspeed, International Civil Aviation Organization (ICAO) defined 4-character codes for aircraft types (e.g., A320 for Airbus-320 aircraft), and an identifier for the performance model used.

Table S 1. Traffic input data required by CoCiP

Variable	Symbol	Unit/Format
Flight number	FlightId	Internal unique integer
Aircraft type	ATYP	ICAO code character*4
Number of waypoints	NW	number of waypoints per hour
UTC time	t	Integer, UTC time in s since 0000 UTC 1 January 2000
longitude, latitude	x, y	degree
Flight Level	FL	feet
True airspeed	TAS	m s^{-1}
Aircraft mass	ACMass	kg
Fuel consumption rate	FF	kg s^{-1}
Overall propulsion efficiency	η	1
BC number emission index	EI_{soot}	kg^{-1}
Performance model	p-source	character*2

For each flight we have a sequence of $N_W > 1$ waypoints defined by time, horizontal position in terms of Northern latitude and longitude East of Greenwich, and flight level referring to pressure altitude in feet in the ICAO standard atmosphere (ISA). CoCiP requires that the flight track segments are provided in hourly segments with uniform track time increments of about 60 s. A pseudo flight number "-1" identifies the end of a track record. A pseudo flight number "-99" marks the end of hourly inputs. The hourly data are expected in ASCII-format files day by day.

2 Data Sources

Information on the 4D-trajectories of flights in time and space inside the European airspace and for flights across its boundary are available from flight planning and observations. Here, we use archived flight track data of type M3 and CPR from EUROCONTROL. The data were provided for this project by the Performance Review Unit (PRU) of EUROCONTROL. The data come day by day. Each day has a unique day number D or character string "yyyymmdd" (representing year, month and day).

M3: Planned and observed flight segment data

Model 3 (M) trajectory is the information captured by EUROCONTROL's Network Manager Operations Systems after the flight has been operated. It corresponds to the last filed flight plan based trajectory updated or recalculated with available position reports (CPR, see below) whenever a flight deviates from its filed flight plan by more than any of the pre-determined thresholds (1 min in time, more than 400 feet in en-route phase, more than 1000 feet in climb/descent phase or more than 10 nautical miles laterally) and upon message updates from air traffic control (ATC). For details see Section 13.3.1 in Niarchakou and Cech (2018).

M3 files are available to registered users from the Demand Data Repository (DDR2) of EUROCONTROL (https://www-test.eurocontrol.int/ddr). The M3 files used here are provided by the PRU coming directly from the Network Manager archives. The M3 files have names "TRAFFIC_CTFM_*yyyymmdd*.so6" with *yyyymmdd* identifying the day D. Each trajectory entry in the M3 files describes a flight segment event in the network, and consists of 20 fields, describing the position at the begin and end point of the segment, and additional information for the segment. The list of fields is shown in

Table S 2 (Wandelt and Sun, 2015). M3 files include typically (in 2019) an order 3 million lines requiring an order 500 MB (Megabyte) per day.

Table S 2. Segment data in EUROCONTROL M3 SO6 files.

Number	Name	Type	Size	Comment
1	Segment Identifier	Char		Name of first segment _ name of last segment
2	Departure airport	Char	4	ICAO code of origin airport, e.g. EDDF for Frankfurt
3	Destination airport	Char	4	ICAO code of destination airport, e.g. EDDH for Hamburg
4	Aircraft type	Char	4	ICAO code of aircraft type, e.g. A388 for Airbus A380
5	Time begin segment	Integer	6	Time of entering the segment, format HHMMSS, padded with 0's from the left
6	Time end segment	Integer	6	Time of leaving the segment, format HHMMSS, padded with 0's from the left
7	FL begin segment	Integer	1-3	Flight level (hundreds of feet) entering the segment, e.g. 250 for 7.620 m
8	FL end segment	Integer	1-3	Flight level (hundreds of feet) leaving the segment, e.g. 260 for 7.925 m
9	Status	Cha		0=climb, 1=descent, 2=cruise
10	Callsign	Char	7	Call sign with ICAO code for airline (e.g., DLH400, for a Lufthansa flight from EDDF to KJFK, or "tail number", e.g. DADLR for the DLR research aircraft HALO).
11	Date begin segment	Integer	6	Date of entering the segment, format HHMMSS, padded with 0's from the left
12	Date end segment	Integer	6	Date of leaving the segment, format HHMMSS, padded with 0's from the left
13	Latitude begin segment	Float		Latitude in minute decimal, e.g. 3002 for 50°1'60'' N
14	Longitude begin segment	Float		Longitude in minute decimal, e.g. 514.233 for 8°34'14'' E
15	Latitude end segment	Float		Latitude in minute decimal
16	Longitude end segment	Float		Longitude in minute decimal
17	Flight identifier	Integer		Unique identifier for the flight, e.g. 172874110
18	Sequence	Integer		Increment at each route segment, e.g. 3 for the third route segment on a flight
19	Segment length	Float		Length of the route segment in nautical miles
20	Segment parity/color	Integer		A format-specific color encoding (values 0-9)

CPR: Correlated Position Report messages - Archived waypoint data

The archived CPR (Correlated Position Report messages) files include flight information records with track waypoint information, see Table S 3, similar to those contained in M3. The reports are "correlated" because CPR fuses flight plan information [flight origin/destination, callsign] with surveillance information [radar / ADS-B time and position report]). Archived CPR files list data waypoint by waypoint. The CPR data include more surveillance data and are therefore considered to be more accurate. However, CPR surveillance data are available only inside the EUROCONTROL observation domain which is smaller than the simulation domain. In particular it misses flights over the North Atlantic west of about 15°W. In contrast, M3 files cover flights inside the domain and flights passing the EUROCONTROL boundary. In order to cover all flights up to the outer boundaries of the European domain, we merge flight track data using CPR data inside the observation domain and M3 data outside. Surveillance methods are described in ICAO (2007).

Table S 3. Waypoint data in EUROCONTROL CPR files.

Number	Name	Type	Size	Comment
1	line number	Integer	8	line number
3	time of reception of CPR data	6 Integers		year/month/day hour:minute:second, e.g. "20/03/28 22:44:30"
4	time	6 Integers		year/month/day hour:minute:second, e.g. "20/03/28 22:44:20"
9	Callsign	Char	7	"Aircraft Id" or" Call sign" with ICAO code for airline, e.g. DLH506 for a Lufthansa flight
10	Departure	Char	4	ICAO code of origin airport, e.g. EDDF
11	Destination	Char	4	ICAO code of destination airport, e.g. SBGR
12	Estimated time of departure			time information as above
13	Position	String of 17 characters		Latitude and Longitude of position in terms degree, min, second and N/S or E/W information, e.g. "53417N 0074440W"
14	Flight Level	Integer	1-3	Flight level (hundreds of feet) at position, e.g. 330
17	Ground speed	Integer	1-4	Ground speed in knots, e.g. 508
18	Rate of climb or descent	Integer	1-5	Rate of climb or descent (ROCD) in feet/minute
21	Flight plan identifier	Char	12	IfpsId, a unique flight plan identifier assigned by the IFPS system (unique within the CPR data)
22	Aircraft address	Hexdigit	6	A unique identification of the aircrafts frame (24-bit ICAO aircraft address)

The CPR flight information results from various tracking systems. The CPR messages for one flight get archived during the day D of the departure or – for flights extending over midnight - during the next day (D+1) when the flight terminates. Pieces of the flight track are distributed in the CPR files, possibly on day D and D+1. Observations result in messages which enter the archive with an order 20 s time delay improve previous messages. CPR data lines are not monotonically ordered with increasing time.

The CPR data come in files with a name "1.*yyyymmdd*1001tacop**3**04ARCHIVED_OPLOG_ALL_CPR" or "1.*yyyymmdd*1001tacop**1**04ARCHIVED_OPLOG_ALL_CPR", containing a fixed part and a string *yyyymmdd* for the given day D.

CPR files include typically (in 2019) an order 8 million lines per day.

Since the M3 and CPR records have no common unique flight identifier, we identify records from both sources for the same flight, with same callsign, with common departure day, and common departure and arrival airports.

NATS data for the Shanwick Oceanic Control Area

For the present study, the company NATS provided flight track data for the Shanwick Oceanic Air Traffic Control Area covering part of the North Atlantic Flight Corridor, mainly between 45°N and 65°N, with eastern boundary at 9°W or 10°W, except west of Ireland where the zone starts at 15°W, and with western boundary near 60°W.

For further information see: North Atlantic Operations and Airspace Manual, V.2020-2.1, Prepared by the ICAO European and North Atlantic Office, on behalf of the North Atlantic Systems Planning Group (NAT SPG), www.icao.int.

The Shanwick data describe the air traffic tracks in terms of oceanic waypoints, typically with 10° spatial resolution. Aircraft position data (longitude, latitude and altitude) is recorded as it passes through pre-defined waypoints along its flight path and are rounded to a full degree. Additional waypoints are recorded when an aircraft is instructed by the air traffic controller to climb/descent in between the pre-defined waypoints. A precise specification of the waypoint, FL and time data accuracy is missing. For eastbound flights, we note that waypoint data are available from the Gander Oceanic Control Area, while waypoints for westbound flights end at 40°W.

The data were provided annually sorted by airlines. The data got resorted by flight and time (by Roger Teoh), and formatted into a sequence of waypoints with callsign, ICAO aircraft type, date and time,

longitude, latitude and FL, day by day. As for M3 data, the ICAO 24-bit code is not included in the data set so that corresponding flights in the CPR data have to be identified based on the callsign, departure/destination airports, and times.

The NATS data include 5 years of data in a CSV file with about 1.5 GB size.

FR24: ADS-B data from Flightradar24

For comparisons, aircraft position data as collected from a distributed net of ground-received ADS-B data and as purchased from Fligthradar24 AB, Stockholm, Sweden (https://www.flightradar24.com/how-it-works) were used (FR24). The FR24 data have a global overage, but here we use data for Europe only.

ICAO 24-bit codes and ICAO aircraft types

A table relating many of the 24-bit codes with aircraft types was made available for this study by Martin Schäfer within OpenSky (Schäfer et al., 2014), https://opensky-network.org/datasets/metadata/. The table lists more than 440000 ICAO codes partly with ICAO aircraft type and other aircraft information, partly including the engine type, including many non-commercial aircraft, but does not cover all aircraft in operation.

Otherwise, the ICAO aircraft type is identified based on the type given in the M3 and NATS data for flights with same aircraft callsign, departure and destination, same day. Sometimes several flights with same callsign etc., but different ICAO aircraft type occur. In such cases, the time of departure is used to find the aircraft types.

In March-August 2019, 22891 different ICAO24-bit codes occurred in the CPR data which were covered by the Opensky list, but 10814 are missing in the Opensky list, so about 1/3 of the total.

For about 93 % of the missing 24-bit codes, the ICAO24-ATYP relation was derived from M3 data. The remainders had to be dismissed. Inspection of examples showed that these were mainly from low-level flights. For 0.5 % of the M3 results, the same ICAO24 code was related to different ATYP codes (e.g. A20N instead of A320). Apparently, operators occasionally decided to use another aircraft.

ICAO Airport Codes

A table "airportlist.txt" relating 4-character ICAO airport codes to latitude and longitude was collected from various sources. The first set was taken from EUROCONTROL data available from the DDR2 depository (https://ext.eurocontrol.int/ddr/datasets). The list was augmented with codes collected by Imperial College (Roger Teoh) over recent years. Frequently occurring missing airports (including recently

opened airports) were added based on web searches. Finally, the position for still missing airport codes were estimated from the first or final flight position below 3000 feet. Still, for few flights with flight track information ending in upper airspace, invalid (e.g. ZZZZ) or unknown airport codes occur. These flights have been ignored.

Load Factor Data

Data from the US Bureau of Transportation Statistics (https://www.bts.dot.gov), from the German Statistical Federal Office (https://www.destatis.de/EN/Home/_node.html), from EUROCONTROL (https://www.eurocontrol.int/sites/default/files/2021-01/eurocontrol-think-paper-8-impact-of-covid-19-on-european-aviation-in-2020-and-outlook-2021.pdf) and from ICAO (ICAO, 2021) suggest lower passenger and freight loadings after March 2020 than in the previous year. The exact values vary. Note that the payload mass load factor LF (payload mass relative to maximum permitted payload mass) used in the paper is not directly proportional to the passenger or freight loading factors. The uncertainty of LF used in this study (LF= 0.7 for 2019 and 0.5 after March 2020) can only be estimated to be of the order of ±0.1.

Engine Data and Soot Number Emission Indices

The method used to derive engine specific soot number emissions has been described earlier (Teoh et al., 2019; Teoh et al., 2020). Soot is often referred to as Black Carbon (BC) (Teoh et al., 2019). Here, the term soot refers to carbonaceous particles formed from incomplete combustion of hydrocarbon fuels (Petzold et al., 2013). For the present study, Imperial College (Roger Teoh) provided a python routine emission.py and an updated data set Aircraft_Engine_EDB_data.csv listing aircraft-engine pairs which cover most of the commonly used commercial aircraft. The table includes up-to-date values found in the ICAO EDB (August 2020 version), https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank as provided by the European Aviation Safety Agency, EASA. The python routines were converted to Fortran subroutines eim_fox, eim_imfox, ein_fa_model, and coupled to BADA3 information for this study. In case of missing information, the soot number emission index was set to 10^{15} kg^{-1}.

ERA5 Reanalysis Weather Model data

ERA5 is a comprehensive reanalysis, from 1979 (soon to be backdated to 1950) to near real time, which assimilates as many observations as possible in the upper air and near surface. ECMWF has a long history with reanalysis (Hersbach et al., 2020), and ERA5 is the fifth generation of atmospheric reanalysis being produced. The ERA5 atmospheric model is coupled with a land surface model and a wave model.

Gridded atmospheric data are available as either hourly or monthly means with a horizontal resolution of 0.25° by 0.25° with global coverage. The vertical coordinate is pressure levels, covering 1000 hPa to 1 hPa on 37 levels.

ERA5 atmospheric model data are provided by the Copernicus Climate Change Service (C3S), https://climate.copernicus.eu/. C3S is one of six thematic information services provided by the Copernicus Earth Observation Programme of the European Union. C3S is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission. After free registration, the data can be accessed programmatically through a Python-based API from the Climate Data Store (CDS), https://cds.climate.copernicus.eu/#!/home.

The data available through CDS is documented in more detail on https://confluence.ecmwf.int/pages/viewpage.action?pageId=151530614 and https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview.

ECMWF-IFS Weather Model Data

The data are from the "deterministic forecast" branch of the operational archive of the medium range ECMWF Integrated Forecasting System (IFS) "Atmospheric Model High Resolution 10-Day Forecast (HRES)". The data come from version 45r until 5 June 2019, version 46r1 until 30 June 2020, and version 47r1 since then (https://www.ecmwf.int/en/publications/ifs-documentation). Data access is limited to registered users.

The data sets have been obtained in netcdf format using two shell-scripts which are designed to be executed on ECMWF's "ECACCESS" system (ecaccess.ecmwf.int). These scripts download the data directly from the Meteorological Archival and Retrieval System (MARS, https://confluence.ecmwf.int//display/UDOC/MARS+user+documentation).

The IFS model has a native horizontal resolution of about 9 km (Oktahedral Gaussian grid, "O1280", https://confluence.ecmwf.int//display/FCST/Gaussian+grid+with+1280+latitude+lines+between+pole+and+equator). The vertical resolution is 137 hybrid-sigma model levels from ground up to 0.01 hPa. The frequency of data is 1-hourly. For the use with the CoCiP model, the archived data has been interpolated onto a regular Latitude-Longitude grid of 0.25 by 0.25 degrees. The interpolation is an integrated component of the MARS service and described on https://confluence.ecmwf.int/display/UDOC/MARS+interpolation+with+MIR.

3 Data Processing

The processing is performed, day by day, in a sequence of jobs (using Fortran codes), reading and writing data as explained in Table S 4.

Table S 4. Traffic processing tasks

Step	Task	Input	Output
1	T_M3	TRAFFIC_CTFM_yyyymmdd.so6 (M3 data) Airport list	M3flights: M3 formatted records for flight segment information for flights starting day D and ICAO: table relating the ICAO ATYP codes together with callsign for flights starting days D-1 to D+1.
2	T3_M3external	M3flights	M3external: M3 external flights, i.e., flights passing the domain boundary, for day D
3	T_M3Combine	M3external	M3Combine: M3 external flights from days D-1, D, and D+1 (with maximum of 16 h before the start and after the end of day D) sorted by flight name and for each flight, by time
4	T_CPR	CPR data 1.yyyymmdd1001tacop104ARCHIVED _OPLOG_ALL_CPR or 1yyyymmdd1001tacop304ARCHIVED _OPLOG_ALL_CPR and ICAO	CPR_WP: CPR formatted records with waypoint information for day D, completed by the ICAO aircraft type code for same flight, airports and closest time
5	T_CPRsort	CPR_WP (CPR formatted records)	CPRsort: CPR records, sorted flight by flight, and for each flight by time, for all waypoints of day D
6	T_Combine	M3Combine and CPRsort	CPRCombine: Combination of CPR with M3 data, flight by flight, for day D. Combines external M3 flights from days D-1 to D+1, and sorted CPR flights from day D.
7	T_Combine _Shanwick	CPRCombine and NATS data	T_Comb_Shanwick: Combination of CPR-M3 data, flight by flight, for day D with NATS flights from days D-1 to D+1. Output with unique integer flight number.

8	NWPERA5	E5_yyyymmdd_00_3h_glob_1d.pl.nc	ERA5Days: ERA5 data in unformatted form in 3-hourly time steps, day by day
9	T_NWP_E5	ERA5Days T_Comb_Shanwick	CPRCombineE5: Flight tracks with wind velocity and air temperature interpolated to waypoints in time and space from global ERA5 data
10	T_ Perform	CPRCombineE5 Airport list BADA3 input tables PS aircraft model parameter table EDB soot emission info	CPRFF: hourly flight track data with ICAO types and performance information (mass, true air speed, fuel flow rate, thrust, soot emission index)
11	NWPFC	5 nc data files for various meteorological variables, all per 12 h period	FCDays: IFS-FC data in unformatted form in 1-hourly time steps, day by day
12	CoCiP	CPRFF: CPR+M3 flights with ICAO types and performance information, day by day and FCDays: ECMWF IFS weather forecast data, day by day Satellite observation coordinates	Various outputs with contrail properties

The jobs perform the following tasks:

Copy M3 segments and generate list of aircraft types

Waypoint data are read and decoded from EUROCONTROL M3 files in code T_M3.f. The data are read for days D-1, D and D+1 to generate a list of callsigns for day D with related ICAO-aircraft type (ATYP). This is done for all M3 records including those from flights on the previous and next day because that information is not always available the same day. Since several flights with the same flight name may occur per day, with different aircraft types, we also record the start and final airport names and the departure time of the flight.

The M3 flight tracks on day D are written to output files waypoint-wise in a Fortran-readable format. The waypoint data used include: time, longitude, latitude, flight level FL (in feet), GS, callsign, and ICAO aircraft type ATYP. This is done for all flight levels. The data are collected from departure to destination, in order to be able to reconstruct the integral fuel consumption along the flight.

Copy M3 segments passing domain boundaries

"External" flights passing the boundary of the European simulation domain are identified in code T_M3external.f. The code reads from the formatted M3 files generated in the previous step, and identifies external flights based on longitude and latitude coordinates outside the domain considered (20°W to 20°E, 35°N to 60°N), and outputs them day by day.

Sort external M3 flights

In T_M3combine.f, the data prepared by T_M3external.f are read and then sorted by flight names and, for each flight name, by time as a preparation for subsequent combination with CPR data. Sorting is performed using the Heapsort method as implemented in a short Fortran subroutine "SORT2" (Press et al., 1986). The sorting is efficient because it requires N log N operations for sorting a sequence with N elements. An alternative is the Quicksort method described in the same reference.

Copy CPR waypoint records and complete with aircraft type

Waypoint data are read and decoded from EUROCONTROL CPR input in code READCPR.f. The CPR flight track data are output into Fortran format for flights day by day, again for all FL>=0.

Sort CPR waypoint data by flight and time

Formatted CPR waypoint data are read in SORTCPR.f. The track data are sorted (with Heapsort) first by combined callsign and dep/des airport information and then for of this extended callsign by increasing waypoint time, day by day.

The data are completed with the ICAO aircraft type based on the callsign/airports and the table produced in T_M3.f. The search in the list of callsigns to obtain the aircraft type is performed after sorting the callsigns and searching within the sorted table efficiently. This is again accomplished using the Heapsort method.

Combine M3 and CPR into flight track data

Flights from the sorted CPR data are combined with the sorted external M3 flight tracks in COMB_M3_CPR.f to extend beyond the Central Europe domain for day D. The completion leaves the flight segments covered by CPR data unchanged but extends the flights forward or backward from ultimate CPR endpoints in upper airspace (FL≥210) by copying M3 information for earlier or later flight segments with times adjusted to match the times at the CPR endpoints.

Thereafter, various quality control and correction steps are performed (call SCPR and SCPR2) to reduce the number flights with FL or position jumps or unrealistic ground speed values. Missing ground speed or climb rate values are replaced by estimates from the position coordinates.

Combine M3-CPR with NATS Shanwick data

The previous output is combined with day-wise sorted NATS flight tracks to replace flight plan data with observed data for the North Atlantic Fight Corridor. In the course of this step, some flights are found in the NATS data not existing in the M3-CPR data. These flights are added to the output.

Add ERA5 wind and temperature data

For all waypoints of the flights written in the previous step (including flights outside Europe), air temperature and horizontal wind speed components are added from linear interpolation in space and time in ERA5 data. For this purpose, the waypoints are read hourly completely into core memory and ERA5-NWP data are read 3-hourly. For each hour, waypoints are filled with weather data.

Add performance data

True air speed is calculated locally for given ground speed and flight direction using the wind data added in the previous step. The ground speed vector analysis requires knowledge of the flight direction which is determined from the positions at the end points of each flight segment. The air speed values are limited by a minimum landing speed (50 m/s) from below and the BADA3-provided maximum operational Mach number from above.

Flight performance (true air speed, mass, fuel consumption, overall propulsion efficiency) is estimated with EUROCONTROL's Base of Aircraft Data, Version 3.15 (BADA3, https://simulations.eurocontrol.int/solutions/bada-aircraft-performance-model/) for the given aircraft type (Nuic et al., 2010).

Alternatively, the PS method is used, in the version as described in Poll and Schumann (2020). That version allows applications for Mach numbers between 0.8 and 1.08 times the optimum Mach number. The optimum Mach number is one of the characteristic aircraft parameters in that method. The traffic data suggest that aircraft sometimes cruise with lower Mach number (e.g. near airports) or with even larger Mach numbers up to the maximum permitted operational Mach number. Here we use a revised PS version covering all occurring cruise Mach numbers.

Contrail segment processing

The hourly segmented and uniformly interpolated traffic data including the aircraft performance data are read in for contrail analyses hour by hour. Contrail analysis is performed using CoCiP, which reads the traffic data together with meteorological data from the Integrated Forecasting System (IFS) of the European Center for Medium Range Weather-Forecasts (ECMWF), both hourly. The code may either use the precomputed performance data or recompute them immediately after reading the traffic input. This option is introduced to enable parameter studies with changed performance data. CoCiP also reads position information on observation data (e.g. the Meteosat SEVIRI longitude-latitude grid and times) for which CoCiP performs contrail and cirrus analysis.

4 Data availability

The CoCiP input data (Table S 1) as used in the reference case of this study, and the contrail model output data are available for scientific studies on request from the lead author. These data will be put into a public data repository in due time. The original traffic data are not available for public distribution.

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