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TÍTOL DEL TFG: Aircraft trajectory optimization according to weather conditions

TITULACIÓ: Grau en Enginyeria d'Aeronavegació

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Títol: Optimització de trajectòries d'aeronaus respecte a condicions meteorològiques

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Resum

En un espai aeri cada cop més congestionat les institucions i empreses usuàries del sector necessiten una òptima organització de les rutes aèries per tal de reduir al màxim tot tipus de despeses gràcies, entre d'altres, a la minimització de les demores i duracions dels temps de vol. És per aquest motiu que en aquest projecte s'han volgut fer unes primeres passes en aquest tema amb el disseny, programació i simulació de noves eines per tal de millorar les trajectòries de les aeronaus en un àmbit específic i rellevant de la navegació aèria: la meteorologia.
Per tant i en primer lloc, s'ha dut a terme un petit estudi introductori sobre els fenòmens meteorològics que puguin afectar directament al vol d'un avió, en general, de tipus comercial. Aquest breu incís situa al futur usuari de l'eina esmentada dins de l'entorn que permet identificar les causes dels resultats obtinguts associats a fenòmens atmosfèrics concrets. Tot seguit, s'ha procedit a explicar la metodologia seguida per tal de dissenyar un programa de Matlab capaç d'optimitzar trajectòries aèries en funció de les condicions meteorològiques presents en les diferents rutes simulades.
Es descriuen, tant l'obtenció de les dades, com el seu processament i la seva respectiva representació cartogràfica a nivell global. A continuació es defineixen els algorismes emprats per minimitzar la durada dels temps de vol a través dels fluxos de vent i àrees de precipitació presents en cada escenari.
Un cop descrit el funcionament del software, s'han realitzat un seguit de simulacions tant de casos reals com teòrics per tal d'aconseguir visualitzar el funcionament del programa en múltiples escenaris. Primerament, com a escenari real s'han simulat tres possibles rutes comercials de llarga, mitja i curta distancia entre Barcelona i tres destinacions diferents: Tokio, Moscou i Viena. I en segon lloc, s'han representat variacions teòriques de les primeres rutes reals on s'han modificat velocitats inicials i el pas d'aquestes a través de fenòmens meteorològics per tal de millorar la comprensió del programa de manera pràctica.
D'aquesta manera, no només s'analitza el correcte funcionament del programa, sinó que es pot també concloure el que suposa la implementació d'un software d'aquest tipus en la planificació de rutes aèries a nivell bàsic però també realista.

Title : Aircraft trajectory optimization according to weather conditions

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Overview

In a currently congested and overbooked airspace, institutions and users of the aeronautical sector increasingly need a major organization and optimization of the air routes in order of reducing any kind of cost and mainly concerning about minimizing aircraft delays and flight time durations. It has been for this reason that this project makes some first steps into this topic with the design, programming and simulation of a sort of new tools in terms of improving airplane's trajectories in a specific and relevant field of the aerial navigation: the meteorology.

First of all, an introductory and theoretical study about aviation weather has been done being directly related with any type of flight, even it has been mainly focused on commercial ones. This short summary, gives a future user of this tool the appropriate environment, allowing him to easily recognize the causes of the obtained results that are associated to specific meteorological phenomena. Secondly, the methodology used to design a Matlab program able to optimize aerial trajectories in function of atmospheric conditions has been explained. In this step, the procedure to obtain the meteorological data has also been detailed including its process and its respective worldwide cartographic representation to furthermore define the required algorithms to minimize the total flight length through wind currents and precipitation in every different scenario.

Once the software's performance has been explained, several simulations have been run for real and theoretical cases in terms of visualizing the functionality of the program for different situations. Initially, as a real scenario, three possible commercial long, mid and short distance routes have been simulated between Barcelona and Tokyo, Moscow and Vienna. Additionally, some fictional simulations have been performed in terms of visualizing how the modification of their initial airspeeds and their path through different weather systems could influence the performance of the software.

The project not only analyzes the appropriate performance of the program, but also explains what could suppose the implementation of a software like this in basic but realistic route planning.

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INTRODUCTION

As a combination of economical interests, ease of people transportation and a continuous passion of flying innate in every human being, aviation has become nowadays a routine of our daily life and a growing industrial sector all across the world.

Regardless, due to an also increasing pressure from the related authorities, companies and different organizations, a big investment in a more ecological and efficient way of flying has already been triggered and will be done in the nearest future to guarantee aviation as a sustainable model of transportation. This is the reason why weather analysis and forecasting have always been determinant aspects to be taken into account when planning and designing any air navigation route, proving the relevance an adequate meteorological assessment could take in order to perform them. Therefore, increasing knowledge of flying through or avoiding different patterns of weather phenomena would also improve aviation in terms of safety, comfort and economy.

As a good way to set the basis of this project, a theoretical study of aviation weather detailing how to deal with multiple weather scenarios is completely essential. But meteorology is as interesting as unpredictable. Small differences in system configurations lead into big changes in events development and magnitude. For example, the location of a low pressure system would transport different air masses depending on where it is situated and influenced by local parameters, as the orographic disposition, resulting into multiple phenomena is likely.

The atmosphere is the layer of gases surrounding the Earth held to the surface by its gravity and where most of the aeronautical activity is performed. For this reason, it has been strongly necessary to analyze this physical environment where flights develop in order to understand the main phenomena or influence involved. Composition of those gases has a big influence in climate' stability, but it has been interesting to consider it as invariant from ground to an altitude of 70 km high, taking into account that almost every flight is performing below those levels [1]. In order to homologate and standardize the different values of the main variables of the atmosphere fundamental to aviation it has been needed to consider an unreal or approximated atmosphere for mid latitudes to be taken as a reference in future calculus where the established values are shown in the following Table A.1:

Parameter	Value
Pressure at sea level	1013,25mb
Temperature at sea level	15ºC
Tropopause altitude	11km
Variation of temperature until tropopause	-0,65ºC/100m

Table A.1: ISA atmosphere characterization values [1].

It is fundamental to analyze how the atmosphere is structured in terms of altitude. The comprehension of its layers will help to understand the different levels of flight, choosing the best height to therefore optimize aircraft parameters as flight time and fuel consumption through weather scenarios allowing safer, more efficient and more economic performances. In Figure A.1 the different layers according temperature vertical profile have been schematized.

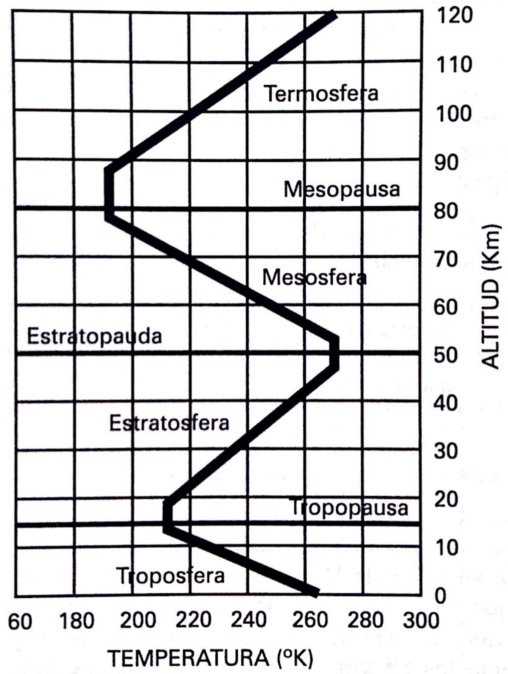


Figure A.1: Average atmospheric vertical temperature profile [1].

Focusing mainly on the flyable layers for commercial airplanes, troposphere and tropopause are the only levels where most of the weather events are likely to occur.

With a major weather phenomena occurrence and an increase of wind speed with altitude it has been important to center the study into the troposphere where the biggest aeronautical activity is done, specially departure and approach procedures. For instance, cruise phases are more likely to be developed in the tropopause, the layer in between the troposphere and the stratosphere. As shown in Figure A.1, for the troposphere temperature generally decreases proportionally with altitude, but when at high levels a stop or even an increase is perceived, this could be associated with the tropopause. Being characterized as a free cloud layer, keeping most of the weather phenomena mainly under its level, airliners take advantage of those properties and concentrate in the tropopause for mid latitudes most of their cruise commercial activity. But some specific scenarios could influence daily routes all along this transitional layer, and related to some tropospheric events, it has been of a big relevance to analyze and study every typical meteorological event that could affect the performance of this project.

As a first approximation to a meteorological assessment of the route, the analysis of surface and low altitude atmospheric conditions is extremely relevant for a real flight. Wind speed and its direction, temperature, humidity, visibility, cloud height and cover, pressure and precipitation amongst many others parameters would determine the performance of takeoff-departure and approach-landing procedures. But in the particular case of this project, those flight phases and consequently the related phenomena have been disregarded in order to simplify the methodology and because there has been no real incidence for the global result of the project. Otherwise, the classification and understanding of phenomena related with higher altitude as cruise flight phase has been essential in order to optimize flight route trajectories in the matter of saving time and money enhancing at the same time safety and comfort.

Therefore, a description of every possible phenomenon in a typical mid-latitude flight route has been needed for the optimal understanding of meteorological aviation information in addition to the adequate development of this project. Taking as a reference significant weather charts commonly used in aviation, an analysis could initially be done dealing with low (Surface - FL 240) and mid (FL 100 - 450) level events but focusing generally in high (FL 250 - 630) level scenarios for the study of cruise flight phases. Choosing a real commercial route scenario could help to evaluate and quantify any event all along the flight paths. Figure A.2 shows a typical high altitude North Atlantic significant weather chart where a disposition of multiple meteorological events have been shown.

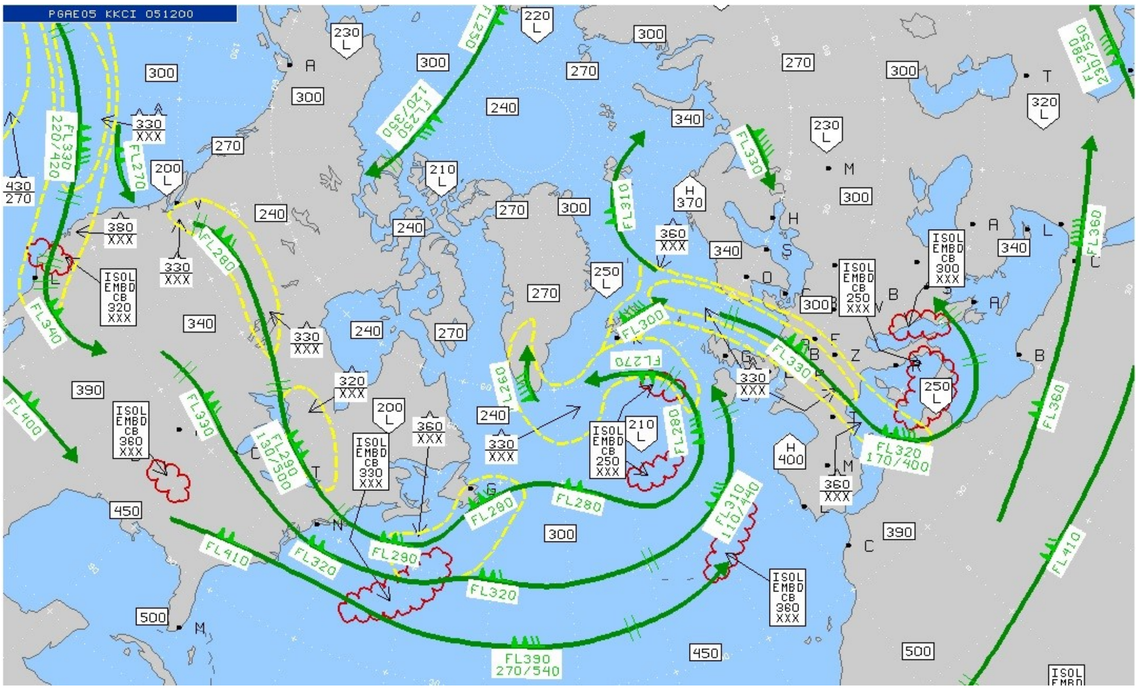


Figure A.2: High level significant weather chart on the North Atlantic area on the 06/02/2017 at 12 UTC [3].

At first sight, and in terms of relating phenomena shown in Figure A.2, a brief description of global circulation has been done. The motion of air masses in the atmosphere influences the behavior and development of weather events influencing strongly the performance of any flight. The main cause of global circulation is the differential heating of the Earth, as shown in Figure A.3, the reason why the atmosphere transports cold air from the poles, where a loss of energy is appreciated, to equatorial or tropical latitudes, where a gain of energy related with a higher incidence of solar radiation is taking place. Earth's rotation is producing as well deflective forces on large-scale wind flows that will influence the behavior and disposition of weather patterns [2].

As a result of the causes of global circulation, the jet stream is a narrow and meandering area of strong winds located in two main breaks of the tropopause in the northern hemisphere: the polar jet (latitude 30 º to 60 º North) and the subtropical jet (20º to 30º North), where winds must blow from at least 50 kt to maximal values of 200 kt in some specific areas in winter to be considered properly as the jet stream [2]. Going mainly from West

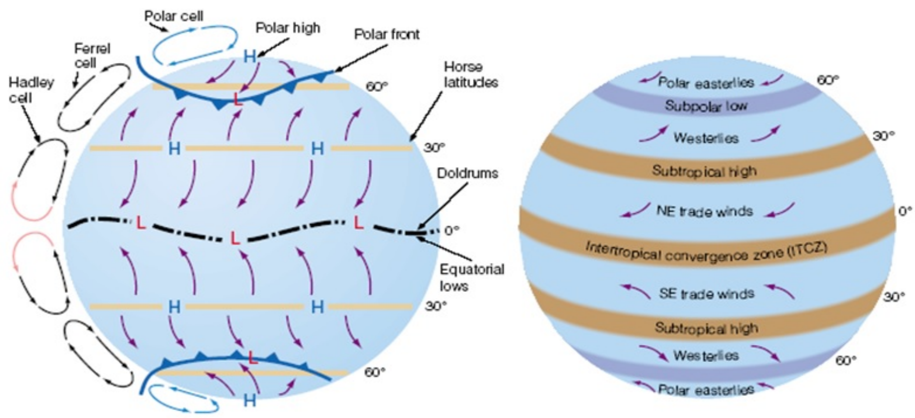


Figure A.3: Three cells global circulation model. Each cell corresponds to an air closed circulation loop [4].

to East in the northern hemisphere and shown as green arrows Figure A.2 with their corresponding altitude and windspeed, it has been of an absolute relevance to be taken into account when planning a flight route at its level as it is understandable that those characteristics could influence flight operations in a serious aspect. The jet stream could cause significant winds inciting changes in the performance of aircrafts. For example, following an eastbound flight, tail wind would benefit fuel consumption and a reduction in the duration of the flight. Otherwise, headwind would induce a big resistance triggering opposite consequences.

Represented as yellow dashed on Figure A.2 and associated to the jetstream clear air (without any visual indication) turbulence might occur. Wind shear turbulence is also a very important parameter to be taken into account. Changes of horizontal or even vertical wind speed in small distances result in severe turbulence. So, a good study or forecast of the jet stream is essential because a change in a few thousand feet could introduce the aircraft in a better or worst turbulence area.

In addition, the interactions between airmasses can affect flight planning. In short, an air mass is a significant portion of the atmosphere with homogeneous characteristics taken from the properties of the geographical region where they come from, known as source region[2]. Source regions are as huge areas where surface and climate conditions are uniform and air keeps calm for a long time coinciding with stationary high pressure systems. This way, the air mass takes the properties that spread depending on the wind. Few examples of the most typical ones are polar surfaces, some parts of oceans, North of Canada, Siberia, Sahara Desert and Gulf of Mexico [1] [2].

The interactions between airmasses with different temperature and humidity produce a front in the boundary between these airmasses. Frontal systems are classified according the airmass behind the front. On the one hand, a warm front occurs when a warm air mass is pushing a cold one that moves back while the warm is lifting along a shallow frontal slope. Those fronts mainly produce stratus and nimbostratus clouds depending on the instability of the air, usually with associated widespread, steady and light to moderate precipitation, even if heavy showers are sometimes related with cumuliform cloudiness. Wind shifts and temperature increase are observed after frontal passage. Icing, freezing rain or drizzle are also common leading to low visibilities that could endanger the safety of the flight as well [2]. On the other hand, a cold front is the event where a cold air mass moves and replaces a warm one at or near the surface. Since cold air has higher density than the warm one, it flows underneath and replaces the warm air. This is triggering a lifting mechanism forcing warm air upwards. Being steeper than warm fronts, it is possible to define as well active cold fronts moving faster than warm ones, turbulent in the frontal zone due to strong pressure gradients, presenting sharp temperature and moisture changes. Moreover, cumuliform and stratiform cloudiness is likely to be related, with associated narrow and small band of heavy precipitation. Icing could also be observable in the frontal passage. Not all the frontal systems are represented at these altitude levels in Figure A.2 but considerable convective cloudiness is displayed as red clouds like to reach those altitudes and in order to be taken into account in any flight.

Additionally, there are also two other kind of fronts, the occluded and the stationary ones, but their characteristics are a bit out of topic in terms of the purpose of this project, that could be developed with the only understanding of the basis of frontal activity.

The election of the best way to deal with a front depends strictly on how dangerous for safety the weather system is, how big are its dimensions and what is the route that the aircraft must follow. For example, in terms of economy, the evaluation of the fuel consumption through or around the front depends implicitly on the size of the system and will vary in function of the additional distance of the alternative route or the winds affecting the performance of the flight through the phenomenon. So, even if the pilot has the knowledge and capability to deal with those meteorological events, the goal of this project has set the basis of optimizing those results and evaluate if a non-human aid could help in order of choosing new trajectory options in terms of planning and facing or avoiding weather events.

In conclusion, in this project it has been desired to verify if the implementation of a software helping in terms of planning and deciding which are the best paths to follow through various weather scenarios in order to optimize flight time and proportionally fuel consumption would be profitable in terms of designing new air routes or the ability of the pilot would just be enough to face complex weather scenarios. So, would a self-designed weather avoidance software help in order of optimizing new aircraft trajectories? An accurate explanation of how this program might be implemented in Matlab environment and a numerous amount of simulations would let to understand its own utility and which are the benefits that could be taken from it.

CHAPTER 1. SIMULATION SOFTWARE AND METHODOLOGY

The goal of this project is to establish the basis of a simulation software able to enhance route planning through different meteorological scenarios. The program has been developed using MATLAB 7.12.0 (R2011a) and has been made easily understandable for further improvements or updates by future students or researchers.

1.1.. Selection of meteorological data

An important part of the project has been data collection. A huge and not always clear amount of information could be found along the web, so a large analysis of it has been very important in order to display and work properly with the desired data.

The selected data source has been the National Oceanic and Atmospheric Administration (NOAA) [5]. In order to ease the growing need for remote access to numerical weather prediction and global climate models and data, some organizations related with those subjects created the NOMADS, that is the NOAA Operational Model Archive and Distribution System project. NOMADS allows the access to four categories of modeled data containing registers of the past, present and future of weather predictions and models. Those categories are [6]:

- Reanalysis.
- Numerical Weather Predictions.
- Ocean Models.
- Climate Prediction.

Numerical Weather Predictions deal with mathematical and physical models of the atmosphere to predict weather basing its computations in current weather conditions. So being maybe the most interesting point in order to display weather conditions that could influence a flight route, Global Forecast System model (GFS) has been chosen to work with it in Matlab. It is a weather forecast model created and sustained by the National Centers for Environmental Prediction[7]. Covering the entire planet and containing lots of meteorological variables from temperatures, winds to precipitation and cloudiness, it has been the perfect model for analyzing multiple scenarios in wide geographical areas and during the last years. Actually, NOAA offers a big amount of data files stored from GFS models.

1.2.. Data reading and processing

In 1985, the World Meteorological Organization approved a general purpose in which bit-oriented data exchange was promoted and known as GRIB or GRIdded Binary. Being a format for gridded data, it is used by the operational meteorological centers for storage and exchange of large volumes of information where each GRIB record contains a single parameter with values located at an array of grid points [8]. Those specifications are the major reason why NOAA's files are under GRIB format.

Consequently, Matlab requires a special toolbox called *NC Toolbox*, providing read-only access to data model datasets. As a brief description of its functionality, this toolbox uses as a data access layer called *NETCDF-Java* and is able to read GRIB or GRIB2 amongst many other file formats[8]. Moreover, the toolbox brings a directory with many demo files that could help to understand how it works properly and which are the adequate commands to get the data.

1.3.. Map projections

A toolbox easing the mapping of the variables has been necessary to display correctly all this data. So, as recommended from the NOAA's website, *M_MAP Toolbox* has been the tool used in the software to get appropriate charts of the desired geographical location. *M_MAP Toolbox* has many functionalities able to represent coast lines, grids amongst many multiple geographical parameters that could be seen in the referenced users guide [9].

In most cases of the project, *Miller's projection* has been selected due to the fact that it is easily adaptable to the required interests. This projection is a modified Mercator's one, being therefore adequate for interactive maps as the one developed in this thesis. Nevertheless, it has been important to remember that this kind of projections present a huge land area distortion the further from the equator the location is [10]. But when computing distances in this software, everything related has been considered, so it has been only a problem for human eye perception and not a computational one.

1.4.. Application and trajectory optimization

It is obvious that the current aeronautical industry has already a huge amount of methods and equipment able to predict, deal with and even avoid undesirable weather systems, but this software has helped to understand this in a simpler but precise way and even let some doors open for students that would like to take benefit of it and carry on with further extensions of the program.

Amongst many available variables stored in the data files downloaded from NOAA's database, Table 1.1 shows the ones which have been used in terms of setting basic weather scenarios that could influence different flight routes.

The resolution of this data based on forecasts obtained from GFS models has been also selectable. Majorly, the resolution taken for the simulations has been 0.5 ^{o}, that is for every 0.5 ^{o} a value of those variables has been associated. The resolution has also been relevant in order to compute the number of waypoints required all along the flight paths where the smaller the resolution the bigger the number of waypoints in order to interpolate more precisely the values displayed during the trajectory. Figure 1.1 shows the wind field (arrows) and convective cloud cover (color contours) at the the tropopause on central Europe on 15/08/2016 at 00 UTC.

Table 1.1: Table of the most used variables in the program

Variable	**Description**	**Units**
lon	Longitude	Degrees [^{o}]
lat	Latitude	Degrees [^{o}]
time	Effective date of the stored data in the file	Days (converted to: hour/day/month/year)
u-component_of_wind_tropopause	Eastward component of wind velocity at tropopause height level	[m/s]
v-component_of_wind_tropopause	Northward component of wind velocity at tropopause height level	[m/s]
Total_cloud_cover_convective_cloud	Cover of convective cloudiness associated to storm activity.	[%]

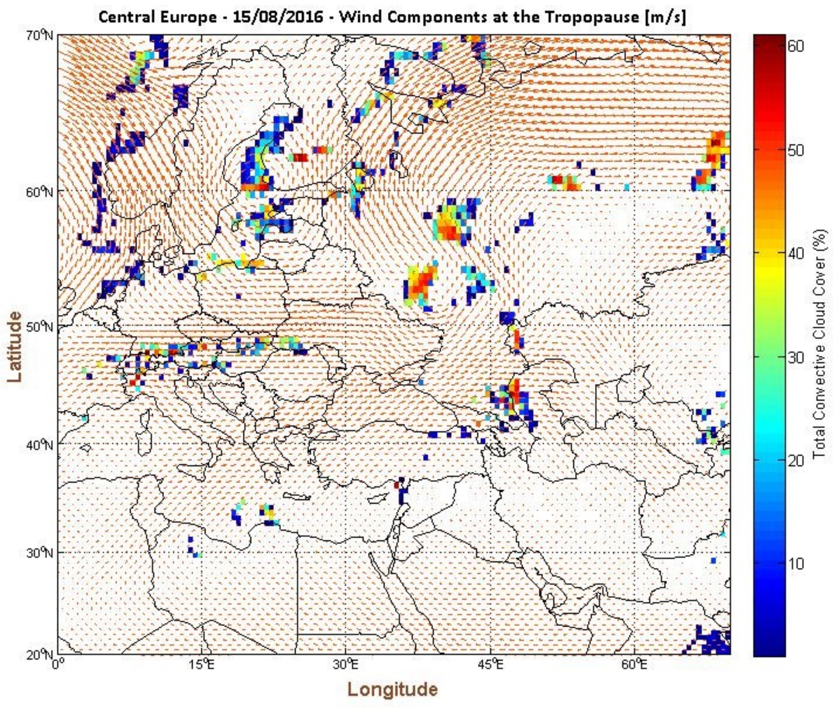


Figure 1.1: Wind field (arrows) and convective cloud cover (color contours) at the the tropopause on central Europe on 15/08/2016 at 00 UTC.

Therefore, once a desired scenario has been set up simulations are ready to be started by defining departure and arrival coordinates of the route. This could be done by introducing specific coordinates as an input but has mainly been established by mouse clicking depending on the meteorological panorama and the desired route to be performed. The basis of the simulation have been to follow the shortest path between two locations, that is following great circle trajectories, and in order to minimize the time of flight an objective function named *getTimeFromPath* has been implemented, where meteorological conditions are related to the computation of the flight time. Basically, in order to get the global time of the flight path the sum of every flight interval time between waypoints has been obtained from:

$$IntervalTime = \frac{IntervalLength}{TotalAirspeed}$$

Being *Total Airspeed*:

Total Airspeed = Airspeed + Added Wind Speed

Where the initial velocitity for the cruise phase of the simulated aircraft (*Airspeed*) has been predefined by the user and selectable in terms of the plane type but while the ground speed of the wind (*Added Wind Speed*) has been obtained from an interpolation of the wind velocity at the specified waypoints, multiplied by its unity vector to therefore be summed up to the original airspeed in order to quantify the influence of the wind component during the flight path. To avoid stormy activity, coordinates of the higher convective areas have been localized and stored as a variable to pretend some countercurrent wind values being associated to those locations in order to make the optimizing function avoid those paths as an intentional lie to program. Depending on the interests of the route, type of aircraft and meteorological phenomena, the storminess weights have been preselected in order quantify the influence of convectivity to the optimized trajectories.

Finally, the optimization has been designed to be based in the prescheduled waypoints, appreciated as the black line in Figure 1.2, and the scenarios all along the flight path allowing Matlab's *fmincon* function to optimize the objective function and compute the shortest path time amongst many iterations, where every iteration has been considered as an improved new route from the previous until the optimal solution has been found, shown as a red path in Figure 1.2. The *fmincon* function could be configured in order of stopping iterations whenever the optimized solutions reach a specific small value of improvement precision.

Flow diagrams corresponding to the software detail the steps of performance of the code and have been attached in Figures 1.3,1.4,1.5,1.6 and 1.7.

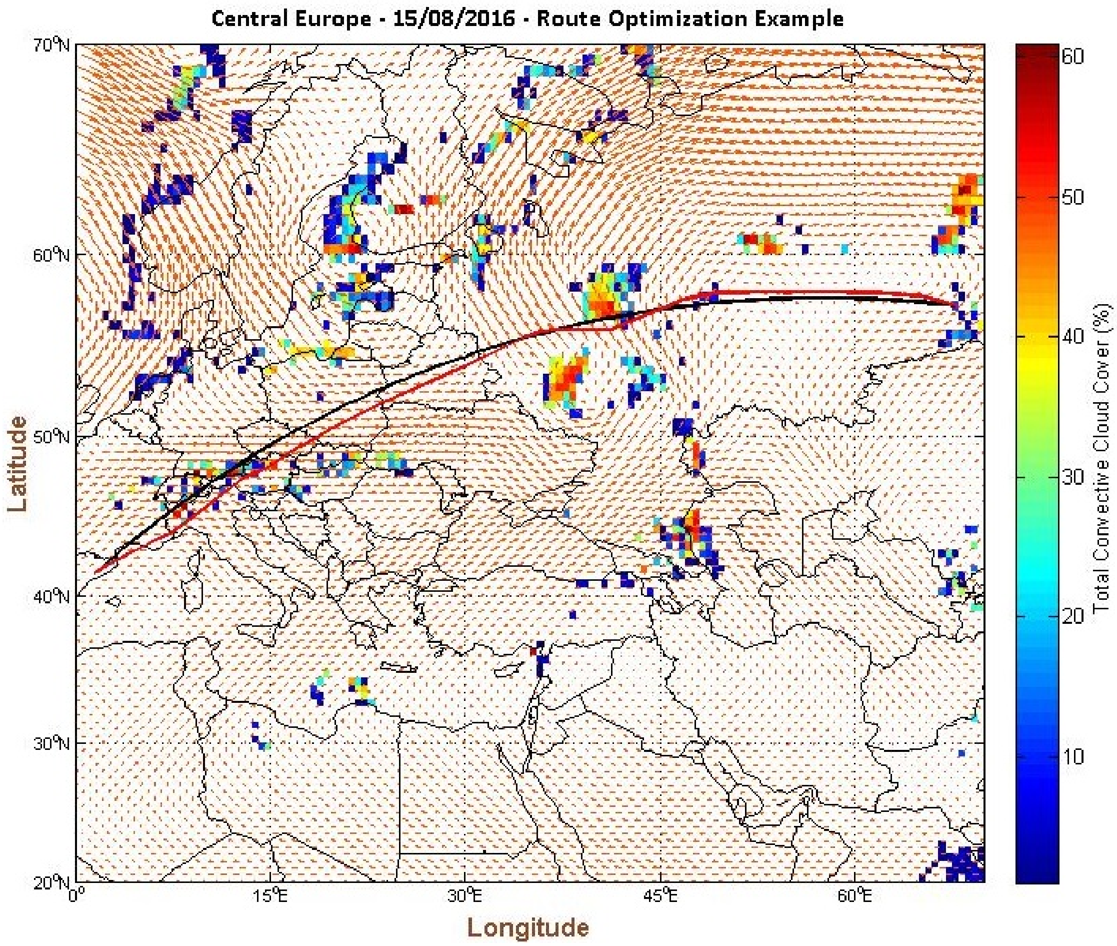


Figure 1.2: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on central Europe on 15/08/2016 at 00 UTC.

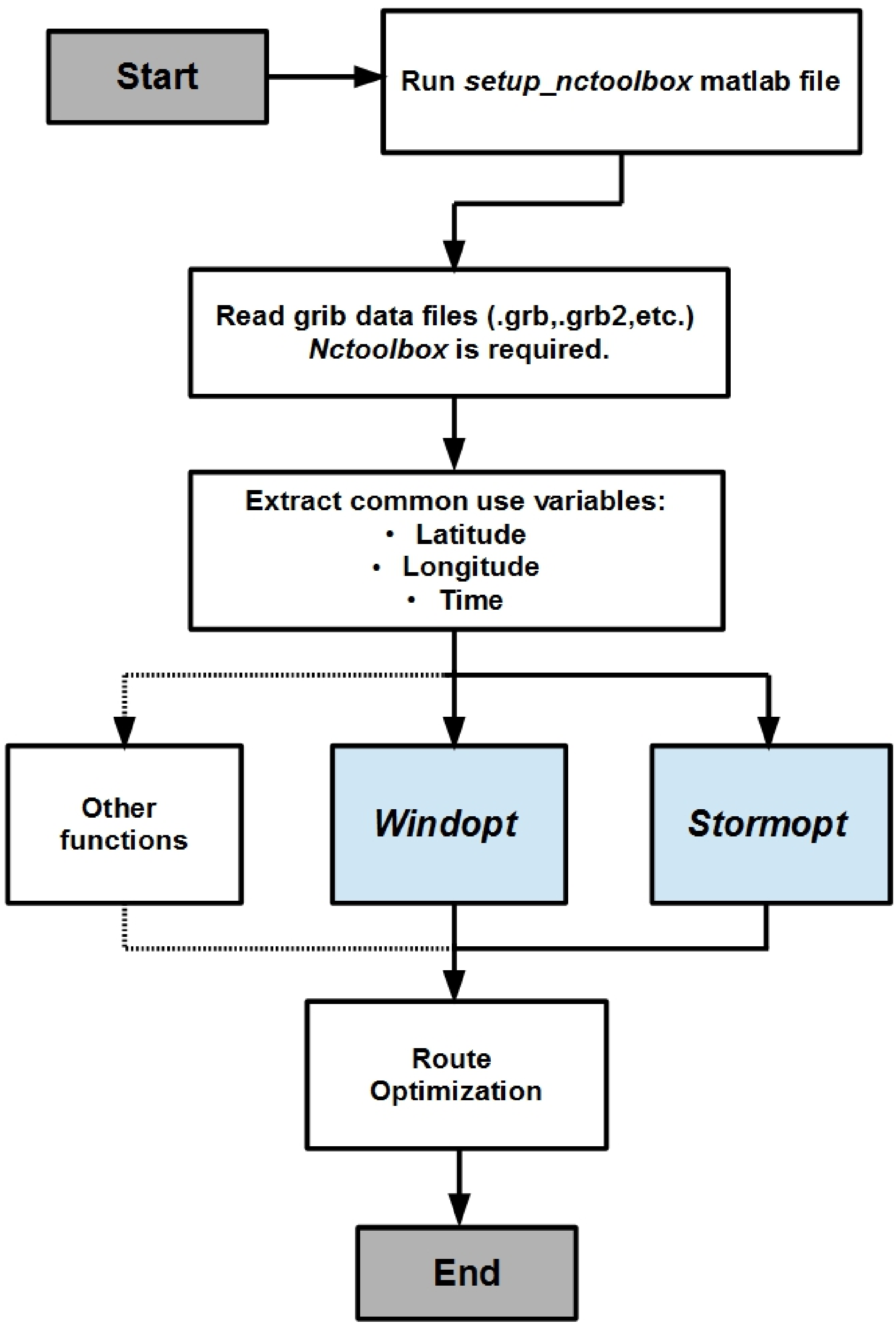


Figure 1.3: Flow driagram showing the overview of the weather avoidance software.

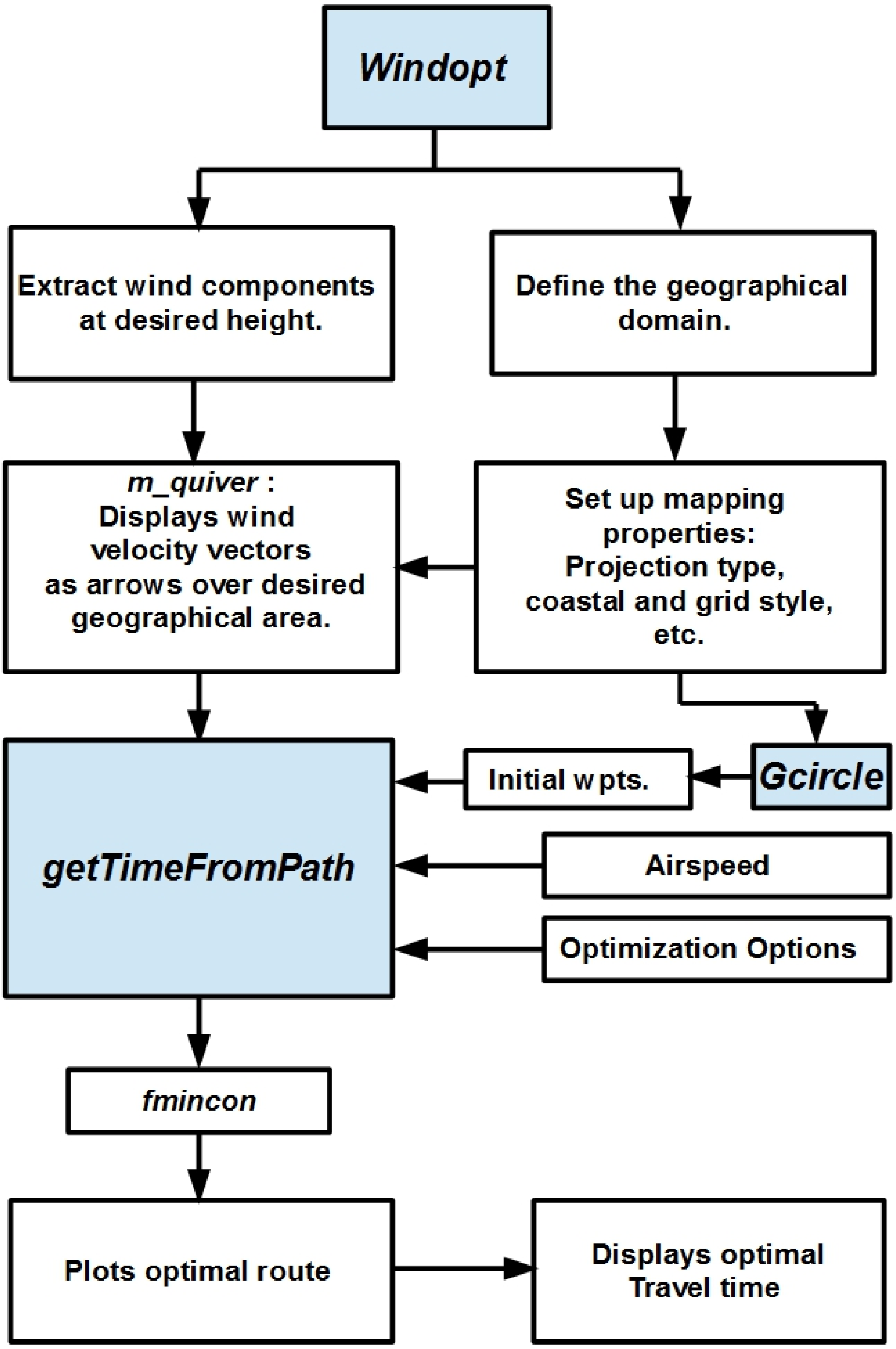


Figure 1.4: Flow driagram showing *Windopt* wind optimizing function.

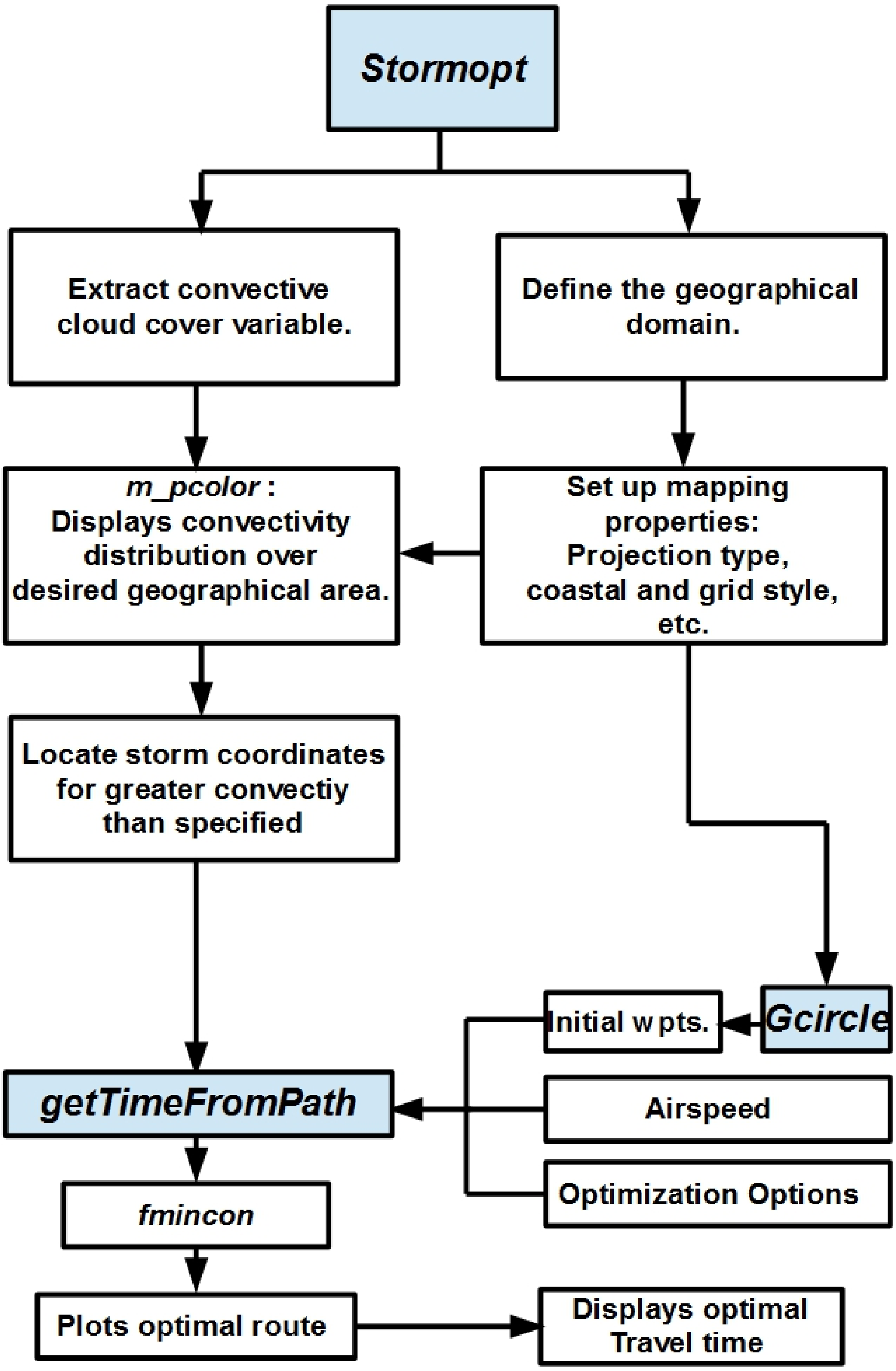


Figure 1.5: Flow driagram showing *Stormopt* convectivity optimizing function.

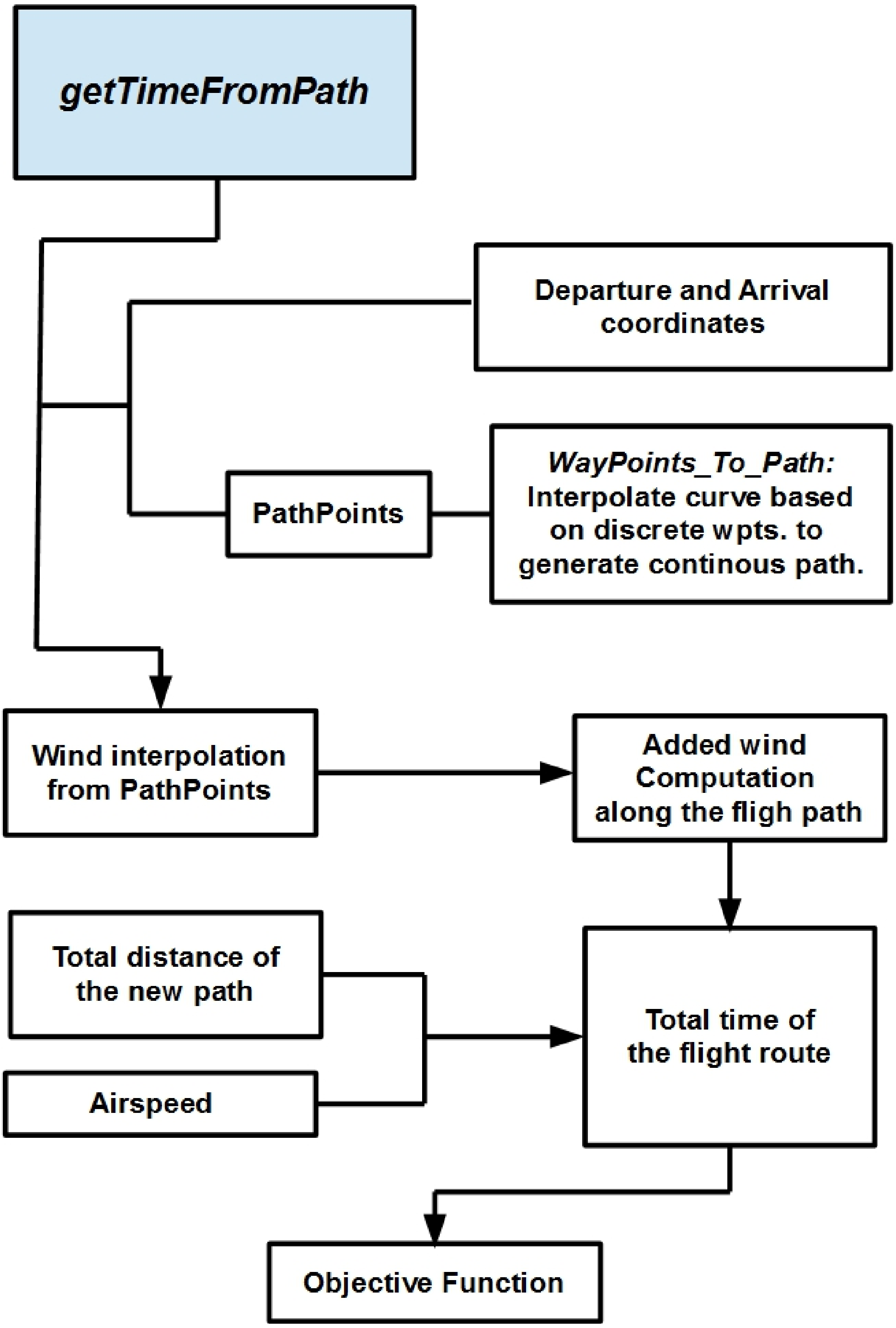


Figure 1.6: Flow driagram showing *getTimeFromPath* time computing function.

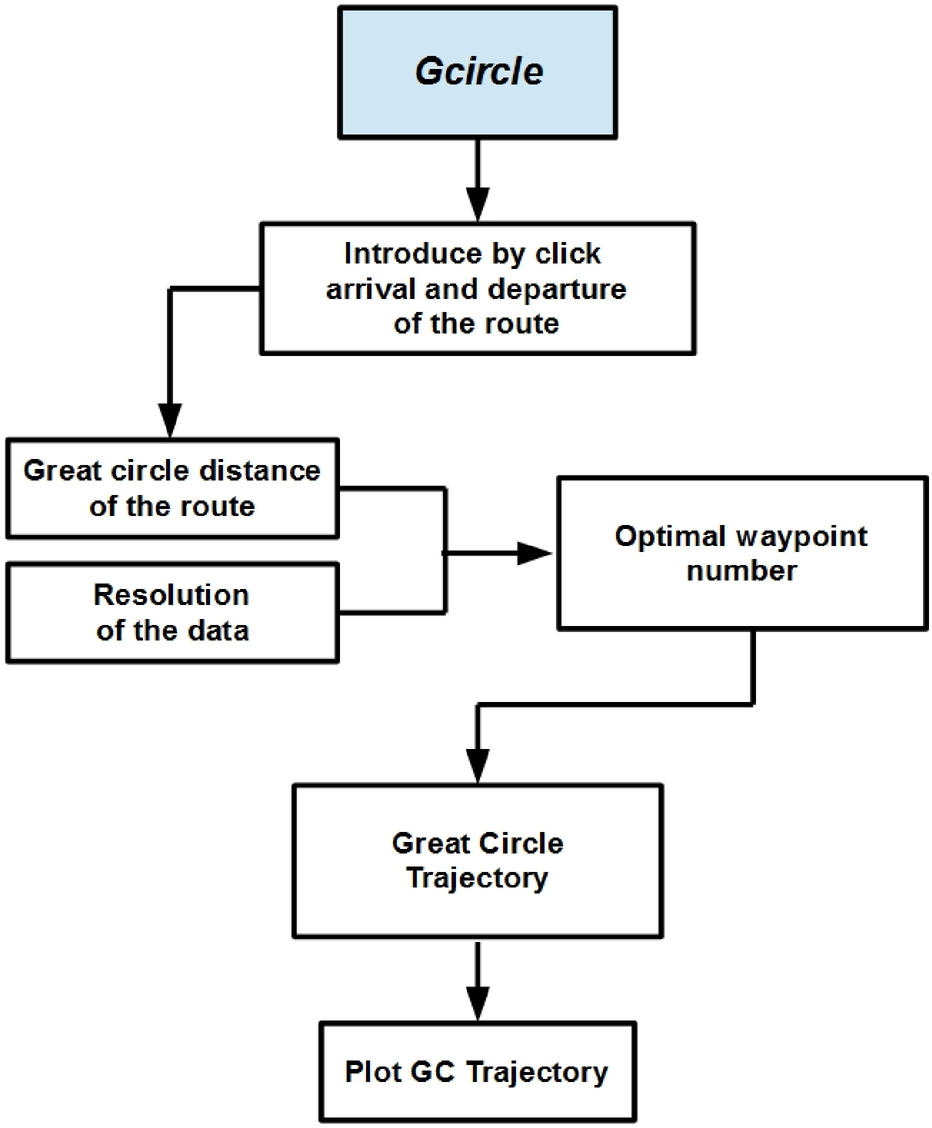


Figure 1.7: Flow driagram showing *Gcircle* Great Circle trajectory function.

CHAPTER 2. SIMULATION AND RESULTS

2.1.. Real case scenarios

In this chapter the simulation results of the project are shown and as visualized in Figure 1.2, black lines represent great circle distance, that is the shortest distance in Earth between two points, and the red ones the weather optimized trajectory all around the great circle one. In terms of keeping a logical order to evaluate all the obtained data a specific schedule has been followed for the same period of time. First of all, three different scenarios have been defined performing long, mid and short range routes between different airports to compute the flight path time for every new trajectory. The main purpose of the simulations is to conclude how an implementation of this kind of software could directly affect or modify the route planning in terms of scheduling and optimizing a commercial route for an airline. Comparing tendencies between different types of routes has led into a better understanding of weather influence in those trajectories.

The simulated routes are realistic and commercial trajectories between Barcelona and three other relevant destinations: Tokyo, Moscow and Vienna. But some settings considerations have been taken into account for the appropriate performance of the software. For example, in terms of choosing the evaluating period of time, the same month of October 2016 has been taken as it has been considered a transitional month between summer and winter in northern hemisphere covering multiple and interesting weather phenomena all along the desired trajectories. Moreover, the airspeed of the simulated aircrafts has been averaged all along the flight paths in terms of simplifying the calculations where the longer the route, the higher the velocity has been, corresponding to a longer cruise flight phase associated to higher airspeeds. Meteorological conditions have been assumed constant along every route and specifically, wind speeds have been taken for cruise phases, corresponding majorly for tropopause flight levels. And eventually, another relevant aspect to consider has been the frame or the boundaries of the plots. In terms of avoiding any error from Matlab when displaying the results into charts wide margins have been preselected around the expected routes. The code has already been adapted for this simulations, so results have been displayed appropriately. Finally, characteristics of those three simulated routes are depicted in Table 2.1.

2.1.1.. Long range route Barcelona - Tokyo

First of all, long range simulations have been performed to evaluate the software's functionality through different weather phenomena and winds at global scale. Those simulations have helped to understand the direct affectations the jet stream has in those kind of flight paths, where an adequate study of its location on every trajectory could considerably reduce flight times. However, in case of head wind and flying against the jet stream or strong wind currents the added flight time could be considerably increased.

As a result of the simulations, Figures 2.1, 2.2, 2.3 and 2.4 graphically show the evolution of the trajectories all along the route for some days of the month where some variations are appreciated in function of winds and weather phenomena influence. Additionally, Table 2.2 numerically depicts daily details of the results.

Route	Departure Coordinates	Arrival Coordinates	Averaged Airspeed	Route Length	Simplified Flight Level	Evaluated Time Period
Long Range Barcelona-Tokyo	Barcelona: 41.3 N 02.1 E	Tokyo: 35.7 N 139.75 E	950 [km/h]	10439 [km]	Tropopause	October 2016
Mid Range Barcelona-Moscow	Barcelona: 41.3 N 02.1 E	Moscow: 55.8 N 37.6 E	850 [km/h]	3021.6 [km]	Tropopause	October 2016
Short Range Barcelona-Vienna	Barcelona: 41.3 N 02.1 E	Vienna: 48.2 N 16.4 E	750 [km/h]	1359.2 [km]	Tropopause	October 2016

Table 2.1: Characteristics of the three simulated routes.

Basically, in order to display the whole route from Barcelona to Tokyo, four different plots have been chosen depending on their features. Those four plots show multiple variations and irregularities in their optimized paths that have been interesting to comment even if their visual quality is not the optimal because of their huge amount of data represented all along the big distance covering almost 10500 km as shown in Table 2.1.

Even if the deviations, observed when approaching Japan for Figures 2.1, 2.2 and 2.3, of the optimized routes from the great circle trajectories could seem negligible their diversions result into hundreds of kilometers introducing huge fluctuations in the numerical values of the flight times. Besides, strong wind currents patterns have been mostly appreciated for those long flight ranges and originating big deviations such as the observed over northern Russia in Figure 2.3, where the improved trajectory is separated from great circle's one for more than 1000 km. Nevertheless, frontal systems and convectivity have not really influenced the performed simulations and no considerable route modifications have been performed. It is also possible that no real endangering weather systems had appeared for those routes in October 2016.

A summary of deviation from great circle trajectories for the whole month are shown in Table 2.2.

2.1.2.. Mid range route Barcelona - Moscow

Secondly, an analysis for a mid distance route is shown in Figures 2.5, 2.6, 2.7 and 2.8. The intention has been to understand if the performance of the software is the same than for longer paths and to visualize at smaller scales the development of the trajectories. For example, in longer routes it has been easy to appreciate the influence of wind field. For shorter routes, it has also been interesting to see if possible deviations due to frontal or convective areas could have been more influencing.

After simulating the itinerary for the whole month of October 2016, one of the most remarkable optimized trajectories is shown in Figure 2.5, where the deviation from the shortest path is considerable and does not traverse at any point the great circle trajectory. It is interesting to notice how the route optimizer function has taken benefit of the prevailing westerlies for mid latitudes (30ºN to 60ºN) to economize time and even avoiding some slightly convective areas just after departure from Barcelona or even over southern Poland.

For the other Figures: 2.6, 2.7 and 2.8, the behavior of profiting westerlies is similar, but something noticeable is observed in Figure 2.6: the way of dealing with the low pressure system situated over Poland. The optimized route moved south in terms of minimizing the effect of counterclockwise winds originated around the eye of the system has been a fact of interest. As Figure 2.6 shows, there is no remarkable convectivity attached to the low, but that does not mean there is no frontal cloudiness associated to it and as the software has been simplified as explained in Chapter 1, convectivity is the only type of these phenomenona with wind activity that could endanger the flight trajectories in this project.

2.1.3.. Short range route Barcelona - Vienna

Finally, the simulation of an usual short and commercial route at European scale has been evaluated. Beyond comparing the tendencies of weather affectation with the other mid and long range routes, the specific goal of this step has been to evaluate for the same resolution, in short routes the software. Figures 2.9 and 2.10 ease the understanding but it has been thanks to the numerical comparison in Table 2.2 that conclusions have been properly extracted.

As a matter of fact, something that could be highlighted for these short range simulations has been the low trajectory modifications that have appeared for most of the charts. Actually, the only simulation that has seriously modified its path is 2.9(a). To explain these changes, the same causes used to analyze Figure 2.5 could be applied due to the fact that the route track corresponds approximately to the first part of the Barcelona - Moscow route for the 1st October 2016.

Furthermore, in Figure 2.10(a) a huge convective system is developed in front of the Catalan, coinciding exactly with the departure of the flight. The software lightly tends north to avoid the system and take benefit of the winds but it has been too close to the origin of the route to completely avoid the system.

2.1.4.. Real case scenarios comparison

In brief and as a conclusive way of analyzing the obtained results, a tabular comparison has been elaborated in Table 2.2. This table shows the numerical data obtained from those three real case simulations. That is, flight time durations in hours for every optimized trajectory, their corresponding deviations in hours and their flight durations in percentage values, where values above 100 % represent a time delay and below 100 % an advance in time, from their respective ideal great circle trajectory times with no meteorological influence. So normalizing those results in terms of great circle values has benefited their comparison aiming to relate tendencies between the different types of routes and leading into a better understanding of weather influence and software behavior in those simulations.

2.2.. Specific scenarios

This section focuses on relevant and more specific cases obtained to identify the causes of the behavior of the program. For example, the particular influence of different initial airspeeds, different weather events and some other aspects that have been arising all along the tests and are highly present in the performance of the new optimized trajectories.

The situations simulated here have been idealized in terms the route trajectories directly hits or is affected by the supposed phenomenon to visualize any possible answer from the software.

2.2.1.. Variation of the initial airspeeds

The behavior of the software and its corresponding resulting trajectories varies as a function of the initial airspeed predefined in the code. This is the reason why in this section the previous studied routes have been displayed for a wide velocity range. The main goal has been to understand the program's behavior for different initial conditions in the same meteorological scenario for every route. Results are appreciated for Barcelona - Tokyo (Figures 2.1, 2.11(a) and 2.11(b)), Barcelona - Moscow (Figures 2.6, 2.12(a) and 2.12(b)) and for Barcelona - Vienna (Figures 2.9(a), 2.13(a) and 2.13(b)) where flight paths have been shown for high, mid and slow airspeed respectively for every sequence of figures.

Initially, different airspeeds were pretended to be related with different aircraft as a way of categorizing also the route in function of the airplane type and therefore its fuel consumption. However, while simulating specially at low velocities some trajectory disturbances appeared. As seen in Figures 2.12(a) and 2.12(b), not too many variations from the original route shown in Figure 2.6 with an original speed of 850 km/h could be noticed. In spite of this fact, strange behaviors have been remarked, specially for 2.11(b), where mainly in the first half of the route over Europe, the optimized route in red color describes a senseless zigzag trajectory. For that reason, the software seems to avoid moving backwards when headwinds components are stronger than the initial speed of the aircraft, real simulations have not been done for slow velocities. Besides, Figure 2.12 shows meaningless diversions even directly through convective weather systems getting worse the optimization results.

2.2.2.. Weather phenomena influence

Something that has also been noticed as an interesting phenomenon has been the way the software deals with meteorological phenomena, especially with convective frontal areas. Some simulations have been executed in order of directly facing storm systems and understanding how the time minimizing function deal with them. For example, as seen in Chapter 1, for Figure 1.2, in the description of the software's performance, Figure 2.14 clearly zooms a local convective system being avoided by the program. Whereas the great circle line goes straight from departure to arrival destination, the optimized line takes benefit of wind components to slightly divert from the original trajectory but perfectly avoids the area of major convective cloudiness represented with yellow and red colors in the center of Figure 2.14. After this deviation, the route recovers great circle trajectory in order to follow the shortest path because no considerable winds are involved.

Moreover, some other trajectories have intentionally been tested in terms of contrasting the influence of wind currents or even the influence of the jet stream for the same route but for different dates such as the comparison between the 2nd and the 3rd October 2016 for Barcelona - Tokyo trajectory, where wind influence has been clearly appreciated in Figures 2.15(a) and 2.15(b) respectively for the second half of the route directly affecting as an increase of flight times for headwind scenarios. For instance, the 2nd October a huge countercurrent wind flow is appreciated for the most part of the route, considerably increasing flight duration. Meanwhile, for the 3rd October, wind field barely affects route performance because of a lower intensity current resulting into a shorter flight time for the exact same route followed the previous day.

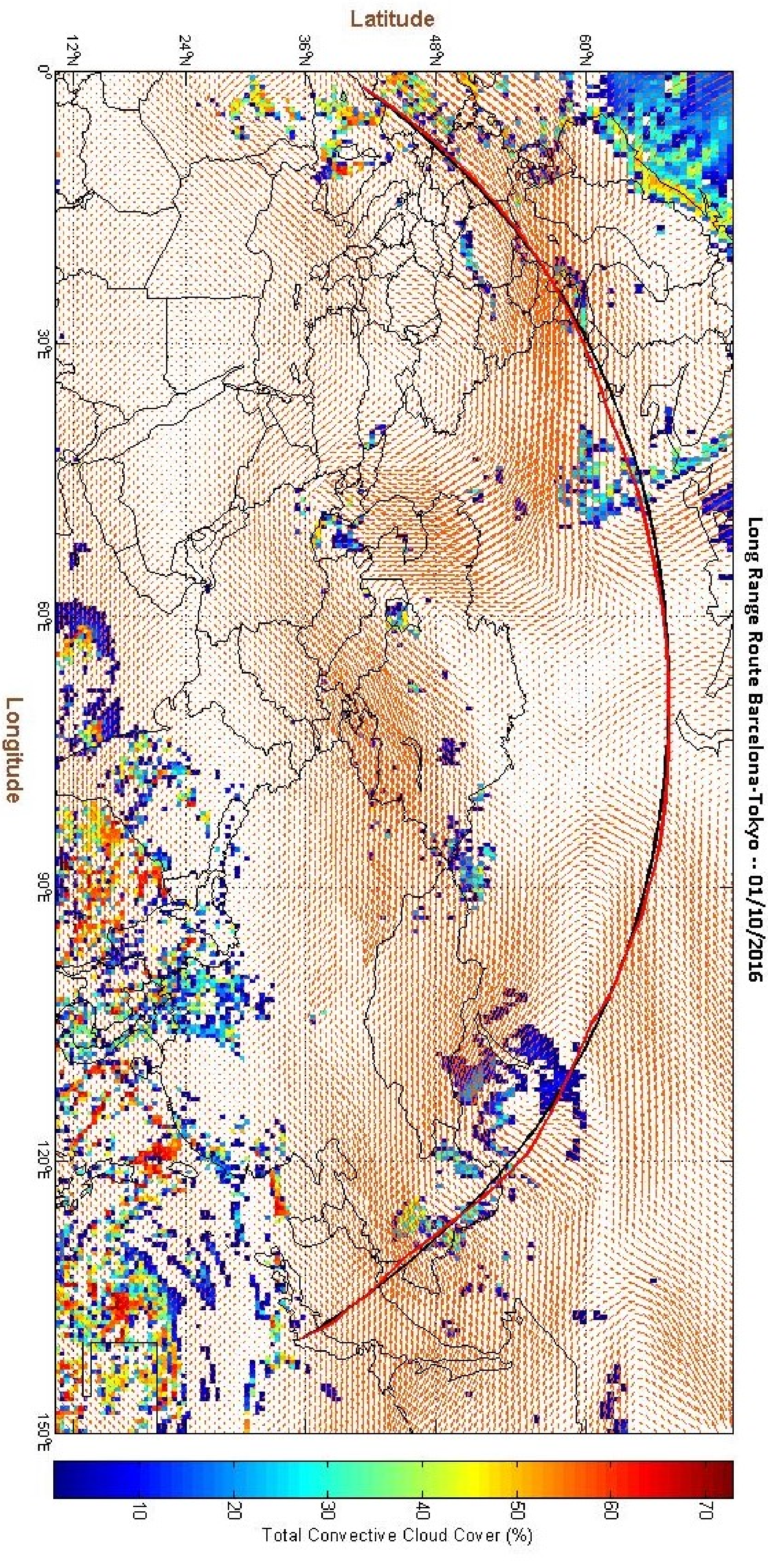


Figure 2.1: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe and Asia on 01/10/2016 at 00 UTC.

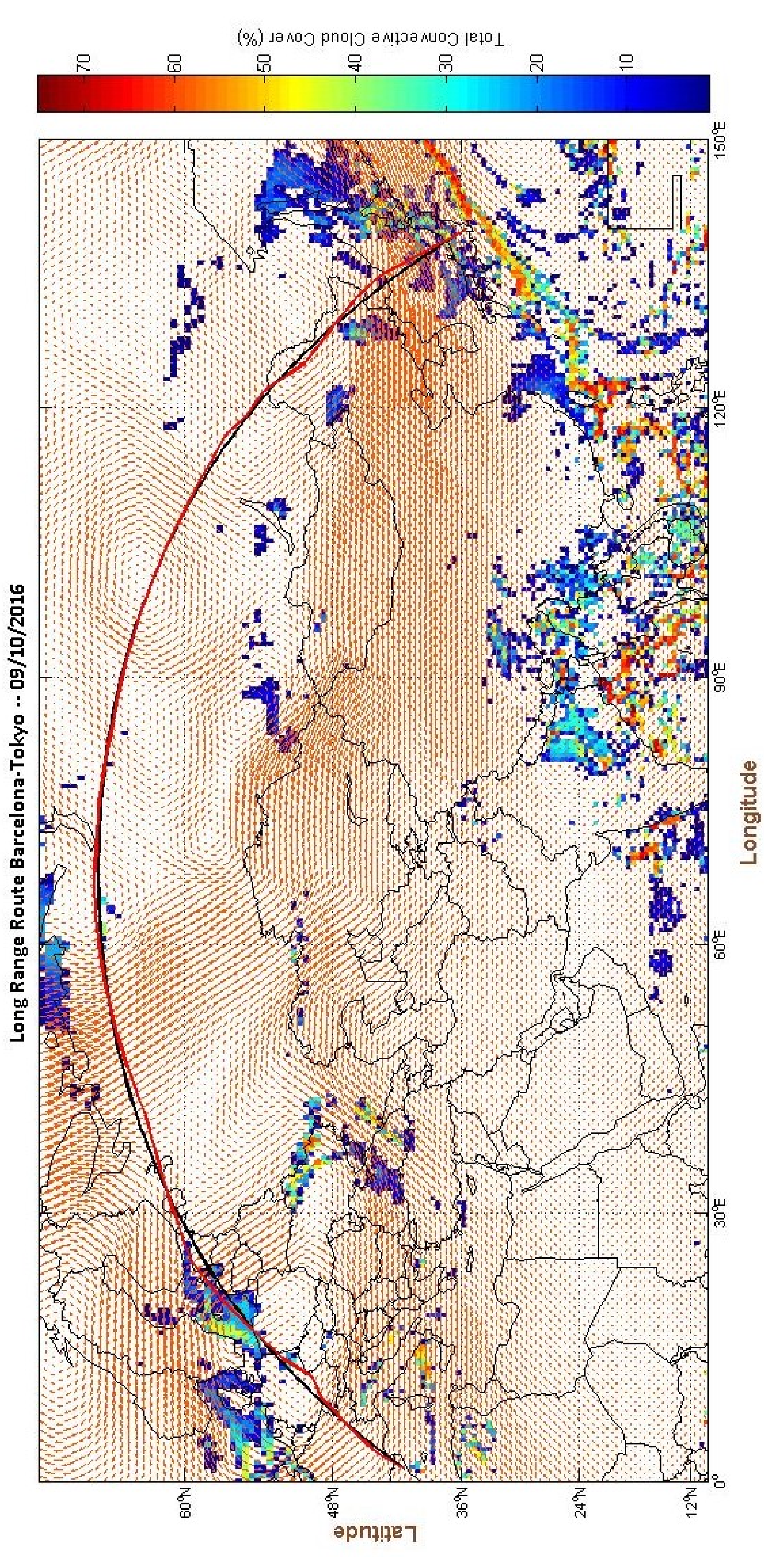


Figure 2.2: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe and Asia on 09/10/2016 at 00 UTC.

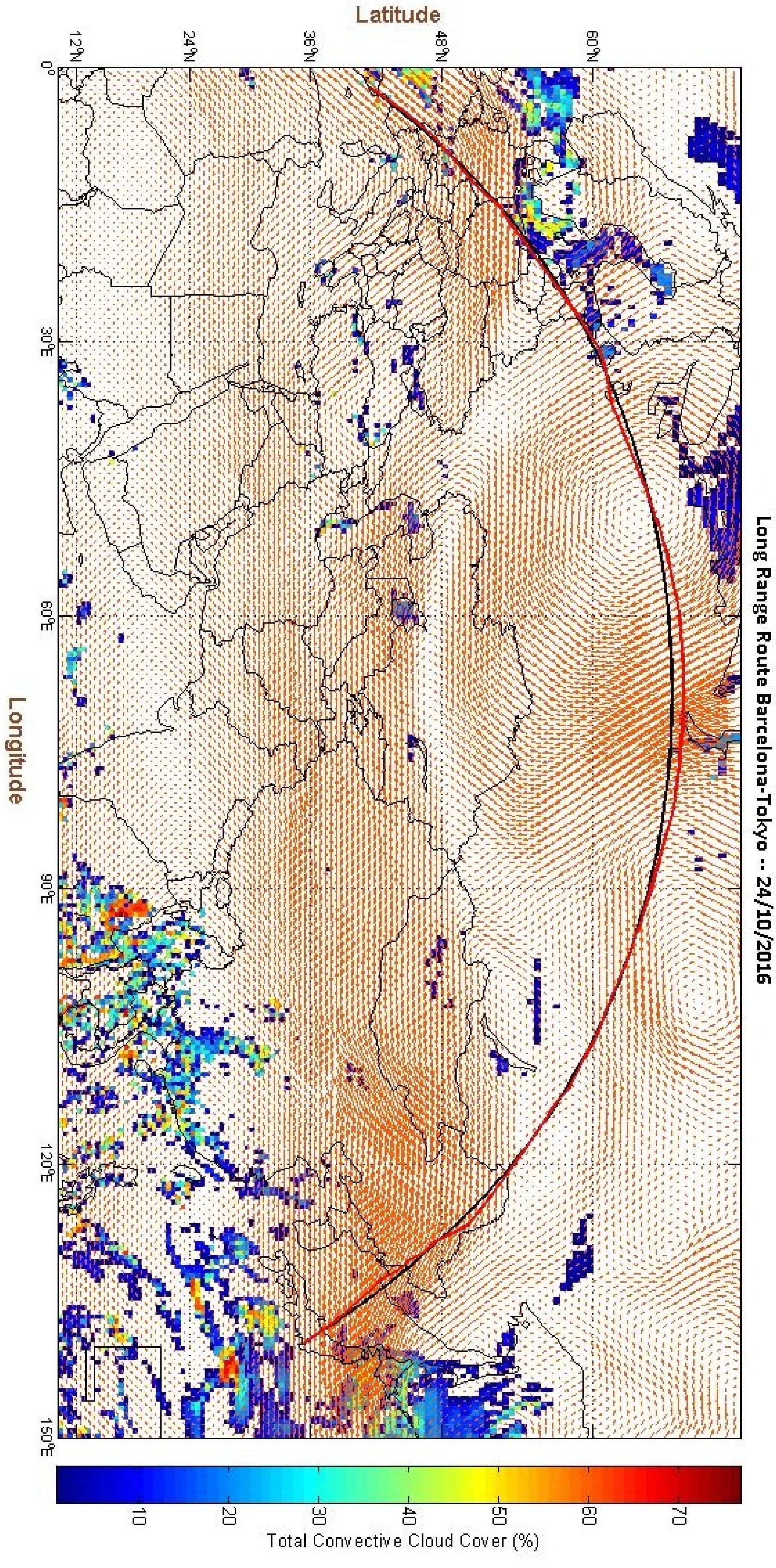


Figure 2.3: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe and Asia on 24/10/2016 at 00 UTC.

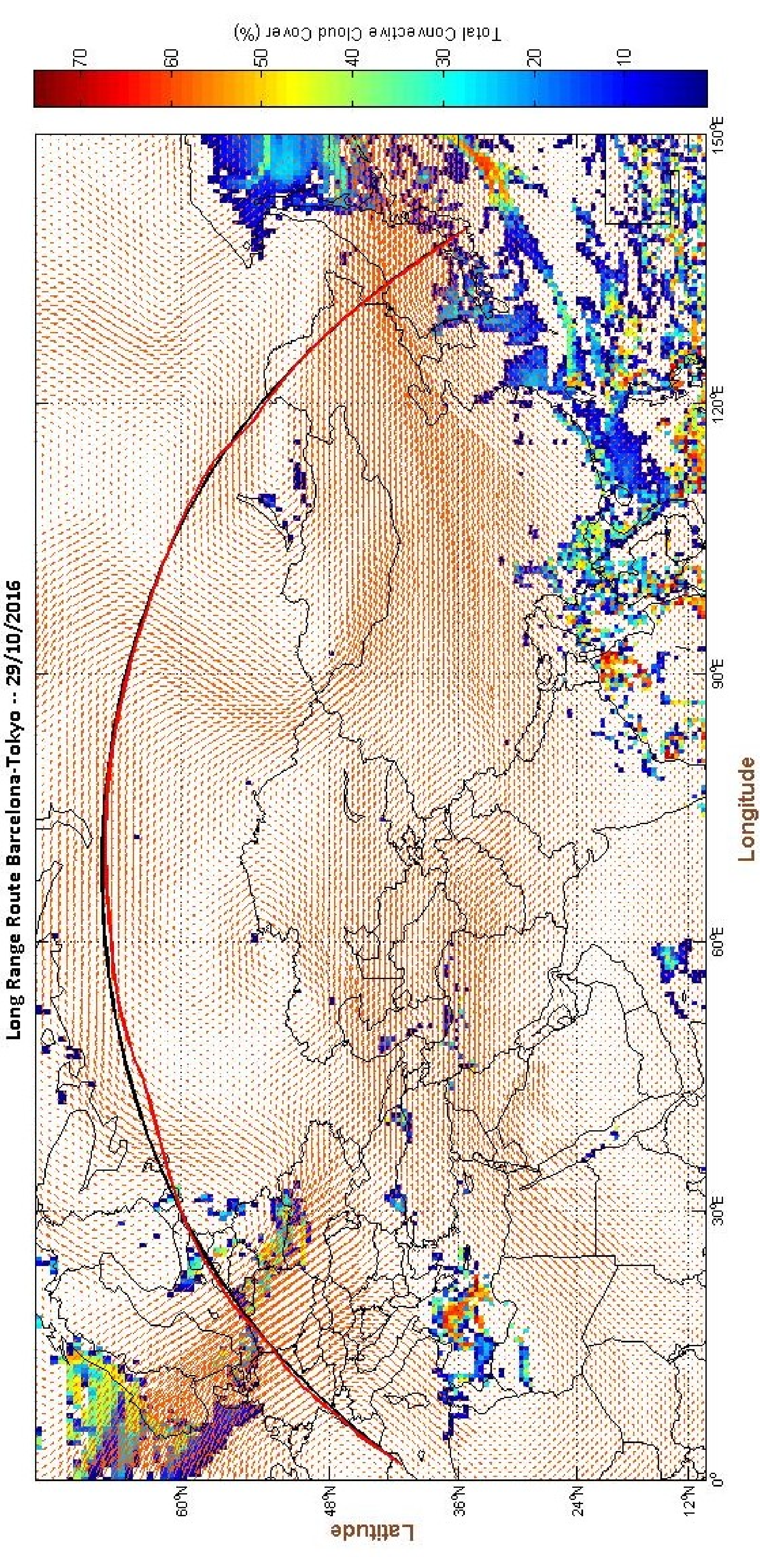


Figure 2.4: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe and Asia on 29/10/2016 at 00 UTC.

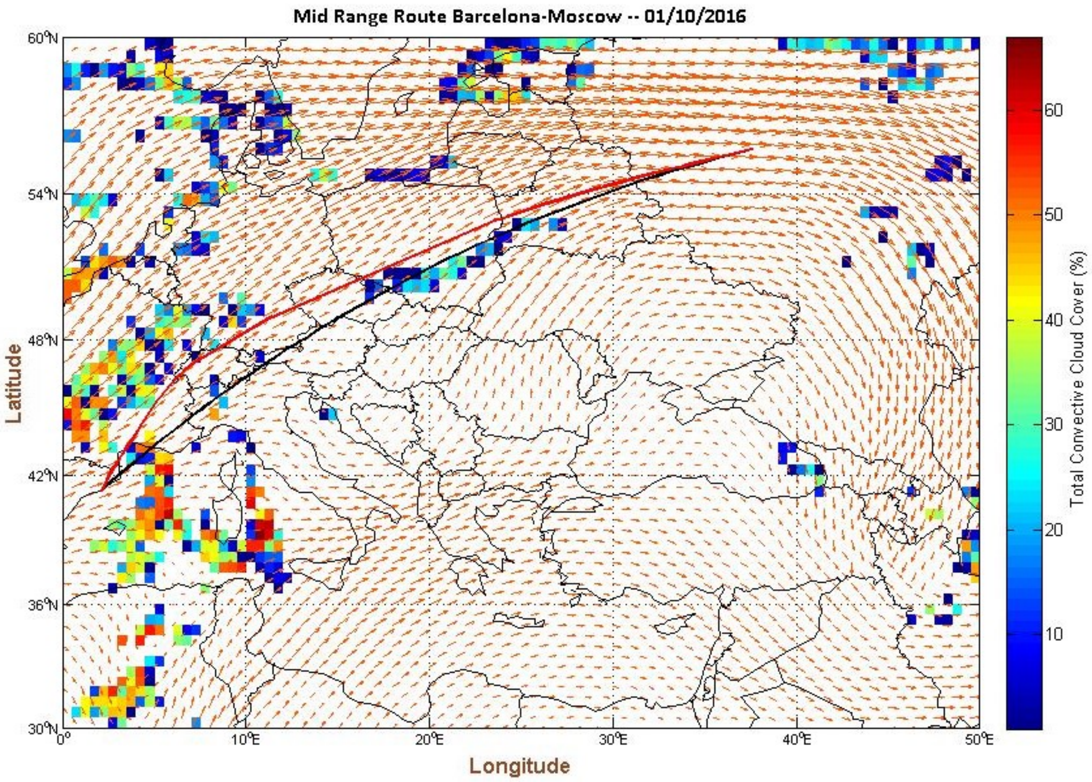


Figure 2.5: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe on 01/10/2016 at 00 UTC.

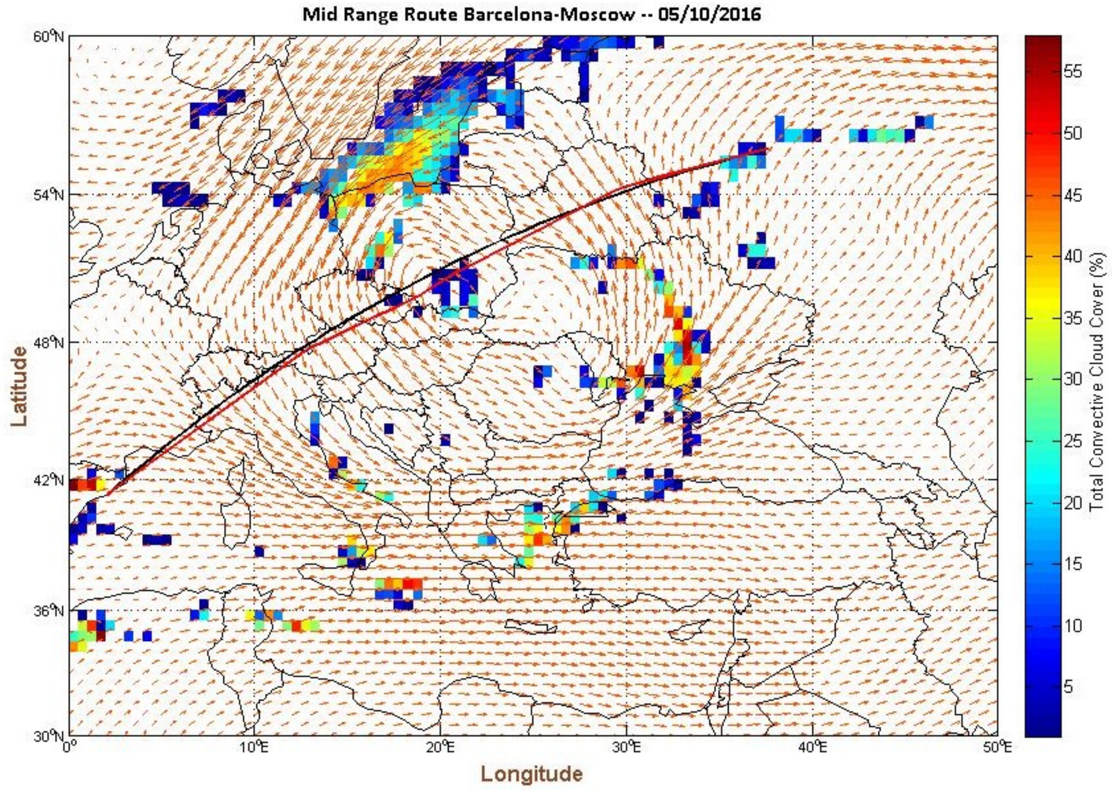


Figure 2.6: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe on 05/10/2016 at 00 UTC.

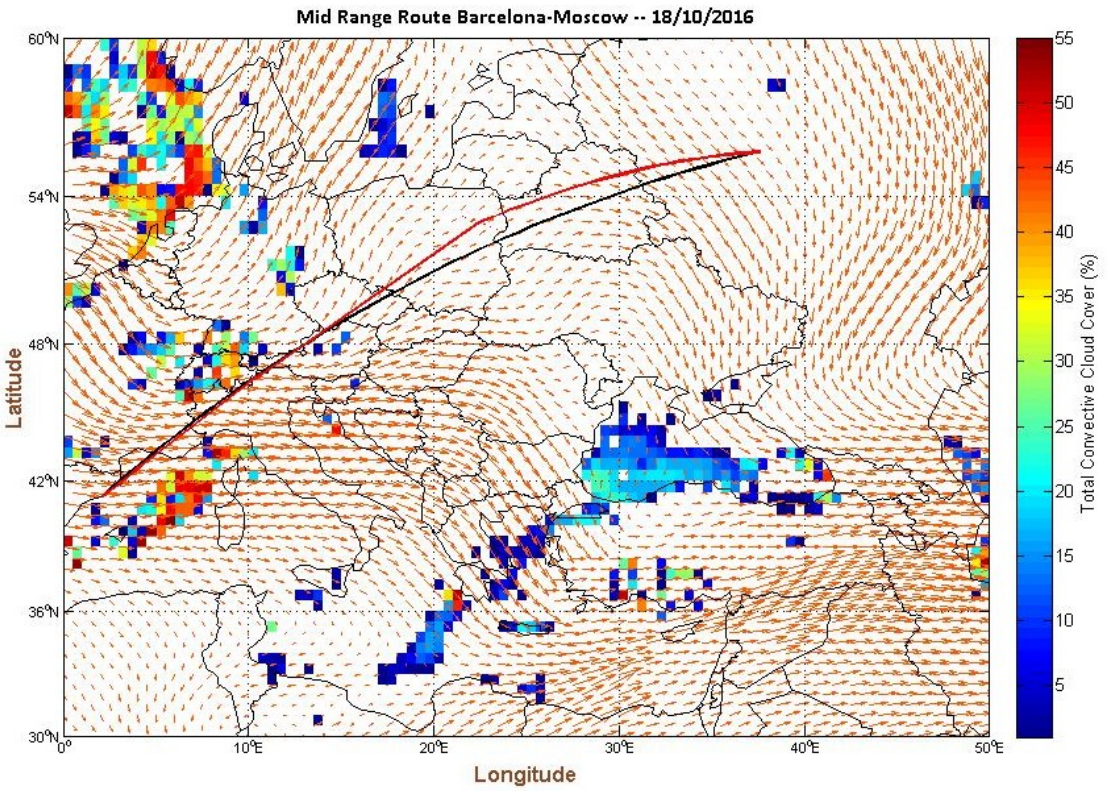


Figure 2.7: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe on 18/10/2016 at 00 UTC.

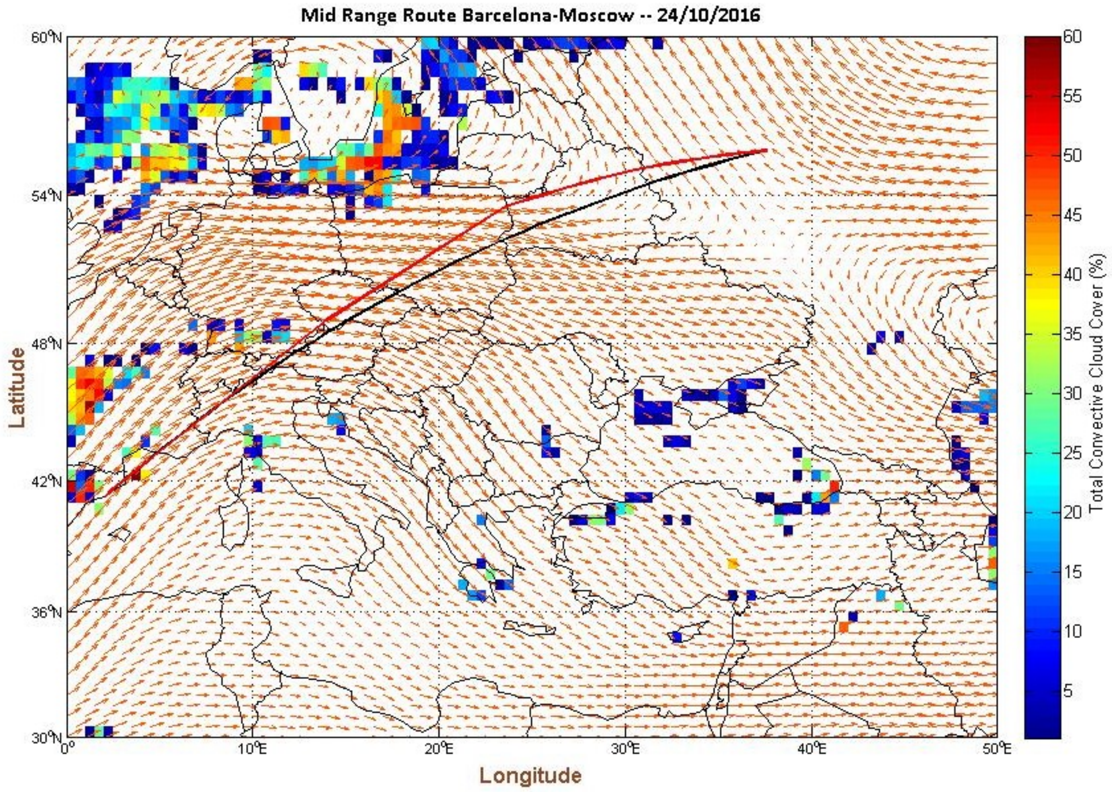
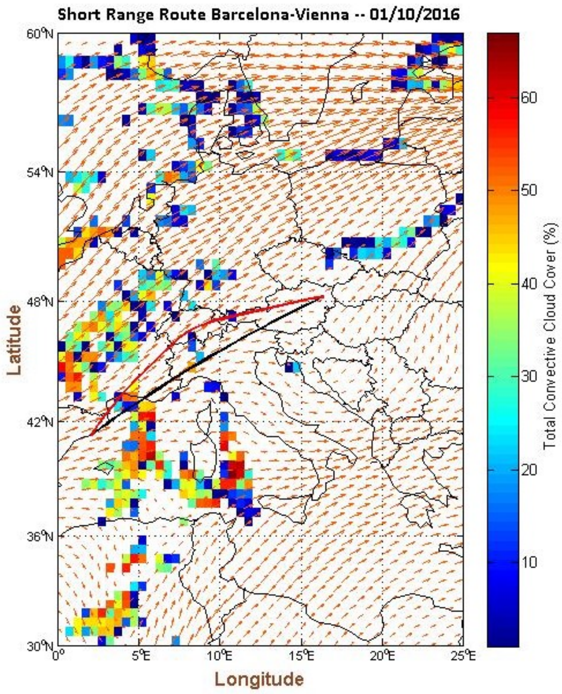
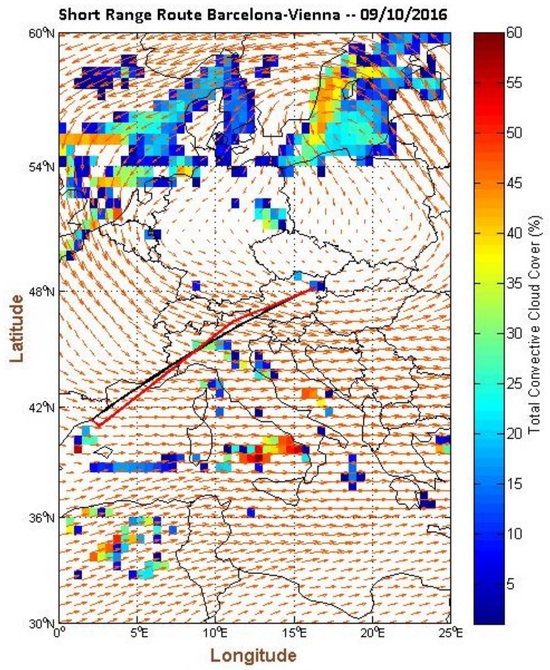


Figure 2.8: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause on Europe on 24/10/2016 at 00 UTC.

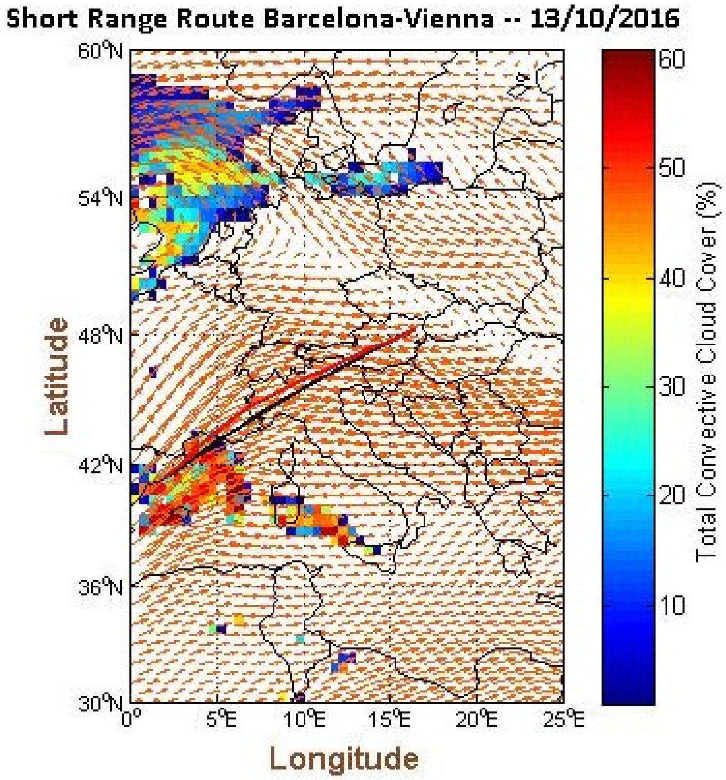


(a) Europe on 01/10/2016 at 00 UTC

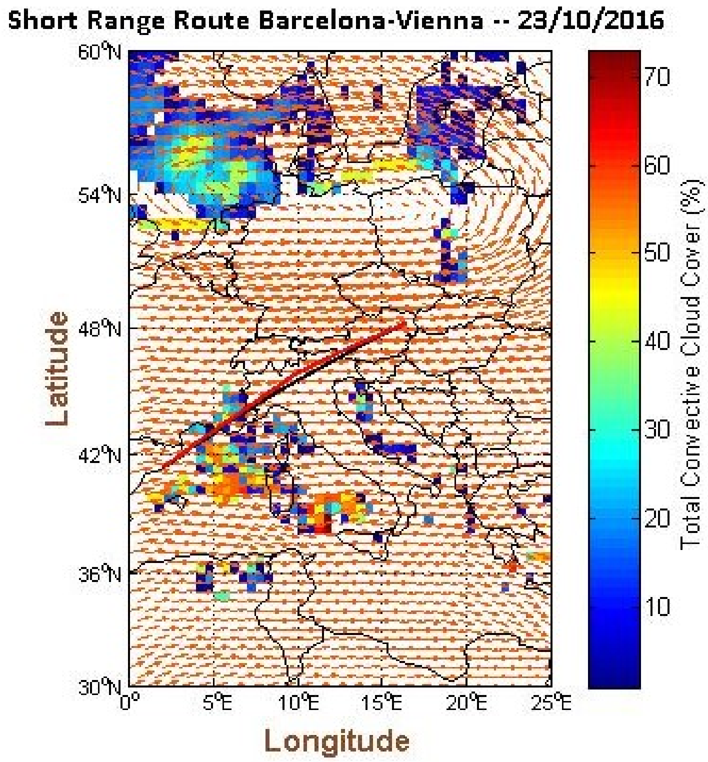


(b) Europe on 09/10/2016 at 00 UTC

Figure 2.9: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause.



(a) Europe on 13/10/2016 at 00 UTC



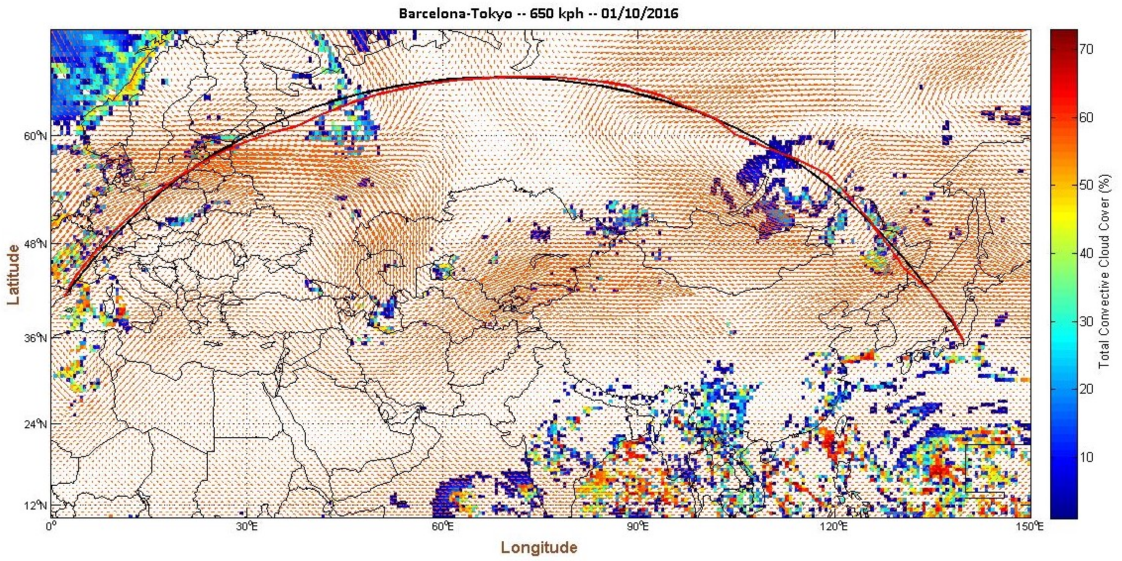
(b) Europe on 23/10/2016 at 00 UTC

Figure 2.10: Great circle trajectory (black line) and optimized trajectory (red line) at the the tropopause.

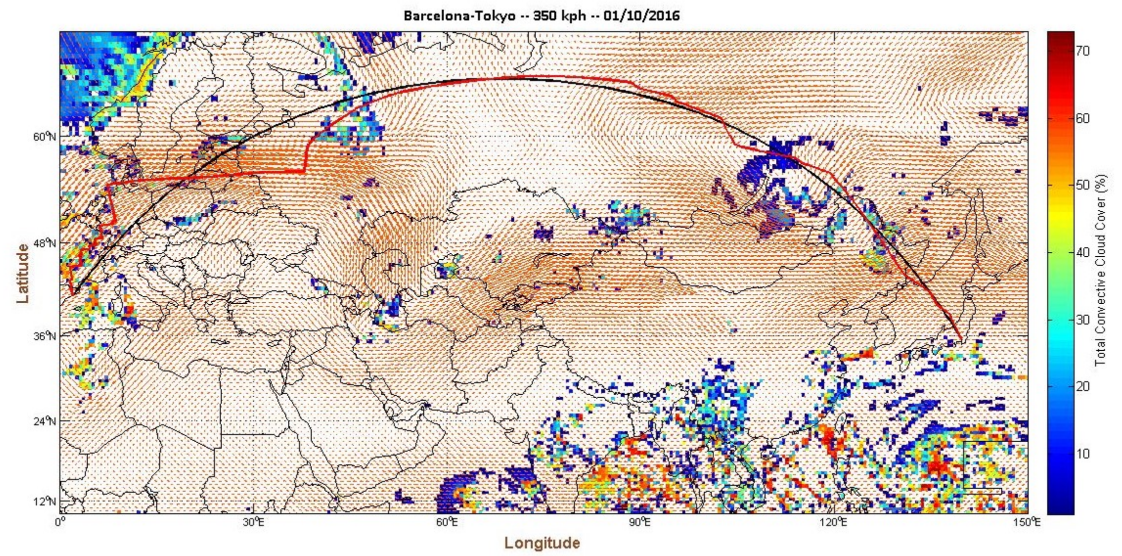
	Date - October 2016																
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15	Day 16	Day 17
Long Range: Barcelona - Tokyo																	
Flight duration [h]	12,64	12,56	9,47	10,22	11,89	12,12	9,74	9,69	12,16	12,46	9,67	12,52	12,16	12,31	9,74	12,22	12,12
Deviation [h]	1,66	1,58	- 1,52	- 0,76	0,91	1,13	- 1,25	- 1,30	1,17	1,47	- 1,32	1,53	1,17	1,32	- 1,25	1,23	1,13
Duration [%]	115,07	114,37	86,18	93,06	108,21	110,26	88,63	88,18	110,66	113,37	87,97	113,93	110,67	112,04	88,66	111,16	110,28
Mid Range: Barcelona - Moscow																	
Flight duration [h]	4,08	2,88	3,03	3,30	2,97	3,05	2,98	2,86	2,91	2,82	2,81	2,93	4,10	2,82	3,03	2,98	3,67
Deviation [h]	0,52	- 0,68	- 0,52	- 0,26	- 0,59	- 0,51	- 0,58	- 0,70	- 0,65	- 0,74	- 0,75	- 0,62	0,55	- 0,73	- 0,52	- 0,58	0,11
Duration [%]	114,67	80,87	85,28	92,73	83,45	85,70	83,73	80,40	81,86	79,32	79,04	82,51	115,38	79,37	85,28	83,83	103,09
Short Range: Barcelona - Vienna																	
Flight duration[h]	2,39	1,37	1,43	1,69	1,37	1,58	1,37	1,38	1,45	1,37	1,37	1,39	2,30	1,37	1,38	1,74	1,86
Deviation [h]	0,58	- 0,44	- 0,38	- 0,12	- 0,44	- 0,23	- 0,44	- 0,43	- 0,36	- 0,44	- 0,44	- 0,42	0,49	- 0,44	- 0,43	- 0,08	0,05
Duration [%]	131,81	75,79	79,10	93,18	75,79	87,29	75,79	76,34	80,02	75,79	75,79	76,71	126,93	75,79	76,25	95,75	102,74

	Day 18	Day 19	Day 20	Day 21	Day 22	Day 23	Day 24	Day 25	Day 26	Day 27	Day 28	Day 29	Day 30	Day 31	Great Circle	Airspeed [km/h]
Long Range: Barcelona - Tokyo																
Flight duration [h]	12,25	12,32	12,52	12,42	12,11	9,81	12,02	12,13	12,16	10,00	11,87	12,05	9,71	12,11	**10,99**	**950**
Deviation [h]	1,26	1,33	1,53	1,43	1,12	- 1,18	1,03	1,14	1,17	-0,99	0,88	1,06	- 1,28	1,12	**0**	
Duration [%]	111,43	112,10	113,96	113,01	110,16	89,23	109,37	110,35	110,69	91,03	108,00	109,62	88,33	110,19	**100**	
Mid Range: Barcelona - Moscow																
Flight duration [h]	3,08	2,84	2,83	2,80	2,79	2,81	2,96	2,99	2,84	3,35	2,79	2,93	3,09	3,08	**3,56**	**850**
Deviation [h]	- 0,48	- 0,72	- 0,73	- 0,76	- 0,76	- 0,74	- 0,60	- 0,57	- 0,72	- 0,21	- 0,77	- 0,63	- 0,46	- 0,48	**0**	
Duration [%]	86,64	79,89	79,56	78,62	78,53	79,14	83,26	83,97	79,89	94,23	78,43	82,37	86,97	86,59	**100**	
Short Range: Barcelona - Vienna																
Flight duration [h]	1,39	1,37	1,37	1,37	1,37	1,38	1,64	1,65	1,64	1,76	1,37	1,54	1,69	1,45	**1,81**	**750**
Deviation [h]	- 0,43	- 0,44	- 0,44	- 0,44	- 0,44	- 0,44	- 0,17	- 0,16	- 0,17	- 0,06	- 0,44	- 0,27	- 0,12	- 0,36	**0**	
Duration [%]	76,53	75,79	75,79	75,79	75,79	75,88	90,69	90,97	90,51	96,85	75,79	84,99	93,36	80,11	**100**	

Table 2.2: Numerical results from the simulations of the three routes from Barcelona to Tokyo, Moscow and Vienna on October 2016.

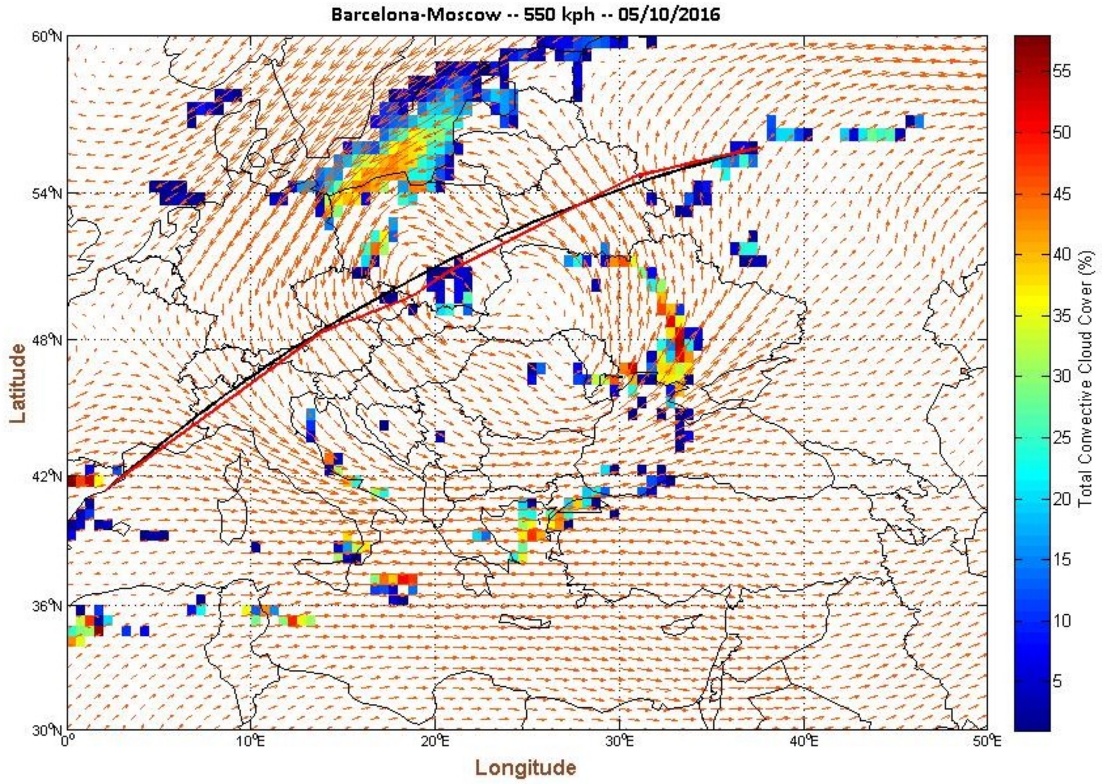


(a) Mid airspeed flight - Europe and Asia on 01/10/2016 at 00 UTC

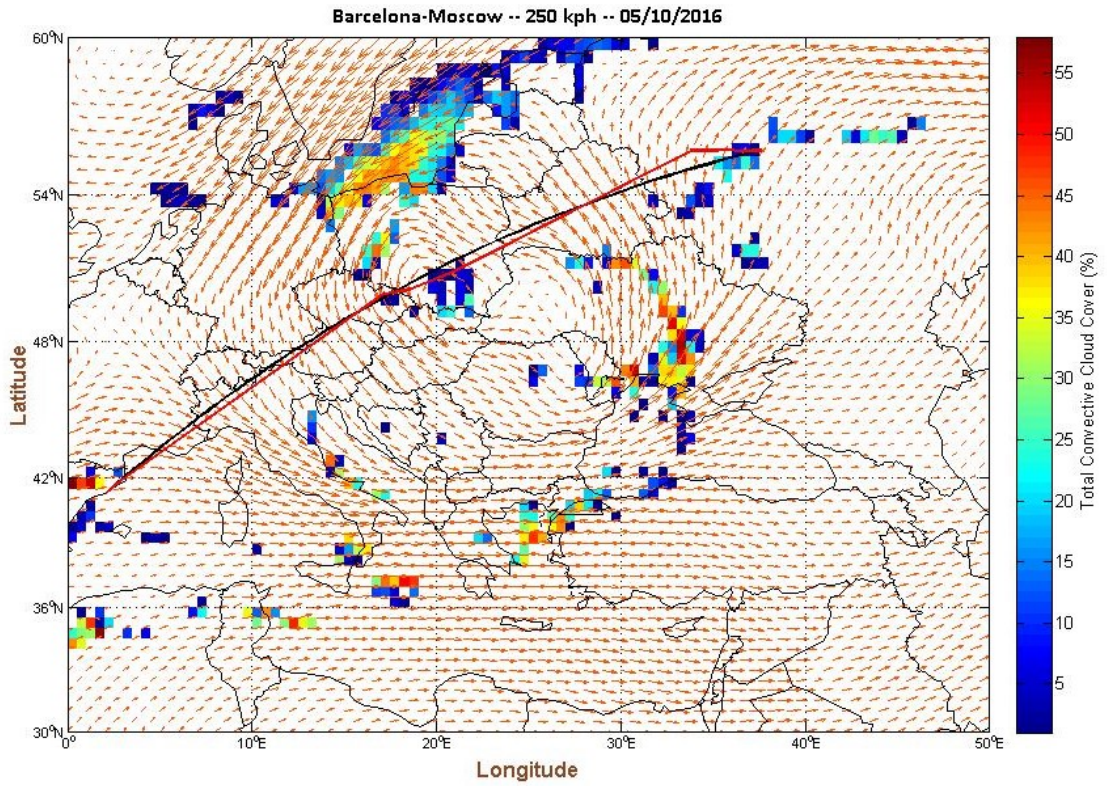


(b) Slow airspeed flight - Europe and Asia on 01/10/2016 at 00 UTC

Figure 2.11: Initial cruise phase velocity comparison for Barcelona - Tokyo.

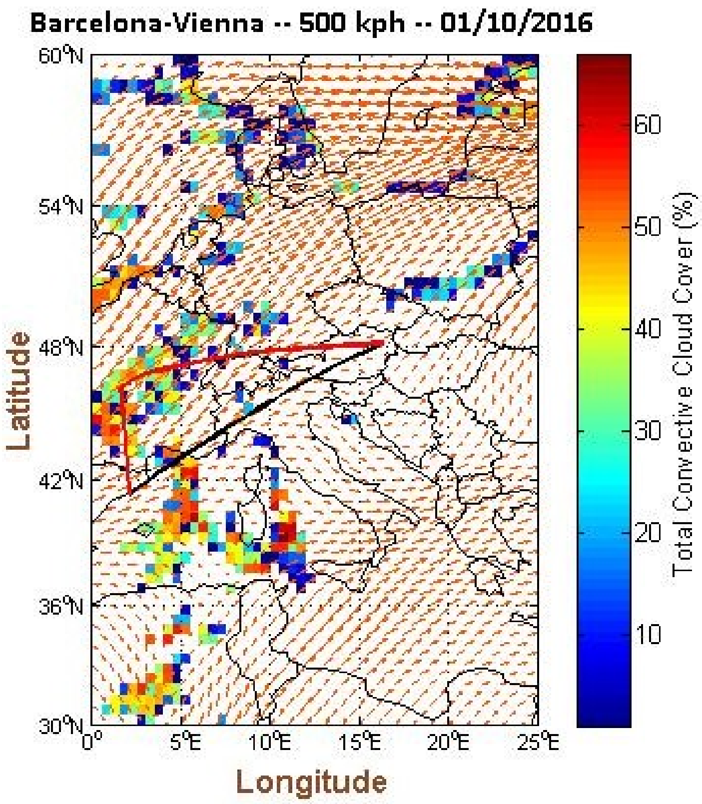


(a) Mid airspeed flight - Europe on 05/10/2016 at 00 UTC

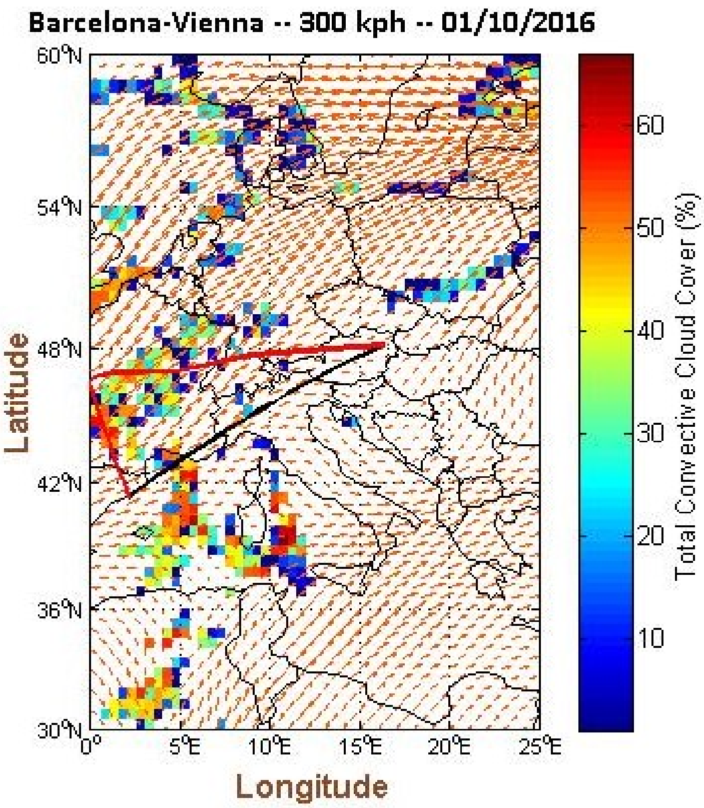


(b) Slow airspeed flight - Europe on 05/10/2016 at 00 UTC

Figure 2.12: Initial cruise phase velocity comparison for Barcelona - Moscow.



(a) Mid airspeed flight - Europe on 01/10/2016 at 00 UTC



(b) Slow airspeed flight - Europe on 01/10/2016 at 00 UTC

Figure 2.13: Initial cruise phase velocity comparison for Barcelona - Vienna.

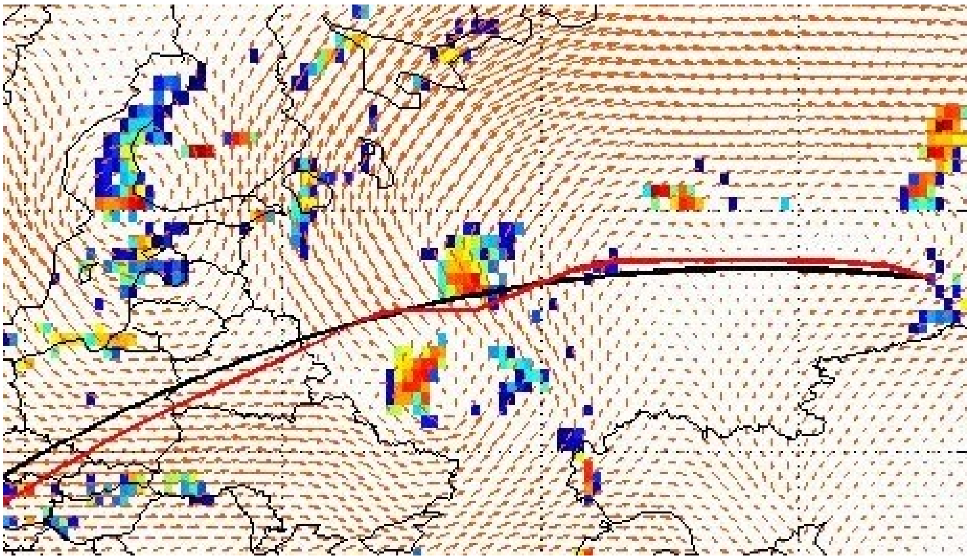
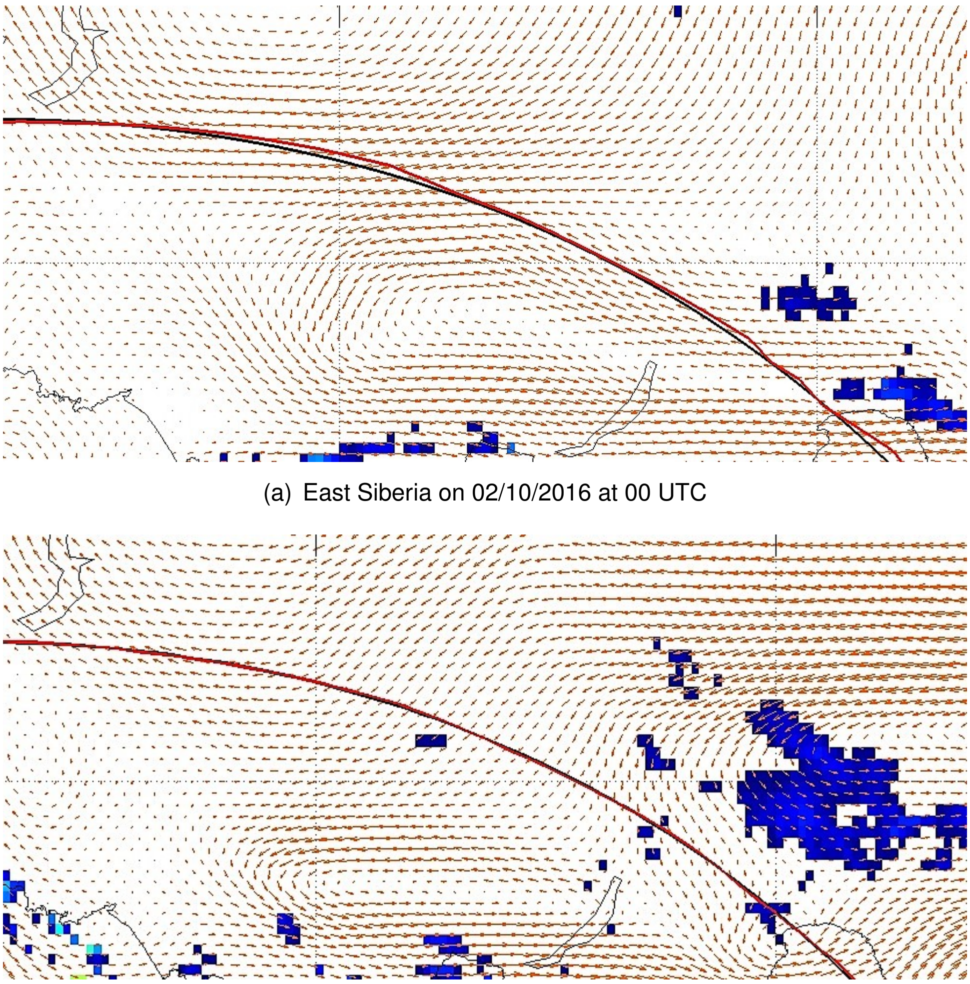


Figure 2.14: Great circle trajectory (black line) and optimized trajectory (red line avoiding a local convective system) on Europe on 15/08/2016 at 00 UTC.



(a) East Siberia on 02/10/2016 at 00 UTC

(b) East Siberia on 03/10/2016 at 00 UTC

Figure 2.15: Wind field (arrows) influence on trajectory optimization (red line).

CONCLUSIONS

The design and implementation in this project of a basic weather avoidance software has led into multiple and different scenarios where new and optimized trajectories have eased a better understanding of meteorological influence in aircraft for real flight situations. Considering the main goal of this thesis has been to conclude if the use of this kind of programs for route planning is profitable and positive, an analysis of all the simulations is done below.

First of all, it has been extremely important to figure out which was the best way of testing the self designed software. The idea of only facing theoretical cases where aircraft had to deal with different phenomena to study the optimizing behavior of the program have seemed initially effective but considerably unrealistic. Due to this fact, possible commercial flight routes have been taken as the conclusive examples to understand the affectation of the software in the creation of more efficient and consequently more economical and safer routes. Therefore, three main routes have been simulated from Barcelona to Tokyo, Moscow and Vienna categorized as long range, mid range and short range flights respectively for a month of autumn with high weather phenomena variability, that has been October 2016. As the resolution of the treated data has been 0.5 ^{o} and has an equivalence of 55 km on Earth surface, it had no sense to use the exact airport coordinates for departures and arrivals where an approximation for the cities location has been more than enough in terms of focusing in cruise flight phases at tropopause levels. So averaging realistically the airspeeds for every route the whole month has been simulated and results displayed in geographical charts as seen in Chapter 2 and numerically in Table 2.2. Another important aspect to be considered has been the selection of the weather variables that would directly affect the software's route planning. Associating weights to wind components and to convective cloudiness, that corresponds basically to stormy activity, the basics influencing aircrafts in all the simulations are set. Additional variables could have been considered, but combining multiple phenomena to minimize flight's duration supposed an increasing complexity as the requirement of a more powerful computer to simulate, a more difficult criteria to define weather avoidance that sometimes overlaps between variables and cause incompatibilities in terms of choosing the appropriate trajectory and a big problem for graphically visualizing this data, that has already been hard to display the charts understandably.

As a matter of fact, graphical conclusions have been easily appreciated. For example, strong wind currents considerably influence route trajectories in terms of taking benefit of tailwinds and avoiding headwinds. However, numerical results have given a huge amount of interesting information that has required an accurate evaluation to be correctly interpreted. In Table 2.2 flight time durations and deviations from the great circle trajectory, that is the shortest distance connecting two points on the surface of the Earth, and without atmospheric influence have been depicted. But in terms of making an easier analysis a graphical representation has been created from Table 2.2. In Figure B.1 all the percentage values of the deviations from the optimal trajectories have been compared between them, where the red dashed line establishes the limit related to the great circle trajectory and then it has been clearly noticed which have been the flight times of the simulations exceeding those values or not, resulting into longer or shorter flight times influenced by the meteorology. In brief, Figure B.1 shows that most of the cases for short and mid distance routes have been improved during the optimization process as flight times have remained under the values of the red dashed great circle line. Nevertheless, long distance trajectories, as Barcelona - Tokyo, have seemed to be more variable and presenting surprisingly higher results than for the other trajectories.

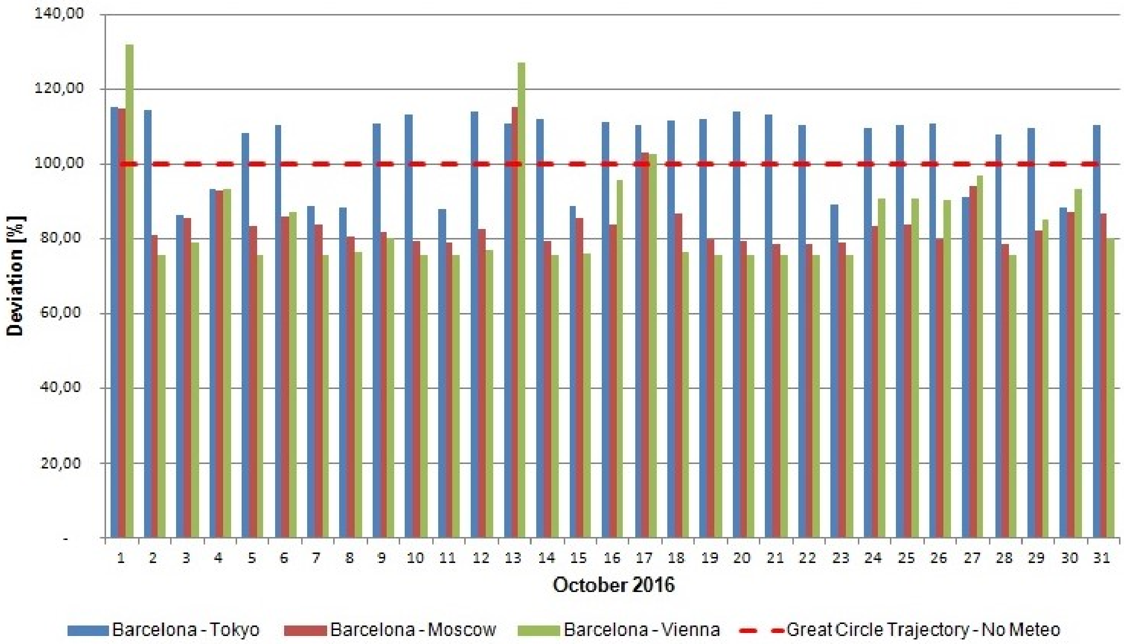


Figure B.1: Comparison between the deviation percentages of the simulations from Great Circle trajectory.

At the origin of those behaviors few ideas have been deduced. First, considering the main goal of the optimizing program has been to minimize flight times for every new trajectory, it has seemed obvious that the program adapts paths to take benefit of tailwind components to considerably reduce flight's duration. For example, predominant westerly winds at mid latitudes in northern hemisphere have benefited short and mid routes as seen for Vienna and Moscow routes. Although, for longer flights as Barcelona – Tokyo, a changing direction of wind components has resulted into irregular values for the whole month simulations. Moreover, those changes could strongly be related to the jet stream location, where a big shortening of flight time has been appreciated for favorable jet stream scenarios such as the comparison between the 2nd and the 3rd October 2016, where in the first half of the route the software has taken benefit of a tailwind stream in both cases, but for the second half part located over Siberia, and as contrasted in Figure 2.15, strong countercurrent winds have considerably increased the numerical results as appreciated in Figure B.1.

It has also been interesting to consider the longer the route is, the more influenced by atmospheric conditions is and more uncertainty is added to the simulations. So, an additional human criterion in terms of selecting the best trajectory options must have been considered for some cases rather than blindly trusting software's predictions. It has also been realized that for specific cases some peak values have appeared such as the 1st or the 13th October 2016 as seen in Figures 2.9(a) and 2.10(a) for Barcelona - Vienna simulations. Those values are probably related to irregularities caused by the optimization function that for sporadic situations, flight times have accumulated stronger wind or meteorological event resistance increasing results more than expected. Owing to the fact that results have been way more illustrative in terms of having a good perception of the improvement or deterioration of the results rather than obtaining extremely precise data.

And eventually, in order to fully comprehend the performance of the simulations, theoretical scenarios have been also run while modifying initial conditions as varying cruise airspeeds, atmospheric conditions, etc. For example, as seen in Subsection 2.2.1. for really slow velocities, when adding headwind to the minimizing function, the program searches constantly for new trajectories to avoid moving backwards and increase flight times. Even for some cases, the optimization results lack of common sense being those useless for a realistic route planning.

In conclusion, after a widespread analysis of the designed software for multiple cases, it has been possible to answer the main question of this project: would a route optimizing software help in terms of trajectory planning through real weather conditions? At first sight, this program has considerably benefited aircraft trajectories instead of only following the shortest distance to destination. Flight time durations have been majorly reduced or at least weather impact has considerably been minimized by varying the paths. This could not be only translated into time reduction by directly affecting punctuality of airspace users but into a huge economic advantage while reducing every type of delay for every phase of the flight even if only cruise phase has been optimized. Besides, time reduction is strongly related with a higher fuel consumption efficiency because of an enhancing of weather resistance and apart from being a commercial benefit it supposes a considerable environmental measure improving as well pollution problematic. On top of that, the use of a weather avoidance software would be able to decrease meteorological associated risks and even an ameliorate passenger and crew comfort when avoiding critical areas of atmospheric disturbance.

Besides, it has also been remarkable to mention that even if any route could be shortened, flight time optimization does not have the same personal and commercial effect for long journeys than for short ones. It is important to take human scale into account in terms of quantifying flight times and concluding the relevance of the optimization because even if the route is equally improved in percentage for long or short distances, the reduced or delayed time in hours would not be the same. That is, five minutes delay does not suppose for human perception the same problematic for a short route than one hour even if the route is very long.

Nevertheless, this design has been a basic weather avoidance software where many simplifications have been employed in terms of adapting the simulations to the available resources to perform them. More data could have been included into the multiple used variables but the guideline of avoidance would have been considerably more difficult to define and leading to the use of a more powerful hardware would have been necessary. Consequently, this software is open to further implementations and researches for a better weather avoidance functionality but inevitably an essential fact has been noticed: human criteria is in terms of piloting through meteorological phenomena the last step before choosing the best way to modify a trajectory.

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APÈNDIXS

APPENDIX A. WEATHER AVOIDANCE SOFTWARE - MATLAB CODE

In this Appendix the code writen to define and optimize trajectories through weather systems has been shown.

```
%% Data plotter

clear all
close all
clc

%% Read GRIB file - NOAA

% run setup_nctoolbox

% Choose file from NOAA database (variables and date)
% Trial file

% nco=ncgeodataset('D:\Z Adria\UPC\6 TFG VGTU\Code\Meteo Code
% \Z_Definitive Files\Data Definitiva Prueba
% \3_Oceanic_15_08_16\gfs_4_20160815_0000_003.grb2');

nco.variables

t = nco.time('time'); % Convert matlab time
t = datestr(t(1)) % Convert to gregorian date - Date of the file

% Extracting Variables

lon = nco.data('lon'); % Extracting Longitude
lat = nco.data('lat'); % Extracting Latitude

lat = double(lat);
lon = double(lon);

%% Example - Wind at Tropopause

% Wind component variables
wind_v_trop = nco.data('v-component_of_wind_tropopause');
wind_u_trop = nco.data('u-component_of_wind_tropopause');

wind_v_trop = double(squeeze(wind_v_trop));
wind_u_trop = double(squeeze(wind_u_trop));

% Choose Geographical Domain
% Example - Eurasian Domain
```

```
min_lat = lat(161) %Position '131' corresponds to 10ºN
max_lat = lat(41) %pos41 = 70ºN

min_lon = lon(1) %Pos 1 = 0º
max_lon = lon(301) %Pos 341 = 150ºE

% Define map projection

m_proj('miller','lat',[min_lat max_lat],...
'lon',[min_lon max_lon])

m_coast('color','k','linewidth',1);
m_grid('fontsize',8,'box','on');

%% QUIVER

% To display wind fields

hold on;

latk = find (lat>=min_lat & lat<=max_lat);
lonk = find(lon>=min_lon & lon<=max_lon);

lat_wind=lat(latk);
lon_wind=lon(lonk);

wind_u_trop = wind_u_trop(latk,lonk);
wind_v_trop = wind_v_trop(latk,lonk);

[lonw,latw] = meshgrid(lon_wind,lat_wind);

quiv = m_quiver(lonw(1:2:end),latw(1:2:end),wind_u_trop(1:2:end),
wind_v_trop(1:2:end),2,'color',[1 0.35 0]);

xlabel('Longitude','FontSize',12,'FontWeight','bold','Color',[.55 .29 .15]);
% x-axis label
ylabel('Latitude','FontSize',12,'FontWeight','bold','Color',[.55 .29 .15]);
% y-axis label
title('Long Range Route Barcelona-Tokyo -- 30/10/2016','FontName','Calibri',
'FontSize',12,'FontWeight','bold','Color','k'); % Set title

%% Storm avoidance

% Set storm weights 'st'

st = 50;
```

```
% Stormopt: Storm Optimizer function
% Avoid storm/convective coordinates

% Read GRIB file - NOAA
% Convective Cloudiness Data

x = nco.data('Total_cloud_cover_convective_cloud'); % Extracting desired variable
x = double(squeeze(x));
x(x==0) = nan;

% Plot desired map projection - Selection geographical area

% Chose projection again
m_proj('miller','lat',[min_lat max_lat],...
'lon',[min_lon max_lon])

a = m_pcolor(lon,lat,x); % Desired variable x in function of lat & long
shading flat; % shades the grid
m_coast('color','k','linewidth',1);
m_grid('fontsize',8,'box','on');

% Extracts and overlay political borders
m_gshhs('hb','save','frontera')
m_usercoast('frontera','color','k','linewidth',1);

cb = colorbar % Choose colorbar properties
ylabel(cb,'Total Convective Cloud Cover (%)');

% Extract coordinates of values > 30
x = x(latk,lonk);
[storm_row,storm_col]=find(x>30); % Selects area where
convectivity values ara major than 30

wind_u_trop (storm_row,storm_col) = st;
wind_v_trop (storm_row,storm_col) = st;

%% Generate waypoints: Origin and Destination

% gcircle function:

%% Select route - Great Circle
% Needs to be applied to every picture

hold on

% Manually introduce coordinates by clicking

disp('Introduce by click Origin and Destination of the route')
```

```
[px,py] = ginput(2);
start = [px(1) py(1)];
dest = [px(2) py(2)];

[plon,plat]=m_xy2ll(px,py);
p = [plat(1) plon(1);plat(2) plon(2)];

pln = plon(1);
plt = plat(1);

plnn = plon(2);
pltt = plat(2);

% Or introduce predefined coordinates for Barcelona - Tokyo - Moscú - Vienna

% pln = 2.1
% plt = 41.33333 %Barcelona

% plnn = 139.7455
% pltt = 35.6586 %Tokyo

% plnn = 37.617778
% pltt = 55.755833 %Moscu

% plnn = 16.363449
% pltt = 48.210033 %Vienna

% d_recto = pdist(p)

resolution=(0.5./360).*m_lldist([0 180],[0 0]).*2; % Resolution of 0,5º corresponds
aprox to 55,56 km on surface

dist = m_lldist([pln plnn],[plt pltt]);
desired_wpts = dist/resolution;
% Number of waypoints adequated to our wind resolution

[range,ln,lt]=m_lldist([pln plnn],[plt pltt],desired_wpts);

m_line(ln,lt,'color','k','linewidth',2);

hold off

xWayPoints = ln';
yWayPoints = lt';

%% Define initial airspeed for the simulations
```

```
AirSpeed=850; %[km/h]

%% Find the optimal path using FMINCON

% Define Objective Function

objectiveFun = @(P) getTimeFromPath(P,wind_u_trop,wind_v_trop,AirSpeed,
pln,plt,plnn,pltt,max_lon,max_lat,desired_wpts,'cubic');

% Set optimization options
opts = optimset('fmincon');
opts.Display = 'iter';
opts.Algorithm = 'active-set';
opts.MaxFunEvals = 20000;

% Initial Conditions
xWayPoints = ln';
yWayPoints = lt';
ic = [xWayPoints(2:end-1)'; yWayPoints(2:end-1)'];
ic = ic(:);

% Bounds
lb = zeros(size(ic(:))); %lb = lower bound
ub = reshape([max_lon*ones(1,desired_wpts);
max_lat*ones(1,desired_wpts)],[],1); %ub = upper bound

% Perform the optimization

optimalWayPoints = fmincon(objectiveFun, ic(:), [],[],[],[],lb,ub,[],opts)


%% Plot the optimal solution:

hold on;

optimalWayPoints = [pln plt; reshape(optimalWayPoints,2,[])'; plnn pltt];


xWayPoints = optimalWayPoints(:,1);
yWayPoints = optimalWayPoints(:,2);
h_wp = m_plot(xWayPoints,yWayPoints,'color','r','linestyle','none',
'marker','x','markersize',1);

PathPoints = WayPoints_To_Path([xWayPoints,yWayPoints],'cubic',max_lon,
max_lat,desired_wpts);
h_path = m_plot(PathPoints(:,1),PathPoints(:,2),'color','r','linewidth',2);

LineTime = getTimeFromPath(PathPoints,wind_u_trop,wind_v_trop,AirSpeed,pln,plt,
```

```
plnn,pltt,max_lon,max_lat,desired_wpts,'cubic');
fprintf('Optimal Travel Time: %d hours, %.1f
minutes\n',floor(LineTime),rem(LineTime,1)*60);

hold off;
```