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# TomTOM: Tom's Trajectory Model, Version 1.1

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## **Abstract**

TomTOM is a trajectory model which calculates either forward or backward trajectories of air parcels. The model is set up in a Matlab® code and uses wind data from the European Centre of Medium Range Weather Forecast ECMWF, which are stored in the institute's MySQL database. Trajectories are calculated on isentropic surfaces with a variable time step. After each time step the horizontal velocity vector is recalculated with new wind data interpolated to the current parcel location. There was a need for this new model because other models freely accessible through the internet, such as the Goddard Automailer and HYSPLIT, do not provide mesospheric trajectories, which were needed for our purposes. The agreement between TomTOM and the aforementioned models is very good at stratospheric altitudes even if the other two do not use ECMWF wind but NCEP/NCAR reanalysis.

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# Chapter 1

## Introduction

Trajectory calculation is a powerful tool to understand atmospheric processes. It is widely used for example in air pollution monitoring or numerical weather prediction. In atmospheric research trajectories are for instance used to study the evolution of trace gases at specific locations. A few models are freely available on the internet: The Goddard Automailer (Schoeberl and Sparling, 1994) is a web-based model which calculates trajectories for a specific time, altitude and location. The user has to enter those parameters on the web page ([http://acdb-ext.gsfc.nasa.gov/Data\\_services/automailer/index.html](http://acdb-ext.gsfc.nasa.gov/Data_services/automailer/index.html)) and receives the calculation as an e-mail ascii file a few moments later. The results are given as latitude and longitude and have to be plotted by the end user. Another web based model is HYSPLIT (Draxler and Hess, 1998) from NOAA to find at [www.ready.noaa.gov/ready/open/hysplit4.html](http://www.ready.noaa.gov/ready/open/hysplit4.html). The procedure is the same, the user sets time, location, altitude and a few more parameters and trajectories are calculated with NCEP/NCAR reanalysis data. The advantage is that not only the datafile but also a plot of the trajectory is provided. A more complex model is the FLEXTRA and FLEXPART trajectory model which was developed by Andreas Stohl. This model needs to be installed on the computer and needs a fortran 77 compiler and a huge disk space. The model uses wind data from the European Center for Medium range Weather Forecast ECMWF, which have to be stored as grib files. Usually these are very large files and the calculation of for instance a 1 week backward trajectory would need almost 15 Gigabyte of disk space. The use of this model is thus a bit more complex than Goddard and HYSPLIT.

Since the institute of applied physics stores ECMWF data in the MySQL database the idea came up to set up an own trajectory model, which uses these data and can also produce mesospheric trajectories. ECMWF winds are available up to 65 km before 2006 and even up to 80 km since then.

TomTOM accesses these data through Matlab<sup>®</sup>, which is a numerical computing environment. Matlab calculates and plots the trajectory. Results are available in a few seconds due to the advantage of the fast MySQL search routines.

# Chapter 2

## MySQL

Collaborative research, in general, is based on share resources. This raises the need of a network tool that can be easily used from anywhere using any PC or workstation. Whenever a critical mass is exceeded in collecting very large amounts of data, the need for specific tools for analysis always arises. Simple solutions based on a combination of Open Source software can be developed to address such requests, exploiting the possibilities offered by the web technologies, and at the same time avoiding the costs and inflexibility of commercial systems. A viable solution consists of MySQL for the data storage and retrieval.

Our institutes runs many instruments measuring non stop and the data are all stored in the MySQL database and its instruments specific tables. The data are stored on a central server and the members of the institute can access it through their own computer. Further atmospheric data from ECMWF are stored in the database. The ECMWF table is organized as follows: Tablename: ECMWF, Fields: "date", "hour", "latitude", "longitude", "level", "p", "z", "T", "PT", "PV", "u", "v", "w", "H2O\_vmr", "O3\_vmr". For every single point on the 1.125° spaced latitude longitude grid values are given for 60 (or 90 since 2006) altitude levels for pressure "p", temperature "T", potential temperature "PT", potential vorticity "PV", zonal wind "u", meridional wind "v", vertical wind "w", water vapor volume mixing ration "H2O\_vmr" and ozone volume mixing ratio "O3\_vmr". The access of these data is very easy through SQL (Simple Query Language). If one is interested in every column of a specific time at a specific location one types: "select \* from ECMWF where date="2008-08-15" and hour=12 order by z". The selected data can be imported into Matlab®. This provides a simple handling for calculation with large amount of data. The functioning of the TomTOM trajectory model is sketched in figure 2.1.

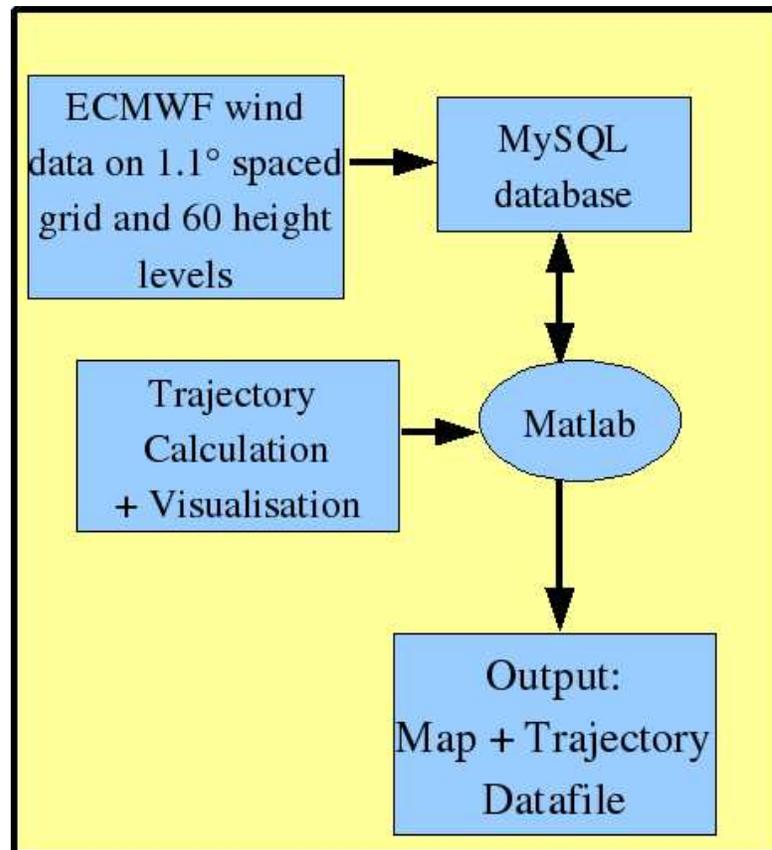


Figure 2.1: Sketch of the interaction of TomTOM Matlab code and the storage of ECMWF data in the MySQL database.

# Chapter 3

## TomTOM Model

The task of the model is to calculate backward or forward in time air parcels starting at a specific location on a specific altitude and time. Air parcels move on surfaces of constant potential temperature  $\Theta$ , called isentropes (surfaces of equal entropy under adiabatic conditions). The potential temperature is defined as follows:

$$\Theta = T \left( \frac{p_0}{p} \right)^\kappa \quad (3.1)$$

where  $T$  is the air temperature in Kelvin at the pressure level  $p$  and  $p_0$  is the standard atmosphere at sea level of 1013 hPa and  $\kappa = R/c_p \cong 2/7$ . The potential temperature is the temperature that an air parcel would reach if it were transported adiabatically from a pressure  $p$  to the sea surface at a pressure  $p_0$ . Air parcels are assumed to undergo adiabatic motion which means that no heat is added to the parcel  $dQ = 0$  and the potential temperature remains constant because of

$$c_p \frac{d\Theta}{\Theta} = \frac{dQ}{T} = dS = 0 \quad (3.2)$$

Equation 3.2 is derived from the first law of thermodynamics and shows the connection of potential temperature and entropy  $S$ . As adiabatic motion is assumed the entropy remains constant and so does the potential temperature. This is the reason why surfaces of constant  $\Theta$  are called isentropes.

The model uses ECMWF wind data which are stored in the institutes MySQL database. These data are provided with a 6 hour frequency for UTC times 0, 6, 12 and 18 and spread on a geographical grid with  $1.125^\circ$  spacing in longitude and latitude. Since the year 2006, 90 altitude levels are given with the upper boundary at around 80 km. The spacing is of less than 1 km up to the lower stratosphere and gets more coarse with increasing altitude. In the mesosphere the levels are spaced by 3 to 5 km.

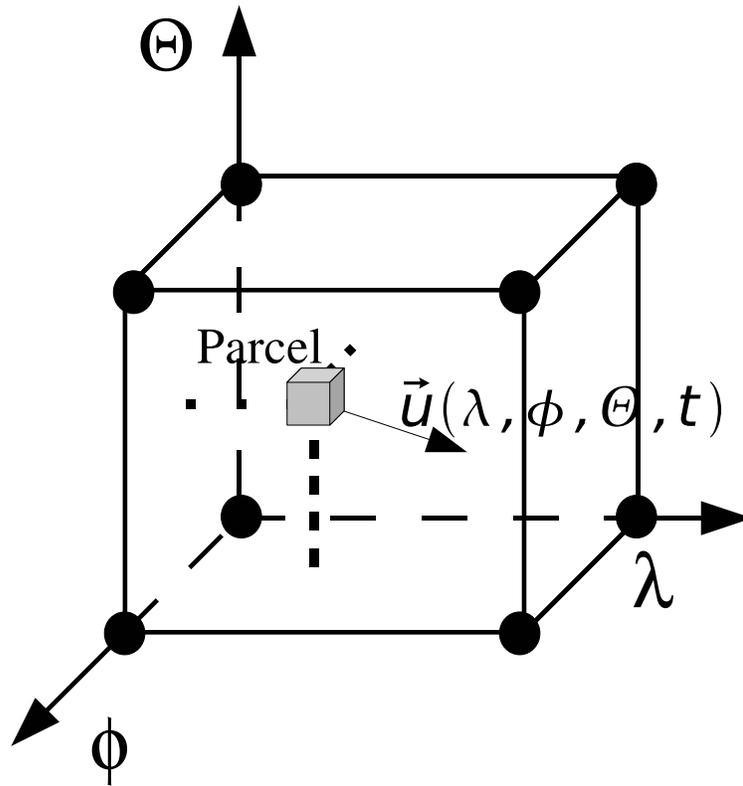


Figure 3.1: A three dimensional grid with potential temperature  $\Theta$  as altitude,  $\phi$  as latitude and  $\lambda$  as longitude. ECMWF data are given for the corner grid points of the cube which are on a  $1.125^\circ \times 1.125^\circ$  horizontal grid and on 60 height levels (90 since 2006). Temporal ( $t$ ) resolution of the data is 6 hours. If the air parcel is not on a grid point, the ECMWF data are interpolated to the real location inside the cube with the Matlab function "griddata3.m".

The trajectory for an arbitrarily air parcel does not have to start on a ECMWF grid point. If the parcel lies in between grid points in space and time, as shown in figure 3.1, the values of the 8 nearest grid points in four dimensions are interpolated to the exact location. In this way a new horizontal velocity vector  $\vec{u}(\lambda, \Phi, \Theta, t)$  is calculated for every time step  $dt$ , which can be chosen in units of hours. The air parcel moves with the calculated speed during the time  $dt$  according to the equations of motion. If for instance the velocity of an air parcel is needed at 15 UTC, the values of the nearest grid points are taken at 12 UTC and 18 UTC, which is the time grid of ECMWF, and the values are linearly interpolated to the time in question. The standard time step is one hour. However, if the wind velocities  $v_i$  are high so that the Courant-Friedrichs-Lewy criterion  $dt < dx_i/\|v_i\|$  (Stohl, 1998) is not fulfilled, the time step  $dt$  has to be adapted.  $x_i$  is the grid resolution, which is constant in our case ( $1.125^\circ$  latitude and longitude).

### 3.1 Equations

A new horizontal velocity vector is calculated after every time step  $\Delta t$  (parameter), which is by default one hour. The covered distance is simply calculated by the wind velocity times time. The wind data are given in units of  $[m/s]$  and the locations on the globe in spherical coordinates. In order to get the new location in degrees of latitude  $\phi$  and longitude  $\lambda$  one has to transform the distances in units of degrees. The notation of the wind speed is  $u$  for the zonal wind, which is positive if it is blowing from west to east (called westerly or eastward),  $v$  is the meridional wind, which is positive if blowing from south to north (southerly or northward) and  $w$  is the vertical wind which is positive if upward directed.

The new coordinates of an air parcel are calculated with interpolated wind speeds according to the equations of motion. One has to consider the non spherical shape of the earth. The radius  $R_e$  is latitude dependent and bigger at the equator ( $R_{eq} = 6378.1$  km) than at the pole ( $R_{pole} = 6356.7$  km), this dependence is given in equation 3.3. The length  $ds$  of a circular arc is the product of its radius  $r$  and the change of angle  $d\phi$  as can be seen in figure 3.2. This length depends is equal to the product of speed  $v$  and time  $dt$ . Thus the angular displacement  $d\phi$  is given in equation 3.6

$$R_e(\phi) = \sqrt{R_{eq}^2 \cos(\phi)^2 + R_{pole}^2 \sin(\phi)^2} \quad (3.3)$$

$$ds = rd\phi \quad (3.4)$$

$$vdt = rd\phi \quad (3.5)$$

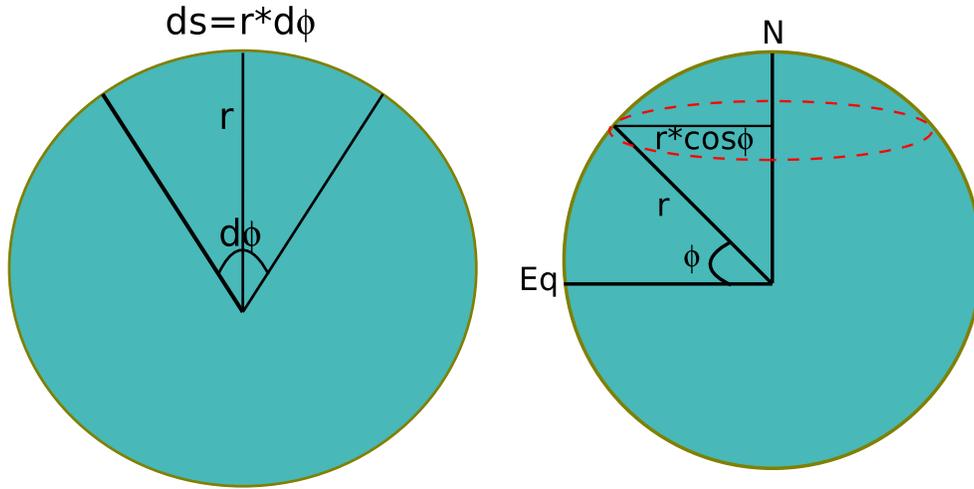


Figure 3.2: Segment and angle calculation on a sphere.

$$d\phi = \frac{v dt}{r} \quad (3.6)$$

The metric distance between two meridians depends on latitude. Figure 3.2 shows that the circumference of a sphere gets smaller from the equator to the pole. In order to calculate the latitude displacement  $d\lambda$  one has to account for this-hence the radius in equation 3.6 has to be changed to  $r \cos(\phi)$ , which is in equation 3.8. Equations 3.7 to 3.10 compute the new location of the air parcel which moves with a velocity vector  $(u; v; w)$  at an altitude  $z$  during a time  $\Delta t$ . The factor  $(-1)^n$  allows to compute forward ( $n$  even) or backward ( $n$  odd) trajectories. The factor  $\frac{180}{\pi}$  transforms radians to degrees. The altitude  $z$  of the air parcel above sea level is always added to the latitude dependent earth radius in order to compute as accurate as possible even if middle atmospheric altitudes (15 to 90 km) are less than 1.5 % of the earth radius.

$$\phi_i = \phi_{i-1} + \frac{(-1)^n \cdot v_{i-1} \cdot \Delta t}{R_e(\phi_{i-1}) + z_{i-1}} \cdot \frac{180}{\pi} \quad (3.7)$$

$$\lambda_i = \lambda_{i-1} + \frac{(-1)^n \cdot u_{i-1} \cdot \Delta t}{(R_e(\phi_{i-1}) + z_{i-1}) \cdot \cos(R_e(\phi_{i-1}))} \cdot \frac{180}{\pi} \quad (3.8)$$

$$z_i = z_{i-1} + (-1)^n \cdot w_{i-1} \cdot \Delta t \quad (3.9)$$

$$t_i = t_{i-1} + (-1)^n \cdot \Delta t \quad (3.10)$$

After the time  $\Delta t$  a new velocity vector is calculated for the new location  $(\phi_i, \lambda_i, z_i, t_i)$  of the air parcel. This process is done iteratively  $N$  times.

# Chapter 4

## Examples

TomTOM is a Matlab® code trajectory model. Matlab® needs to be installed, in order to run TomTOM. Further an access to the institutes MySQL database 'atmospheres' must be guaranteed to access the wind data. The Matlab® function 'tomtom' needs input parameters such as time, longitude, latitude, potential temperature (as altitude), number of time steps in hours, time step in units of hours, forward or backward calculation. Given these parameters TomTOM accesses the MySQL database 'atmospheres' table ECMWF and looks for the velocity vector corresponding to the input parameters. If these data are available for every parcel location on the trajectory the calculation is performed, otherwise an error message is displayed. Once you have installed Matlab® and are in possession of the code tomtom.m and erdradius.m you can run the function like follows: In a Matlab® window type and enter

$$[P, \text{lat}, \text{lon}, z, \text{pv}, \text{tem}, \text{vz}, t, \text{o3}] = \text{tomtom}(\phi, \lambda, \text{datetime}, \theta, N, \text{dt}, r)$$

The output will be stored in the variables defined in the brackets on the left handside. On the right there is the function name and its input in brackets. Latitude  $\phi$ , longitude  $\lambda$ , datetime and potential temperature  $\theta$  are the initial 4 dimensional coordinates for the air parcel. dt is the time step to be set in units of hours. r is the forward (r even) or backward (r odd) factor. The output will be vectors of length N, which is the number of time steps, and a trajectory plot. P is pressure, lat is latitude, lon is longitude, z is altitude, pv is potential vorticity, tem is temperature, vz is vertical velocity, t time, o3 ozone volume mixing ratio. For the following example ECMWF data are already in our MySQL database. We would like to calculate a 2 day backward trajectory starting in Switzerland at 46.5°N and 7°E on approximately 20 km which corresponds to 500 K potential temperature (see

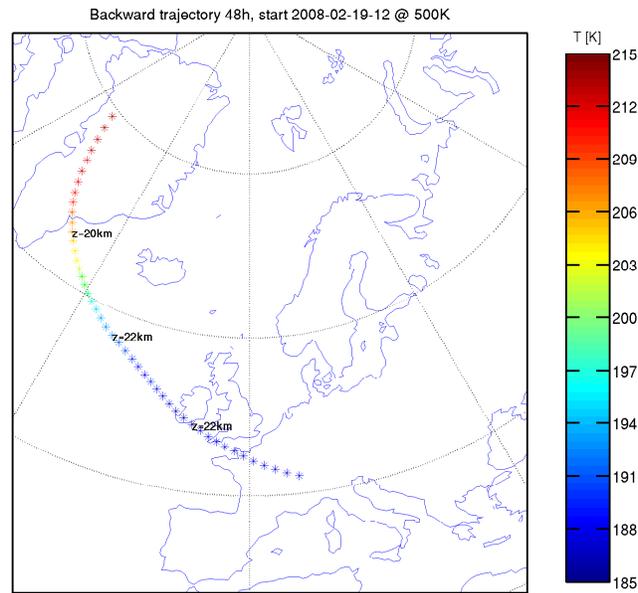


Figure 4.1: 2 day backward trajectory. The air parcel is arriving on February 19 at 46.5 N and 7.5 E. On its way the air parcel rose up and cooled down illustrated with the z-altitude value and the colours.

table 4.1) on 19 February 12 UTC, 2008. In Matlab® one has to type the following:

```
[P,lat,lon,z,pv,tem,vz,th,t,o3]=tomtom(46.5,7,'2008-02-19-12',500,48,1,1)
```

The pressure, parcel location, altitude, potential vorticity, temperature, vertical velocity, potential temperature, time and ozone VMR along the track will be stored in the variable P, lat, lon, alt, pv, tem, vz, th, t and o3. This example shows an air parcel arriving at 46.5°N and 7°E on February 19 at 12 o'clock after a journey of 48 hours. The parcel started on February 17 12 o'clock above north-west Greenland and crossed south-west Ireland. The plot shows the trajectory and the air parcel's temperature denoted with colours and its altitude every 12 hours. It is interesting to see the correlation of both states. The parcel cools adiabatically when it rises and warms up when it sinks. In this example the parcel started at 20 km altitude with a temperature of about 215 K, then it rose to 22 km above Switzerland and cooled down to 190 K.

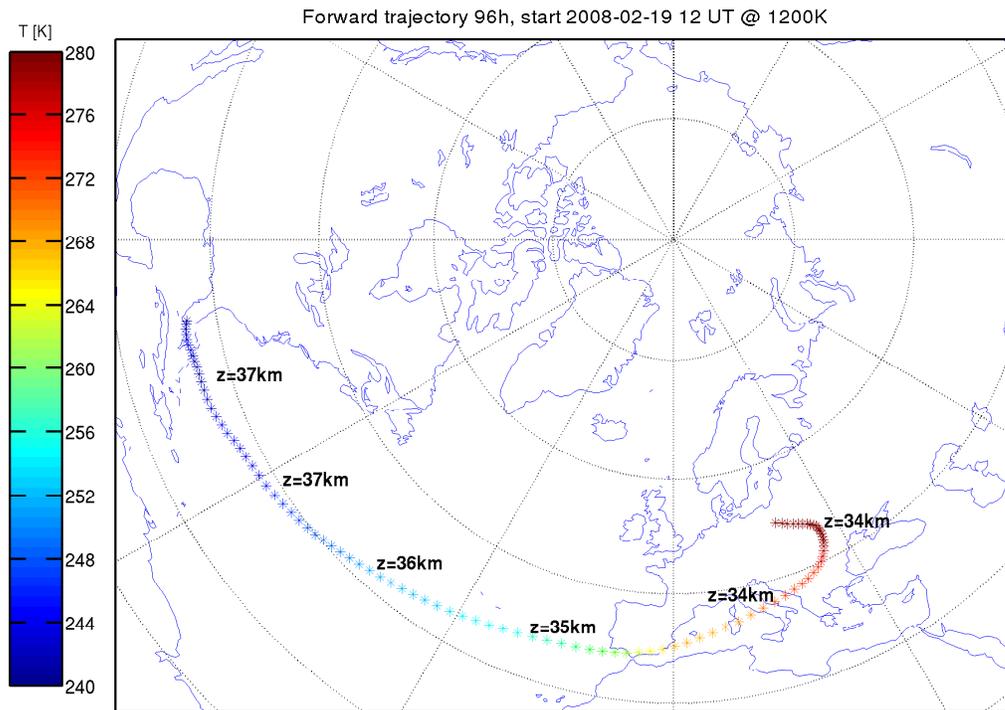


Figure 4.2: 4 day forward trajectory starting above Florida on February 19. The air flows on the 1200 K level towards Europe. The descent of the parcel warms it by more than 40 K! This phenomenon is called sudden stratospheric warming, which occurred in February 2008 above Europe.

If one wishes to calculate a forward trajectory the parameter  $r$  has to be set to an even number, for example  $r = 2$ . In the following a 96 hour forward trajectory is calculated starting above Florida on 19 February 12 UTC, 2008 at 26° N and 81° W at 1200 K. The trajectory is illustrated in figure 4.2.

$$[P, \text{lat}, \text{lon}, z, \text{pv}, \text{tem}, \text{vz}, \text{t}, \text{o3}] = \text{tomtom}(26, -81, '2008-02-19-12', 1200, 96, 1, 2)$$

We see an example of a so called sudden stratospheric warming. The air is transported from tropical latitudes toward mid latitudes in Europe. On its way the air parcel is descending and warms up by a large amount as is visible in the colours turning from blue to red.

Altitude [km]	Temperature [K]	Pressure [hPa]	Potential Temperature [K]
0	288	1013.3	288
5	256	540.5	307
10	223	265	327
15	217	121.1	398
20	217	55.3	498
25	222	25.5	636
30	227	12.0	807
35	237	5.7	1043
40	250	2.3	1426
45	264	1.5	1702
50	271	8.0(-1)	2091
55	261	4.3(-1)	2405
60	247	2.2(-1)	2757
65	233	1.1(-1)	3170
70	220	5.2(-2)	3709
75	208	2.4(-2)	4374
80	198	1.1(-2)	5205
85	189	4.5(-3)	6416
90	187	1.8(-3)	8250

Table 4.1: Example of typical values of physical parameters for atmospheric purposes. From the U.S. Standard Atmosphere (1976). Potential temperature is calculated according to equation 3.1 with  $p_0 = 1013$  hPa.

The initial coordinates needed for TomTOM hence define the start of the air parcel for a forward trajectory and the endpoint for a backward trajectory.

# Chapter 5

## Validation

As it was mentioned in the introduction TomTOM was made to cover the gap for mesospheric trajectories. Thus for altitudes higher than 40 km no comparisons could be made by the time. But trajectories were compared for stratospheric altitudes. TomTOM is compared to the HYSPLIT and Goddard Automailer trajectory models. Figure 5.1 shows examples of three day backward trajectories at 500 K, which is about 20 km altitude. A sudden stratospheric warming happened during the chosen dates. This is a rather complex situation with a change in zonal and meridional winds in the stratosphere. HYSPLIT and Goddard use NCEP/NCAR reanalysis data whereas TomTOM uses ECMWF winds. The agreement of the three models is very good. Hence it is a very good sign for the data assimilation and the trajectory models that for this special situation the trajectories agree that good.

Figure 5.2 shows TomTOM trajectories calculated with different settings compared to the HYSPLIT model. The trajectories are all started on 19 February 2008 at 12 UTC at 47° N and 7° E and at a potential temperature of 800 K. The black and red solid lines used a time step of 1 hour. The difference of black and red is that for the black TomTOM trajectory data were interpolated in time. The agreement to HYSPLIT is quite good but a little bit better for the run with temporal interpolation (black).

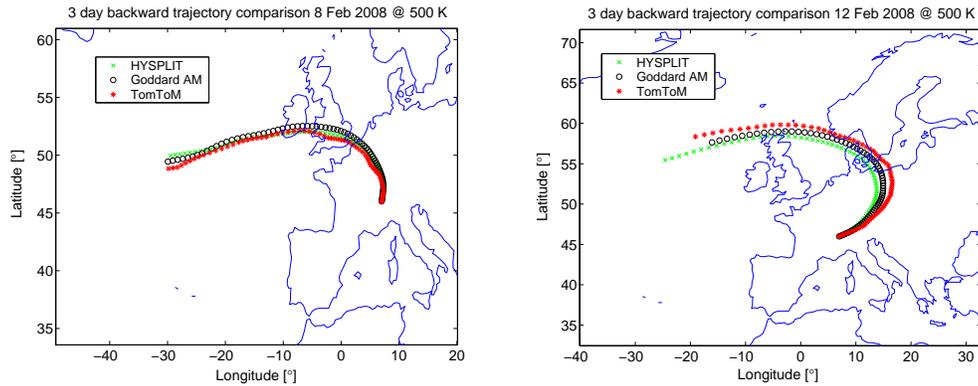


Figure 5.1: Comparison of 3 days backward trajectories from TomTOM, HYSPLIT and Goddard Automailer at 500 K (20 km). HYSPLIT and Goddard use NCEP reanalysis data and TomTOM uses ECMWF. Initialization time was 8 February 2008 for the left figure and 12 February 2008 for the right. The agreement is very good.

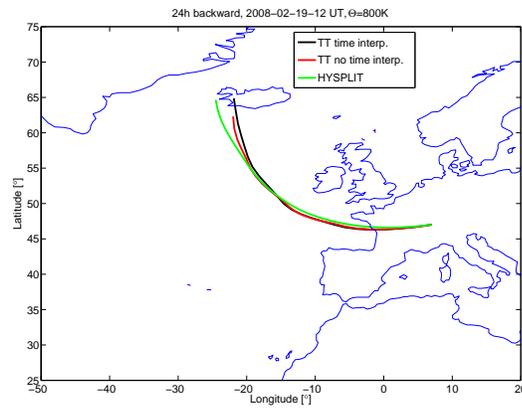


Figure 5.2: Comparison of different TomTOM versions with and without temporal interpolation of the data (interp.). The black TomTOM trajectory with wind data interpolated in time agrees best with the green HYSPLIT trajectory.

# Chapter 6

## Conclusions

TomTOM is an air parcel trajectory model based on a Matlab code. Trajectories are calculated with ECMWF wind data using a few simple equations. Despite its basic setup the trajectories calculated are in good agreement with well established trajectory models such as NOAA HYSPLIT and the Goddard Automailer. The advantage of TomTOM is its speed; trajectories are calculated and plotted in a few seconds. Hence, TomTOM is capable to give quickly qualitative results for air mass transport, which is important for middle atmospheric water vapor and ozone studies. However if more sophisticated trajectory studies are needed the user is referred to other models such as FLEXTRA, LAGRANTO (Stohl et al., 2001) or the other two models mentioned above.

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