

Review paper

The behavior of the atmosphere in long-range transport

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Abstract

Long-range transport of gases and aerosols depends on vertical and horizontal air shifts: studies on atmospheric transport have to be based on the meteorological conditions of the environment. The aim of this paper is to review the physical principles on which meteorological models are based, and to make an exhaustive inventory of the main models used for the prognosis and diagnosis of air masses and a list of the long-range transport models associated to them. URL addresses are provided for all of these models to allow the reader to check their usefulness. A practical application is included with reference to trajectories followed by air masses that reach the Iberian Peninsula at various altitudes, depending on the synoptic meteorological situation. Further examples describe air masses entering Europe with desert dust from Africa. This dust may eventually develop into freezing nuclei and form hailstones in summer storms.

1. Introduction

There is growing public concern about atmospheric pollution, which has led to an increasing interest in the study of the atmosphere as a carrier of pollutants. The function of the atmosphere, however, is not only to transport pollutants, but also other materials, such as pollen. Aerial transport, therefore, also has a positive action in spreading life.

The aerial transport of solid and liquid material (aerosols) involves different spatial and temporal scales. Thus, even though the origin of the aerosols lies in a different continent, a time span of between 3 days and 1 month may be enough for the material to reach any point of the earth (Stohl et al., 2002).

Long-range transport (hereafter LRT) is a direct consequence of atmospheric currents, which require the use of a certain amount of energy. This point of view considers the atmosphere a huge self-regulated heat machine that transports energy all over the world and controls the climatic system (McIveen, 1998).

This paper will present the basic tenets that rule the behavior of the atmosphere in LRT. It will also describe the main meteorological and transport models and provide the Uniform Resource Locator (URL) addresses where more information about these models can be found. In some cases, the models can even be tested on the web. The paper includes the example of a straightforward practical application of one of these models for LRT analysis.

2. Modeling the atmosphere

It is not an easy task to set up a comprehensive model that reflects the behavior of the atmosphere. The equations that rule the shifts of air masses may be extremely complex, since there are many different processes interacting in the atmosphere, including feedback processes capable of modifying the balance with only small changes in a particular parameter. Fortunately, for most aims it is enough to take into account only a few processes in order to obtain sufficiently accurate results.

Atmospheric models are based on the three classical conservation equations: mass, moment and energy. Depending on their spatial range, they may be classified into three groups: micro-scale models (one square kilometer), macroscale models (about one thousand kilometers), or mesoscale models, which correspond to an intermediate range.

As far as the complex interactions in the atmosphere are concerned, one example is the fact that clouds are related to:

- The number of condensation nuclei in the atmosphere;
- Atmospheric humidity;
- Vertical updrafts, that may produce condensation by cooling;
- The total amount of energy, which comes from the sun and may reach the lower layers of the atmosphere;
- Atmospheric temperature;
- The cleaning of aerosols, if the cloud produces precipitation;
- The transport of oceanic heat to the atmosphere when the evaporation–condensation–precipitation cycle ends.

From all the interactions that occur in the atmosphere, it is common to select those that have the most obvious effects on air masses. Thus, meteorological models can be developed that will serve as a basis for transport models.

3. Meteorological models

Meteorological models are mathematical representations of the atmosphere that reveal areas or bodies in 2 or 3 dimensions, respectively, by applying approximate functions of the properties

that are being studied. They play a fundamental role in weather forecasts. Nowadays, no weather forecast is carried out without the help of one of the many numerical models available. In addition, meteorological models establish their numerical forecasts and constantly check the results against the actual state of the atmosphere. This way they illustrate in a very reliable way the meteorological situation in the world every day.

The main differences between the meteorological models available refer to the temporal and spatial scales employed and to the approach used in applying the equations (advection, conservation of mass or continuity, hydrostatic, thermodynamic, state, water vapor), as well as to the techniques employed in their resolution.

An initial classification of the models divides them into diagnostic models and prognostic models. The former do not contain time-tendency terms, as they simply interpolate and extrapolate available meteorological measurements. The latter are used to forecast the evolution of the atmospheric systems by solving the full time-dependent equations. Another classification distinguishes between hydrostatic and non-hydrostatic models, depending on whether they apply a hydrostatic approach or not. Most prognostic models are hydrostatic. Complex terrain simulation and small-grid applications, however, require the use of more complex non-hydrostatic models.

Meteorological models are important for aerial transport, since their output is used as input for long-range transport models of pollutants. Some of the most commonly used meteorological models are listed in Table 1, together with the URL addresses where more detailed information about them is available.

4. Transport models

Meteorological models have served as a basis to develop other models specifically for determining aerosol transport. These transport models make use of the meteorological databases and of the output from one or more of the meteorological models available. Large-scale air pollution models can successfully be used in different environmental studies.

Table 1. URL addresses of the most widely used meteorological models

Model	URL
ALADIN	http://www.cnrm.meteo.fr/aladin/ http://omsz.met.hu/english/kfo/neo_aladin_en.html
AVN, ETA12, MRF, NGM, RUC, Ensemble, ARPS, ECMWF, MM5, NOGAPS, RAMS	http://www.srh.noaa.gov/ssd/nwpmodel/html/ngm.htm
COAMPS	http://meted.ucar.edu/nwp/pcu2/coamps/index.htm http://www.nrlmry.navy.mil/coamps-web/web/home
ECMWF	http://www.ecmwf.int/products/forecasts/guide/The_ECMWF_global_atmospheric_model.html http://www.ecmwf.int/products/forecasts/guide/The_model_formulation.html
ETA	http://meted.ucar.edu/nwp/pcu2/etapcp1.htm
GSF	http://meted.ucar.edu/nwp/pcu2/avintro.htm
HIRLAM	http://hirlam.knmi.nl/ http://www.inm.es/web/infmet/modnum/hirlam.html http://met.no/english/r_and_d_activities/method/num_mod/hirlam.html
JMA	http://www_pcmdi.llnl.gov/projects/modeldoc/amip2/jma_98a/jma-a.html
MASS	http://www.meas.ncsu.edu/mass/ http://www.ces.ncsu.edu/depts/pp/bluemold/masstext1.htm
MM5	http://cng.ateneo.net/cng/wyu/resources/mm5/ http://www.mmm.ucar.edu/mm5/
NOGAPS	http://meted.ucar.edu/nwp/pcu2/nogaps/index.htm
RAMS	http://www.lamma.rete.toscana.it/rams/docrams/documentirams-eng.html http://meteo9.uibk.ac.at/rams/intro/intro.html http://atmet.com/html/docs/rams/ug44-rams-intro.pdf http://rams.atmos.colostate.edu/ http://www.metnet.8k.com/rams.htm
RUC	http://meted.ucar.edu/nwp/pcu2/rucintro.htm http://maps.fsl.noaa.gov/ruc2.tpb.html
several	http://www.srh.noaa.gov/ssd/nwpmodel/html/ngm.htm
UKMO, ECMWF, NECEP, NOGAPS, JMA, NOAA LR, MASS, DWD, CGSM	http://www.geocities.com/CapeCanaveral/Lab/6799/model.htm
UKMODEL	http://www_pcmdi.llnl.gov/projects/modeldoc/amip2/ukmo_98a/

The following types of models can be distinguished, following Zannetti (1993):

- Plume-rise models: Thermal buoyancy (due to the difference in temperature between many of the pollutants injected into the atmosphere and air temperature) and vertical momentum (of fumes and gases released by chimneys) contribute to increasing the average height of the plume above that of the smokestack. This type of model aims at calculating the vertical shift and at analyzing the behavior of the plume in the initial dispersion phase.
- Gaussian models: They are based on the assumption that the concentration of the plume at a particular distance from the source follows a Gaussian downwind distribution, both horizontally and vertically. These are the most widely used models. In fact, almost all the models recommended by the U.S. Environmental Protection Agency (EPA) are of the Gaussian type.
- Semi-empirical models: Their main feature is their conceptual simplicity, together with a high number of empirical parameterisations (i.e. box models and other parametric models). They have been devised for practical applications mainly.
- Eulerian models: These are models which solve numerically the atmospheric diffusion equation, i.e. the equation for conservation of mass of the pollutant (Eulerian approach). These are generally used for weather forecasts.

Table 2. URL addresses of the most widely used transport models for local, regional and long range transport

Model	URL
ADAMS-3	http://www.cerc.co.uk/
ADMS-Roads-Extra	http://www.cerc.co.uk
ADMS-Urban	http://www.cerc.co.uk/
AERMOD-HNS	http://www.levegokornyezet.hu
AIPOC	http://www.fluid.mech.ntua.gr/
Air quality simulation models	http://www.ess.co.at/GAIA/models/aria.htm
AirQUIS-EPISODE	http://www.nilu.no
ALOHA	http://www.ess.co.at/AIR-EIA/MODELS/aloha.html
	http://response.restoration.noaa.gov/comeo/alotech/alotech.html
BUO-FMI	http://www.fmi.fi/research_air/air_17.html
CALGRID	http://mercator.src.com
CALINE4	http://www.dot.ca.gov/hq/InfoSvcs/EngApps/
CALPUFF	http://www.src.com/calpuff/calpuff1.htm
	http://www.epa.gov/ttn/scram/7thconf/calpuff/calpeer.pdf
	http://earthtec.vwh.net/download/calpuff.pdf
	http://www.ofcm.gov/atd_dir/pdf/calpuff.pdf
	http://www.epa.gov/scram001/7thconf/calpuff/conseq.pdf
CAMx	http://www.camx.com
CAR-FMI	http://www.fmi.fi/
CFX.TASCflow	http://aix.meng.auth.gr/atreus/models.htm
CHIMERE	http://euler.lmd.polytechnique.fr/chimere
CPB3	http://www.tfhr.gov/structur/pubs/02036/intro.htm
DEHM	http://www.copernicus.org/EGU/acp/acpd/3/3525/acpd-3-3525_p.pdf
DEM	http://www2.dmu.dk/AtmosphericEnvironment/DEM/
DISPERSION21	http://www.smhi.se/foretag/m/dispersion_eng.htm
EMEP Unified Model	http://www.emep.int
FARM	http://www.aria-net.it/eng/code_modules.htm
FLEXPART	http://www.forst.uni-muenchen.de/LST/METEOR/stohl/flexpart.html
FLEXTRA	http://www.forst.uni-muenchen.de/LST/METEOR/stohl/flextra.html
GASTAR	http://www.cerc.co.uk/
GRAL	http://fvkma.tu-graz.ac.at/
GRAM	http://www.gre.ac.uk/
Hilatar	http://www.fmi.fi/research_air/air_25.html , http://lib.hut.fi/Diss/2003/isbn9512264811/index.html
HYSPLIT	http://www.arl.noaa.gov/ready/hysplit4.html
IFDM	http://www.vito.be/
IMSM	http://pandora.meng.auth.gr/mds/showlong.php
INPUFF	http://www.ess.co.at/GAIA/models/inpuff.htm http://www.ofcm.gov/atd_dir/pdf/inpuff.pdf
ISCST3	http://beeline-software.com/ISCST3.htm
IVL	http://www.ivl.se/
LASAT	http://www.janicke.de/htm/e_home.htm
LED	http://pandora.meng.auth.gr/mds/showlong.php
LONGZ	http://www.ess.co.at/GAIA/models/longz.htm
MAP	http://www.fluid.mech.ntua.gr
MARS	http://aix.meng.auth.gr/lhtee/projects/
MEMO	http://aix.meng.auth.gr/lhtee/projects/
MESOPUFF	http://www.ess.co.at/GAIA/models/mesopuff.htm
MESOPUFF II	http://www.esm.versar.com/emlimes/air.htm
METPHOMOD	http://www.giub.unibe.ch/klimet/metphomod/
MOGUNTIA	http://www.moguntia-global-modelling.de/

Table 2. Continued.

OML	http://oml-international.dmu.dk
ONM9440	http://www.zamg.ac.at/
Panache	www.fluidyn.com
PolluMap	http://www.meteotest.ch/products/pollumap/
RADM	http://www.acri.fr/ , http://www.acri.fr/English/Products/RADM/radm.html
REMSAD	http://remsad.saintl.com/
SAFE-AIR-II	http://www.fisica.unige.it/~atmosfe/
SMOG	http://www.aria-net.it
SPRAY	http://www.aria.fr http://www.aria-net.it http://www.aria.fr
STEM	http://www.cgrer.uiowa.edu
TAPM	http://www.dar.csiro.au/tapm/
THOR	http://thor.dmu.dk
UDM-FMI	http://www.fmi.fi/
VADIS	http://www.dao.ua.pt/gemac

- Lagrangian models: They describe the fluid elements that follow the instantaneous flow. They break down plumes into simpler elements.
- Chemical modules: It is sometimes necessary to include modules that account for the chemical changes that may take place during the transport of aerosols or gases. The complexity of these modules depends on the reactions that are considered (from a simple, first-order reaction to those describing complex reactions).
- Receptor models: As opposed to dispersion models, receptor models start from the concentrations found in the receptor and search for the different sources that contribute to these concentrations. It is necessary to know the chemical composition of the source and the receptor.
- Stochastic models: They are based on a series of statistical or semi-empirical techniques that analyze trends, periodicities and interrelations between the parameters that measure atmospheric pollution. These models are not properly scientific models, since they do not analyze cause-effect relations: they simply describe the situations without attempting to explain the reasons why they occur. However, the mere description of the situation is often enough for a large number of practical applications.

Table 2 lists some of the most widely used transport models, together with URL addresses

including additional information about their main features, applications, input, output, etc.

5. Case studies

An interesting aspect of LRT is determining the back trajectories of the air masses. This refers to knowing the track followed by an air parcel that reached a particular point at a particular time. From the point of view of LRT, this is useful because it informs about whether the air has previously been in touch with a source of pollution, or an area with a high pollen concentration, or any other source of aerosols (Castro et al., 1998).

In the application described here, three-dimensional back trajectories were used from the synoptic wind field and from the vertical speeds provided by the European Centre for Meteorological Weather Forecast (ECMWF). The calculation of these back trajectories has been described in detail in Martin et al. (1987), and further validated in Martin et al. (1990).

The meteorological services of all European countries provide information about this type of back trajectories. The four coordinates that are necessary are the following: two coordinates for the geographic location of the point of arrival of the air mass (typically latitude and longitude), another coordinate to indicate altitude above sea level (it may be expressed in relation to the pressure), and the last one to fix the exact time of

Table 3. Example of coordinates (longitude, latitude, altitude) of the position of the air mass, at hourly intervals, until the time of arrival

Day	Hour	Long	Lat	Alt (hPa)	Long	Lat	Alt (hPa)	Long	Lat	Alt (hPa)
89/6/13	20	-5.583	42.317	900.000	-5.583	42.317	500.000	-5.583	42.317	200.000
89/6/13	19	-5.510	42.356	901.664	-5.802	42.190	506.350	-6.142	42.136	202.822
89/6/13	18	-5.445	42.382	903.278	-6.024	42.061	513.021	-6.658	41.928	205.971
89/6/13	17	-5.387	42.398	904.847	-6.250	41.931	519.576	-7.145	41.700	208.998
89/6/13	16	-5.339	42.404	906.377	-6.480	41.798	525.622	-7.619	41.455	211.495
89/6/13	15	-5.301	42.400	907.875	-6.714	41.663	530.831	-8.094	41.192	213.197
89/6/13	14	-5.275	42.387	909.346	-6.953	41.526	534.969	-8.578	40.912	214.119
89/6/13	13	-5.257	42.370	910.739	-7.199	41.389	537.860	-9.082	40.625	214.601
89/6/13	12	-5.241	42.355	911.996	-7.453	41.253	539.609	-9.607	40.343	215.060
89/6/13	11	-5.229	42.342	913.118	-7.716	41.120	540.598	-10.148	40.074	215.753
89/6/13	10	-5.221	42.331	914.106	-7.987	40.989	541.229	-10.700	39.820	216.680
89/6/13	9	-5.215	42.323	914.962	-8.265	40.859	541.683	-11.260	39.580	217.703
89/6/13	8	-5.211	42.316	915.686	-8.551	40.730	542.064	-11.827	39.358	218.543
89/6/13	7	-5.213	42.313	916.254	-8.844	40.599	542.574	-12.406	39.160	218.942
89/6/13	6	-5.222	42.317	916.641	-9.143	40.462	543.355	-13.005	38.986	218.928
89/6/13	5	-5.239	42.326	916.850	-9.445	40.322	544.363	-13.627	38.830	218.765
89/6/13	4	-5.263	42.341	916.880	-9.745	40.181	545.550	-14.274	38.688	218.713
89/6/13	3	-5.296	42.361	916.730	-10.041	40.039	546.885	-14.945	38.561	218.933
89/6/13	2	-5.338	42.385	916.394	-10.333	39.897	548.357	-15.636	38.449	219.503
89/6/13	1	-5.393	42.413	916.035	-10.624	39.753	549.749	-16.352	38.351	220.432
89/6/13	0	-5.465	42.444	915.828	-10.921	39.605	550.761	-17.092	38.262	221.674
89/6/12	23	-5.554	42.477	915.786	-11.225	39.454	551.279	-17.850	38.185	223.163
89/6/12	22	-5.661	42.511	915.911	-11.539	39.304	551.303	-18.620	38.126	224.690
89/6/12	21	-5.787	42.545	916.259	-11.868	39.153	550.916	-19.400	38.095	226.012
89/6/12	20	-5.933	42.578	916.916	-12.215	39.001	550.098	-20.193	38.098	226.972
89/6/12	19	-6.094	42.600	917.972	-12.576	38.847	549.039	-21.019	38.129	227.711
89/6/12	18	-6.262	42.605	919.514	-12.945	38.687	547.898	-21.899	38.176	228.478
89/6/12	17	-6.439	42.591	921.577	-13.323	38.524	546.633	-22.836	38.237	229.264

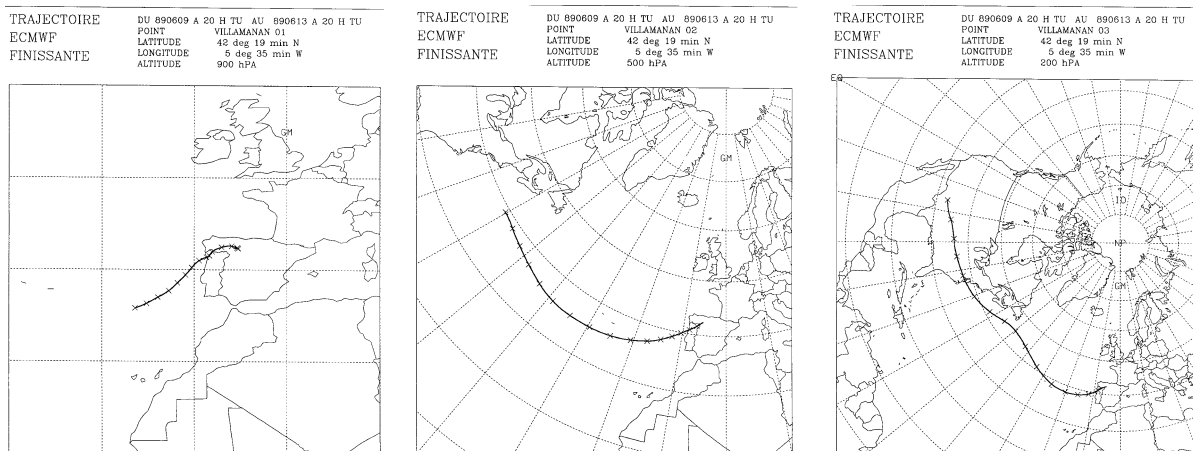


Figure 1. Example of the horizontal projection of the back trajectories on June 13th 1989, ending at 2000 UTC, at 900, 500 and 200 hPa.

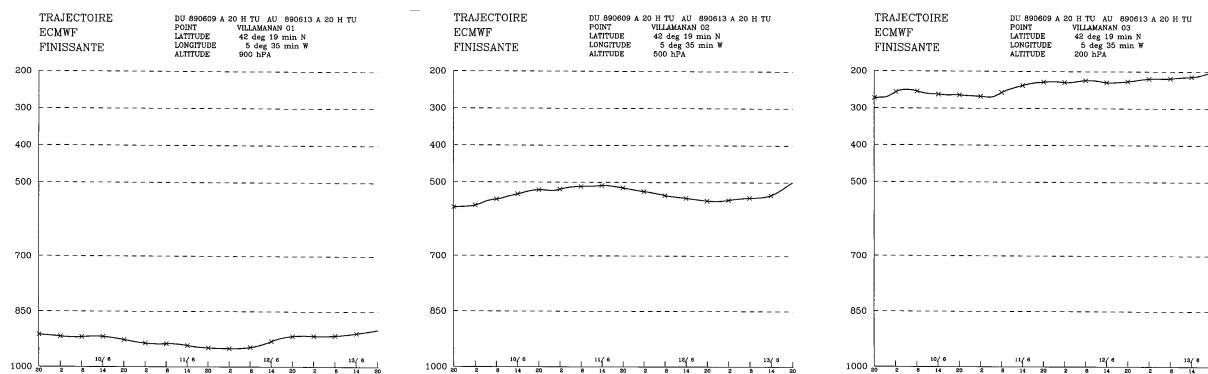


Figure 2. Example of the vertical projection of the back trajectories on June 13th 1989, ending at 2000 UTC, at 900, 500 and 200 hPa. Vertical units are hPa.

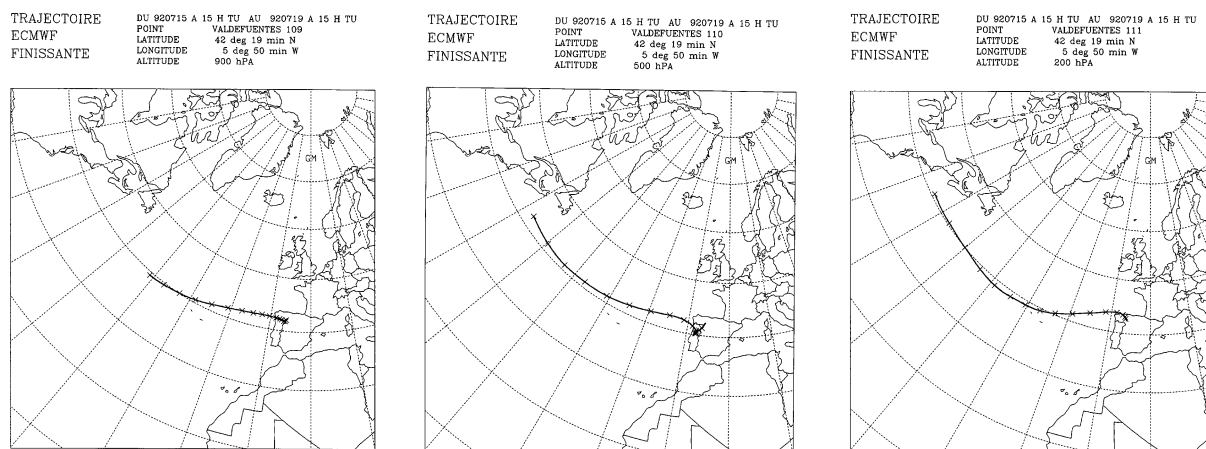


Figure 3. Example of the horizontal projection of the back trajectories on July 19th 1992, ending at 1500 UTC, at 900, 500 and 200 hPa. Wind direction is the same in the three levels.

arrival (date and time). The outputs of the model are the coordinates (x, y, z) of the position of the air mass, at hourly intervals, from the moment chosen until the time of arrival (Table 3). The geographic coordinates (x, y) may be represented on a map: Figure 1 shows the points from Table 3, joined by segments. The crosses indicate the points at intervals of 6 h. Figure 2 represents variable z in relation to time.

The focus has been on the study of back trajectories because they are fundamental in the case that will be analyzed here. However, it is

clear that the same method can be used to calculate the trajectories (the trajectory of an air mass beginning at a particular time and place). The applications of these trajectories are also clear. For example, Albergel et al. (1988) have applied this method to the study of the evolution of air masses coming from the Chernobyl area during the 10 days after the nuclear accident.

In the case study included in this paper we used the output of the model to determine the provenance of the air that arrived into a number of storms that produced hail. The back trajectory-

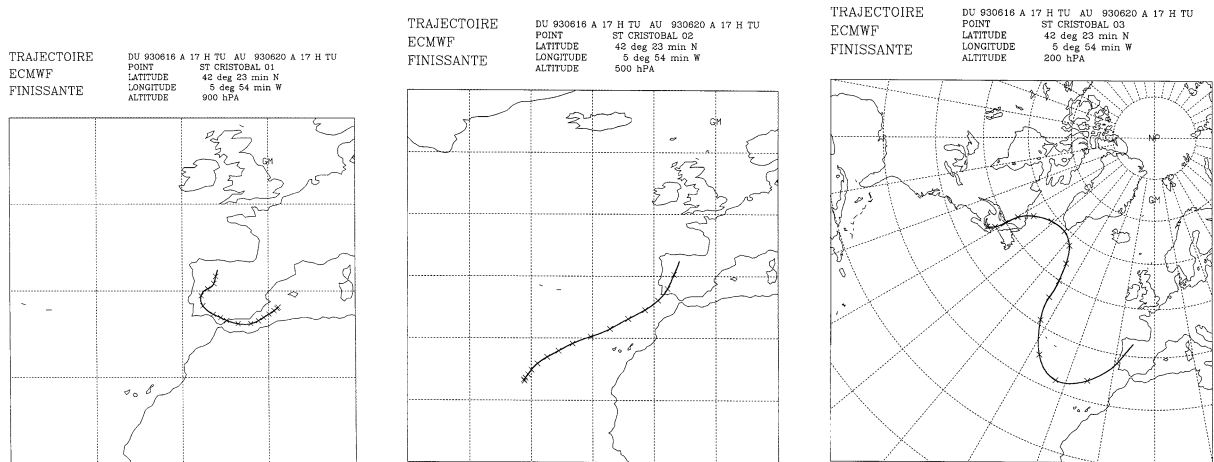


Figure 4. Example of the horizontal projection of the back trajectories on June 20th 1993, ending at 1700 UTC, at 900, 500 and 200 hPa. Wind direction is completely different in the three levels.

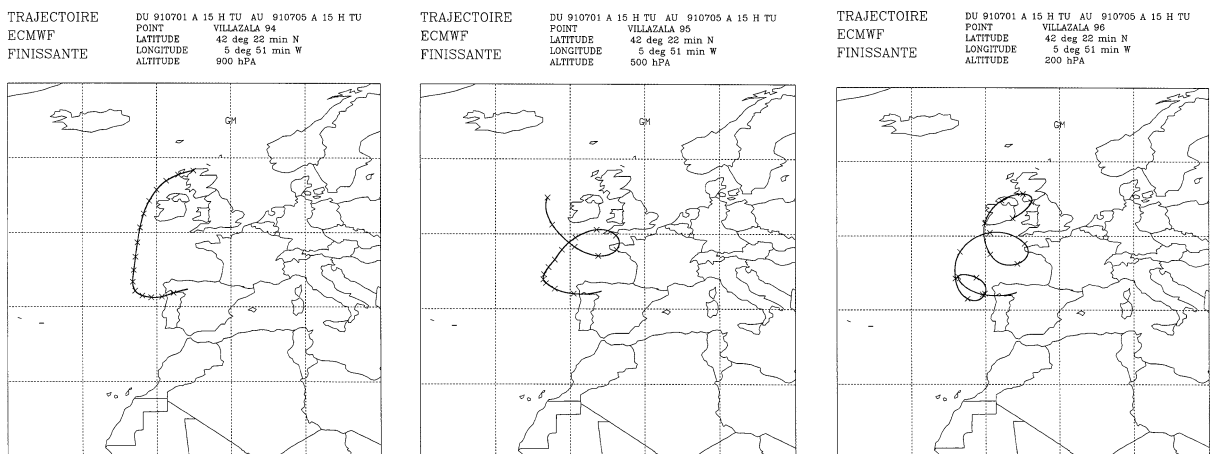


Figure 5. Example of the horizontal projection of the back trajectories on July 5th 1991, ending at 1500 UTC, at 900, 500 and 200 hPa. The air can be seen to turn around the low-pressure centre in the three levels.

TRAJECTOIRE	DU 950704 A 18 H TU	AU 950708 A 18 H TU
ECMWF	POINT	JOARILLA MATAS 144
	LATITUDE	42 deg 17 min N
FINISSANTE	LONGITUDE	5 deg 11 min W
	ALTITUDE	200 hPa

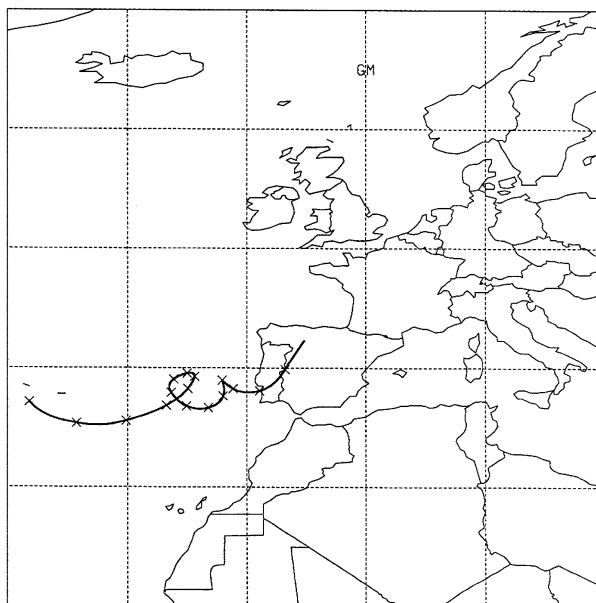


Figure 6. Example of the horizontal projection of the back trajectories on July 8th 1995, ending at 1500 UTC, at 200 hPa. The sudden change in the wind direction due to a front is represented by the angular shape of part of the trajectory.

ries were calculated at three levels: at 900, 500 and 200 hPa from 4 days before the hailfall (Figure 1 and 2). The crosses indicate intervals of 6 h. It was observed that the distance covered by an air parcel at low levels is always much smaller than at high levels. In fact, as the trajectories were represented at higher altitudes, it became necessary to change the scale of the maps in order to be able to represent the whole trajectory. For instance, the air that reached the final point at 850 hPa was 90 h before in the Iberian Peninsula. On the other hand, the air parcel that arrived at 500 hPa was found 4 days before over America, and the same occurred with the air that arrived at 200 hPa.

The study of the back trajectories at different altitudes is by no means redundant. There are cases where the trajectories followed by air masses coincide at different altitudes (Figure 3), but most often the origin of an air parcel that arrives in a particular place is different depending on the altitude taken into account. It may even be the case that the trajectories at different altitudes differ greatly, as in the example shown in Figure 4.

Depending on the meteorological situation, the trajectories take on characteristic forms. For example, if the air parcel lies in a low-pressure area, the cyclonic flow can be clearly seen in the trajectory (Figure 5). On the other hand, if the air mass is affected by a front, there will be a sudden change in its speed, which is represented by the angular shape of the trajectory (Figure 6).

A study of this type indicates only the trajectory followed by an air parcel. However, it is obvious to assume that the material that has reached a particular point has followed the same trajectory, especially in the case of gases. In any case, possible chemical reactions have to be taken into account, and, in the case of aerosols, phenomena such as deposition, coagulation or degradation due to any reason. In addition, in the case of living organisms it will be necessary to consider the time elapsed during the trajectory and the atmospheric conditions (humidity, temperature, pressure, solar radiation, etc.).

An inorganic aerosol will serve as an example. For a storm to form hailstones, a sufficient number of freezing nuclei must be available (Dessens

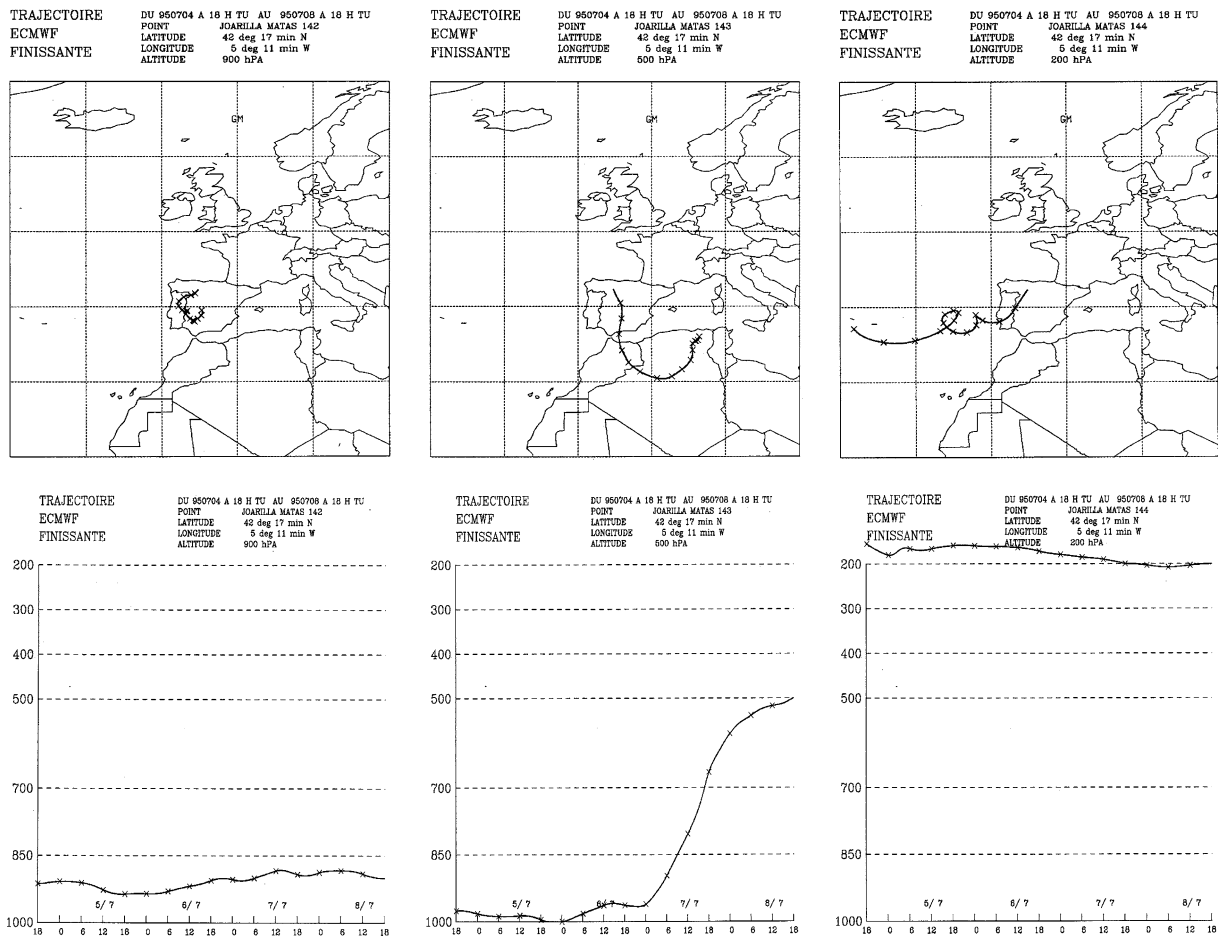


Figure 7. Example of the horizontal and vertical projections of the back trajectories on July 8th 1995, ending at 1800 UTC, at 900, 500 and 200 hPa. The air parcel at 500 hPa was found to move at a very low altitude over Africa 42 hours before.

et al., 2001). It was believed that, on some occasions, desert dust could be a source of freezing nuclei in hailstorms, since this hypothesis was proved to be true in latitudes higher than ours (Stevenson, 1969). Figure 7 represents the back trajectories (at 900, 500 and 200 hPa) of a hail-fall registered in the province of León on July 8th 1995. The air parcel that arrived in León at 900 hPa had remained at a similar altitude during the four previous days, and the same occurred with the air at 200 hPa. However, the air mass that arrived at the hailfall at 500 hPa was found to lie 2 days before at pressures of 1000 hPa and more, sweeping over the surface of Africa for over 50 h. As a result, that air parcel gathered great numbers of dust particles that could eventually have formed freezing nuclei in the hailfall.

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