Diurnal Cycles in the Western Mediterranean and Associate Long-range Transport of Pollutants during the European RECAPMA Project

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1 Introduction: recirculatory patterns observed in the western Mediterranean basin

The western Mediterranean basin is surrounded by high coastal mountains. In summer it becomes isolated from the travelling lows and their frontal systems, which affect the weather at higher latitudes. During daytime conditions, the east and south-facing slopes of the coastal mountains (Atlas mountains and eastern Iberian mountain ranges) are strongly heated and favour the early formation of up-slope winds, which combine with the sea-breezes and their complementary (return) and compensatory flows (i.e. subsidence over the coast and the sea) to create closed-loop circulations. These processes result in the formation of stacked layers along the coast with the most recently formed layers at the top and the older ones closer to the sea (Millán et al. 2000). Layering has been documented to reach 2 to 3 km in depth and extend out over the sea to more than 300 km (Millán et al. 1992, 1996 and 1997). During the night the land-based processes die out, and the layers formed on the previous day(s) can drift along the coast, acting as reservoir layers of aged pollutants. Finally, the next morning's sea breeze brings the lower layers inland and closes the recirculations. Tracer experiments on the Spanish east coast have shown than turnover times for these recirculations range from 2 to 3 days. Similar processes involving either vertical recirculations and/or oscillations of the aged air-masses have also been documented in the Central Mediterranean (Ciccioli et al. 1987; Fortezza et al. 1993; Georgiadis et al. 1994; Orciari et al. 1998). Under strong summer insolation, the coastal recirculations become 'large natural photo-chemical reactors' where most of the NOx emissions and other precursors are transformed into oxidants, acidic compounds, aerosols and O_3. Relevant aspects of this problem are: (1) that a higher percentage of the observed O_3 at any surface monitoring station in the area, e.g. mountain tops and coastal sites, may result from advection within the recirculating air masses, and (2) that these situations are the norm rather than the exception for the western Mediterranean in summer. Daily average concentrations of O_3 for mountain stations on the Iberian eastern coast (1100-1300 m.a.s.l.) are about 100 $\mu g/m^3$ from March to September, while at sea-level coastal stations or upper-valley sites, these higher concentrations are registered as peack values after midday (Millan et al. 2000). Night and early-morning meteorological conditions in the coastal areas (sea level) and inland valleys favour O_3 depletion due to titration within a surface boundary layer decoupled from the upper O_3 reservoir layers: 20 to 30 $\mu g/m^3$ hourly averages for the coastal stations and 60 to 80 μg/m3 for the inland valley stations are found during these periods. Thus, daily concentrations throughout the warm season are well above the vegetation protection threshold of current Directive 92/72/EEC, 4 times above the WHO guideline for the protection of crops and semi-natural vegetation and also higher than the vegetation-related target value for O_3 in the year 2010.

The main objective here is to reproduce the diurnal cycle of stabilization and mixing over the western Mediterranean basin, at a sufficient space/temporal resolution, with the corresponding three-dimensional flows associated with a typical recursive synoptic condition during the warm season. We have used the meteorology and air pollution data gathered during the flight tracks of the European Project RECAPMA -**RE**gional **C**ycles of **A**ir **P**ollution in the west-central **M**editerranean **A**rea, 1990-1992- (Millán et al. 1997). A second objective is the search for the origin of the pollution over the area, looking for the reason-s for the concentration of such a high level of O_3 during such a long period. Estimations of re-circulation times for a marked air parcel entering the area should be of great interest.

2 Climatological evidences of cycles in the western Mediterranean basin

In summer, atmospheric circulations across southern Europe are dominated by the Azores High at the west and the Asian Monsoon system at the east, and pressure differences of up to 30-40 hPa can develop between the Atlantic coast of Portugal and the Arabian peninsula. Mesoscale thermal lows develop over the major land masses (peninsulas and islands) during the day and decay during the night. The ITCZ is placed in north Africa following a low pressure belt which extends from south-east to north-west up to a higher latitude of 20-25^{O} N, to the southern slopes of the Atlas mountains (Figure 1). Subordinate to the major weather systems, other large mesoscale circulations develop with marked diurnal cycles, i.e. the Iberian, Italian and Anatolian Thermal Lows with their compensatory subsidence over the seas which will influence the evolution of the regional flows.

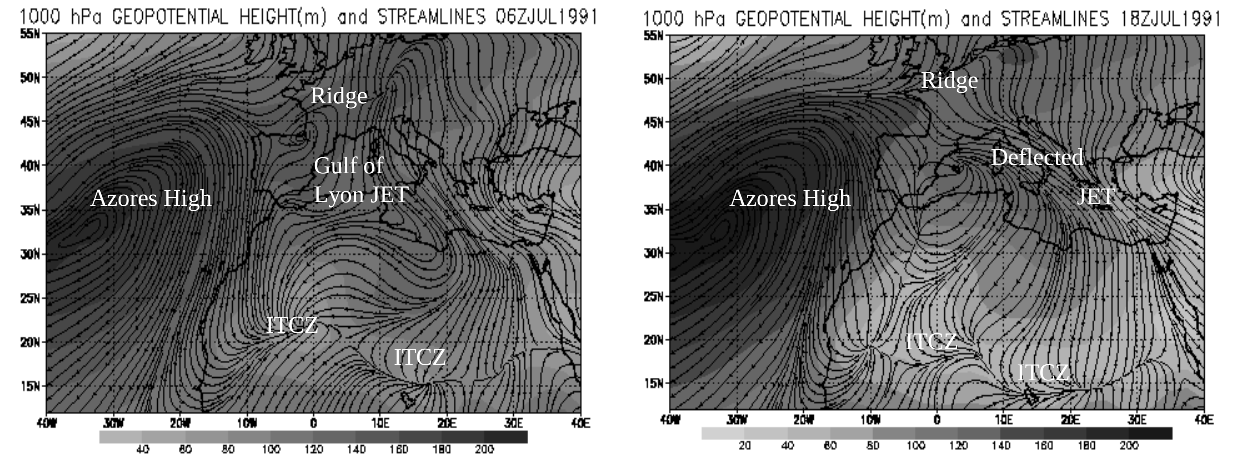

Figure 1a-b: monthly means (July 1991) of the 1000 hPa geopotential height and streamlines (CDAS/reanalysis data archive) at 06 and 18 UTC. The diurnal oscillation of the jet-like flow over the Gulf of Lyon is shown.

Figure 1 depicts monthly means –for July 1991- at 06 and 18 UTC, of the geopotential height of the 1000-hPa isobar, as well as streamlines on that isobar. Data are from the Climate Data Assimilation System (CDAS/reanalysis) of the USA National Weather Service; they have a grib format with a horizontal resolution of 2.5º x 2.5º. The main feature of the air-flow over the western Mediterranean is the diurnal oscillation of the jet flow associated with the eastern edge of the Azores high, which enters the Mediterranean region between the Iberian and the Italian peninsulas: during night time conditions (06 UTC) it crosses N to S, while during the daytime it is deflected to the east. This is a consequence of the formation of a diurnal relative high pressure over the western Mediterranean associated with a large mesoscale sinking. Sea breezes and up-slope flows over the coastal areas of the western basin generate a compensatory sinking over the whole basin, and the flow under an average height of 1500 m (coincident with the average height of main topographic features which close the basin), becomes anticyclonic. Details of this flow pattern can only be seen at a higher spatial resolution (see section 3). At a finer scale, the nocturnal jet crossings between the Pyrenees and the Alps onto the western basin are associated with the Tramontana and Mistral winds which blow almost permanently over the area as long as the Azores High is placed at the position shown in Figure 1, with a ridge of high pressures over northern Iberia. North-to-south surface winds at night over the eastern coast of Iberia and its diurnal deflection to the east is a frequent feature during the warm season, as can be deduced from the monthly means of the CDAS/reanalysis data archive, and can last from May to September. Most of the inter-annual differences are more related to the initial and ending period of the weather pattern.

3 Results during the RECAPMA flight campaign and mesoscale model results

We are now using the meteorological and pollution data obtained during the flight program to assess the results of our mesoscale model, applied at a sufficient resolution. This work must be done before extracting any further conclusions about the main mesoscale weather regimes and their implication in the transport and dispersion of pollutants over the area of interest. Flight plans included horizontal tracks between 150 and 200 m above sea level and spiral flights on interesting locations from sea level up to 3500 m. The area covered the coastal region between Marseille, Barcelona, Valencia and the Balearic Islands, at the western edge of the Mediterranean basin. Data were gathered on 16, 18 and 19 July 1991.

The Regional Atmospheric Modeling System (RAMS version 3b; Pielke et al., 1992) has been employed to reproduce the observed meteorological processes. It is a non-hydrostatic prognostic model and non-homogeneous initialization with non-stationary boundary conditions was used. The model was run for 114 h, starting at 00 UTC 15 July, to allow for numerical spin-up and to cope with the whole flight period. The four-dimensional data assimilation technique was used for the simulations, nudging the boundary of the larger domain to the conditions established by the ECMWF analysis data (1º horizontal lon-lat resolution) at 00, 06, 12 and 18 UTC. Three different simulations using 3 nested grids for each were used. The fine grid (grid 3) was run with a 6-km gridcell size and its horizontal domain was different at each simulation: all three finer grid domains covered the whole flight area. This solution was shown to have a computational time saving. The coarse grid (grid 1) was run with a 96 km gridcell size and covered a domain of 4128 km by 2976 km centered at 40.2 N, 7.67 E. The medium grid (grid 2) was run with a 24 km gridcell size and covered a domain of 1080 km by 984 km centered at 39.97 N, 0.34 E. Both the medium and the large domains were common to all three simulations. In the vertical, 64 levels were used for all the domains in order to cope with the highest complexities of the vertical wind shear and temperature profiles observed during the flight tracks. The same vertical geometric grid stretching that increases with height was allowed for all domains. Thus, all domains use the same vertical spacing up to a height of 12000 m. Two-way nesting was allowed between the grids. Topography was interpolated to the model grids from the global 30’’ lat-lon data, and the U.S. Geological Survey data set was used for defining land use. Sea-surface temperature was retrieved from the NOAA satellite data (Badenas et al., 1997 a, b): the average of 17 and 18 July was used for the whole 5-day simulation period (15-19 July).

Selected horizontal winds on the flight tracks of days 16 and 18 are shown in Figure 2. Figure 2.a documents the night and early morning position of the Tramontana-Mistral jet-like flow (6-10 ms^{-1}) over the Gulf of Lyon and the transition to the sea-breeze regime at the eastern coast of Iberia during day 16. The jet is crossing the Carcasonne gap into the Mediterranean and bringing 50-65 ppb of O_3 of continental origin. The O_3 concentration in the tracks over the Spanish coastal area is even higher: 65 to 75 ppb between Tarragona and Barcelona and increasing from 55 to105 ppb between Tarragona and Valencia. There are no late-evening data for the same area on this day. Thus, we represent the data for day 18 instead (Figure 2.b): the jet-like flow over the Gulf of Lyon has been deflected to the east (6-15 ms^{-1}). No sea breeze was detected at the French coastal area, while it is well developed over the Spanish eastern coast.

Sea-breeze regimes at the coastal sites and the associated compensatory subsidence over the sea have developed, as has the anticlyclonic vortex over the western basin. The vortex, centered at a relative high pressure over the area, is seen more clearly in the model results for the same time: Figure 3 shows the horizontal wind vectors at 165 m above the terrain and the vertical wind over the sea for 06 and 18 UTC on July 18th. Compared with the morning conditions (Fig 3.a), it is evident that in the evening conditions there is a generalized sinking (0-8 cms^{-1}) over the sea as well as a deflection of the jet-like flow over the Gulf of Lyon. We conclude that the model has been able to reproduce at a rather good level of accuracy the details of the flow within the region of interest. This flow, which has been shown to be an ‘average’ weather pattern under a height of approximately 1500 m.a.s.l, shows a daily bi-modal behavior (Figs 3a-b) and the Carcasonne gap seems to be the main entrance of ‘fresh’ (50-65 ppb of O_3) Atlantic-continental air into the lower airshed of the western Mediterranean basin.

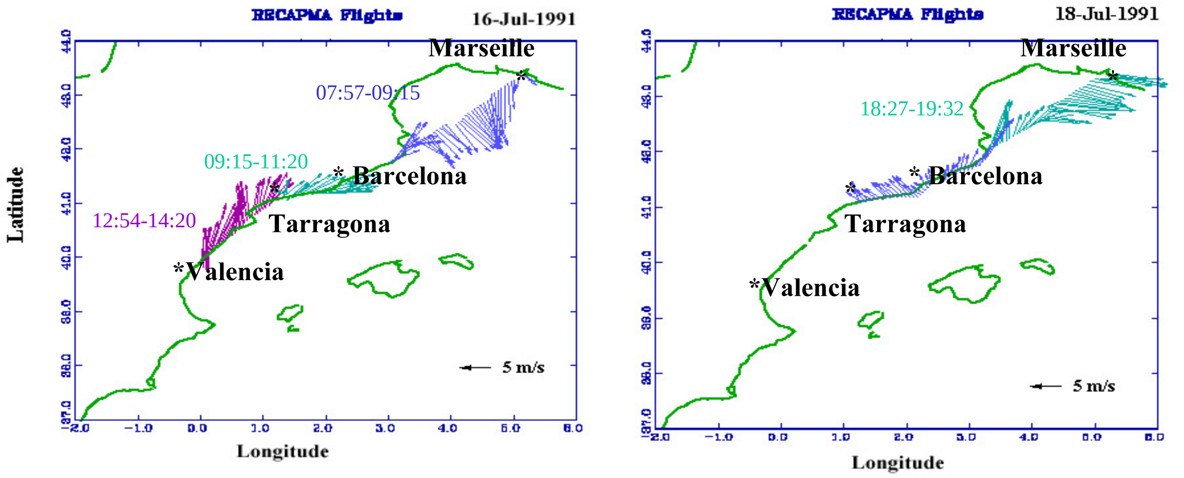

Figure 2a-b:horizontal winds at marked flight tracks (150-200 m.a.s.l) during the morning to afternoon transition (left) and during the evening (right). UTC flight time is shown for every sub-track; 5ms^{-1} wind scale is depicted in lower-right corner.

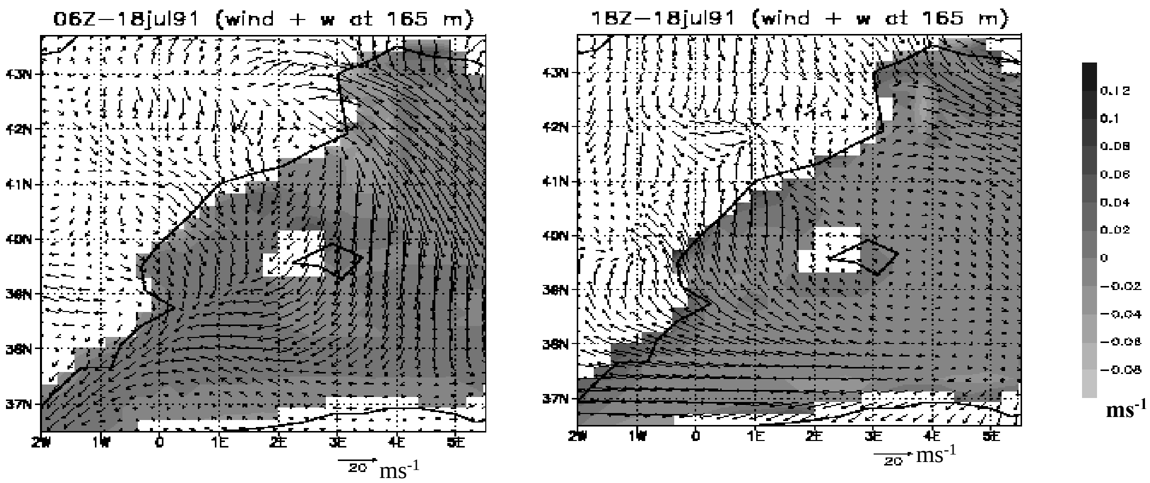

Figure 3a-b: horizontal wind field at 165 m above the terrain and vertical wind (shaded grey) over the sea, evaluated by RAMS at 06 and 18 UTC July 18 in grid #2 (simulation with grid #3 centred in the Gulf of Lyon): during the evening, deflection of the Gulf of Lyon flow jet and clockwise rotation with a generalized sinking over the whole basin is observed.

4 Modeled transport and recirculation processes

The main consequence of these diurnal cycles on the dispersion of pollutants in the western basin has been investigated by tracking the trajectories of passive particles –in a Lagrangian framework-flowing out of the Gulf of Lyon (41.9 N, 3.7 E). Individual trajectories were generated by using the high-resolution 3-D wind field at each hour of the simulation period. Care was taken not to skip any grid cell during a time step in the calculation of the individual trajectories. Thus, the Courant-Friedrichs-Lewy criterion served as an upper limit for the selected flexible time step. The differential trajectory equation was solved by using the ‘constant acceleration’ solution, which result in an accurate approximation at an acceptable computational cost (A.Stohl, 1998): time saving is more evident when there are large horizontal and vertical variations in the wind field at consecutive time instants, as is the case. The main result of these single-particle Lagrangian computations (not shown) was to put in evidence recirculations lasting longer than the simulation period (5 days) for trajectories entering the western basin at the Gulf of Lyon. The residence time was observed to be highly dependent on the instant of the emission. The largest residence times corresponded to transport within the night time position of the jet, which lets the pollutants penetrate deep into the middle of the western basin or drift parallel to the eastern Iberian coast. Then, they are frequently trapped and re-circulated by the sea breezes for the following days. On the other hand, daytime emissions at the Lyon jet find their way out of the area via two types of trajectories: (1) in stable layers over the sea, between the Italian peninsula and north Africa and (2) in 'unstable' trajectories, over land. Topographically aided injections in Corsica, Sardinia and the Italian Peninsula help particles to get out of the area following a general eastward trajectory.

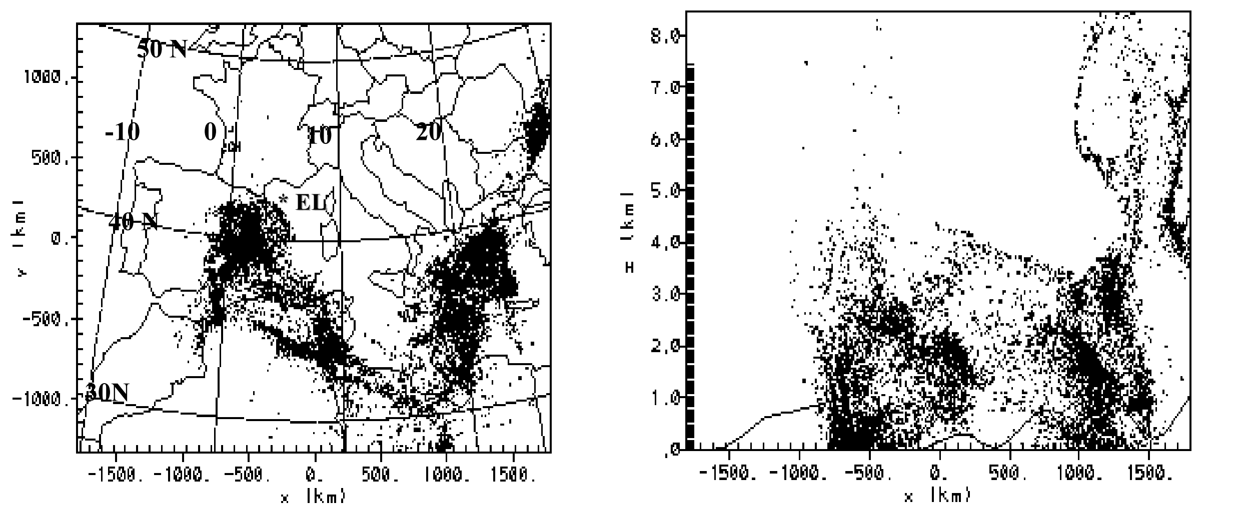

Figure 4a-b: horizontal (left) and W-E vertical distribution (right) of particles evaluated by HYPACT/RAMS at 10 UTC July 19 after 4 days and 4 hours from the starting time of the tracer release at site marked EL in the Gulf of Lyon.

In order to enlarge the representativeness of the single-particle approximation to the main problem of residence time, we used the HYPACT model (Walko and Tremback, 1995) which simulates the motion of multiple particles under the influence of winds and turbulence. Gridded time series of horizontal and vertical wind components, potential temperature and turbulent kinetic energy were provided by the RAMS model. For this study, the selected dispersion domain was 4128 x 2976 km centered at 40.2 N, 7.6 E. Figure 4 shows the particle position at 10 UTC July 19 after being emitted during a period of 72 hours, starting at 06 UTC July 15. A vertical emission line of 1500 m height was placed at the point marked EL (41.9 N, 3.7 E) in Figure 4, in order to simulate final distribution of 'fresh air' entering the Mediterranean. The cloud of particles located at eastern Iberia is near the point of emission, after 5 days of re-circulation (at the end of the simulated period it still remained over the area). The cloud of particles at the eastern edge of the same Figure, above latitude 40 N, and now at a reduced dimension, was getting out of the domain after 3 days of travel time at a higher altitude –4000 / 9000 m- (E and N-eastward trajectories after topographic- and storm-aided injections). The cloud of particles located at the southeast, between Greece and north Africa was first observed drifting at stable layers to the south-east between Sicily and north- Africa (0-2000 m). After that point (3 days of travel time) part of it suffered from successive daytime topographically aided injections over the near-land while being transported to the southeast. Thus, at the end of the 5 days of simulation, the particles at this cloud are observed distributed below 4000 m. No large differences in the final distribution of tracers are observed by using other line emissions near the jet –like flow at the Gulf of Lyon.

Acknowledgements

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