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Origin and transport of Mediterranean moisture and air

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Abstract

Considering the Mediterranean as a region of high evaporation and low precipitation, evaluations of the moisture and precipitation sources and sinks in the Mediterranean basin have been carried out within the frame of the CIRCE project. In addition, residence time and stagnation/ventilation have been analysed to investigate transport to and from the Mediterranean basin and in the basin itself. A Lagrangian moisture diagnosis method calculating budgets of evaporation minus precipitation was applied to a 5.5 year (October 1999–April 2005) trajectory data set and evaluated for eight Mediterranean regions of interest. The Mediterranean basin has been identified as a major source of moisture and precipitation to the surrounding land area and to the basin itself. Regions of stagnation have been identified through the analysis of the average 24-hour and 5-day displacements for the four seasons, and the Po basin was identified as being strongly affected by stagnation. Evaluation of the transport to and from the basin shows that the Mediterranean is a crossroad of airstreams where air enters mainly from the northwest and continues in two separate airstreams: one turns towards southwest, passing over North Africa into the trade wind zone while the other one continues northeastwards through Central Asia.

1 Introduction

Recently, investigation of sources and sinks of moisture and precipitation for a specific region has become a topic of interest, for example in the context of the heavy floods in Central Europe in 2002 and 2005. One of the regions in the world which are especially interesting is the Mediterranean region, at the intersection between the westerlies of the midlatitudes, the South Asian and African monsoons, and the trade wind regimes (e.g., Alpert et al., 2006; Luterbacher and Xoplaki, 2003; Xoplaki et al., 2003, and references therein). Exhibiting a pronounced seasonal cycle with dry and warm summers and wet winters (Peixoto et al., 1982; Lolis et al., 2008), it has also been identified as one of the “hot spots” for present and future climate change (Giorgi, 2006).

Various large-scale atmospheric circulation patterns are connected, to a larger or smaller extent, with the Mediterranean weather, e.g., the North Atlantic oscillation (Hurrell, 1995, 1996; Rodo et al., 1997; Krichak et al., 2002; Krichak and Alpert, 2005). Rainfall anomalies in the Eastern Mediterranean and their connection to the North Atlantic climate variability have been investigated by Eshel and Farrel (2000).

Water in the atmosphere is important for the climate system in many ways, e.g., by modifying the Earth’s radiation budget, and by the influence of precipitation on the thermohaline circulation and water fluxes (Weaver et al., 1999; Bethoux and Gentili, 1999). The hydrological cycle in the Mediterranean has also effects on the atmospheric moisture flux in adjacent regions such as into northern Africa (Ward, 1998) or into the Alpine region. Sodemann and Zubler (2009) analysed moisture sources of the Alpine region stating that the seasonal fluctuations and unsteadiness of the Mediterranean as a moisture source could be a cause for precipitation extremes such as droughts or floods. Additionally, they concluded that especially for the southern Alpine slopes the Mediterranean has a significant influence on the amount of precipitation.

Therefore, we found it interesting to investigate the fate of the atmospheric water vapour evaporated from the Mediterranean basin, with respect to atmospheric humidity as well as precipitation. This is closely related to the transport pathways of air to and from the Mediterranean in general, which in turn are also key determinants for air quality (Lelieveld, 2009).

Precipitation in a region may have, according to Brubaker et al. (1993), three origins: moisture already present in the atmosphere, moisture advection, and evapo(transpi)ration from the surface below, the latter also referred to as recycling of precipitation (Eltahir and Bras, 1996). Moisture transported from sources outside the respective regions, related to global atmospheric water fluxes, have been investigated by Newell et al. (1992), who analysed global tropospheric water vapour fluxes on a daily time scale and found “tropospheric rivers” supplying moisture in warm conveyor belts (see also Eckhardt et al., 2004). Zhu and Newell (1998) found that for the meridional transport at the middle latitudes the tropospheric rivers account for nearly all of the total water vapour transport. Trenberth (1999) defined recycling as the amount of contribution of evaporation in an area to the precipitation in the same area, so recycling as function of the domain's length scale and depending on the domain size.

Projects that presently investigate such features in the Mediterranean region include CIRCE[1] (Climate Change and Impact Research: the Mediterranean Environment), HyMeX[2] (HYdrological cycle in the Mediterranean EXperiment) (Drobinski and Ducrocq, 2008) and MedClivar[3] (Mediterranean CLImate VARiability and Predictability) (Lionello et al., 2006). Beyond issues of the hydrological cycle, they aim at a better understanding of climate change and its various effects in the Mediterranean basin and its surroundings. The study presented here was carried out in the frame of CIRCE.

Lelieveld et al. (2002) identified air mass trajectories during the MINOS (Mediterranean intensive oxidant study) campaign for the lower, middle and upper troposphere and concluded that in the lower troposphere inflow from the North prevails whereas in the free troposphere the westerlies dominate. In the upper troposphere the Mediterranean is influenced by an anticyclone with its center located over the Tibetan Plateau. Inflow from continental Europe into the Mediterranean prevails in the lower troposphere whereas in the middle and upper troposphere inflow from Northwest and Southeast dominates. Analyses of transport pathways of middle-lived pollution from and to the Iberian Peninsula (Nieto et al., 2008b; Nieto and Gimeno, 2006) for time periods ranging from 3 to 10 days showed similar pathways as identified by Lelieveld et al. (2002) and also showed that the Iberian peninsula acts as one of the main potential contributors of Mediterranean middle-lived pollution.

Stohl and James (2004, 2005) used Lagrangian analysis to evaluate the surface freshwater flux $E-P$ using ECMWF data and applied their method to the case study of the heavy flooding event in August 2002 in Central Europe. They concluded that

[1]http://www.circeproject.eu/

[2]http://www.cnrm.meteo.fr/hymex/

[3]http://www.medclivar.eu/

the major source region of evaporation contributing to the precipitation event was the Mediterranean. In addition, they applied their method to a 4-year period and analysed $E-P$ budgets for 39 river catchments. A climatological analysis of the precipitation, evaporation and moisture flux in the Mediterranean region for the past 50 years has been carried out by Mariotti et al. (2002) who used reanalysis data and compared the results with observational datasets and estimated the climatological river discharge using historical hydrological data. They showed that the annual mean of the budget $E-P$ is positive over the Mediterranean Sea indicating that the atmosphere gains moisture from the Mediterranean.

Lagrangian evaluations of moisture sources and sinks in other regions than the Mediterranean have been carried out by Drumond et al. (2008) who analysed the moisture sources for the Rio Plata basin and Central Brazil, Nieto et al. (2006) concentrated their analyses on the Sahara and its moisture sources, Nieto et al. (2007) analysed contributions to the Icelandic moisture budgets and Nieto et al. (2008a) analysed the Orinoco basin in South America. In all four studies the data set used was compiled by Stohl (2006).

This paper investigates residence times and stagnation/ventilation of air moisture and precipitation sources and sinks in the Mediterranean based on the Stohl (2006) data set.

2 Method

The Mediterranean basin is a region surrounded by mountain ridges in the north (Massif Centrale, Alps, Dinaric Mountains, Carparthians), west (Pyrenees, mountains of Iberian peninsula), east (Anatolian highlands) and parts of the south (Atlas Mountains). These mountains, and especially the gaps between them, lead to wind systems such as the mistral, the bora, the ponent, the scirocco and the etesians. The Italian peninsula until its Appenine mountain range and the Greek mountains divide the Mediterranean basin. To account for the influence of these wind systems and the topography Regions

Of Interest (ROI) were defined inside the Mediterranean basin. In total, eight ROIs have been defined (Fig. 1): one is the Mediterranean itself, the other seven are the following sub-regions: (1) Western Mediterranean, (2) Central Mediterranean, (3) Adriatic Sea, (4) Eastern Mediterranean, (5) Balearics, (6) Etesian region, and (7) the region between Cyprus and Israel.

Moisture and precipitation sources and sinks have been analysed using a Lagrangian particle dispersion data set produced by Stohl (2006) for a study of transport into the Artic. The model FLEXPART (Stohl et al., 1998, 2005) had been used in the global domain-filling mode to simulate a 5.5-year period starting on 27 October 1999 and ending on 1 May 2005. This period includes some extreme weather periods, especially the heavy floods in Central Europe in 2002 and the unusually hot and dry Summer 2003. Input data were the operational analyses at 00:00, 06:00, 12:00, and 18:00 UTC, and 3-h forecasts at intermediate times (03:00, 09:00, 15:00, 21:00 UTC) of the European Centre for Medium-Range Weather Forecast (ECMWF). A horizontal resolution of $1^{\circ}\times 1^{\circ}$ of the T319 model with 60 model levels was used. Approximately 14 levels are below 1500 m and 24 below 5000 m. Trajectories had been calculated using the interpolated mean winds from the input data plus random motions to account for turbulence.

At the start of the simulation 1 398 801 particles were released which filled the atmosphere homogenously. One of these particles represents about 3×10^{12} kg of air. Particles move freely with the winds during the simulation. Output of particles' ID number, position (latitude, longitude, height above msl, height above ground), and interpolated meteorological parameters from the input analyses (temperature T, specific humidity q, air density ρ, atmospheric boundary layer (ABL) height and the tropopause height at the particles' position) were recorded every six hours.

Restricitons of this method are related to the limited amount of particles and time resolution in the dataset, the accuracy of the trajectory calculations and the calculation of the Lagrangian time derivates of humidity. Examinations of the data set have shown that in a few rare cases specific humidity suddenly dropped from one time step to the next from plausible values to nearly zero specific humidity, probably indicating a bug in the FLEXPART data set. Linear interpolation has been used to replace buggy specific humidity values with one time step before and one time step after the drop. As analyses are carried out using large temporal and spatial averages these effects can be neglected.

Moisture and precipitation budgets, residence times, and a stagnation/ventilation index have been evaluated on a $1^{\circ} \times 1^{\circ}$ grid for all eight ROIs. In the following, the definitions and calculations of these parameters is introduced.

2.1 Residence time

The residence time is defined as the average of the time that all those particles have spent in the respective evaluation grid cell that were in the ROI during the defined time window. Residence times have been calculated in forward and backward mode for three different vertical layers: 0–1000 m agl, whole troposphere, and the whole atmosphere, and four different transport times windows Δt: 0–1 days, 0–5 days, 0–30 days, and 0–90 days.

Residence times are shown on an annual basis. The residence time is normalised with the number of particles in the ROI and Δt in days, and is expressed in units of seconds per particle, receptor day, and grid cell. As grid cells are defined in a latitude-longitude grid, these values have been corrected to standard grid cell size (as at the equator). Forward transport calculations show the fate of Mediterranean air, while backward calculations show the origin of air in the Mediterranean. Particles are counted in the forward mode if they resided initially in the ROI, in the backward mode if they arrived finally in the ROI. “Initially” and “finally” means within time windows Δt as defined above.

High residence times indicate, on one hand, areas with stagnation, and on the other hand, transport pathways. Thus they are especially relevant for air pollution budgets.

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2.2 Stagnation/Ventilation

The residence times give already an idea of regions where the air stays a long time, and especially residence times with short time intervals are related to stagnant conditions. To show such areas more clearly, additional analyses for stagnation (and, on the other side of the scale, ventilation) have been carried out (see Allwine and Whiteman, 1994, for background to this concept). Ventilation/stagnation is defined as the vectorial mean of the particle velocities, or in other words, the distance between start point and end point of a particle divided by the length of the time interval. Low values indicate strong stagnation tendency, high values ventilation.

Stagnation has been calculated for the four seasons and different time intervals Δt all over the globe. These time intervals are shorter than time intervals used for the residence times, namely one and five days. These are local parameters, not a relationship between a source (receptor) region and the rest of the world, thus it is not appropriate to do separate ROI calculations. Results are shown for the Mediterranean region only.

2.3 Moisture budget

Moisture source and sink tracking along the trajectories has been done using a method based on James et al. (2004); Stohl and James (2004, 2005) and Sodemann (2006), also used by Nieto and Gimeno (2006); Nieto et al. (2006, 2007, 2008a) and Drumond et al. (2008).

The change in the moisture content q of the air parcel n in a time interval Δt, $\Delta q_n/\Delta t$, can be written as the balance of effects of evaporation E minus precipitation P:

$$\frac{\Delta q_n}{\Delta t} = E - P \quad (1)$$

Evaluations are carried out on a fixed 6-hour time interval. Results of Δq_n have units of $\mathrm{g\,kg^{-1}\,(6\,h)^{-1}}$. The moisture change between two time steps is calculated

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as $\Delta q_n = q_n(t) - q_n(t-1)$, where $q_n(t)$ is moisture at time t and $q_n(t-1)$ is the moisture at the previous time step.

In order to distinguish between moisture originating inside and outside the ROIs, two different moisture variables are defined. We track moisture originating inside the ROIs, qm_n, with its changes between the timesteps, Δqm_n, and moisture originating outside the ROI, qo_n, with changes Δqo_n.

An increase of qm_n can be found if Δq_n is positive and the particle is inside the ROI, with

$$\Delta qm_n = \Delta q_n \tag{2}$$

and

$$\Delta qo_n = 0. \tag{3}$$

If the particle is outside of the ROI, $\Delta qo_n = \Delta q_n$ and $\Delta qm_n = 0$.

With a decrease of a particles' moisture between two timesteps (negative Δq_n) both qm_n and qo_n loose moisture pro-rata. In this case Δqm_n and Δqo_n can be calculated as:

$$\Delta qm_n = \frac{qm_n}{(qm_n + qo_n)} \Delta q_n \tag{4}$$

$$\Delta qo_n = \frac{qo_n}{(qm_n + qo_n)} \Delta q_n. \tag{5}$$

Final results are evaluated as means over all relevant particles for the four seasons and the whole year, averaged over 1°×1° grid boxes. The fraction of the total moisture which evaporated inside the ROI, $qm_i(x,y)$, can be written as:

$$qm_i(x,y) = \sum_n \frac{qm_n}{(qo_n + qm_n)} \tag{6}$$

where n are the particles in the gridbox. This fraction $qm_i(x,y)$ is then averaged over the seasons.

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2.4 Precipitation budget

The attribution of precipitation with respect to its origin in the ROIs was done in a similar way as the moisture calculations. The moisture changes inside and outside the ROI are evaluated and the moisture loss in the atmospheric column is taken as precipitation.

The fraction $pm_i(x,y)$ of the precipitation which contains water evaporated in the ROI, is calculated in a way similar to the moisture fraction $qm_i(x,y)$, where instead of qm_n and qo_n the quantities Δqm_n and Δqo_n, if <0, as defined in Eqs. (4) and (5) are used. Thus $pm_i(x,y)$ can be written as:

$$pm_i(x,y) = \sum_n \frac{\Delta qm_n}{(\Delta qo_n + \Delta qm_n)}. \tag{7}$$

This value indicates the fraction of the precipitation in a grid cell that stems from moisture which evaporated inside the ROI. It has to be considered that a small ROI will of course contribute less moisture to any precipitation downwind than a larger ROI.

3 Results

3.1 Moisture budget

Seasonally averaged values of $qm_i(x,y)$ (i.e., the fraction of moisture evaporated inside the ROI) have been calculated for eight ROIs. Results for the Mediterranean basin as a whole (Fig. 2) show that the highest fractions of moisture are formed over the basin itself with the centre located between the Italian and Hellenic peninsulae. These structures of the moisture fraction $qm_i(x,y)$ can be found in all four season, especially in the three summer months June, July, and August (in the following JJA) where two centres with values between 50% and 70% can be found. One centre is located in the Ionian Sea and the other one between the south cost of Turkey and Cyprus. In autumn and winter, when the evaporation from the sea is large, due to high SST compared to air

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temperature, and advection strong, the contribution of $qm_i(x, y)$ with fractions of 10% and more to regions outside the Mediterranean is larger compared to spring and summer. Contributions even reach Kazakhstan and European Russia as well as Egypt and Libya.

In the main outflow region, the northeastern part of the Mediterranean, $qm_i(x, y)$ shows some influences inland, e.g., in Turkey and Bulgaria. Contributions of Mediterranean moisture can be found, although with a very low fraction, in the whole northern hemisphere. The spatial distribution of $qm_i(x, y)$ mainly reflects the predominant flows in the corresponding seasons. Moisture transport to the northeast is strong especially in SON and DJF when SST is high and westerlies are more intense than in the other seasons.

Results of the seven sub-basins show similarities with those for the Mediterranean basin having as a whole the absolute maximum inside the ROI, although on a smaller scale. Outflow from the western Mediterranean basin, ROI 1 (Fig. 3), is directed primarily to the northeast and east contributing to precipitation in these areas, especially in autumn. In summer, we see minor ingestion into the trade wind regime through the Strait of Gibraltar, and into the ITCZ through Algeria and Libya. Sodemann and Zubler (2009) showed that the western Mediterranean sector, covering in our definition ROI 1 and ROI 2, plays a major role for Alpine precipitation throughout the seasons, especially in August and September, again related to ocean evaporation. The central Mediterranean, ROI 2, has only weak influences on regions outside the Mediterranean, partially because the basin is smaller. Although the influences are small, they still can be found close to the northern border of Chad with up to 20% moisture in summer. The main outflow goes to the northeast. ROI 4, the eastern Mediterranean (Fig. 4), delivers contributions to the region itself and to the Near East. The outflow of ROI 4 is divided into two airstreams, one towards the east and one going southward into the ITCZ. Influences to the south reach further into North Africa than that of any other major basin, being present in all four seasons and strongest in spring and autumn. Towards the west, no moisture transport can be indentified and only a little is going north.

For the other four small sub-basins influences do not reach far outside the ROIs themselves. The Balearic basin moisture mixing ratio (Fig. 5) has contributions on the Iberian peninsula showing that the thermal circulation between the Balearic Sea and the Iberian continent is present even in the coarse ECMWF model (see Sect. 2 for desription of input data). Additionally, some influence can be found on Italy too. This influence is strongest in summer while being present, although on a smaller scale, in the other seasons too. The Adriatic basin, ROI 3, shows more influence on the western part of the Balkan than on Italy. Looking more into the details, one can discover that the Po basin has a significant moisture fraction originating in the Adriatic, and that there is a strong gradient over the western Alps. Switzerland receives virtually no Adriatic moisture, whereas southern and eastern Austria do. In the Etesian basin, the impact of Mediterranean moisture is distributed locally with flows influencing the Black Sea and Turkey in winter and spring, and the Sahara region in summer and autumn. Small flows going northeast and south to Africa are visible. The Cyprus basin results have similar results compared to the Etesian but with flow directions to the east and southeast. Impacts can be found in the region between the Eastern Mediterranean shoreline and Iraq. In contrast to the Etesian region, shallow flows of the moisture originating from the Cyprus basin are sucked into the atmosphere over Africa.

3.2 Precipitation budget

As described in Sect. 2.4, the fraction $pm_i(x,y)$ of the precipitation on a grid cell stemming from moisture evaporated inside the ROI is presented. Patterns of these precipitation fractions are of course similar to those of the moisture. However, the maxima are clearly higher, and the mimina lower.

In the Mediterranean basin (Fig. 6), the fraction of authochtonous precipitation is at least 40% throughout the year. In summer, it is highest with values between 50% and 70%, showing quite sharp boundaries compared to the other seasons. Results for autumn show, like in the moisture analyses, the influence of the higher SST in autumn compared to spring. Outflow pathways can be clearly identified, having a strong dominant branch towards the northeast and a second, weaker one towards central Africa, especially to the eastern part of the continent, whereas western North Africa receives less Mediterranean rainwater. A third maximum can be found in the region of Gibraltar, reaching into the trade wind zone in summer although with a very low fraction. A fourth predominent maximum, in spring and autumn is located over eastern Central Europe, related to the well-known higher frequencies of meridional circulations in these seasons, connected with Vb-like cyclone tracks (Van Bebber, 1891).

The western Mediterranean basin (Fig. 7) influences the Algerian and Tunisian coast, the Balearics and southern Sardinia especially in summer. In summer, a strong gradient in the north of the basin across the Alpine region is visible. Also a weak transport into the trade wind zone can be found. In autumn and winter, when precipitation originating in the western Mediterranean reaches into Central Asia, the influences in the north east are larger than in summer whereas the influences on the Iberian peninsula are comparably higher in spring and summer with more than 20% of precipitation originating in the Mediterranean. Contributions to the Adriatic Sea and Italy can be found too, except for winter. In the central Mediterranean the influence of precipitation originating in that basin is changing little over the seasons. In summer and autumn, transport into northern Africa is visible, influence to the northeastern areas is strongest in winter and autumn. Results for the eastern Mediterranean (Fig. 8) show its contribution to Egypt, Turkey, Israel, Lebanon, Jordan, and Syria. A large impact in spring, summer, and autumn can be found in Cyprus. Especially in summer and autumn, effects on Africa are large. Furthermore, impacts of the westerlies are large in winter, spring and autumn. Another contribution can be found in the northwest of Chad in the Tibesti mountains where the Mediterranean precipitation is lower than the 3% in the north, east, and south of the mountain ridges.

Precipitation patterns of moisture evaporated in the Balearic basin show that in summer the region with highest impact is located between the Balearic islands and the coast of Valencia. Impacts can also be found in the Alpine region except in winter, and in summer also in southern France, cyclones in the western Mediterranean are

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known to cause heavy precipitation in these regions, and probably a substantial fraction of this water comes from the Balearic sub-basin. Transport with the trade winds and with the westerlies is almost absent. Similar results can be found for the Adriatic basin (Fig. 9) insofar as influences are only local. Fractions are highest in the southern Adriatic Sea, especially in summer. In contrast to moisture, the Po Basin in northern Italy is not a feature for precipitation. From the land areas, the Dinaric coast has the highest fraction of Adriatic water in precipitation. However, in the main precipitation season (autumn), it is only about 25%, so that other sources of atmospheric moisture contribute as well. As in the moisture results, the precipitation originating from the Etesian sub-basin is mostly relevant for the ROI itself. The 3% zone reaches into Egypt with the trade winds in summer, in winter transport with the westerlies comes close to Crimea. Results for Cyprus show not much difference to the moisture results, though with larger precipitation influence towards Africa.

3.3 Residence times

Forward and backward residence time evaluations have been analysed only for the Mediterranean basin on three different vertical layers and four different time intervals (see Sect. 2.1). Results of the 1-day residence times evaluations (Fig. 10) show that maxima can be found in the middle of the ROI reflecting a tendency towards stagnation with low wind velocities and/or recirculation. Additionally, residence times are clearly higher over the Mediterranean Sea than over adjacent land confirming tendencies towards recirculation. Results of the comparison of forward (Fig. 10) residence times for two of the three different layers (Fig. 10 left shows 0–1000 m, right shows the troposphere) show that for 1-day residence times the values are very similar, as expected for the short transport time. Furthermore, the backward evaluations clearly show that the Alps act as a northern barrier (Sodemann and Zubler, 2009) for the Mediterranean region. Influences from other orographic barriers and local wind systems can be found in the east (Etesians) and in the southwest (Atlas range).

Five-day residence times show patterns similar to the 1-day residence times. The

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maximum, a sign towards stagnation, is located in the Tyrrenian Sea between Southern Italy and Turkey. Influence of the Etesian winds is now more clearly visible than in the 1-day residence times, with inflow from the Black Sea through the Sea of Marmara into the Aegean and outflow to the eastern part of Northern Africa, which is visible even in the annual means. This leads to lower residence times in the eastern part of the Mediterranean on the 5-day time scale. The overall tendency towards stagnation is still visible in the 5-day evaluations (Fig. 11). Influence of the topography surrounding the Mediterranean basin is clearly recognisable by minima in the 0–1000 m residence times over the mountains where the air partly flows around, and if going over the mountains it has high velocities. Another indicator for that can be seen especially in the region of the Atlas mountains where the air is channelled around them. The 5-day residence times show which influence the Mediterranean air has in northeast Europe compared to the rather small influence in northwest Europe. Influences into the Red Sea and into North Africa can also be identified as well as influences of the Ahaggar mountains and the Tibesti mountains at the southern borders of the Sahara.

The 30-day residence times illustrate the position of the Mediterranean in the global circulation. The role of mountains and sea straits becomes nicely visible both in the boundary layer and the troposphere. Alps, Pyrenees, Atlas, Tibesti, Ahaggar, the Arabian and Anatolian plateau as well as the Himalayas and the Tibetan Plateau are clearly identifiable as regions of minima in the residence times. This is because the air patterns have a tendency to flow around them, resulting in higher wind velocities. Two main transport routes of Mediterranean air can be identified: one enhanced outflow direction through the Strait of Gibraltar and the Red Sea and one outflow pattern over Mesopotamia, a lowland between the high lands of Iran and Arabia. Another air stream for inflow as well as outflow, leads over the Dardanelles. Longer residence times can be found over the Western and Central Mediterranean, both in forward and backward transport, indicating an area of high recirculation tendencies. The forward residence times calculations clearly explain the transport of Mediterranean moisture and precipitation with the two outflow directions into the westerlies and into trade winds.

The evaluation of the residence times for the 90-days intervals (Fig. 12) shows very clearly the role of the Mediterranean in the global circulation, and confirms that it can be called a crossroad of air streams (Lelieveld et al., 2002). As a broad picture, the air enters the Mediterranean mainly from the Northwest, with a 90-day tropospheric source area consisting of Central and Western Europe and the North Atlantic. High-latitude regions including the Arctic also contribute to the airflow going into the Mediterranean. The outflow is split into two big flows with opposite direction. One follows the Silk Road through Central Asia north of the Tibetan Plateau to the Pacific coast. The other one leads over Northern Africa into the tropical Atlantic towards South America and the Caribbean. Arctic latitudes are very little influenced on this time scale.

3.4 Stagnation/Ventilation

Results of the 1-day and 5-day residence times have already shown a tendency towards stagnation and/or recirculation. 1-day stagnation evaluation (Fig. 13) shows that in winter a dominant streak with strong transport enters the Mediterranean at the gulf of Lyon, a consequence of large-scale channelling between the Alps and the Pyrenees. Interestingly, it continues through the strait between Tunisia and Sicily and then in weaker form passes south of Crete and reaches even the eastern end of the Mediterranean basin. In summer, the dominant region with low stagnation (i.e., strong displacements) is the Etesian region in the Aegean Sea. This flow continues over the whole Mediterranean basin into North Africa. Autumn and spring are a mixture of these two patterns, with much more stagnation over North Africa in autumn than in spring. Areas of stagnation are the Po basin, known to be an area with high air pollution (Dosio et al., 2002), the Gulf of Venice, the Atlas mountains, the Sicilian Sea and Turkey. In spring and autumn the regions of stagnation are distributed very similar with low transportation in the Balearic Sea and Adriatic Sea. Furthermore, one can identifiy the different topographic influences on the Mediterranean as the mistral in winter, spring and autumn, the etesians which are strongest in summer, and the Po basin in winter. 5-day stagnation results (Fig. 14) show that the region with strongest stagnation in

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summer is the western Mediterranean basin and the region around Cyprus, which is also present in the other three seasons. Strongest stagnation values for land masses can be found over Italy and the Iberian coast, especially the western Mediterranean shows strong stagnation tendencies in summer. In winter and autumn stagnation dominates in the easternmost part of the basin. A small, interesting spot of stagnation can be found in the southern Adriatic basin in spring.

4 Conclusions

Evaluations of the fate of Mediterranean atmospheric moisture and air have been carried out based on a Lagrangian transport data set generated with 1° operational ECMWF data and the Lagrangian particle dispersion model FLEXPART (Stohl et al., 2005). The period 27 October 1999–1 May 2005 has been investigated, a period containing on one hand two extreme events, the heavy Central European flooding event in 2002 and a drought event in 2003, and on the other hand has no extremes of climate modes such as ENSO or NAO. As mentioned previously the coarse resolution of the data set is not suitable to make single year or even one season analyses, therefore only averages over the full period have been analysed.

Results of the moisture and precipitation analyses show that the Mediterranean basin contributes to the whole northern hemisphere, although with a low fraction. Highest fraction of atmospheric moisture and precipitation can be found in the Mediterranean itself with a maximum in summer. Sub-basin analyses show that the western Mediterranean basin has its main influence on the European continent and the Alpine region, a conclusion also drawn by Sodemann and Zubler (2009). Influences of the eastern Mediterranean basin are mainly in the area of the Middle East and northern Africa. On a smaller scale as for the Adriatic basin or the Balearic basin relevance is mainly locally, although the Adriatic basin shows its relevance for the Balkan countries, Austria and the Po basin in northern Italy and the Balearic basin shows a significant contribution on the adjacent portion of Spain. An increase of the precipitation fraction can be

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found in autumn when higher SSTs influence the evaporation from the ocean reaching its maximum in November and December (Mariotti et al., 2002).

Residence time analyses, especially of the 30-day and 90-day residence times, show that the Mediterranean is a crossroad of air streams (Fig. 15) where the air arrives mainly from the Northwest and the flow is split into two major airstreams. The first one continues eastwards through Central Asia. The second one bends southwards into North Africa and continues towards southwest over the tropical Atlantic following the trade winds. The source regions for the Mediterranean indicate that the high-latitude regions over the North Atlantic and Canada contribute, while the outflow does not enter any high latitude regions within 90 days. This gives a climatological confirmation of the conclusion Lelieveld et al. (2002) have drawn from the mean air mass trajectories during their MINOS campaign in 2001.

Another interesting feature is the channelling by mountains and sea straits which is best visible in the 5-day and 30-day residence times with minima over the mountains and maxima along the straits, e.g., the strait of Gibraltar, the Red Sea and the Dardanelles. Another channelled outflow route is over Mesopotamia, a lowland between the highlands of Iran and Arabia. The Gulf of Lyon between the Pyrenees and the Alps is a preferred inflow channel. Longer residence times are found over the Western and Central Mediterranean than over the Eastern Mediterranean which is strongly influenced by the Etesian wind crossing the basin.

Stagnation results show a strong seasonal dependency. In winter and spring, the Po Basin, the Adriatic Sea and the region of Turkey-Cyprus show the strongest stagnation. In summer, also the Balearic region and the surrounding of the Italian peninsula have a tendency towards increased stagnation.

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References

Allwine, K. J. and Whiteman, C. D.: Single-station integral measures of atmospheric stagnation, recirculation and ventilation, Atmos. Environ., 28, 713–721, 1994. 21432

Alpert, P., Baldi, M., Ilani, R., Krichak, S., Price, C., Rodo, X., Saaroni, H., Ziv, B., Kishcha, P., Barkan, J., Mariotti, A., and Xoplaki, E.: Relations between Climate Variability in the Mediterranean Region and the Tropics: ENSO, South Asian and African Monsoons, Hurricanes and Saharan Dust, chap. 2, in: Mediterranean Climate Variability, 149–177, Elsevier, 2006. 21426

Bethoux, J. P. and Gentili, B.: Functioning of the Mediterranean Sea: Past and present changes related to freshwater input and climatic change, J. Marine Syst., 20, 33–47, 1999. 21427

Brubaker, K. L., Entekhabi, D., and Eagleson, P.: Estimation of continental crecipitation recycling, J. Climate, 6, 1077–1089, 1993. 21427

Dosio, A., Galmarini, S., and Graziani, G.: Simulation of the circulation and related photochemical ozone dispersion in the Po plains (northern Italy): Comparison with the observations of a measuring campaign, J. Geophys. Res., 107(D22), 8189, doi:10.1029/2000JD000046, 2002. 21440

Drobinski, P. and Ducrocq, V. (Eds.): HYMEX: White Book, http://www.cnrm.meteo.fr/hymex/, 2008. 21428

Drumond, A., Nieto, R., Gimeno, L., and Ambrizzi, T.: A Lagrangian identification of major sources of moisture over central Brazil and La Plata basin, J. Geophys. Res., 113, D14128, doi:10.1029/2007JD009547, 2008. 21429, 21432

Eckhardt, S., Stohl, A., Wernli, H., James, P., Forster, C., and Spichtinger, N.: A 15-year climatology of warm conveyor belts, J. Climate, 17, 218–237, 2004. 21427

Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling, Rev. Geophys., 34, 367–378, 1996. 21427

Eshel, G. and Farrel, B. F.: Mechanisms of Eastern Mediterranean rainfall variability, J. Atmos. Sci., 57, 3219–3232, 2000. 21427

Giorgi, F.: Climate change hot-spots, Geophys. Res. Lett., 33, L08707, doi:10.1029/2006GL025734, 2006. 21427

Hurrell, J.: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, Science, 269, 676–679, 1995. 21427

Hurrell, J. W.: Influence of variations in extratropical wintertime teleconnections on Northern

Hemisphere temperature, Geophys. Res. Lett., 23, 665–668, 1996. 21427
James, P., Stohl, A., Spichtinger, N., Eckhardt, S., and Forster, C.: Climatological aspects of the extreme European rainfall of August 2002 and a trajectory method for estimating the associated evaporative source regions, Nat. Hazards Earth Sys., 4, 733–746, 2004. 21432
Krichak, S. O. and Alpert, P.: Decadal trends in the east Atlantic-west Russia pattern and Mediterranean precipitation, Int. J. Climatol., 25, 183–192, 2005. 21427
Krichak, S. O., Kishcha, P., and Alpert, P.: Decadal trends of main Eurasian oscillations and the Eastern Mediterranean precipitation, Theor. Appl. Climatol., 72, 209–220, 2002. 21427
Lelieveld, J.: The Pyhsical Geography of the Mediterranean, chap. Air pollution and climate, 599–614, Oxford University Press, Oxford, 2009. 21427
Lelieveld, J., Berresheim, H., Borrmann, S., Crutzen, P. J., Dentener, F. J., Fischer, H., Feichter, J., Flatau, P. J., Heland, J., Holzinger, R., Korrmann, R., Lawrence, M. G., Levin, Z., Markowicz, K. M., Mihalopoulos, N., Minikin, A., Ramanathan, V., de Reus, M., Roelofs, G. J., Scheeren, H. A., Sciare, J., Schlager, H., Schultz, M., Siegmund, P., Steil, B., Stephanou, E. G., Stier, P., Traub, M., Warneke, C., Williams, J., and Ziereis, H.: Global Air Pollution Crossroads over the Mediterranean, Science, 298, 794–799, 2002. 21428, 21440, 21442
Lionello, P., Malanotte-Rizzoli, P., Alpert, P., Artale, V., Boscolo, R., Garcia-Herrera, R., Kull, C., Li, L., Luterbacher, J., Oguz, T., May, W., Planton, S., Rodo, X., Theocharis, A., Trigo, R., Tsimplis, M., and Ulbrich, U.: MEDCLIVAR: Mediterranean CLImate VARiability and predictability project, PAGES News/CLIVAR Exchanges. Joint Edition of the IGBP Past Global Changes Project (PAGES) News and the WCRP Climate Variability and Predictability Project (CLIVAR) Exchanges, 11(37), 3–5, 2006. 21428
Lolis, C. J., Metaxas, D. A., and Bartzokas, A.: On the intra-annual variability of atmospheric circulation in the Mediterranean region, Int. J. Climatol., 28, 1339–1355, 2008. 21426
Luterbacher, J. and Xoplaki, E.: 500-year Winter Temperature and Precipitation Variability over the Mediterranean area and its Connection to the Large-scale Atmospheric Circulation., chap. 4, in: Mediterranean Climate: Variability and Trends., 133–153, Springer Verlag, Berlin, New York, 2003. 21426
Mariotti, A., Struglia, M. V., Zeng, N., and Lau, K. M.: The hydrological cycle in the Mediterranean region and implications for the water budget of the Mediterranean Sea, J. Climate, 15, 1674–1690, 2002. 21429, 21442
Newell, R. E., Newell, N. E., Zhu, Y., and Scott, C.: Tropospheric rivers? A pilot study, Geophys.

Res. Lett., 19, 2401–2404, 1992. 21427

Nieto, R. and Gimeno, L.: Atmospheric transport towards the Iberian Peninsula in the 3- to 10-day range. Sources of middle-lived pollutants and aerosols., Scientific World Journal, 10, 1041–1047, 2006. 21428, 21432

Nieto, R., Gimeno, L., and Trigo, R.: A Lagrangian identification of major sources of Sahel moisture, Geophys. Res. Lett., 33, L18707, doi:10.1029/2006GL027232, 2006. 21429, 21432

Nieto, R., Gimeno, L., Gallego, D., and Trigo, R.: Identification of major sources of moisture and precipitation over Iceland, Meteorol. Z., 16, 37–44, 2007. 21429, 21432

Nieto, R., Gallego, D., Trigo, R., Ribera, P., and Gimeno, L.: Dynamic identification of moisture sources in the Orinoco Basin in Equatorial South America, Hydrolog. Sci. J., 53, 602–617, 2008a. 21429, 21432

Nieto, R., Trigo, R., and Gimeno, L.: Potential outflow pathways for Iberian atmospheric middle-lived pollution, Open Atmos. Sci. J., 2, 18–22, 2008b. 21428

Peixoto, J. P., de Almeida, M., Rosen, R. D., and Salstein, D. A.: Atmospheric moisture transport and the water balance of the Mediterranean Sea, Water Resour. Res., 18, 83–90, 1982. 21426

Rodo, X., Baert, E., and Comin, F. A.: Variations in seasonal rainfall in southern Europe during present century: Relationships with the North Atlantic Oscillation and the El Niño Southern Oscillation, Clim. Dynam., 13, 275–284, 1997. 21427

Sodemann, H.: Tropospheric transport of water vapour: Lagrangian and Eulerian perspectives, Ph.D. thesis, ETH Zurich, Logos Verlag, Berlin, 230 pp., ISBN 3-8325-1384-1, 2006. 21432

Sodemann, H. and Zubler, E.: Seasonality and inter-annual variability of the moisture sources for Alpine precipitation during 1995–2002, Int. J. Climatol., 10, 2009. 21427, 21435, 21438, 21441

Stohl, A.: Characteristics of atmospheric transport into the Arctic troposphere, J. Geophys., 111, D11306, doi:10.1029/2005JD006888, 2006. 21429, 21430

Stohl, A. and James, P.: A Lagrangian analysis of the atmospheric branch of the global water cycle: 1. Method description, validation, and demonstration for the flooding in Central Europe, J. Hydrometeor., 5, 656–678, 2004. 21428, 21432

Stohl, A. and James, P.: A Lagrangian analysis of the atmospheric branch of the global water cycle: 2. Earth's river catchments, ocean basins, and moisture transports between them, J. Hydrometeor., 6, 961–984, 2005. 21428, 21432

Stohl, A., Hittenberger, M., and Wotawa, G.: Validation of the Lagrangian particle dispersion model FLEXPART against large scale tracer experiments, Atmos. Environ., 32, 4245–4264, 1998. 21430

Stohl, A., Forster, C., Frank, A., Seibert, P., and Wotawa, G.: Technical Note: The Lagrangian particle dispersion model FLEXPART version 6.2., Atmos. Chem. Phys., 5, 2461–2474, 2005, http://www.atmos-chem-phys.net/5/2461/2005/. 21430, 21441

Trenberth, K. E.: Atmospheric Moisture Recycling: Role of Advection and Local Evaporation, J. Climate, 12, 1368–1381, 1999. 21428

Van Bebber, W.: Die Zugstraßen der barometrischen Minima nach den Bahnenkarten Deutschen Seewarte für den Zeitraum von 1875–1890 , Meteorol. Z., 8, 361–366, 1891. 21437

Ward, M. N.: Diagnosis and short-lead predictions of summer rainfall in tropical North Africa at interannual and multidecadal timescales, J. Climate, 11, 3167–3191, 1998. 21427

Weaver, A. J., Bitz, C. M., Fanning, A. F., and Holland, M. M.: Thermohaline circulation: High-latitude phenomena and the difference between the Pacific and Atlantic, Annu. Rev. Earth Pl. Sc., 27, 231–285, 1999. 21427

Xoplaki, E., González-Rouco, J. F., Luterbacher, J., and Wanner, H.: Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs, Clim. Dynam., 20, 723–739, 2003. 21426

Zhu, Y. and Newell, R. E.: A Proposed Algorithm for Moisture Fluxes from Atmospheric Rivers, Mon. Weather Rev., 126, 725–735, 1998. 21427

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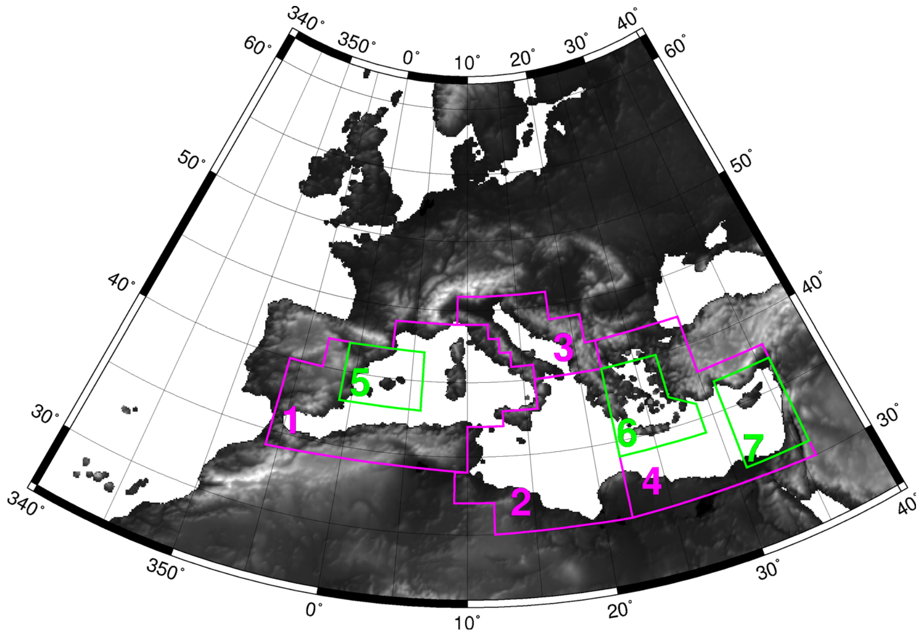

Fig. 1. Definition of the Mediterreanean basin and the seven sub-basins. (1) Western Mediterranean, (2) Central Mediterranean, (3) Adriatic Sea, (4) Eastern Mediterranean in magenta as they can be seen as natural boundaries, and (5) the Balearics, (6) the Etesian basin, and (7) the Cyprus basin in green as small, wind-influenced basins.

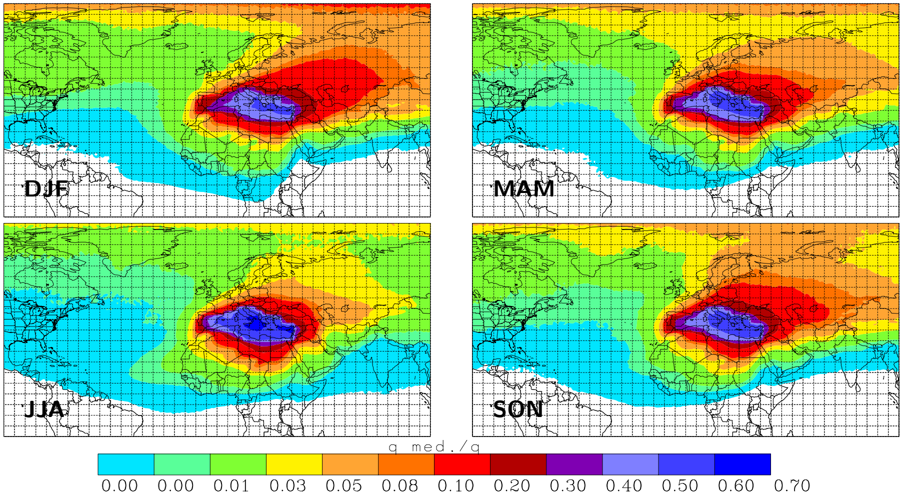

Fig. 2. Seasonal averages of the mixing ratio of the Mediterranean moisture to non-Mediterranean moisture for the Mediterranean basin as a whole on a horizontal grid of 1°×1° (lat-lon lines on the map are 5°).

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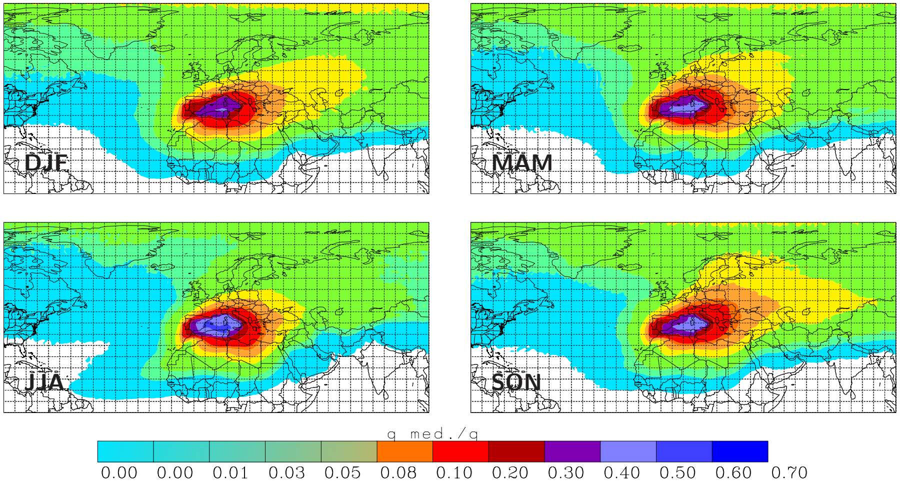

Fig. 3. Same as Fig. 2 (moisture ratio) but for the western Mediterranean basin.

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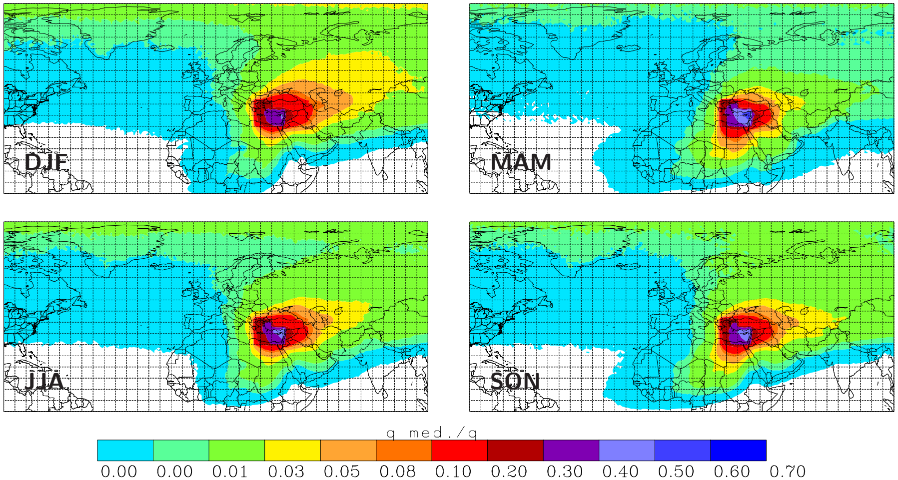

Fig. 4. Same as Fig. 2 (moisture ratio) but for the eastern Mediterranean basin.

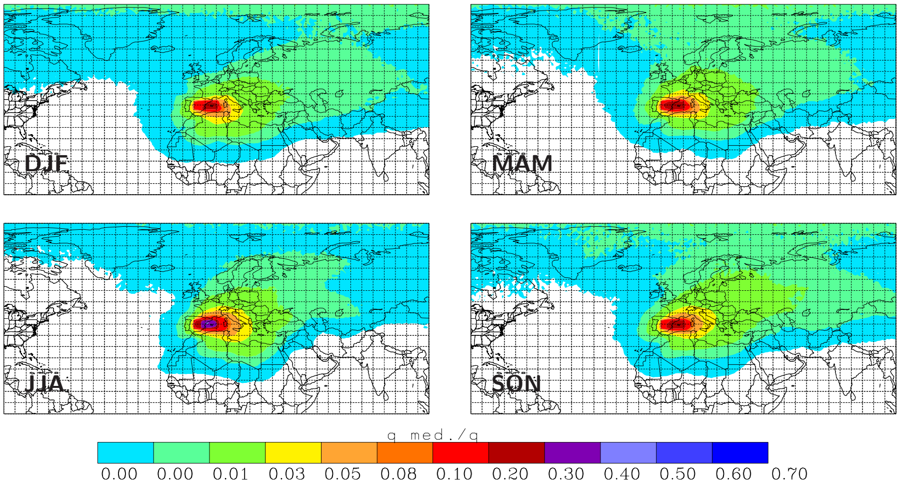

Fig. 5. Same as Fig. 2 (moisture ratio) but for the Balearic basin.

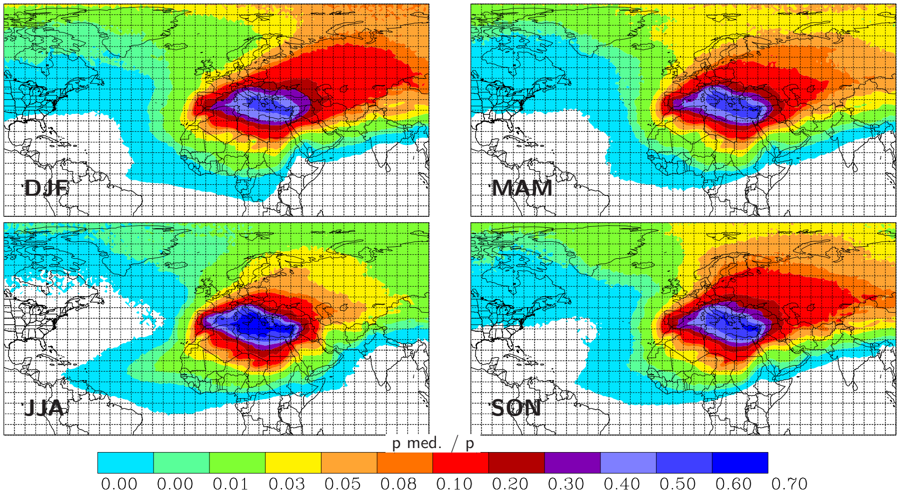

Fig. 6. Fraction of precipitated water that evaporated inside the Mediterranean basin.

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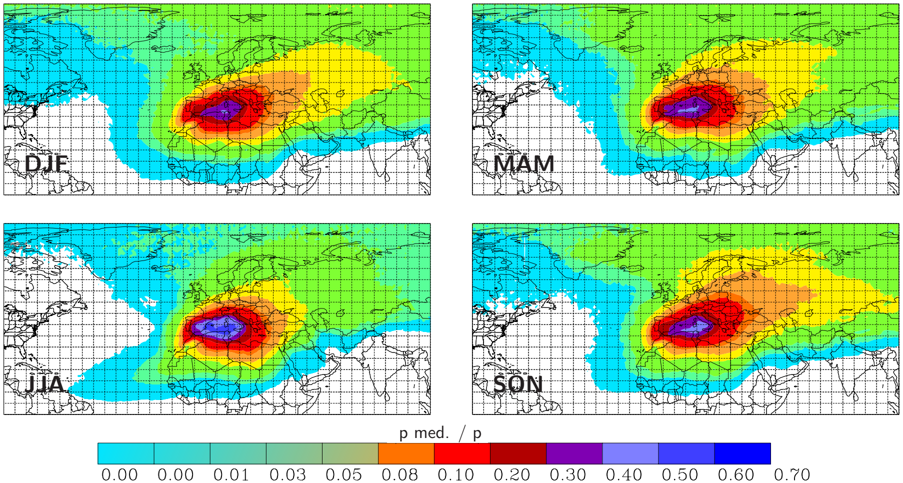

Fig. 7. Same as Fig. 6 (precipitation fraction) but for the western Mediterranean basin.

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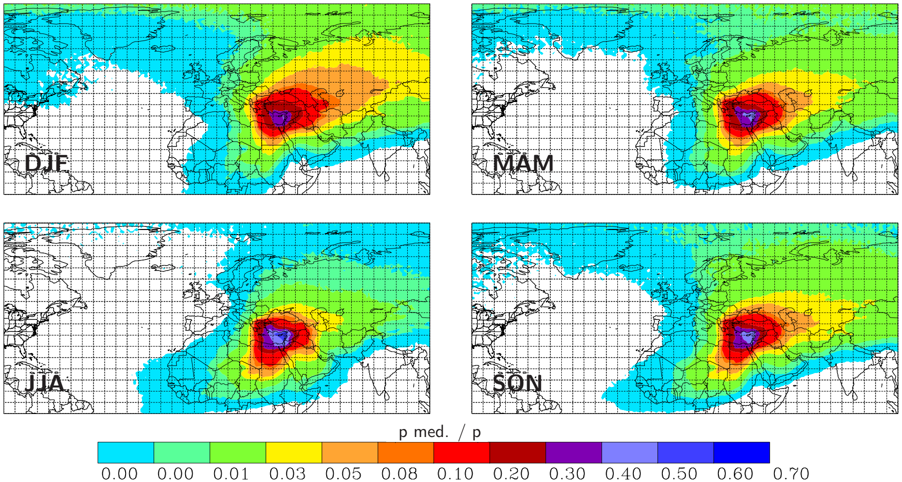

Fig. 8. Same as Fig. 6 (precipitation fraction) but for the eastern Mediterranean basin.

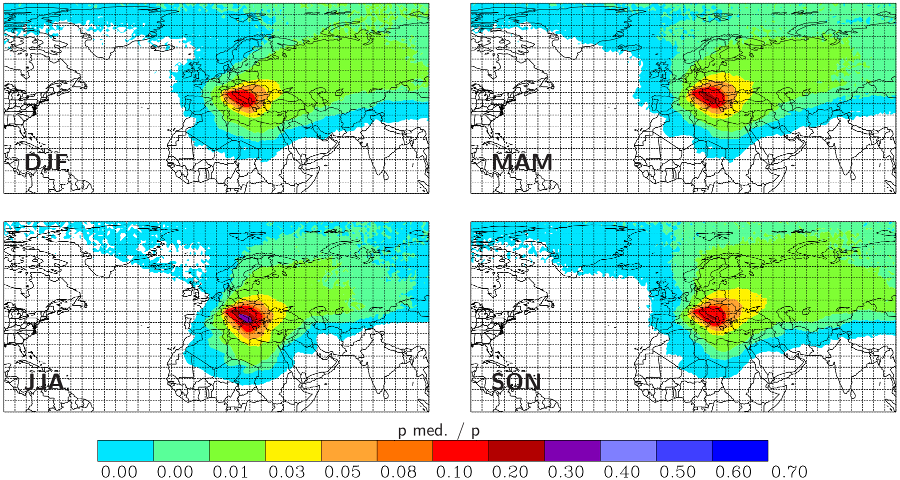

Fig. 9. Same as Fig. 6 (precipitation fraction) but for the Adriatic basin.

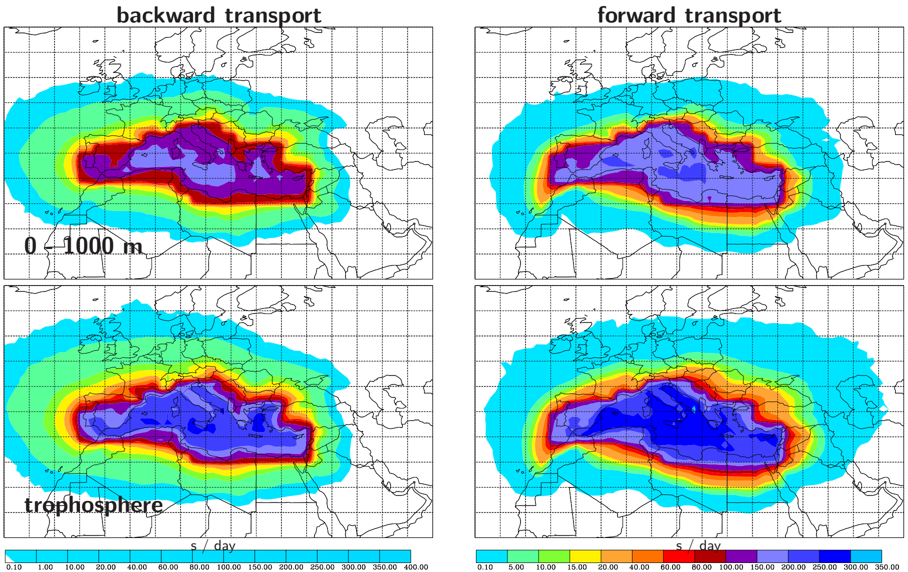

Fig. 10. One-day residence times in s/d for the Mediterranean basin calculated for the lowest layer, 0–1000 m (left), and the whole troposphere (right) in forward mode.

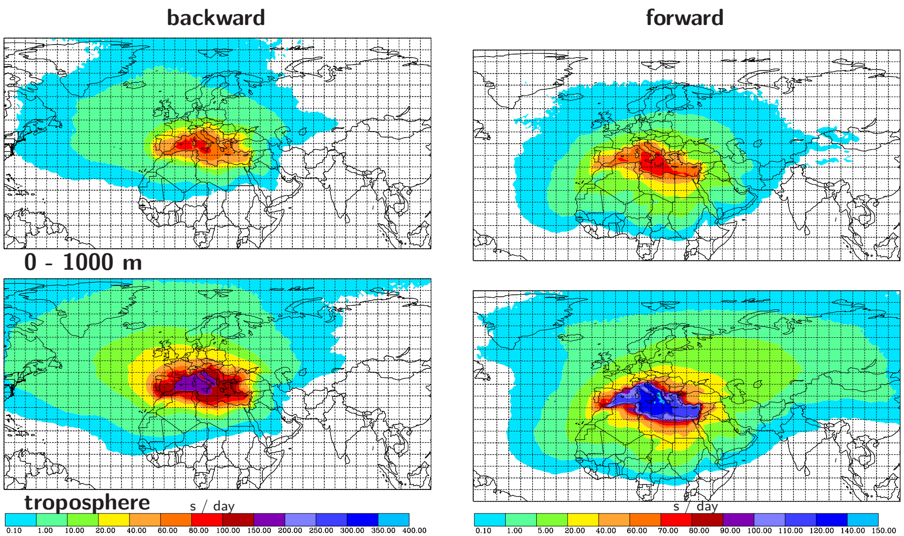

Fig. 11. Five-day residence times.

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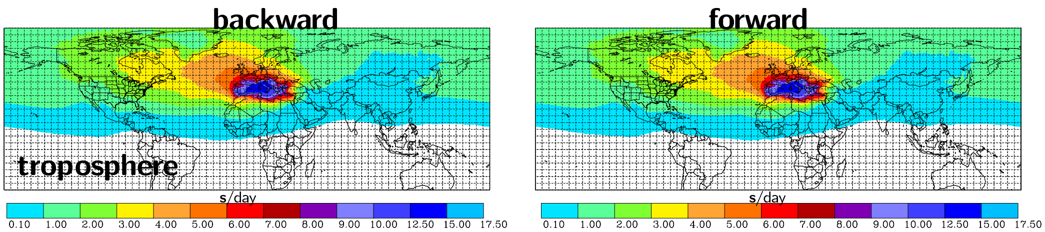

Fig. 12. 90-day residence times.

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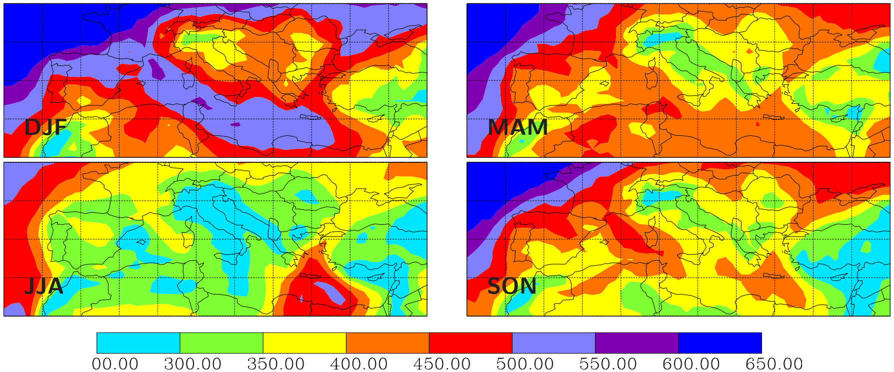

Fig. 13. Seasonally averagered one-day stagnation/ventilation results in the Mediterranean basin, units of km (small values indicate strong stagnation).

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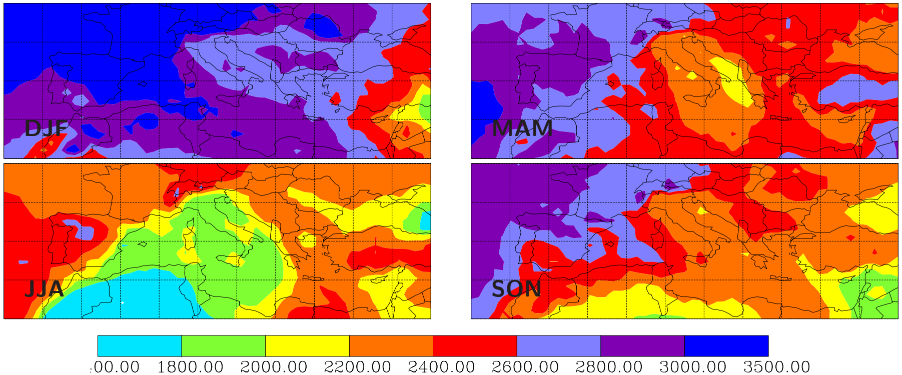

Fig. 14. As Fig. 13 but for five day stagnation/ventilation.

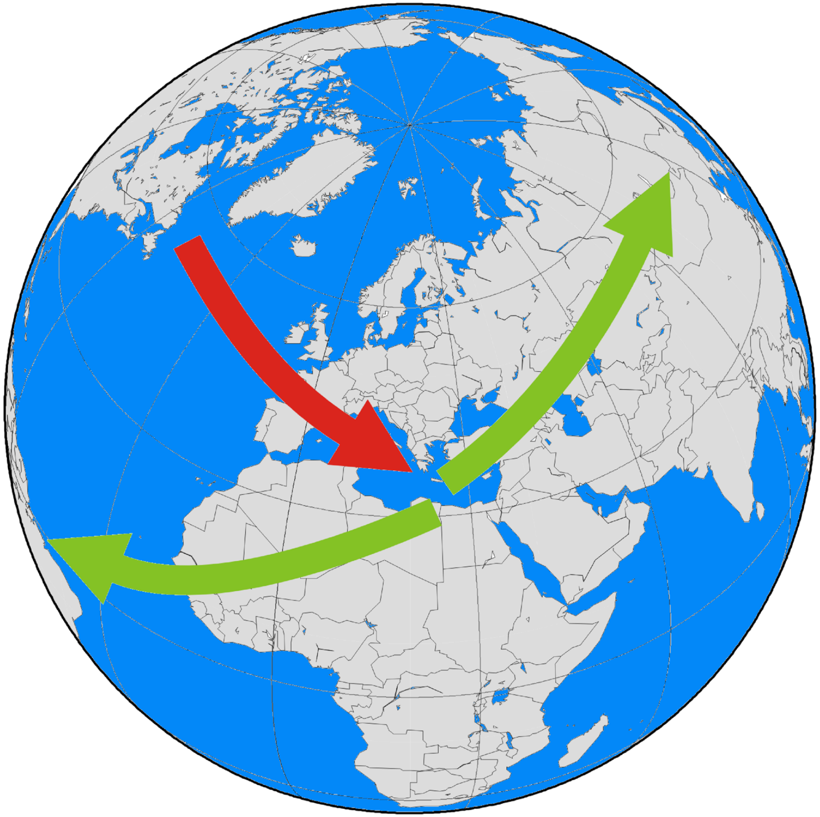

Fig. 15. Air flow crossroads over the Mediterranean basin, red the incoming air, in green the two main outflow patterns.

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